Mapping the geothermal potential of Cenozoic aquifers in Gippsland, Victoria

C.D. O'Neill, M.J. Hocking, and C.P. Riley

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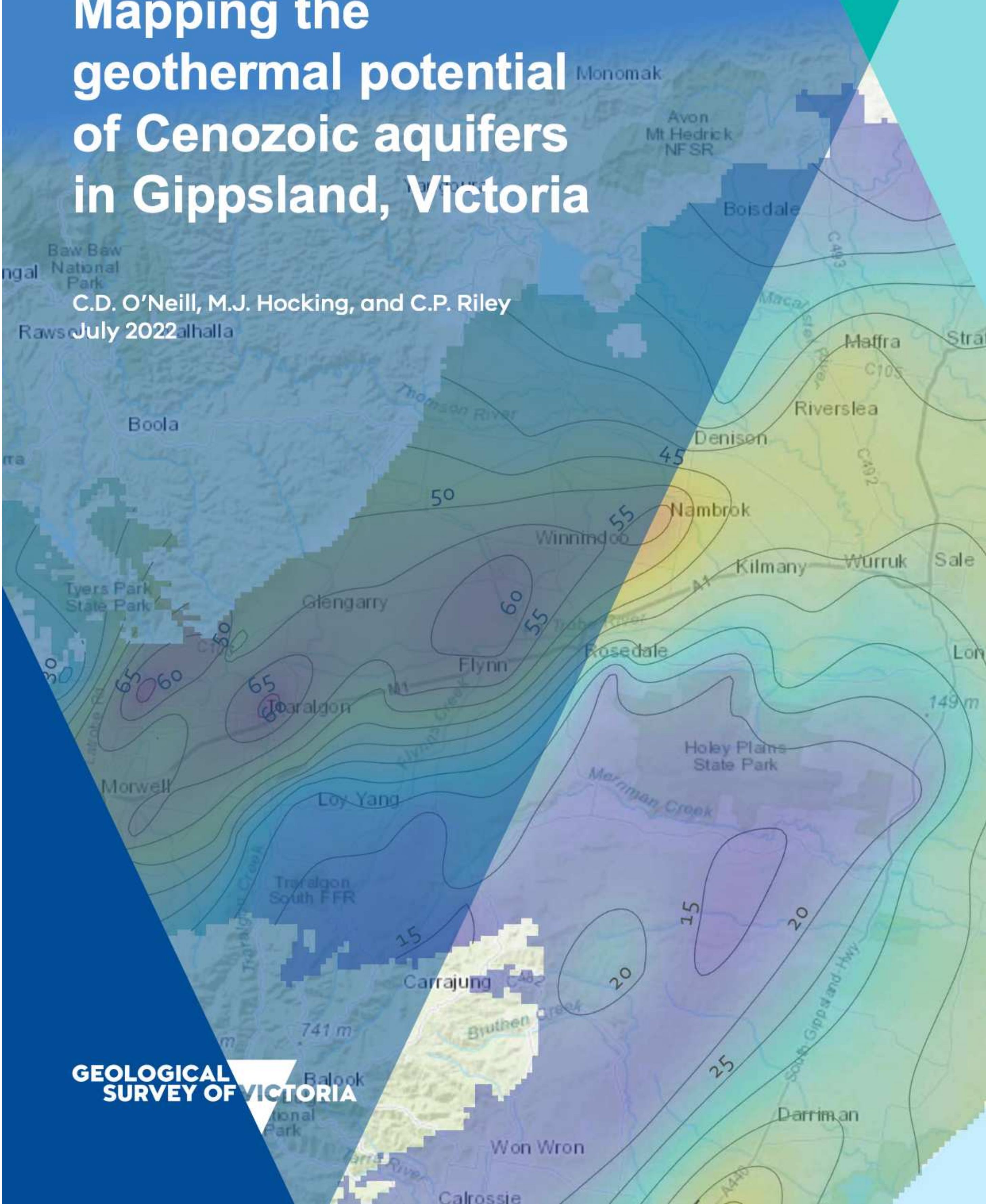

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About the Geological Survey of Victoria
The Geological Survey of Victoria (GSV) is the Victorian Government's geoscience agency and sits within the Department of Jobs, Precincts and Regions. GSV provides evidence-based knowledge and information to Government, industry, academia, and the community, on Victoria's earth resources, using the latest geoscience technologies and methods. For more details visit earthresources.vic.gov.au/gsv

Cover picture
Temperature map of Lower Tertiary Aquifer.

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Summary

Geothermal energy is used around the world for direct heating of buildings, greenhouses, aquaculture ponds and swimming pools, and in industrial processes. The Gippsland Smart Specialisation Strategy (GS3) identified direct use geothermal energy as a potential competitive advantage to help with the economic transition away from fossil fuel power generation in the Latrobe Valley (The University of Melbourne, 2021). Direct use geothermal can replace gas in many heating applications, reducing CO_2 emissions and costs. As part of the Geothermal Innovation Group of GS3, the Geological Survey of Victoria (GSV) has collaborated with the University of Melbourne (UoM) to deliver the preliminary geological mapping necessary to establish an online geothermal investigation tool.

This report presents geological datasets that underpin assessments of geothermal energy potential across Gippsland. It details the collection of new geothermal data, the collation of historical geothermal data, and the methods used to create maps of aquifer temperature and geothermal gradient (the rate at which temperature increases with depth). The data are intended to support a future on-line geospatial cost-benefit tool that will allow landowners or other stakeholders to investigate the temperature and depth of underlying geothermal aquifers and to view examples and cost estimates of potential uses.

This study is intended to reduce the geological uncertainty, and thereby the risk, for uptake of direct use geothermal energy in Gippsland by mapping the temperature of aquifers alongside other properties including depth, thickness, water quality and transmissivity. The study builds on previous work by King et al. (1987), Driscoll (2006), and Taylor & Mather (2015), combining knowledge from a diverse range of studies including heat flow modelling (Taylor & Mather, 2015), groundwater modelling (Hocking et al., 2020), the Victorian Aquifer Framework (GHD, 2012 & SKM, 2009), previously unpublished and newly collected geothermal data.

Twenty-six new precision borehole temperature logs were collected throughout Gippsland as part of this project, increasing the total number of precision temperature logs in the region to 60. These continuous temperature profiles have resulted in accurate definition of aquifer temperatures and calculation of geothermal gradients. In addition, historical temperature measurements from known depths were attributed to specific aquifers and corrected to a top of aquifer equivalent. Temperature data from petroleum wells were also assessed and included in the database, where appropriate, to increase knowledge of aquifer temperatures at locations and depths inaccessible for present day temperature logging.

New maps were produced detailing the temperature, geothermal gradient, depth to the top of aquifers, transmissivity and groundwater quality (dissolved solids) of the Gippsland region. The study confirms that the Lower Tertiary Aquifer is the largest and most prospective of the geothermal aquifers in Gippsland, with a maximum observed temperature commonly exceeding 60°C from a depth of 600 m in the Latrobe Valley and 1000 m in the Lake Wellington Depression. Prospectivity for direct use geothermal energy is highest within the Latrobe Valley between Morwell and Sale, and parallel to Ninety Mile Beach between Lake Wellington and Metung. Prospectivity also appears relatively high near Seaspray and east of Yarram.

The cause of the elevated aquifer temperatures appears to be associated with regionally extensive, thick, thermally insulating formations which decrease the slow outward conduction of the Earth's internal heat, resulting in a build-up of 'trapped' heat. Brown coal acts as the thermal insulator beneath the Latrobe Valley and around Yarram, whereas thick limestone sequences act as the insulator between Lake Wellington and Metung. The potential for hot upwelling groundwater along major faults, and its impact on local aquifer temperatures, remains unconfirmed.

1. Introduction

Geothermal energy from hot aquifers is used around the world for direct heating of buildings, greenhouses, aquaculture ponds and swimming pools, and in industrial processes (Figure 1.1). Direct use of geothermal energy can replace gas in many of these heating applications, reducing CO_2 emissions and costs. Hot groundwater was recognised (and occasionally used) as an energy resource in the Latrobe Valley before aquifer dewatering for coal mining began in the 1960s. Despite this, there has been no previous consolidated attempt to map the geothermal resource. Over the past 50 years, coal mine dewatering has removed approximately 1,300 GL of hot (40 – 60°C) groundwater from Latrobe Valley aquifers (Hocking et al,. (2020). There has been no systematic review of long-term pumping records to confirm whether sustained production has impacted groundwater temperatures.

The Gippsland Smart Specialisation Strategy (GS3), managed by the Latrobe Valley Authority, has identified direct use of geothermal energy as a potential competitive advantage to help Gippsland navigate an economic transition away from a focus on coal-fired power generation in the Latrobe Valley. As part of the Geothermal Innovation Group of GS3, the Geological Survey of Victoria (GSV) collaborated with the University of Melbourne (UoM) to compile relevant geological information to support a future on-line geospatial cost-benefit tool that will allow stakeholders to investigate the temperature and depth of underlying geothermal aquifers and to view examples and cost estimates of potential uses for the geothermal energy from aquifers.

Several past assessments of the geothermal potential of Gippsland have focussed on the potential for electrical power generation (e.g. Driscoll, 2006). Others, however, identified direct use of geothermal energy as having broad regional relevance and promising economics (e.g. King et al., 1987). No previous study has produced maps of aquifer temperature along with other relevant aquifer characteristics. This study focused on mapping aquifer hosted geothermal resources appropriate for direct use developments. The report details the development of data layers to underpin a future online geospatial mapping tool for interrogating geothermal cost and ideal use at point locations in Gippsland. The online map-based tool will allow a 'click' on a specific location to return estimates of aquifer temperatures and other properties, potential beneficial uses for the geothermal energy, and estimated levelised cost of energy.

In 2005, the State of Victoria passed the *Geothermal Energy Resources* Act (GER Act), which provides a framework for the large-scale commercial exploration and extraction of geothermal energy in Victoria at depths greater than 1000 m, and at temperatures greater than 70°C. Small-scale projects such as geothermal hot springs, ground source heat pumps and aquaculture are regulated under planning, environmental and water legislation.

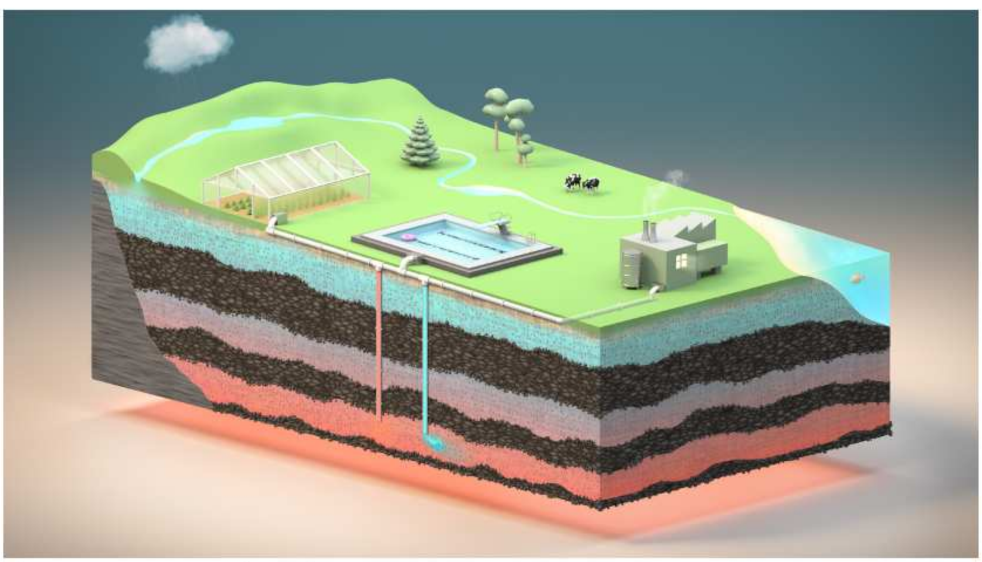

Figure 1.1 Direct-use geothermal energy.

1.1. Project objectives

There are several areas of uncertainty around the geothermal energy potential of Cenozoic aged aquifers in Gippsland, many of which can be addressed through consolidation, augmentation and interpretation of existing data and the collection of new data to fill gaps. The objective of this project was to deliver reliable data layers to support a future online geospatial cost and beneficial use tool. The specific data layers include:

1. Maps of aquifer temperature
2. Maps of aquifer depth
3. Maps of aquifer thickness
4. Hydraulic conductivity of aquifers and aquitards
5. A database of newly acquired and historically relevant borehole temperature records.

1.2. The Gippsland Smart Specialisation (GS3) Strategy

The Smart Specialisation Strategy is a methodology developed by the European Union that is a place-based innovation concept where regions identify their strongest research, innovation and entrepreneurial assets to prioritise where they can build critical mass in areas of comparative advantage (Interreg Europe, 2021). This methodology is being applied in the Gippsland region and is known as the Gippsland Smart Specialisation (GS3) Strategy. The Geothermal Innovation Group of GS3 established the project as a collaboration between the Geological Survey of Victoria (GSV) and the University of Melbourne (UoM) to deliver foundation elements for an online mapping and economic analysis tool. The project involved two parallel programs of 'below ground' and 'above ground' studies. To provide context for the tasks undertaken by the GSV, the overall project is summarised below.

The hydro geoscience team of the GSV led the 'below ground' tasks that included:

- Collate archival data for the Latrobe Valley/Gippsland, including data from previous geothermal investigations, historical production records from Hazelwood mine dewatering bores, plus any additional data sources uncovered during the review.
- Map the temperature, geothermal gradient, hydraulic conductivity, thickness, and water quality of aquifers in Gippsland by integrating borehole temperature data with the Victorian Aquifer Framework and hydraulic properties from groundwater modelling.
- Log additional bores to improve data spatial resolution.

UoM led the 'above ground' tasks that included:

- Develop an algorithm to predict sustainable thermal power relative to mean surface air temperature as a function of location, depth, temperature, and production lifetime.
- Consult with drilling companies to develop a generalised drilling cost model for the Latrobe Valley / Gippsland as a function of location, depth, temperature, production rate and project lifetime.
- Construct energy demand curves for a series of standard end uses (e.g. greenhouses, barramundi farms, spa resorts, district heating) in consultation with existing and potential operators.
- Identify system components other than boreholes and heat exchangers required for geothermal projects (e.g. borehole pumps, heat pumps, condensers).
- Build 'levelised cost of geothermal energy' algorithms applicable for end uses.

The study was a collaboration between GSV and UoM with direct input from Southern Rural Water, the Department of Environment, Land, Water and Planning (DELWP), local drilling contractors, Latrobe City Council, the Latrobe Valley Community Power Hub, and other Geothermal Innovation Group members. The Earth Resources team within the Department of Jobs, Precincts and Regions (DJPR) holds data related to geology, coal, and geothermal energy resources, while the Office of Water within DELWP holds data related to Victorian aquifers.

1.3. Geothermal energy

Geothermal energy is recoverable thermal energy (heat) contained within accessible portions of the Earth's crust. About half of the heat in the Earth's interior can be attributed to primordial planetary accretion, with the remainder generated by the radioactive decay of naturally occurring potassium, thorium, and uranium isotopes (e.g. Beardsmore & Cull, 2001). Geothermal energy resources are unevenly distributed. The temperature of the earth generally increases with depth. However, the geothermal gradient can vary significantly from the average due to differing geological conditions. Recoverability of the resource is also closely tied to geological conditions.

Economic prospectivity for geothermal energy is generally greatest where thermal gradients are highest, resulting in lower drilling costs to access and produce the heat (Driscoll, 2006). High thermal gradients may result from young magmatic bodies, areas of crustal thinning, the presence of rocks enriched in radioactive isotopes, or the trapping of heat by thick thermally insulating rocks (Rawling et al., 2013). Groundwater can also efficiently transfer heat from deeper to shallower levels by convection, while aquifers that are confined by impermeable layers inhibit hot water from migrating and dispersing to shallower aquifers. The confined hot water may be extracted via drilled wells, from which the quantity of produced geothermal energy is proportional to the production temperature and volume.

Hot sedimentary aquifers are typically hosted within the sediments and groundwater present within sedimentary basins. The heat is derived from processes deeper within the earth. As this heat travels towards the earth's surface, it can be trapped within the sedimentary aquifers by thick layers of insulating rock. Heat is extracted by pumping the geothermally heated groundwater from the naturally hot sedimentary aquifers. Groundwater can be recycled back into the aquifer via reinjection, minimising the impacts on groundwater availability. Sedimentary basins such as the Gippsland Basin and Otway Basin have potential to host hot sedimentary aquifers.

Geothermal energy can be used directly as heat in a range of heat intensive operations such as water heating for swimming pools and aquaculture, space heating for buildings and horticulture and process heating for food production and industry. Relevant temperatures for specific industries are outlined in Figure 1.2 (GNS Science, 2021). These uses are grouped under the common term of 'direct use'.

This study aims to reduce the risk of uptake of low temperature (<100 °C) geothermal resources in Gippsland by reducing the uncertainty of aquifer temperatures. Direct use applications extract heat directly from pumped groundwater for immediate use. Such applications of geothermal energy are attractive for uses that require constant heat over long periods of time (King et al., 1987). Electricity production, either by producing steam or organic Rankine cycle' binary technology requires temperatures higher than 100 °C and are not the focus of this study.

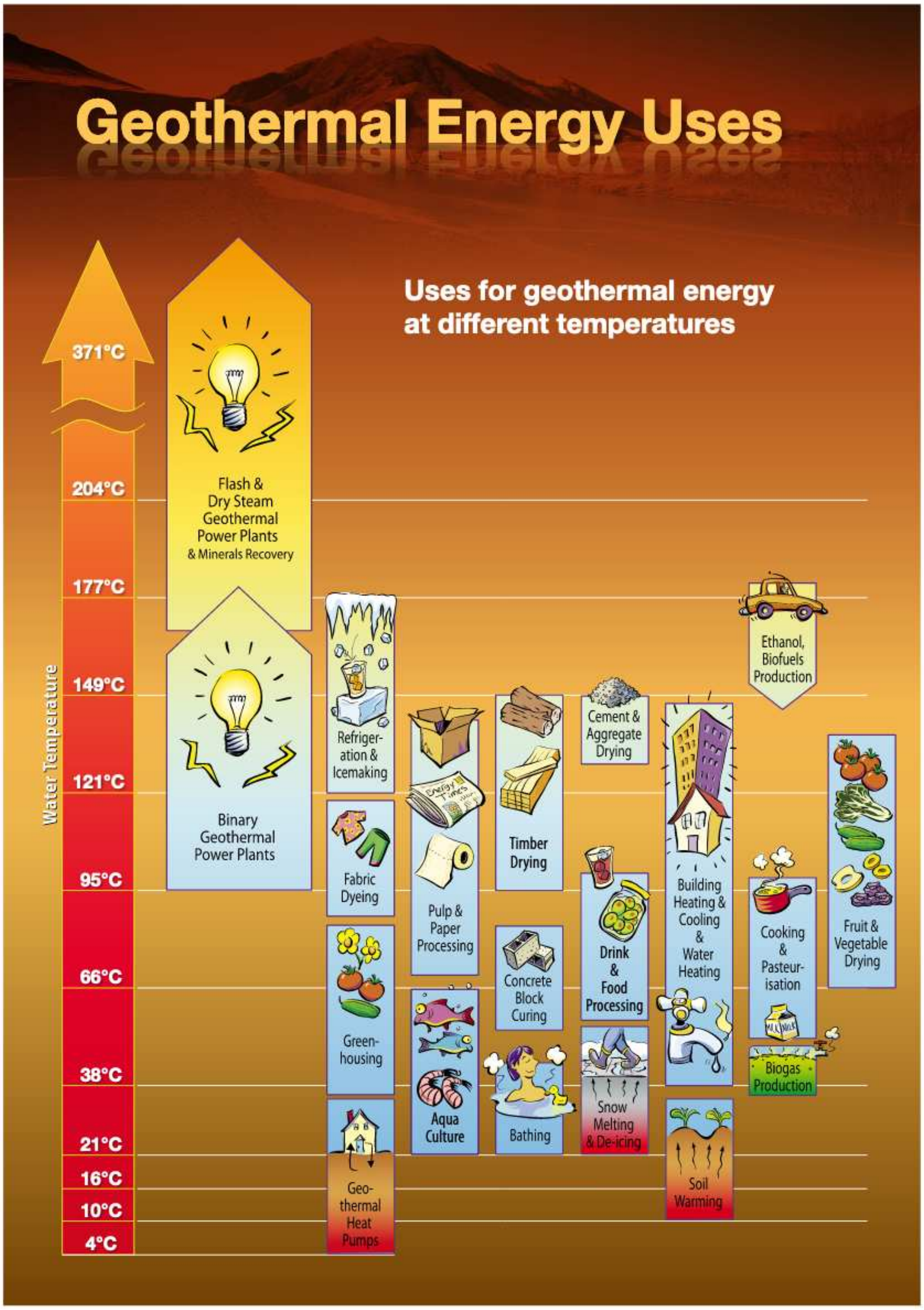

Figure 1.2 Geothermal energy uses (GNS Science, 2021).

1.4. Study area

The study area includes the portion of the onshore Gippsland Basin where Cenozoic sediments are present in the subsurface (Figure 1.3). The area is bound to the north by the Great Dividing Range, to the west by the Strzelecki Ranges, to the east by the Cann River and to the south by Ninety-Mile Beach and Wilsons Promontory. The study area spans approximately 230 km east to west and 100 km north to south and covers an area of approximately 8,000 km^2.

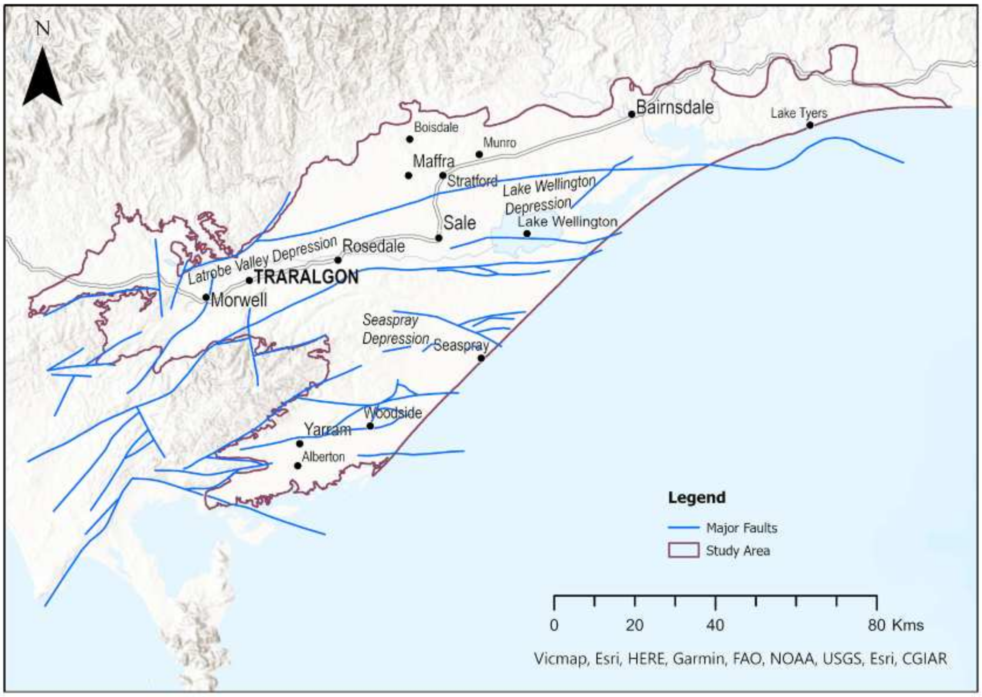

Figure 1.3 Area mapped for geothermal aquifers.

1.5. Geology

The Gippsland Basin consists of a thick sequence of sedimentary and volcanic rocks deposited on older Palaeozoic basement. The basin contains oil, gas, brown coal, geothermal heat, groundwater resources and carbon dioxide storage potential. The geological knowledge of the Gippsland Basin is extensive due to the continuous exploration for these resources in the basin for more than 100 years. Since early exploration in the 1920s, thousands of wells have been drilled, surface geological surveys conducted, and geophysical investigations completed.

This study is concentrated on the aquifer bearing Cenozoic sediments in the Gippsland region between the Latrobe Valley and Marlo. The depth of interest ranges between 50 m and 1000 m beneath brown coal deposits and limestones. These sequences are thermal insulators which decrease the outward heat flow resulting in local accumulations of the Earth's internal heat. This heat can be accessed by pumping groundwater from the aquifers beneath the insulating layers. The distribution of the coal is extensively modelled (Jansen et al., 2003), and the groundwater system is generally well understood (GHD, 2012 & SKM, 2009).

1.6. Hydrostratigraphy

Groundwater abstraction is fundamental to the direct use of geothermal energy, so it is useful to consider geothermal energy within a groundwater management framework. In Gippsland, the distribution of groundwater systems is defined by the Victorian Aquifer Framework (VAF) (GHD, 2012 & SKM, 2009). The VAF provides a consistent terminology for groundwater resource description and investigation. Aquifer and aquitard names referenced in this study are defined by the VAF and listed in Table 1.1. The naming convention associated with these aquifers relates to their age within the Tertiary geologic time-period. The Tertiary period nomenclature is now superseded by the Neogene and Paleogene time periods. To aid with cross referencing, the original 'Tertiary' naming convention is retained in this publication but should be regarded as a naming reference rather than an indication of geological age. The VAF provided the framework for associate groundwater parameters such as temperature, geothermal gradient, hydraulic conductivity, depth, and thickness.

Table 1.1 The Victorian Aquifer Framework hydrostratigraphy for the Gippsland Basin.

Aquifer/aquitard	Hydrogeological units	Lithology
Upper Tertiary Quaternary Aquifer (UTQA)	Haunted Hill Formation, Eagle Point Sand.	Sand
Upper Tertiary Quaternary Aquitard (UTQD)	Boisdale Formation (Nuntin Clay)	Clay
Upper Tertiary Aquifer Fluvial (UTAF)	Boisdale Formation (Wurruk Sand)	Sand
Upper Tertiary Aquitard (UTD)	Hazelwood Formation, Yallourn Formation, Jemmys Point Formation, Sale Group	Coal
Upper mid-Tertiary Aquifer (UMTA)	Alberton Formation, Balook Formation, Cobia Subgroup, Gurnard Formation, Morwell Formation, Morwell M1-2 aquifers, Turrum Formation, Yarragon Formation	Coal/sand
Upper mid-Tertiary Aquitard (UMTD)	Giffard Sandstone Member, Gippsland Limestone, Lakes Entrance Formation, Seaspray Group, Tambo River Formation	Limestone
Lower mid-Tertiary Aquifer (LMTA)	Morwell 2 Coal Seam aquifer – (Rosedale, Lake Wellington Depression, Seaspray Depression, Traralgon Syncline) and Seaspray Group sands	Coal/sand
Lower Tertiary Aquifer (LTA)	Burong Formation, Childers Formation, Honeysuckle gravels, Latrobe Group, (Morwell 2 Coal Seam aquifer – when basal aquifer), Traralgon seams and aquifers, Yarram Formation	Sand/coal

1.7. Previous geothermal studies

The geothermal potential of the Gippsland region has been recognised and investigated by numerous workers since the 1970s (Thompson, 1975, 1979, 1982; Akbarzadeh & Thompson, 1984; Leonard & King 1992; King et al., 1987; Driscoll, 2006; Harrison, 2015; Taylor & Mather 2015). Their work focused on both the shallow (<1000 m) low temperature (30 - 70 °C) resource and the deeper (>1000 m) high temperature resource (>100 °C).

In the 1970s, hot groundwater was observed in coal exploration bores throughout Gippsland (Thompson 1975, 1979, 1982). Temperatures were systematically measured in observation and dewatering bores associated with the Latrobe Valley coal mines (Nahm & Reid, 1979) and the cause of the heat was debated (Thompson, 1979). A state-wide program investigating the potential for geothermal energy promoted the development of low temperature geothermal energy projects in the Latrobe Valley (Akbarzadeh & Thompson, 1984; King et al., 1987). Geothermal gradients were estimated by Cull & Beardsmore (1992) using assumed thermal rock properties and bottom of hole temperatures.

Various mechanisms have been suggested to explain anomalous geothermal heat throughout Gippsland. Thompson (1979) suggested the insulating properties of the coal seams along with intermixing of groundwaters by faulting in the Morwell area. This was supported by Driscoll (2006) who noted the insulating effect of coal in the Latrobe Valley. However, the lack of coal at Bairnsdale rules out coals as the primary cause of the high aquifer temperatures in that location.

To encourage private sector investment in developing deeper, hotter geothermal resources, Driscoll (2006) compiled state-wide data and produced a map predicting the depth to 150°C. This map was based on historical borehole temperature measurements, which frequently underestimated the true temperature. To address this, the Victorian Government, in collaboration with other agencies and student researchers (such as Taylor & Mather, 2015), undertook precision borehole temperature logging and core sampling across the state as part of the Geothermal Atlas Project in the early 2010s to build a robust temperature database. Geothermal gradient was calculated for each bore, which, when coupled with rock thermal properties, resulted in a calculation of heat flow, more accurate geothermal models, and an improvement in the depth to 150°C map (Taylor & Mather, 2015).

Thompson (1979) suggested that the hot groundwater within Gippsland is confined to an east - west band around 10 km wide that runs from the Latrobe Valley to the coast with additional pockets of geothermal water intersected at Gelliondale and Bairnsdale. Nahm & Reid (1979) supported the interpretation and hypothesised that the Rosedale Monocline divides the Gippsland Basin into a warmer section to the north and a cooler section to the south. King et al. (1987) also supported such a hypothesis and reported that hot groundwater between 30 - 80°C is present in the Latrobe Valley and parts of coastal Gippsland but that the hottest water is found in the Latrobe Valley and Lake Wellington Depression. Driscoll (2006) identified high geothermal gradients in the Latrobe Valley, Gelliondale, and Bairnsdale areas. Deep precision temperature logs collected by Taylor & Mather (2015) suggest that the geothermal gradient reverts to 'normal' within the Strzelecki Group beneath the Latrobe Valley. This supports the hypothesis that increased aquifer temperatures within the Latrobe Valley are related to the insulation provided by the coal, not an elevated crustal heat source.

The earliest temperature data were collected in Gippsland to facilitate temperature correction of hydrographs to produce accurate potentiometric groundwater surfaces (Nahm & Reid, 1979). Subsequent data collection targeted the potential for direct heat applications such as heating for buildings, swimming pools, agriculture, aquaculture, and industrial processes (Thompson, 1979; King et al., 1987; Leonard & King, 1992). King et al. (1987) disregarded higher temperature, deeper geothermal resources that could be utilised for electricity generation, deeming them uneconomic at the time. More recent assessments by Driscoll (2006) and Taylor & Mather (2015) suggested locations where the economics of geothermal power generation might warrant re-evaluation.

Parallel programs of temperature logging were carried out by Harrison (2015), Taylor & Mather (2015) and Antriasian et al. (2015) throughout the Gippsland Basin and Victoria. Precision borehole temperature logs were collected to ascertain crustal heat flow and to estimate the depth to 150°C. Forty of these temperature logs fall within the bounds of the current study area and were integrated into new maps of aquifer temperature.

2. Precision borehole temperature logs

2.1. Introduction

Precision temperature logs provide detailed and accurate continuous (with depth) temperature data for the subsurface. These temperature measurements enable the creation of temperature profiles of the groundwater system, which help to understand and predict which aquifers are hot and why. The prospectivity of a geothermal aquifer can be assessed by integrating these temperature measurements with hydrogeological information such as depth, aquifer thickness and hydraulic conductivity. Geothermal gradients can be calculated for aquifers and aquitards from precision temperature logs, which, in turn help us to identify geothermal opportunities in new areas.

New precision temperature logs were collected as part of this study to infill previously acquired data sets. Together these were used to develop maps of aquifer temperature and geothermal gradient. The new temperature logs improved the spatial density of borehole temperature measurements throughout Gippsland and helped to:

- Define aquifer temperatures for mapping,
- Define geothermal gradients of individual aquifers and aquitards,
- Appraise the likely source of elevated aquifer temperatures,
- Improve the understanding of the temperatures of deeper (500 m – 1000 m) aquifers.

Acquisition of new precision temperature logs was restricted to open boreholes with a strong reliance on the state groundwater monitoring network (SOBN). In total 26 new precision temperature logs were collected throughout Gippsland between 2019 and 2020, with an emphasis on the areas around the Latrobe Valley, Lake Wellington, Seaspray, and Alberton. Data remains sparse near the coast east of Lake Wellington. Logged bores (Figure 2.1), include 20 completely new profiles (red), three profiles that were relogged (green), three profiles that were extended to a greater depth (yellow), forty profiles that were previously logged and were collated by Taylor & Mather (2015) (grey).

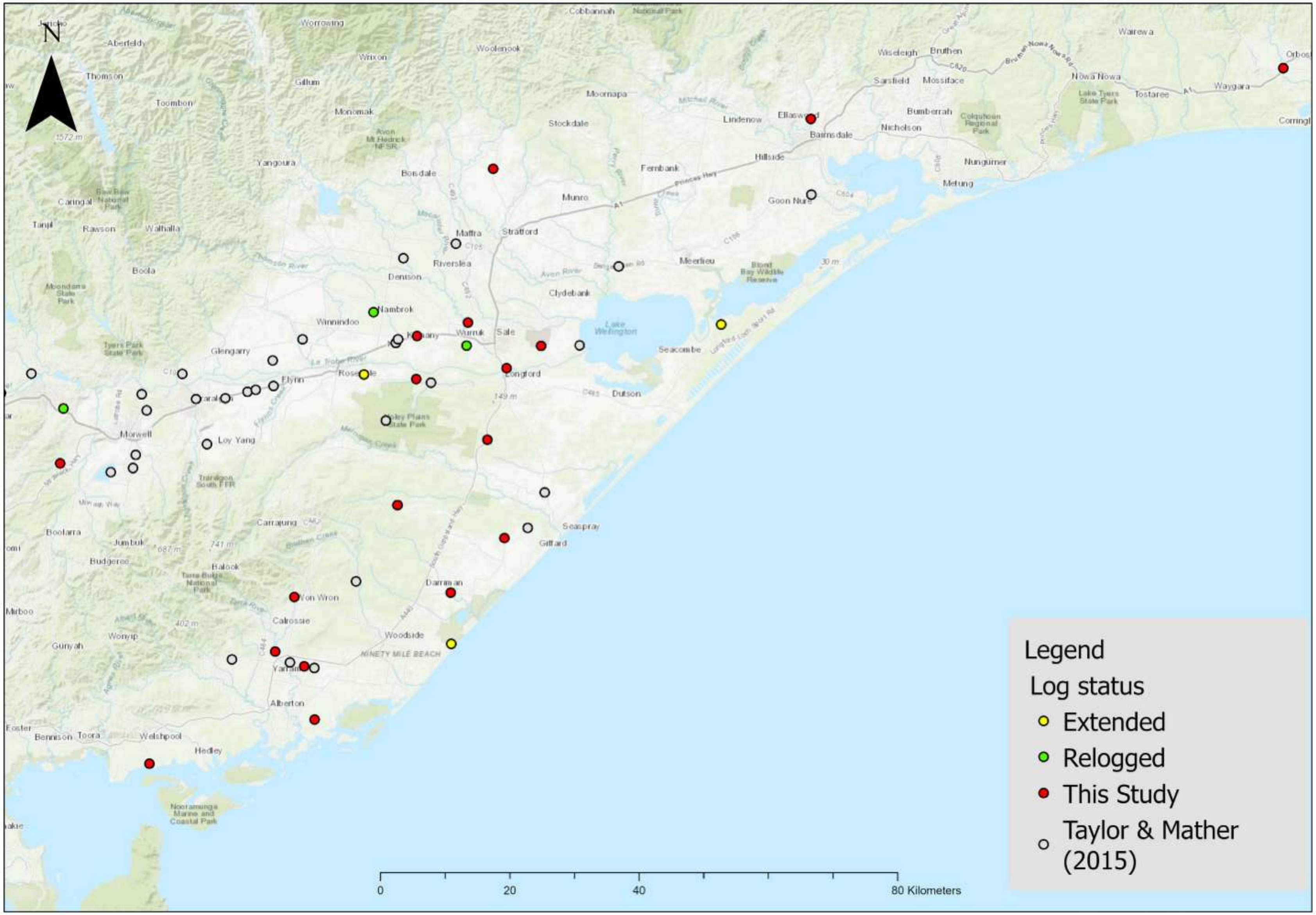

Figure 2.1 Location of precision temperature logs.

2.2. Methods

2.2.1 Field method

This project adopted the methods of Taylor & Mather (2015) and utilised the same equipment and techniques. The only significant difference between the previous and current logging program was the depth that could be logged, which was extended from 750 m to 1000 m through improvements to equipment which enabled the safe deployment of the temperature probe to greater depths.

The precision temperature logs were collected by lowering a temperature probe down an open bore hole and pausing to allow the sensor to stabilise to the *in-situ* temperature at each measurement point. The equipment used by GSV enabled detailed thermal logs to be generated to a maximum depth of 1000 m, and a minimum depth interval of 0.1 m between readings, but typically one metre intervals. The equipment consisted of a thermistor-based resistance probe with a cable and reel (Figure 2.2 a & b), which were deployed into suitable bores using a jockey wheel and depth counter (Figure 2.2 c) and produced real-time electrical resistance data (correlated with temperature) at the surface via a high-resolution electrical multi-meter (Figure 2.2 d).

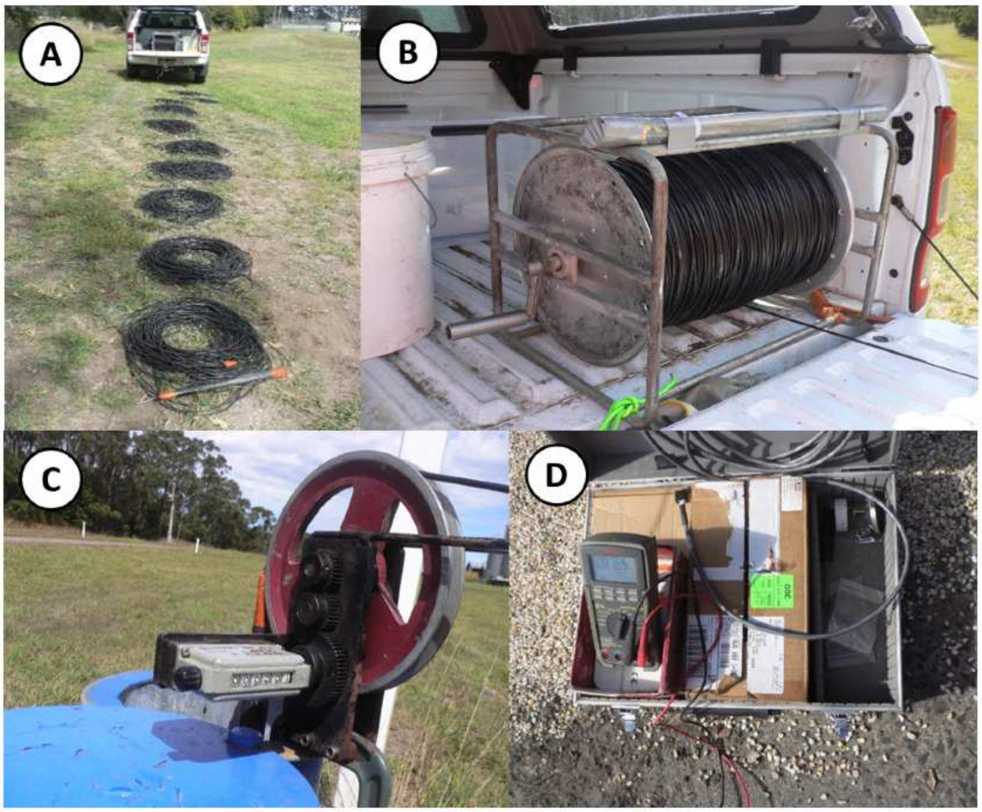

Figure 2.2 Temperature logging equipment used by GSV.

2.2.2 Temperature calibration

The precision temperature probe incorporated a thermistor sensor that effectively measured temperature in terms of electrical resistance across the sensor. Measurement precision was achieved to within approximately one millikelvin (1/1000th of a degree Celsius). Calibrations were performed to determine the correlation between sensor temperature and electrical resistance. The resulting relationship (Equation 1) was used in all subsequent calculations to interpret the temperature profile for each bore. The sensor precision allowed for typical geothermal gradients, between 20 – 50 °C/km, to be easily quantified even within thin aquifers.

Equation 1:

$$T = {}^{3703.5}/_{((\ln(ohms)+3.8682)-273)}$$

where *T* = temperature in degrees Celsius, and *ohms* = measured electrical resistance across the thermistor sensor in ohms.

The probe was lowered slowly to ensure minimal disturbance of the water column prior to each reading. The results were recorded manually at discrete intervals after stabilisation of the readout to four decimal places. Unusual or external factors which may have influenced the tests were recorded.

Electrical resistance data from the field were manually transcribed to spreadsheets, with data points then converted to temperature using Equation 1 to produce temperature profile and geothermal gradient logs. The results were then assessed for consistency and reliability by comparison with historical measurements to provide an overall evaluation of thermal conditions for each bore site. The raw data, calculations, logs, and findings are retained by GSV, in addition to comparative logs from other organisations.

2.2.3 Depth calibration

The logging equipment was commissioned and assembled specifically for GSV's purposes and includes an electrical power cable wound on a reel and controlled by a precise winding mechanism. The cable is composed of copper wire shielded with plastic insulation. It contains no strengthening component (as is the case with more expensive logging cables) so is susceptible to both elastic and inelastic stretching when the probe is deployed. Inelastic stretching is accounted for by using the trip counter pulley at the surface. Elastic stretch has been factored into subsequent data calculations.

GSV addressed the issue of elastic stretching by applying a correction factor to adjust measured depth readings to 'true' depth values. An assumption of 4% stretch was previously adopted (Taylor & Mather, 2015), and has been carried forward in this data release. It is acknowledged that due to the cumulative weight of the cable a constant correction factor may overestimate the correction required at shallower depths and underestimate the correction required at greater depths. The maximum stretch is unknown; however, coal seams at a depth of 1038 m in Seacombe-7 were not detected by precision temperature logging to a depth of 984 m (uncorrected), which indicates a cable stretch of less than 54 m (5.4%) conversely at Woodside-12 coal seams at 992 m were detected at a depth of 932 m (uncorrected), which indicates a cable stretch of 60 m (6%).

2.3. Results

A total of 26 SOBN bores were precision logged for temperature during the 2019 - 2020 data collection period, increasing the total metres logged in Gippsland by 7,605 m. The maximum depth logged was 1,023 m. A list of the newly measured bores and the corresponding maximum temperature is provided in Table 2.1. A complete list of precision temperature logs, including previously unpublished and published logs are included in Appendix A1 (Precision temperature logs). Precision temperature logs are also included in Attachment A.

Table 2.1 New precision temperature logs collected during the 2019/20 period.

WMIS ID	GEDIS ID	Parish ID	Max temperature °C	Log depth (m)	Aquifer	Logging status
58937	58937	DENISON 57	58	710.37	LTA	Relog
84156	84156	NARRACAN 3284	23	172.24	LTBA	Relog
89809	89809	ROSEDALE 301	43	835.58	LTA	Extended
92175	92175	STRATFORD 19	18	95.68	LTA	New
104536	104536	WOODSIDE 12	34	1008.8	LMTA	Extended
105220	105220	WORANGA 15	14	28	UMTA	New
105548	105548	WURRUK WURRUK 13	20	180	UTAF	Relog
90614	50857	SEACOMBE 7	60	1023.36	UMTD	Extended
52754	52754	BUNDALAGUAH 10	55	881.92	LTA	New
64835	64835	GLENCOE SOUTH 7	24	237.12	LTA	New
67442	67442	HOLEY PLAINS 192	23	145.6	UMTA	New
90148	90148	SALE 23	17	118.56	UTAF	New
90149	90149	SALE 24	16	146.64	UTAF	New
92118	92118	STRADBROKE 69	14	214.24	LTA	New
105134	105134	WOOUNDELLAH 11	27	272.48	UMTA	New
105728	105728	WY-YUNG 8	24	140.4	LTA	New
110729	333912		19	110.24	LTA	New
110731	325327		18	108.16	LTA	New
115732			15	31.2	UMTD	New
145092			15	49.92	UTQA	New
147173	987865		19	208	LMTA	New
WRK059110			29	368.16	UMTA	New
WRK059112			20	180.96	LTA	New
WRK059119			15	120.64	UMTD	New
WRK059123			13	20.8	UMTA	New
WRK059126			23	187.2	LTA	New

Precision temperature logs and calculated three metre running average temperature gradient logs were correlated with aquifers and aquitards as per the VAF to enable visualisation of aquifer temperatures and thermal insulation properties (intervals of high gradient correlate with elevated thermal insulation) at each bore's location. Temperature profiles are presented for key bores, illustrating the measured temperature (red), calculated geothermal gradient (blue), intervals of aquifers and aquitards, lithology, and stratigraphy where available. A representative example from two regions – the Latrobe Valley (Figure 2.3) and Lake Wellington (Figure 2.4) are presented below. The full set of temperature profiles is included in Appendix A2 (Figures A2.1–A2.14).

In the Latrobe Valley (Figure 2.3) the Morwell coal seams provide the bulk of the thermal insulation. This is indicated by the high geothermal gradients (~140°C/km) observed, especially over the Morwell 1B seam. The Morwell seams in total are associated with an increase in temperature from 23°C to 57 °C over a depth interval of 360 m. The temperature gradient is mildly elevated in the Traralgon Formation beneath the Morwell coal measures, but less so because the seam thickness decreases in this location. The maximum temperature recorded in the bore was 62.6°C at a depth of 696 m.

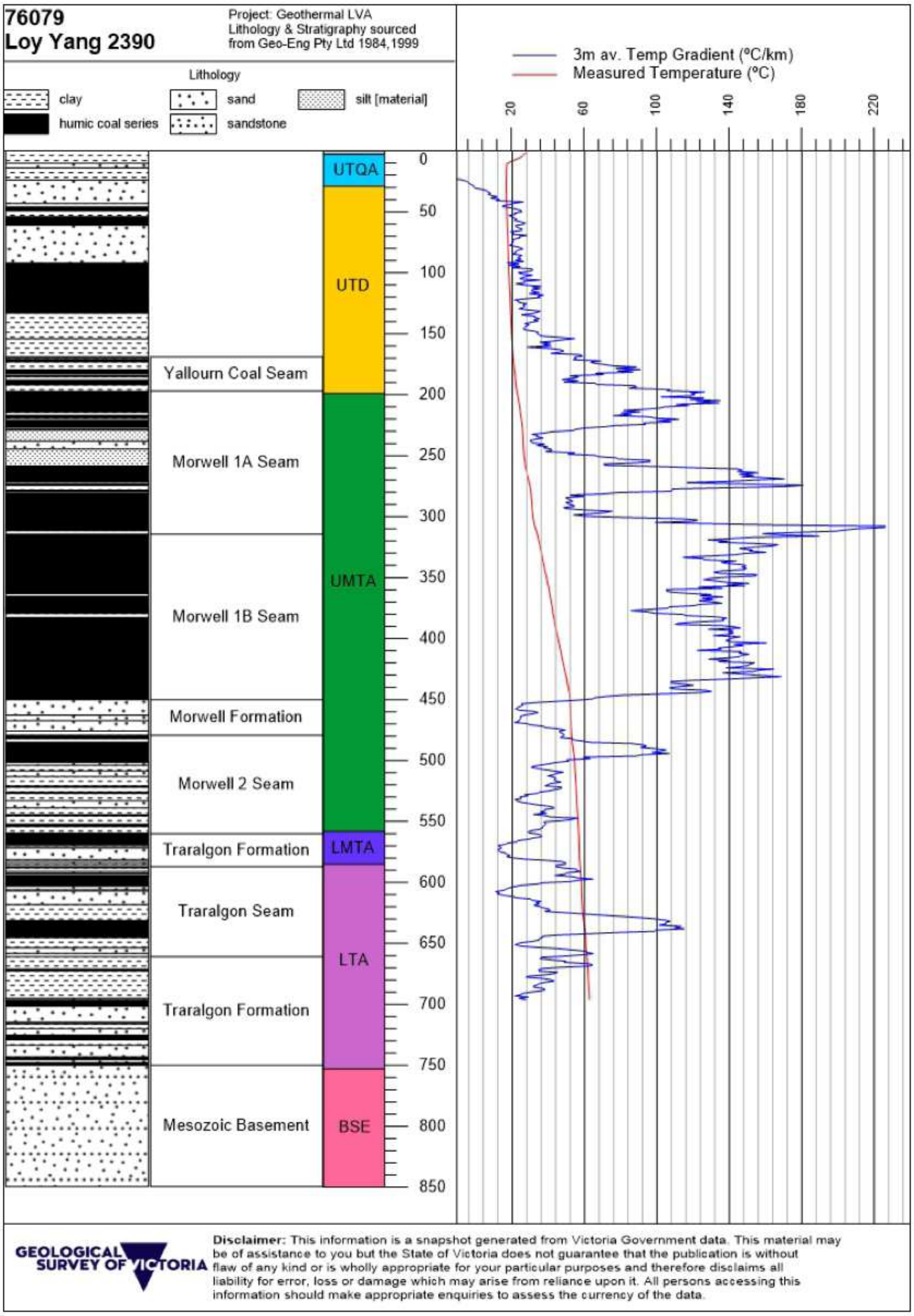

Figure 2.3 Temperature profile of the Latrobe Valley (Loy Yang 2390).

The geothermal conditions in the deeper sections of the Gippsland Basin are illustrated by the precision temperature log for Seacombe-7 (Figure 2.4). Collected from a borehole at the eastern end of Lake Wellington, this profile is typical of the Lake Wellington geothermal conditions. The temperature gradient is relatively high (~50°C/km) through the full thickness of limestone and marl, resulting in 60°C temperature at 1000 m depth. The Traralgon coal measures depicted at the base of the lithology log are likely to be associated with higher geothermal gradients but lay beyond the accessible depth limit of GSVs logging equipment. Different relative abundances of limestone versus coal result in generally lower average geothermal gradients in the Lake Wellington region (limestone) compared to the Latrobe Valley (coal). The temperature of the Lower Tertiary Aquifer is greatest where Traralgon coal measures are thickest and are overlain by thick thermal insulators, either the Morwell coal measures in the Latrobe Valley or the Gippsland Limestone along the coast. Groundwater flow can remove heat and must be considered alongside insulating rock layers.

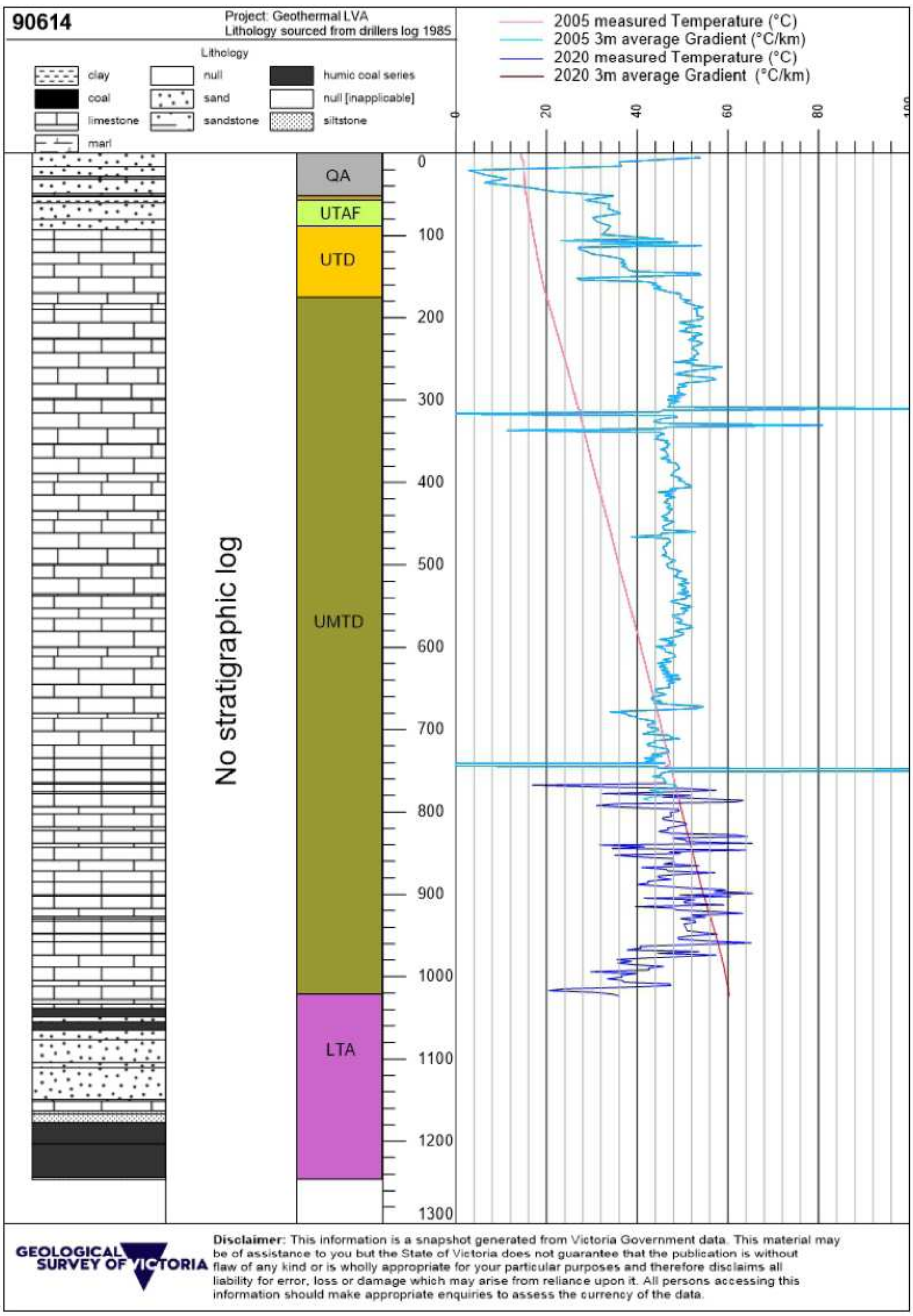

Figure 2.4 Temperature profile of the Lake Wellington Depression (Seacombe 7).

Precision temperature logs revealed the temperature through each aquifer and aquitard in multiple locations throughout Gippsland. The temperature at the shallowest boundary of each aquifer was defined as the reference temperature for the aquifer at each bore location. This provided a consistent reference point for temperature maps but underestimates the average temperature of aquifers.

Precision temperature logs also enabled geothermal gradients to be calculated within each aquifer and aquitard at multiple locations throughout Gippsland. The geothermal gradient was calculated as the difference in temperature between the shallowest boundary and deepest logged depth of each aquifer and aquitard at each bore location. Geothermal gradients provide a convenient method to estimate the average temperature of a thick aquifer, or the likely temperature of an aquifer where it extends below the deepest logged depth. High geothermal gradients in the coal seams indicate that their insulative properties are the likely cause of the geothermal heat, particularly in the Latrobe Valley. Moderate geothermal gradients observed in limestone formations indicates that they are also insulating rocks, although with only about half the efficiency of the coals. Low geothermal gradients over sand aquifers indicate their lack of insulation and that the cause of the geothermal heat is unlikely to be upwelling hot water.

Previous work by Taylor & Mather (2015) shows that climatic and solar effects at the surface can overprint geothermal temperature effects at depths as great as 50 m - 100 m. In this study caution is used with any temperature records shallower than 50 m.

Temperature logs were converted to relative depth (m.AHD) and aquifer top and base were correlated to specific depth values on the temperature logs. The shallowest temperature reading within each aquifer was recorded as the 'top of aquifer temperature' and the deepest temperature reading the 'bottom of aquifer temperature'. These typically represent the minimum and maximum temperatures, respectively, for the aquifer in each location. However, the deepest logged temperature did not always correlate with the actual base boundary of the aquifer, particularly for the Lower Tertiary Aquifer. The geothermal gradient was calculated by dividing the temperature increase across the aquifer interval by the thickness of the interval.

A Gippsland Geothermal Database including temperatures for each of the aquifers/ aquitards in Gippsland is presented in Attachment A. Temperatures are cited with the original source, depth and any corrections that were applied.

3. Historical temperature data

A review of historical borehole temperature data from Gippsland uncovered a wide range of data including point measurements, pumping measurements, wireline logging measurements, and formation tests. Such data typically have a lower level of reliability compared to precision logs but can provide valuable information in areas that lack precision temperature logs. The spatial distribution of historical temperature data exceeds the distribution of modern precision temperature logs (Figure 3.1).

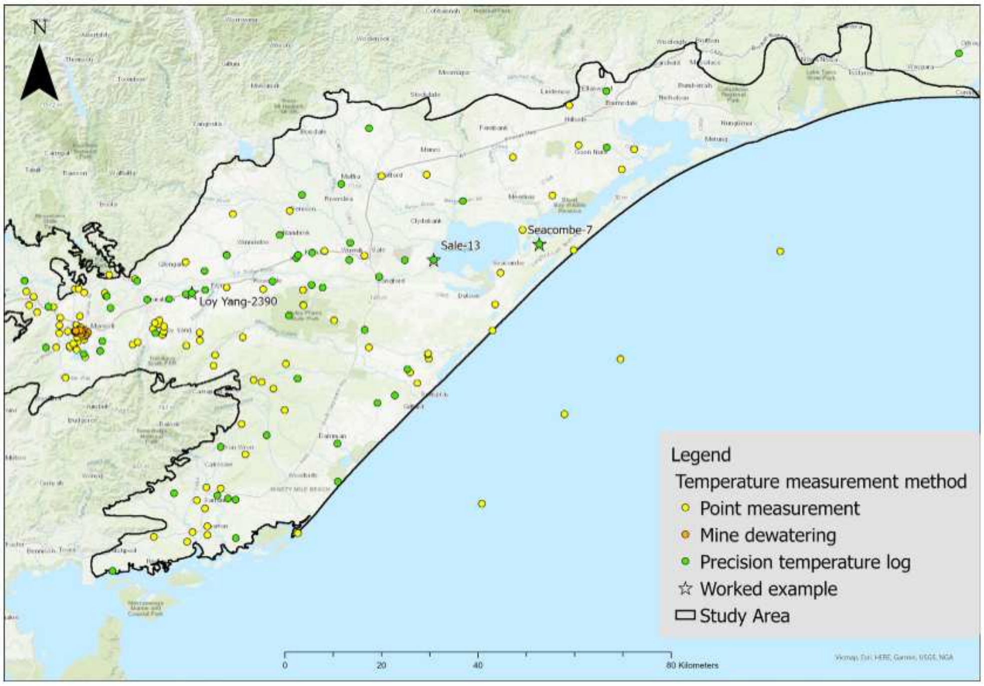

Figure 3.1 Temperature measurement locations and methods.

3.1. Data review

The quality and reliability of many historical temperature datasets have been widely critiqued (e.g., King et al., 1987; Jessop, 1990; Taylor & Mather 2015). Inaccuracies stem from three main causes:

- Thermal disturbance from fluids pumped down the hole whilst drilling,
- insufficiently detailed records of the time between the end of drilling fluid circulation and temperature measurement and,
- low precision and thermal response of many wireline logging tools.

Most drilling disturbances bias measurements towards underestimating true temperature. In Gippsland, this is demonstrated by the groundwater monitoring bore Sale-13. An historic bottom hole temperature of 58.7 °C was recorded at a depth of 1,050 m. This compares to a precision logging temperature of 67.2 °C at a depth of 950 m. Similar biases are likely to affect many historical temperature data throughout Gippsland. Historical data remain important because they can reveal regional temperature trends in the absence of modern precision temperature logging. A summary of the types of historical data used and the relative weighting of assumed data reliability in subsequent evaluations.

3.1.1 Point measurements

Point data represent the temperature at a particular depth within a bore, commonly the 'bottom hole temperature'. Point data are prevalent amongst historical temperature data sets. Point measurements are collected by lowering a single thermometer down a borehole on the end of a cable. They record the temperature either at a set depth within the bore or the maximum temperature encountered in the bore. Thermal disturbance of the bore column must be minimised, and time must be given for the thermometer to stabilise with the surrounding temperature for these measurements to be accurate. Nahm & Reid (1979) made 71 point measurements in observation bores throughout the Latrobe Valley to enable a temperature correction of hydraulic head measurements. No information on the stability of the temperature measurement was recorded. SKM (2005) extended the database of point measurements throughout Gippsland to 82, including new temperature data and repurposed data initially published by Nahm & Reid (1979).

3.1.2 Dewatering bores

Dewatering records from the Hazelwood open cut coal mine near Morwell have provided time-series temperature data for the Upper mid-Tertiary Aquifer (UMTA). The data were collected from 32 dewatering bores centred around the mine and represent 32 of the 93 temperature measurements available for the UMTA.

The Hazelwood mine dewatering bores were designed to extract groundwater from the aquifers beneath the Morwell 1 and 2 coal seams. Aquifer temperatures range from 28 °C to 66 °C with higher temperatures generally associated with the deeper Morwell 2 aquifer and lower temperatures associated with the shallower Morwell 1 aquifer. Temperature data from the Morwell 1 and 2 aquifers have been grouped into the UMTA for the purposes of this study in accordance with the Victorian Aquifer Framework (GHD, 2012 & SKM, 2009).

3.1.3 Wireline temperature data

Temperature data are routinely collected as ancillary information during wireline logging operations in petroleum wells, and occasionally in groundwater bores. These temperature data are typically 'maximum temperature' records and are compromised by a lack of borehole thermal equilibrium if they were collected too soon after drilling activities ceased. This often leads to an underestimation of bottom hole temperatures. A database of wireline temperature data was compiled by Driscoll (2006) and, where sufficient additional information was available, temperatures were corrected using Horner plots (e.g. Corrigan, 1997). For many petroleum wells these represent the only available temperature data. Sets of wireline temperature measurements from different depths in thermally equilibrated wells can give a good indication of how temperatures vary with depth and as a function of the formations that they pass through.

3.1.4 Formation tests

Temperature data from petroleum wells is routinely generated during formation tests such as Drill Stem Tests (DST). Temperature recorded during DSTs can be less impacted by drilling activities because they relate to fluids extracted from the reservoir not the bore void. DSTs are expensive to conduct so there are typically fewer (if any) measurements made and temperature data are for a specific depth and cannot be readily converted into a temperature profile. DST temperature data the Gippsland Basin has been compiled by Driscoll (2006). DST data have been further constrained and modelled by Edwards (2020) who provides important insights into the likely temperatures to be encountered at depths greater than 1,000 m in the Gippsland Basin.

3.1.5 Conversion to top of aquifer equivalent temperature

A reference surface for temperature data was required because aquifer temperature maps are 2D and aquifers are intrinsically 3D. The top of the aquifer was chosen because it provided an unambiguous definition and intersected with the most temperature data.

Precision temperature logging indicates geothermal gradients can vary by as much as 100°C/km over different vertical intervals in the Latrobe Valley due to the large thermal conductivity contrast between the thick coal seams and other lithologies. Significant temperature increases can occur vertically across an aquifer if the geothermal gradient is high, or the aquifer is thick. Temperature data from Bengworden South 6 provides an example of this. Two different temperatures were presented by SKM (2005) in the Lower Tertiary Aquifer; 50°C and 67°C at depths of 1,057 m and 1,225 m, respectively. This variation was due to the geothermal gradient. The top of the aquifer was intersected at a depth of 947 m. To be able to integrate different temperature measurements effectively into a consistent regional map, the conversion of historical temperature data into a 'top of aquifer' equivalent temperature was required.

Historical temperature data frequently do not coincide with the top of the aquifer. This is particularly the case for deeper state observation bores and petroleum wells. Deep bores also frequently intersect the LTA which can be hundreds of metres thick. This means that deep sections of the LTA require the greatest correction when converting temperature data to 'top of aquifer' equivalence.

Conversion to 'top of aquifer' temperature relied on two pieces of information: the difference in depth between the top of the aquifer and the temperature measurement, and the geothermal gradient. An example of applying the correction is presented in Table 3.1 for the Bengworden South 6 bore, which results in a 'top of aquifer' equivalent temperature of 45°C.

Table 3.1 Top of aquifer temperature calculated from point measurement.

Bore	Measurement depth (m.AHD)	Measured temperature (°C)	Aquifer top (m.AHD)	Geothermal gradient (°C/km)	Corrected Temperature (°C)
Bengworden South 6	-1055	50	-947	46	45

3.2. Results

In deeper parts of the Gippsland Basin and along the coast, modern precision temperature data were unavailable and historical data was used to constrain temperatures. In these locations a lack of state or private observation bores made access for temperature logging difficult. The use of historical data was constrained by a hierarchy of assumed reliability of the measurement method. This hierarchy, in order of decreasing reliability, was as follows: point measurements, dewatering bores, formation tests, Horner (1951) corrected wireline data, and uncorrected wireline data. As a quality check, when integrating historical data into the present database, the data was compared to the geothermal gradients developed from precision temperature logs. The full dataset of historical data used is available in Attachment A.

4. Geothermal maps

4.1. Introduction

A range of aquifer properties including temperature, geothermal gradient, depth to the top of aquifers, transmissivity, and groundwater quality (dissolved solids) across the study area have been collated and mapped using a common GIS platform to improve the spatial understanding of the hydrogeological and geological characteristics that control shallow geothermal prospectivity in Gippsland aquifers.

The maps are based on the VAF (GHD 2012, SKM, 2009) which provides a recognised hydrostratigraphic framework upon which the geothermal knowledge can also be presented. Other groundwater researchers in Victoria also compile their knowledge around this framework, so the geothermal knowledge will be readily accessible and relatable to other researchers. This knowledge includes:

- the depth of aquifers throughout Gippsland, an important component for calculating bore development costs
- the salinity of the water, essential for quantifying environmental impact and establishing potential uses
- the transmissivity of the aquifer, essential for modelling bore yield, injectivity, and the evolution of cold-water plumes
- groundwater extraction licence information, essential for understanding if reinjection is required.

4.2. Method

Aquifer temperatures were gridded to predict temperatures away from known control points. Top of aquifer temperature data compiled as described in Section 3 was gridded using the kriging function in Surfer®. Automatic variogram fitting was used with parameters limited to the relevant minimum and maximum control point settings. Node spacing was set at 400 m in both the x and y directions. There was more confidence closer to control points with confidence decreasing away from control points.

4.3. Temperature

All temperature data in Gippsland are consistent with a thermally conductive setting, with temperature differences mostly due to depth of burial and lateral variations in thermal insulation. Minor lateral variations in basal heat flow may also be relevant, however, this is not obvious in the data. There is no evidence of geothermal activity (volcanic activity or hydrothermal convection). Aquifers within 50 m of the surface can also be influenced by atmospheric temperature related to the annual variation in surface temperature. All data are consistent with thermal conduction, temperature increases with depth, and the thermal gradient appears to be inversely proportional to thermal conductivity.

Upper Tertiary Quaternary Aquifer (UTQA)

The UTQA is a shallow aquifer with minimal insulation. This is demonstrated by low temperatures and a narrow temperature range (11°C - 21°C). A map of temperature at the top of the UTQA is available in Figure 4.1. These temperatures may be influenced by seasonal variation in atmospheric temperature.

Upper Tertiary Aquifer Fluvial (UTAF)

The UTAF is a shallow aquifer with minimal insulation. This is demonstrated by low temperatures and a narrow temperature range (13°C - 25°C). Higher temperatures are observed where the aquifer is more deeply buried, consistent with conductive geothermal gradients. A map of temperature at the top of the UTAF is available in Figure 4.2. These temperatures may be influenced by seasonal variation in atmospheric temperature.

Upper Tertiary Aquitard (UTD)

The UTD is a shallow aquitard with minimal insulation. This is demonstrated by low temperatures and a narrow temperature range (14°C – 19°C). Higher temperatures are observed where the aquitard is more deeply buried, consistent with conductive geothermal gradients. A map of temperature at the top of the UTAF is available in Figure 4.3.

Upper mid-Tertiary Aquitard (UMTD)

The UMTD is a thick aquitard overlain by minimal insulation. This is demonstrated by low temperatures and a narrow temperature range at the top of the aquitard (14°C – 19°C). Considerably higher temperatures are observed at the base due to the thickness of the aquitard. A map of temperature at the top of the UMTD is available in Figure 4.4

Upper mid-Tertiary Aquifer (UMTA)

The UMTA is a thick aquifer comprised substantially of coal and overlain by coal insulation. This is demonstrated by medium to high temperatures and a wide temperature range at the top of the aquifer (14°C – 53°C). Temperature observations from the Hazelwood mine are historical and may be influenced by large-scale dewatering associated with the mine. Temperatures can be considerably higher at the base of the aquifer due to the thickness and composition of the aquifer. A map of temperature at the top of the UMTA is available in Figure 4.5.

Lower mid-Tertiary Aquifer (LMTA)

The LMTA is a thick sand aquifer overlain by coal insulation. This presents as medium to high temperatures and a wide temperature range at the top of the aquifer (14°C – 67°C). Shallower sections in the aquifer are associated with cooler temperatures and deeper sections are hotter. A map of temperature at the top of the LMTA is available in Figure 4.6.

Lower Tertiary Aquifer (LTA)

The LTA is a thick sand and coal aquifer overlain in many places by coal and limestone insulators. This presents as medium to high temperatures at the top of the aquifer (13°C – 68°C). Cooler temperatures are associated with shallower sections of the aquifer and areas with less insulation. Hotter sections are associated with deeper sections of the aquifer with thicker insulators, typically the Latrobe Valley and Lake Wellington Depression. In the Latrobe Valley the insulation is provided by the Yallourn, Morwell, and Traralgon coal seams. Insulation in the Lake Wellington Depression is provided by the Gippsland Limestone and the Traralgon coal seams. A map of the temperature at the top of the LTA is available in Figure 4.7.

The Latrobe Valley contains geothermal water at shallower depths, (typically around 600 m) with 495 km^2 of land having access to groundwater above 50°C. The highest temperature measured in the Latrobe Valley is located beneath Traralgon where it is 69°C at a depth of 574 m.

The Lake Wellington Depression hosts geothermal water at greater depths, (typically around 900 m) with 560 km^2 of land having access to groundwater above 50°C. There is significant potential for higher temperatures in the Lake Wellington Depression with the highest recorded temperature located at the petroleum well East Reeve 1 where it is 81.1°C at a depth of 1,621 m.

Warm groundwater was observed from the six new temperature profiles collected between the Sale and Rosedale areas. This area coincides with a transition from the insulating coal seams in the Latrobe Valley to the insulating Limestone in the Lake Wellington Depression. The insulation value in this area is reduced.

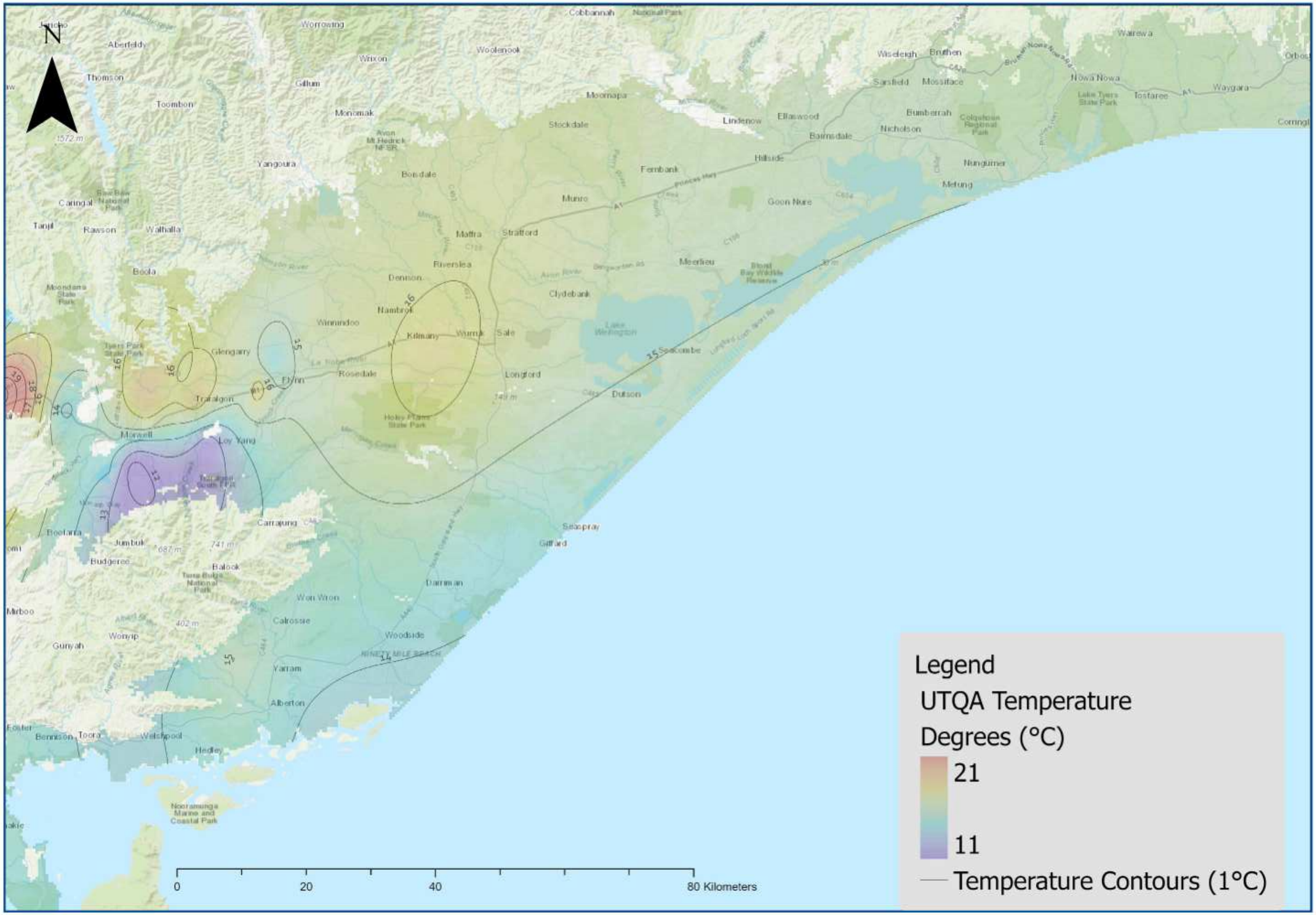

Figure 4.1 The temperature range (11°C – 21°C) at the top of the Upper Tertiary Quaternary Aquifer (UTQA).

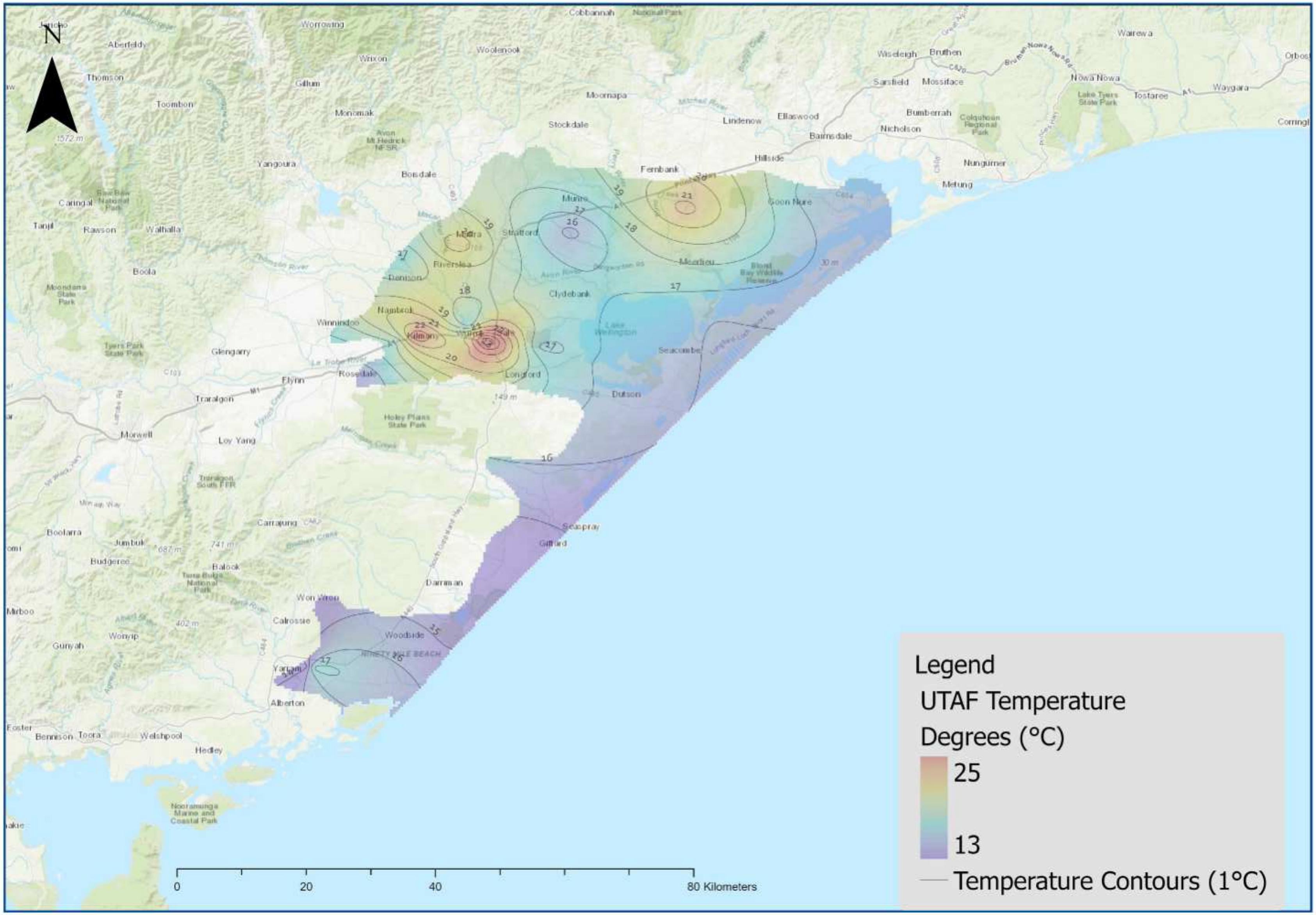

Figure 4.2 The temperature range (13°C – 25°C) at the top of the Upper Tertiary Aquifer Fluvial (UTAF).

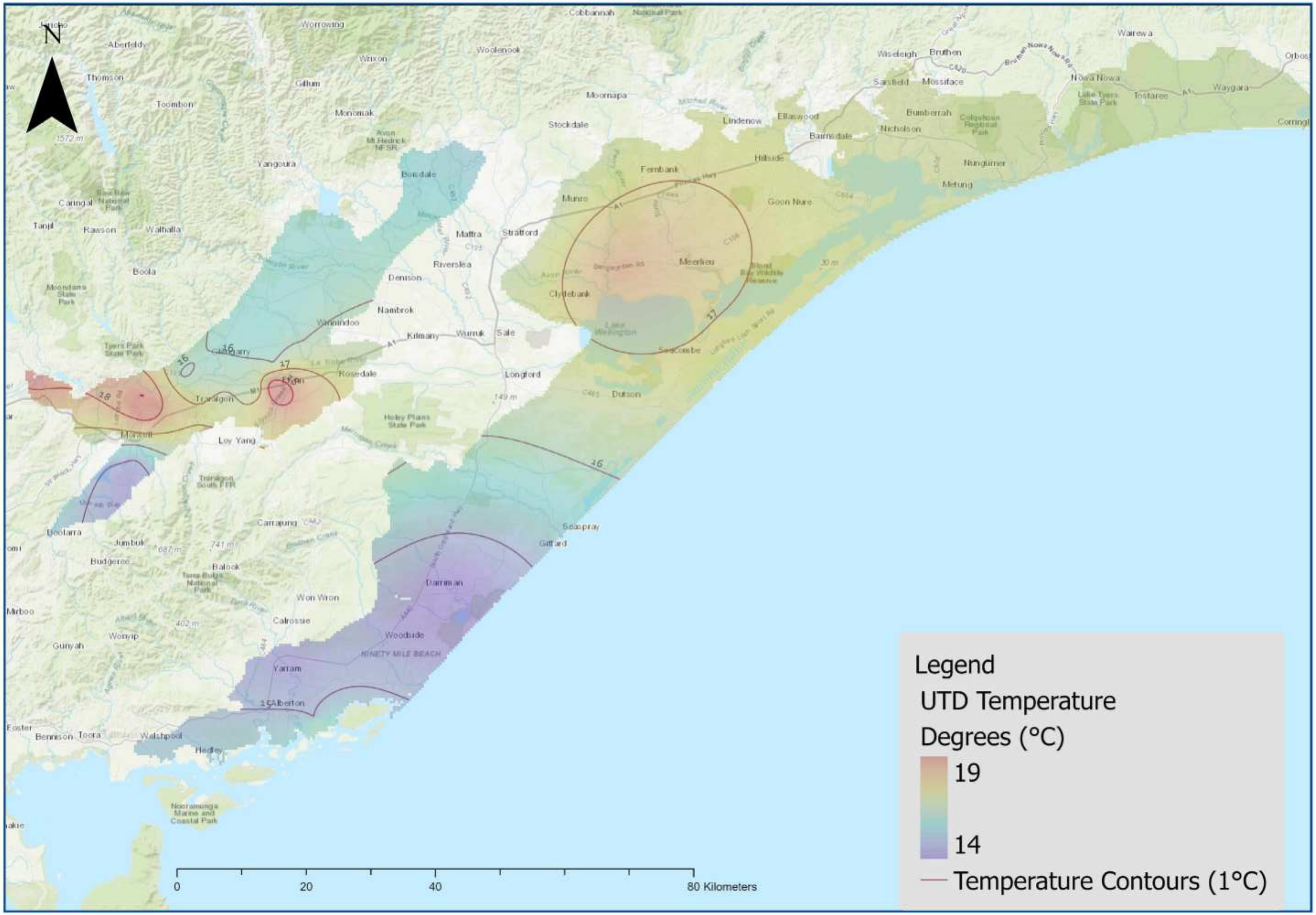

Figure 4.3 The temperature range (14°C – 19°C) at the top of the Upper Tertiary Aquitard (UTD).

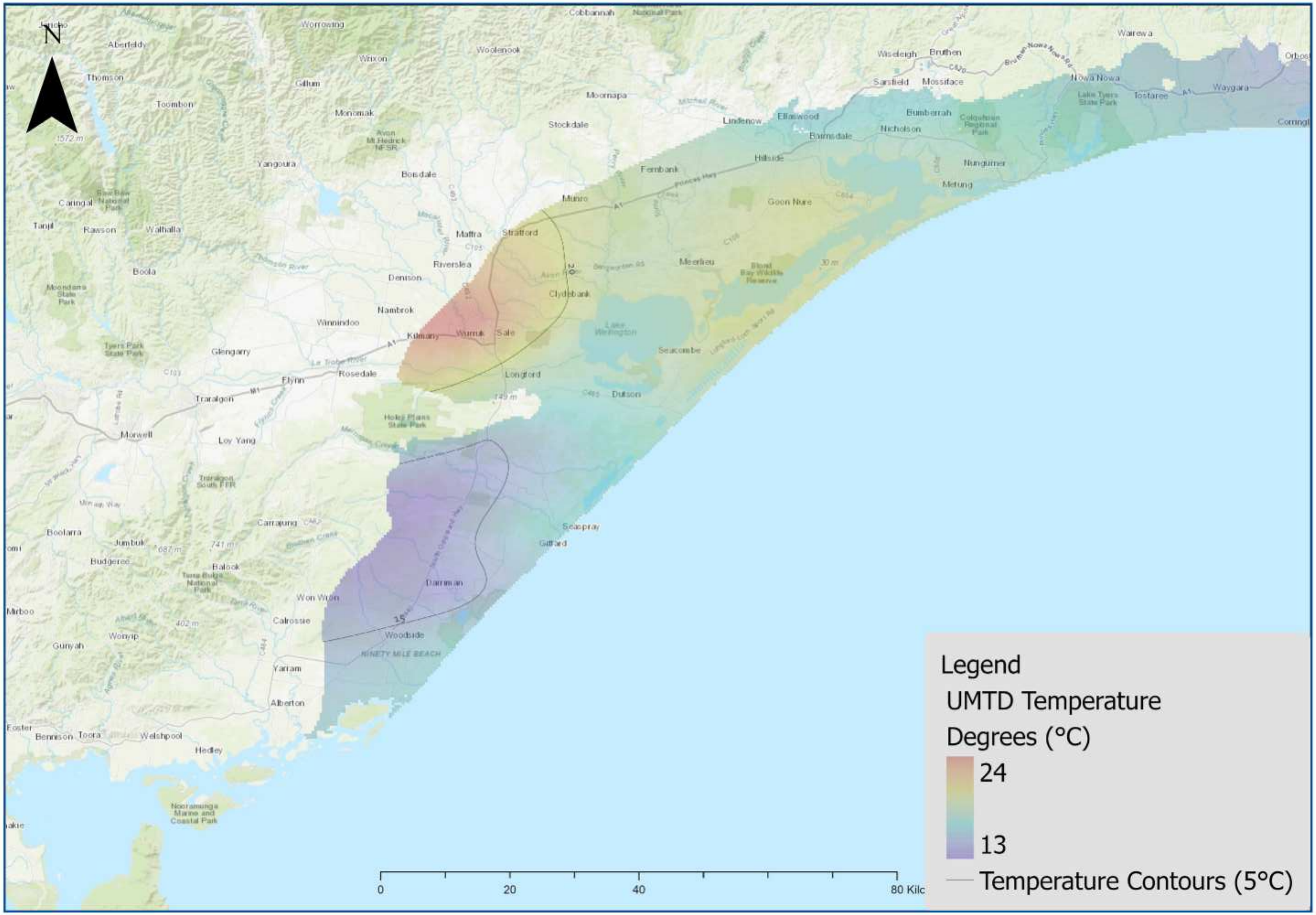

Figure 4.4 The temperature range (13°C – 24°C) at top of the Upper mid-Tertiary Aquitard (UMTD).

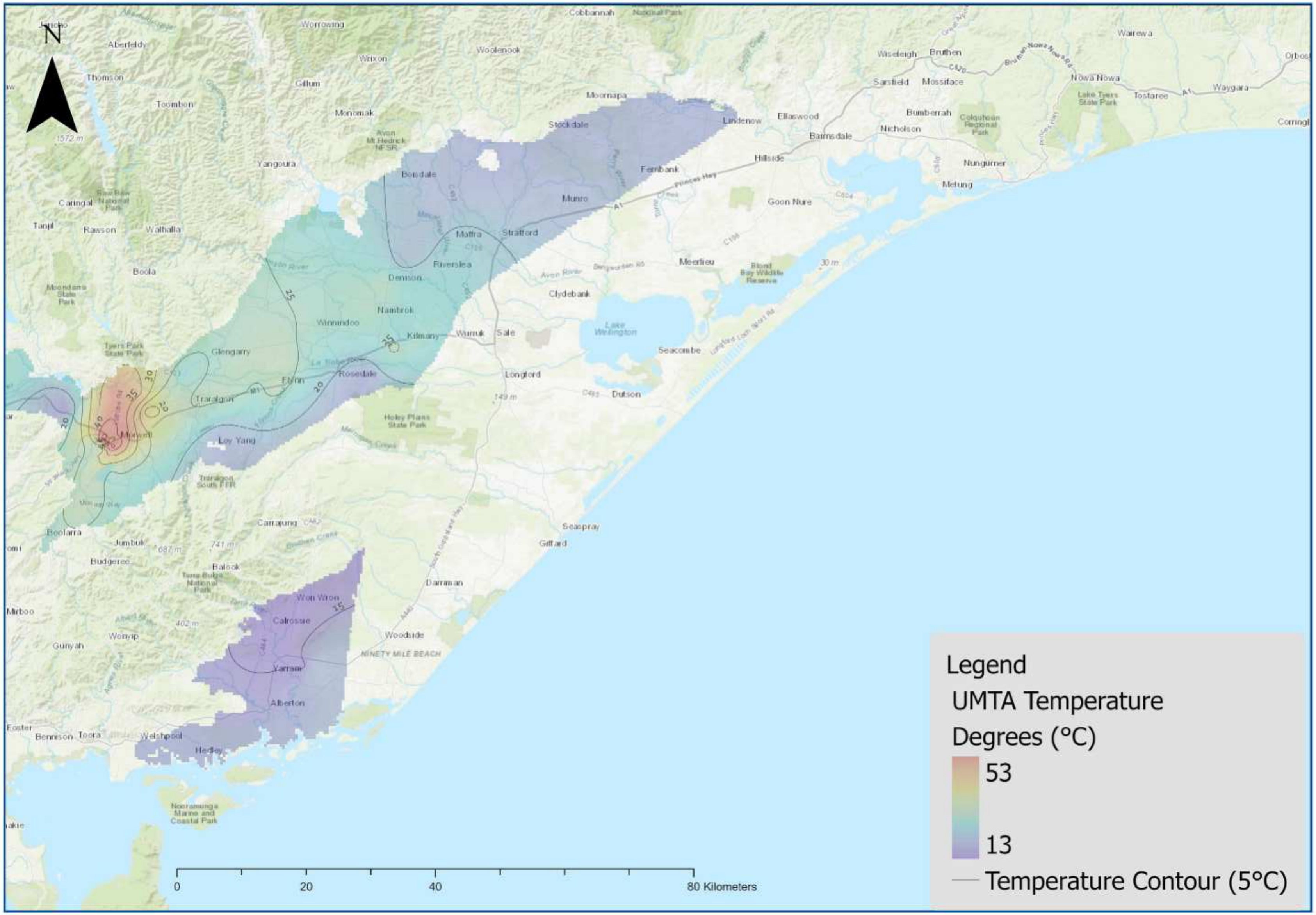

Figure 4.5 The temperature range (13°C – 53°C) at top of the Upper mid-Tertiary Aquifer (UMTA).

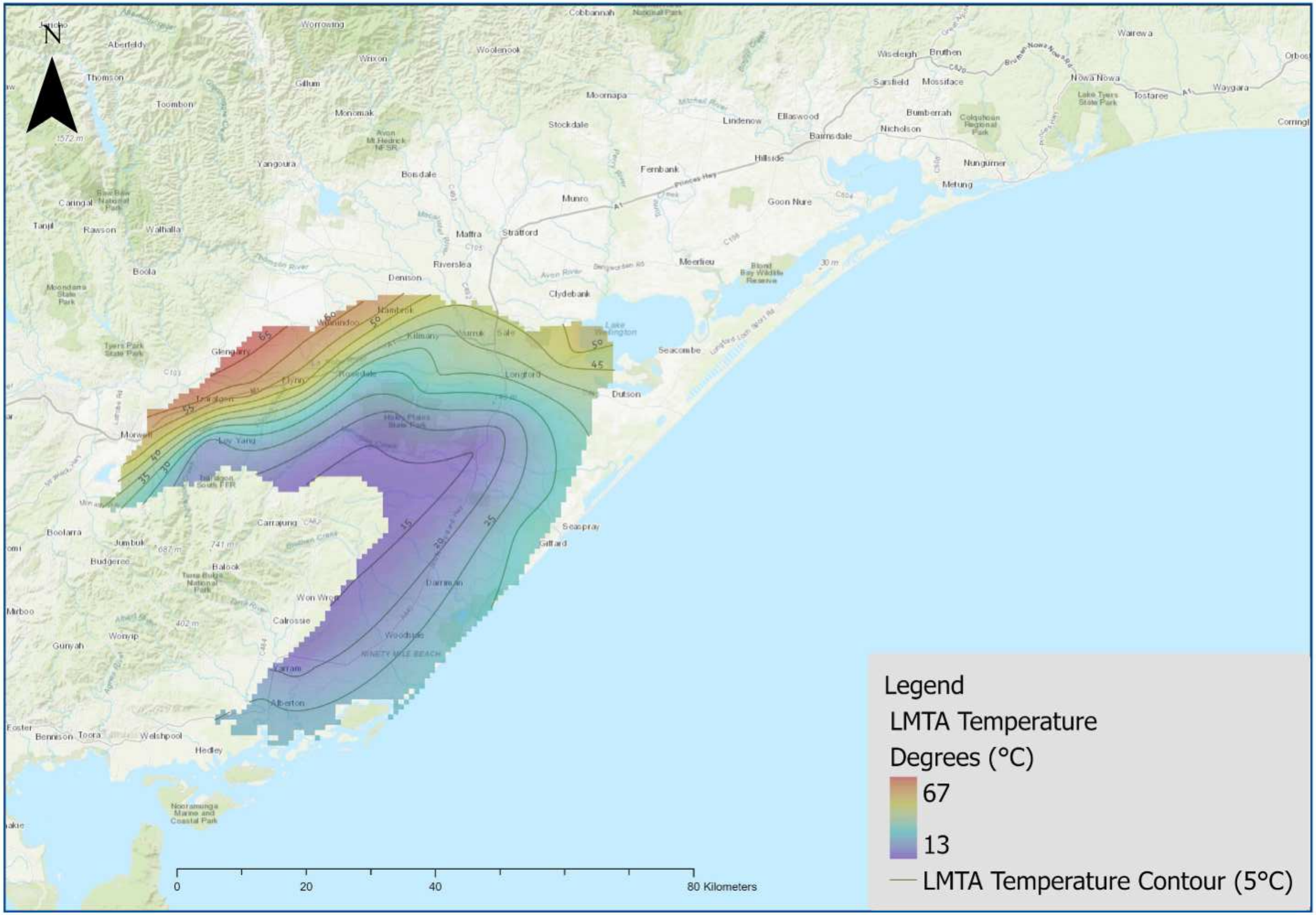

Figure 4.6 The temperature range (13°C – 67°C) at the top of the Lower mid-Tertiary Aquifer (LMTA).

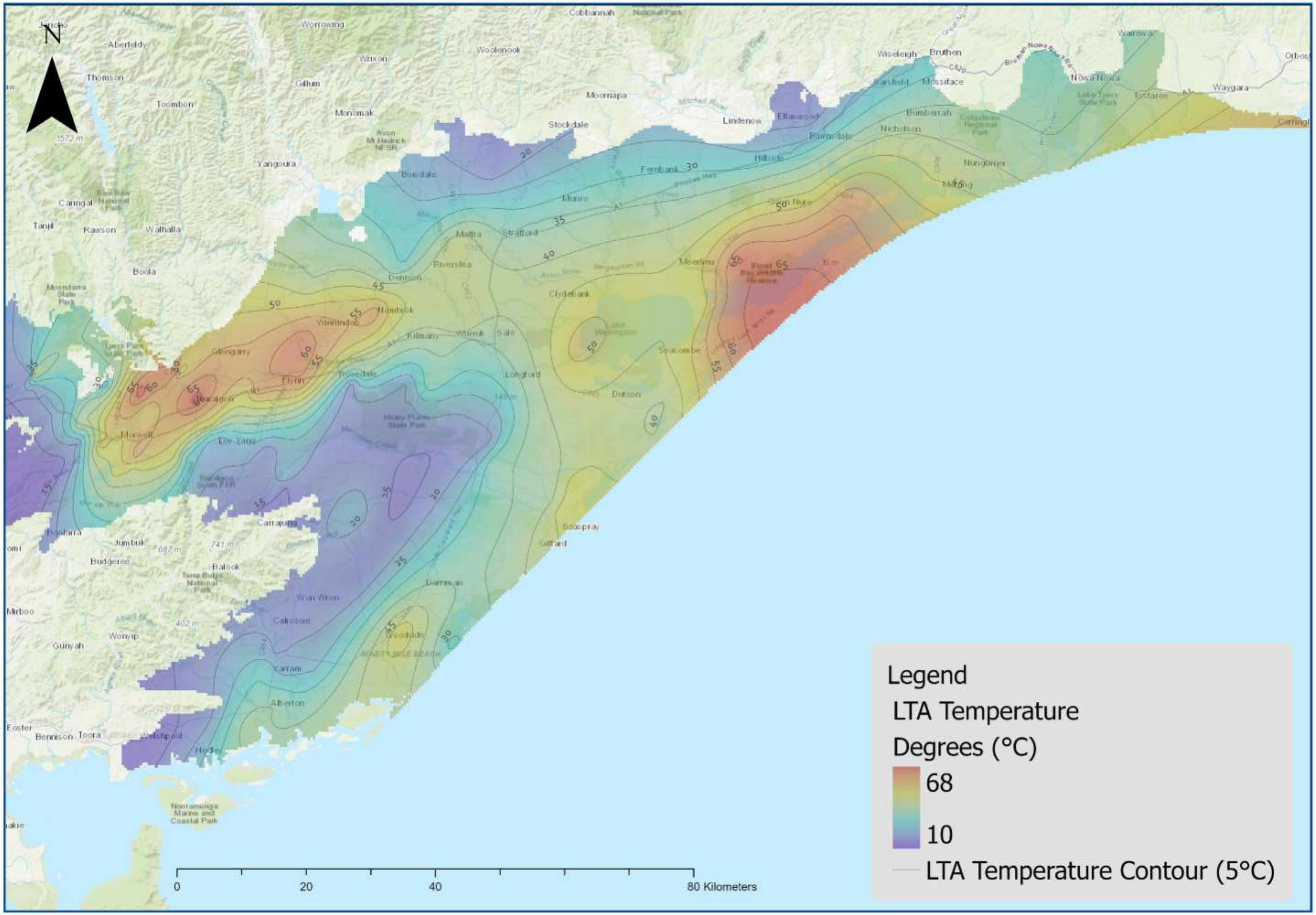

Figure 4.7 The temperature range (10°C – 68°C) at the top of the Lower Tertiary Aquifer (LTA).

4.4. Geothermal gradient

All geothermal gradient data in Gippsland are consistent with a thermally conductive setting, with differences mostly due to lateral variations in lithology and thermal insulation. Aquifers within 50 m of the surface are often influenced by annual variations in atmospheric temperature. Minor variations in geothermal gradient due to groundwater flow may also be relevant, however, this is not apparent in the data. There is no apparent evidence of geothermal activity (volcanic activity or hydrothermal convection). All data are consistent with thermal conduction, temperature increases with depth, and the thermal gradient appears to be inversely proportional to thermal conductivity. Geothermal gradients are higher across coal seams and limestone which comprise large areas of the Gippsland Basin. Geothermal gradients are lower across quartz rich sand aquifers.

Geothermal gradients were gridded to predict values away from precision temperature log control points. Geothermal gradients determined by the methods described in Section 3 were gridded using the kriging function in Surfer®. Automatic variogram fitting was used with parameters limited to the relevant minimum and maximum control point settings. Node spacing was set at 400 m in both the x and y directions. There was greater confidence in values closer to control points, decreasing with distance from control points. The inferred geothermal gradients are generally consistent with the rock thermal conductivity measurements reported by Antriasian et al. (2015).

Upper Tertiary Quaternary Aquifer (UTQA)

The range of geothermal gradients (29°C/km – 36°C/km) within the UTQA suggests typical background geothermal gradients with minimal additional insulation (Figure 4.8).

Upper Tertiary Aquifer Fluvial (UTAF)

The range of geothermal gradients (7°C/km – 86°C/km) within the UTAF suggests a wider range than typical background geothermal gradients would provide (Figure 4.9). Low gradients near Seaspray are representative of the thick quartzite aquifers lacking insulators. High gradients near Maffra coincide with the aquifer thinning out and include a coal seam intersected at Bundalaguah-8. The inclusion of coal in the aquifer potentially represents a mistake in the aquifer modelling.

Upper Tertiary Aquitard (UTD)

The range of geothermal gradients (11°C/km – 113°C/km) within the UTD suggests some elevated geothermal gradients and insulating rock layers (Figure 4.10). Low gradients near Boisdale and Munro could represent less insulating marl or limestone. Higher gradients near Morwell are related to coal seams.

Upper mid-Tertiary Aquitard (UMTD)

The range of geothermal gradients (3°C/km – 63°C/km) within the UMTD suggests some elevated geothermal gradients and insulating rock layers (Figure 4.11). Lower gradients in the south near Alberton suggest that the Gippsland Limestone has lower insulating properties in comparison to the higher insulative properties to the north.

Upper mid-Tertiary Aquifer (UMTA)

The range of geothermal gradients (0°C/km – 119°C/km) within the UMTA suggests elevated geothermal gradients and insulating rock layers (Figure 4.12). Lower gradients near Alberton represent areas where the coal seams are either thin or not included within the UMTA. Higher gradients in the Latrobe Valley are associated with the thick Morwell coal measures. Lower gradients between the Latrobe Valley and the Lake Wellington Depression are associated with the thick quartz rich aquifers of the Balook Formation and thinning coal seams.

Lower mid-Tertiary Aquifer (LMTA)

The range of geothermal gradients (5°C/km – 88°C/km) within the LMTA suggests elevated geothermal gradients and insulating rock layers (Figure 4.13). Lower gradients around the margin of the Strzelecki Ranges are groundwater recharge areas where insulating formations are thin or absent. Higher gradients near Loy Yang correlate with coal seams which are included in the LMTA in this area.

Lower Tertiary Aquifer (LTA)

The range of geothermal gradients (12°C/km – 138°C/km) within the LTA suggest that the geothermal gradient is strongly influenced by the presence and thickness of insulating coal layers (Figure 4.14). Generally, where geothermal gradients are highest, the Traralgon coal seams are thick and acting as effective insulators. This is evident at Sale-13 where the temperature increases by 14°C across 100 m sequence of Traralgon coal. Where gradients are low, the Traralgon coal seams are thin or absent, this occurs at Holey Plains-185 where the temperature increase by 1.7°C across 81 m of Balook sand aquifer.

Precision temperature log data in the LTA is biased towards shallower areas and often does not capture the full thickness of the LTA. This is due to a scarcity of deep groundwater observation bores and the large areas over which the LTA and the Traralgon coal seams occur at depths greater than the 1 km limit for precision temperature logs.

This has resulted in isolated high geothermal gradients that capture the Traralgon coal seams but not the quartz rich sand aquifers beneath. These occur in the Latrobe Valley, Yarram and Lake Wellington areas and appear as anomalies. These geothermal gradients may be replicated in other portions of the LTA, where thick coal seams are present but not precision temperature logged. Geothermal gradients are likely to be higher than those mapped south and east of Lake Wellington. Beneath the Traralgon coal seams the geothermal gradient drops significantly.

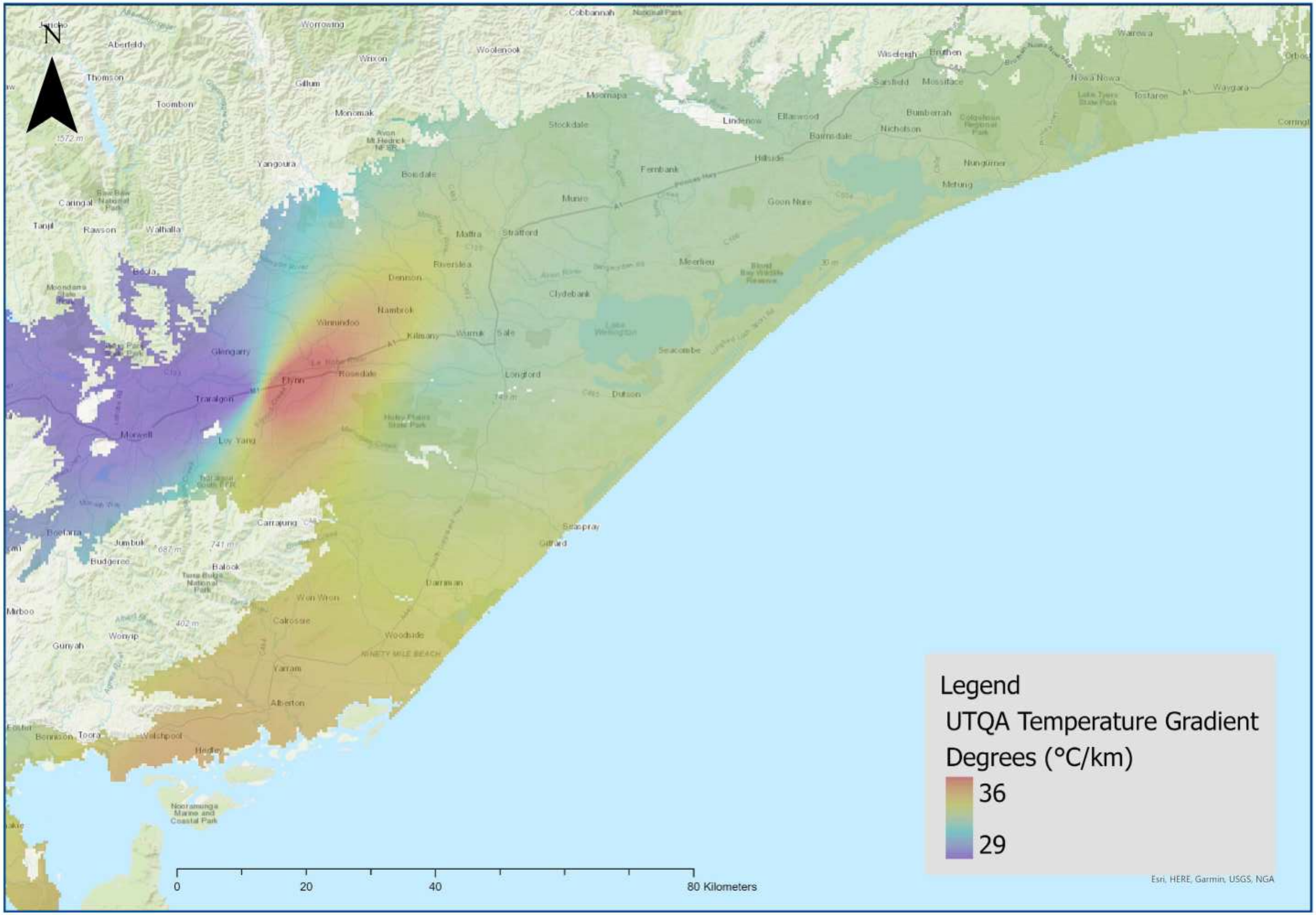

Figure 4.8 Temperature gradient in the Upper Tertiary Quaternary Aquifer (UTQA).

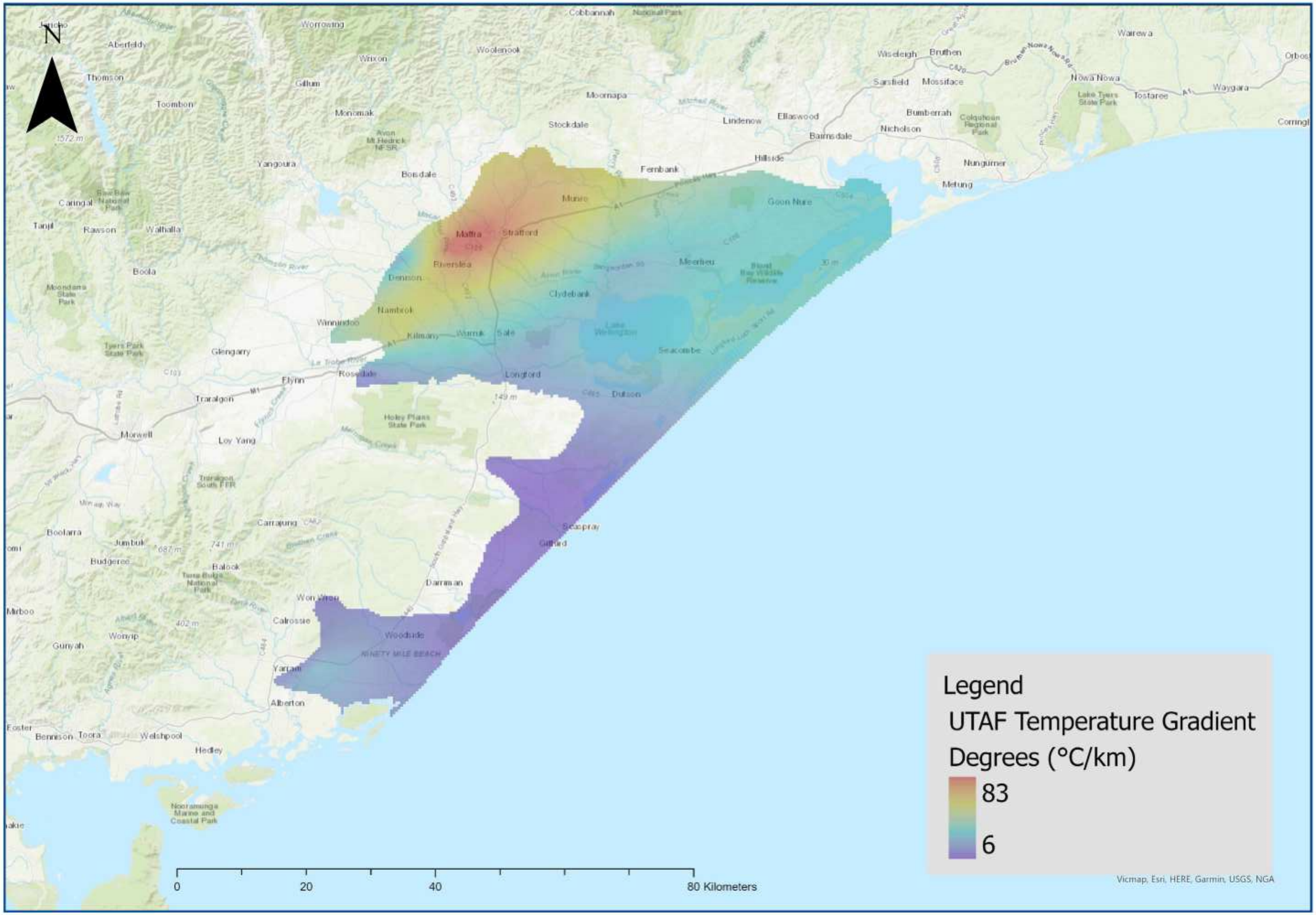

Figure 4.9 Temperature gradient in the Upper Tertiary Aquifer Fluvial (UTAF).

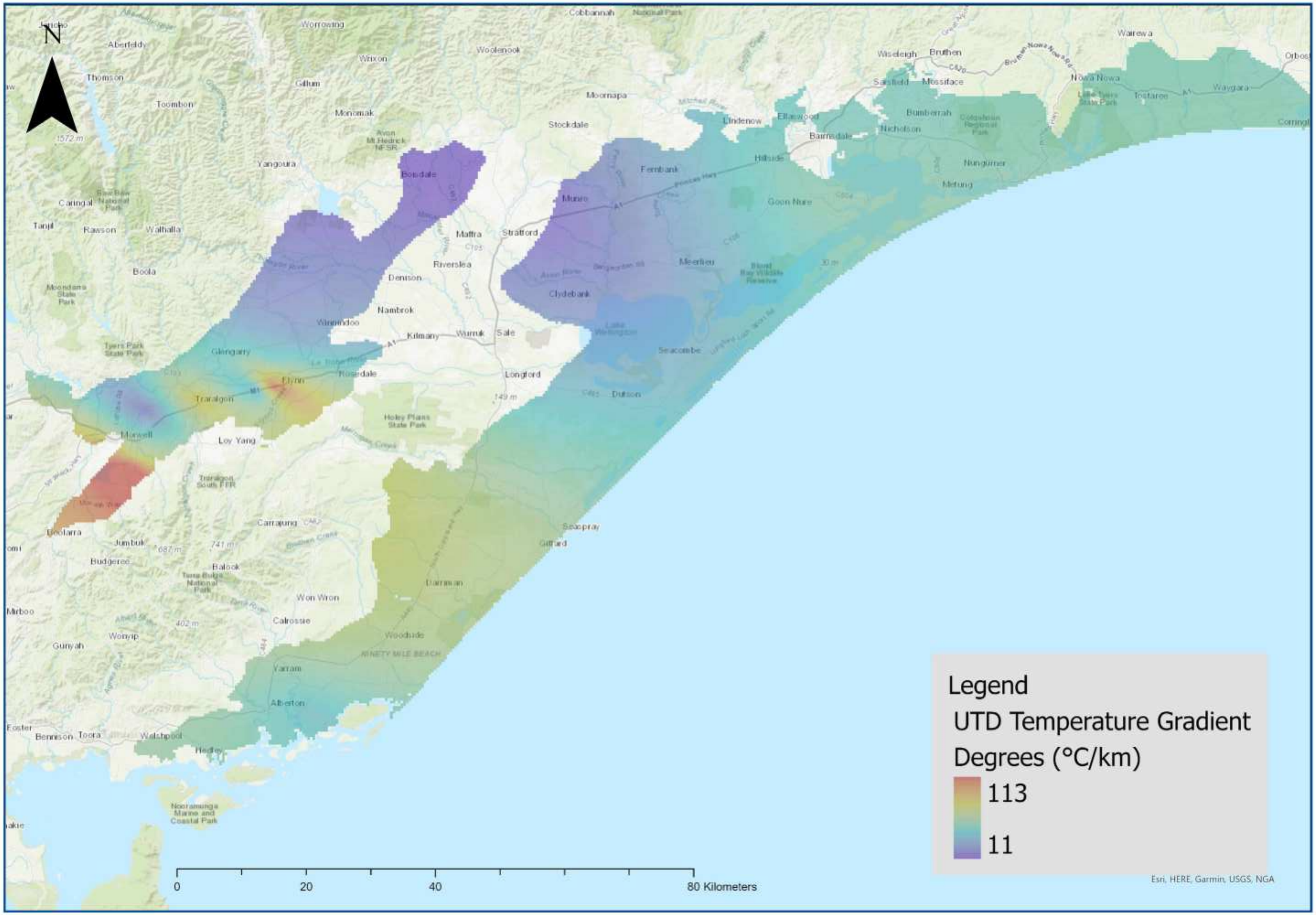

Figure 4.10 Temperature gradient in the Upper Tertiary Aquitard (UTD).

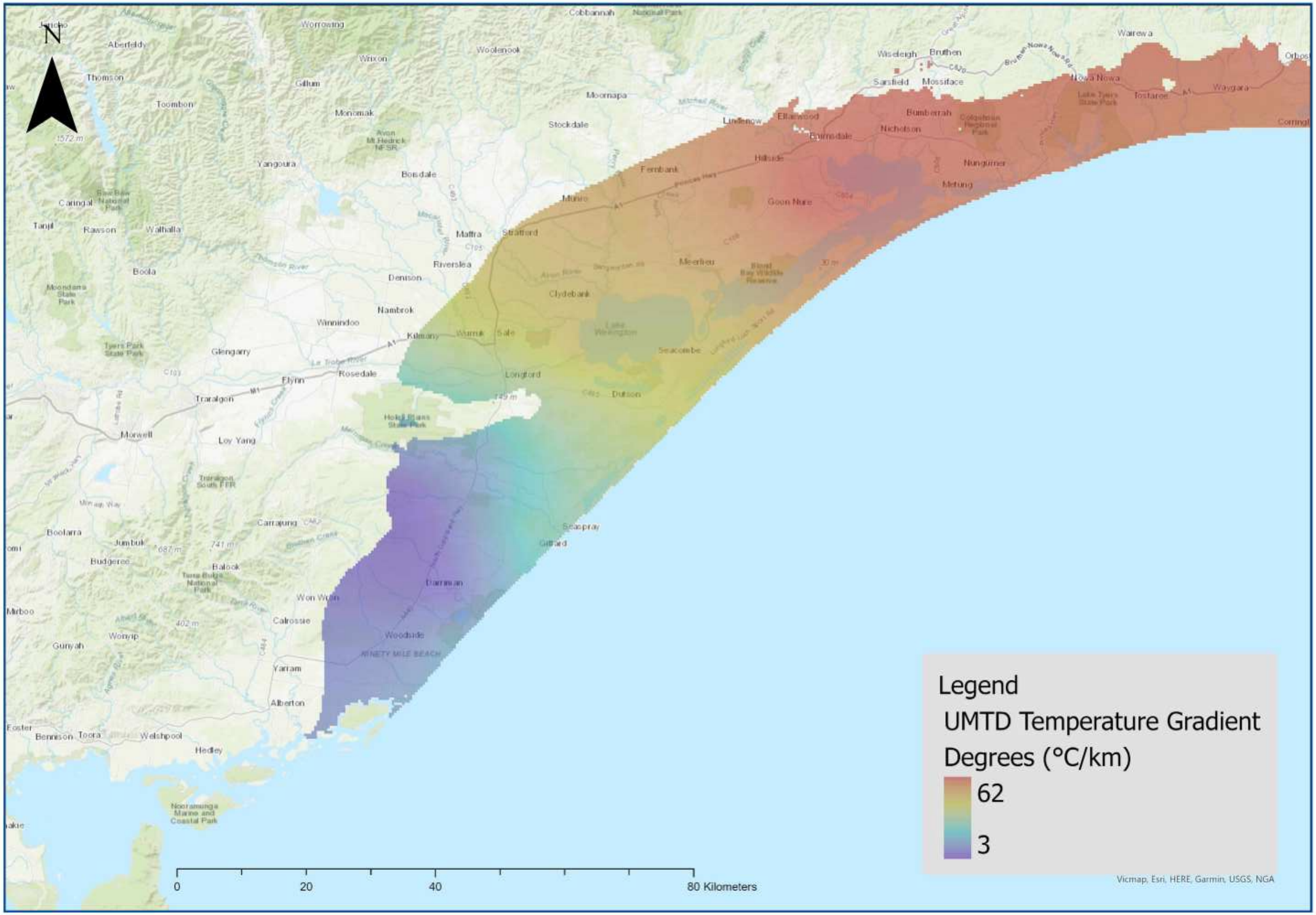

Figure 4.11 Temperature gradient in the Upper mid-Tertiary Aquitard (UMTD).

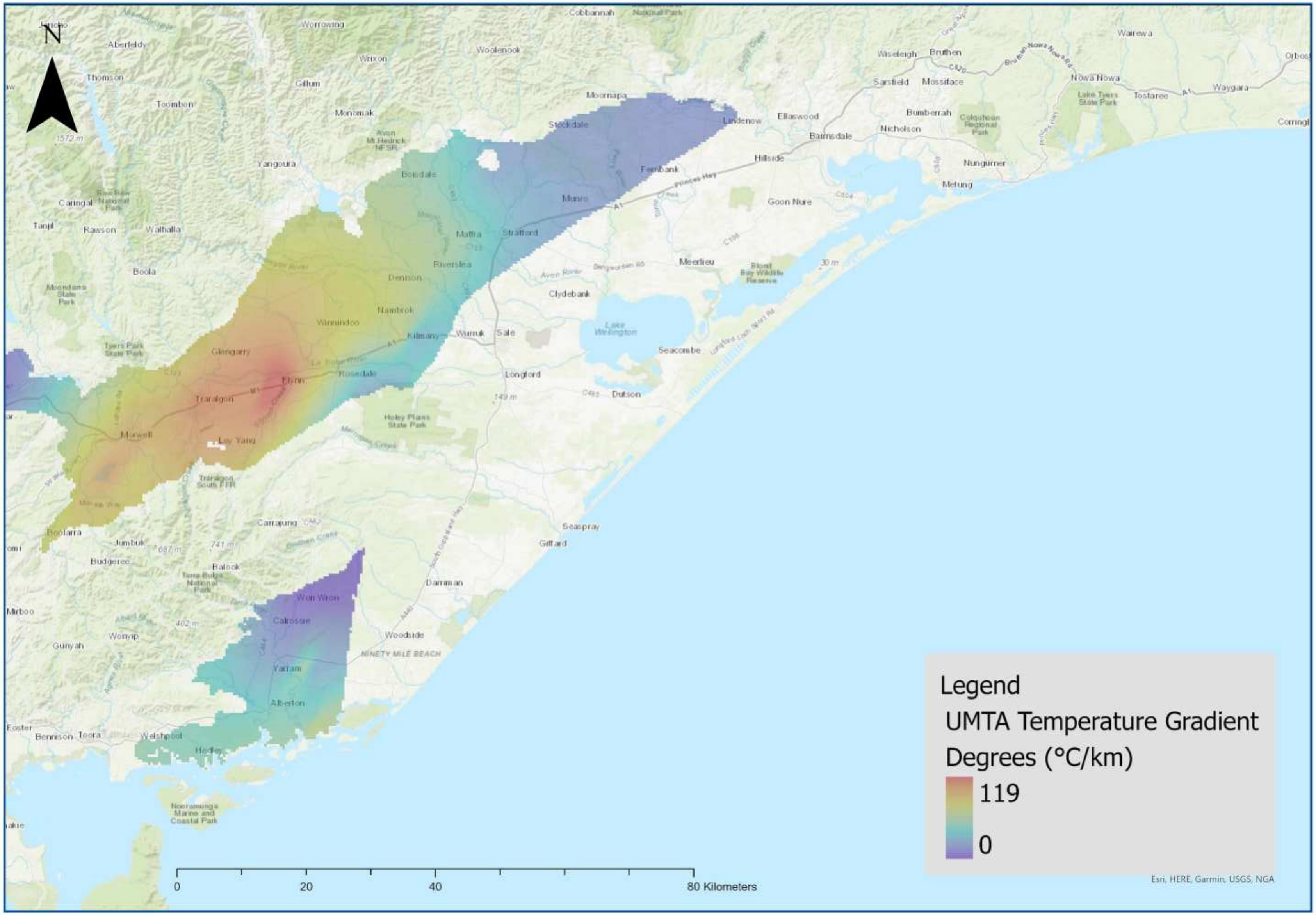

Figure 4.12 Temperature gradient in the Upper mid-Tertiary Aquifer (UMTA).

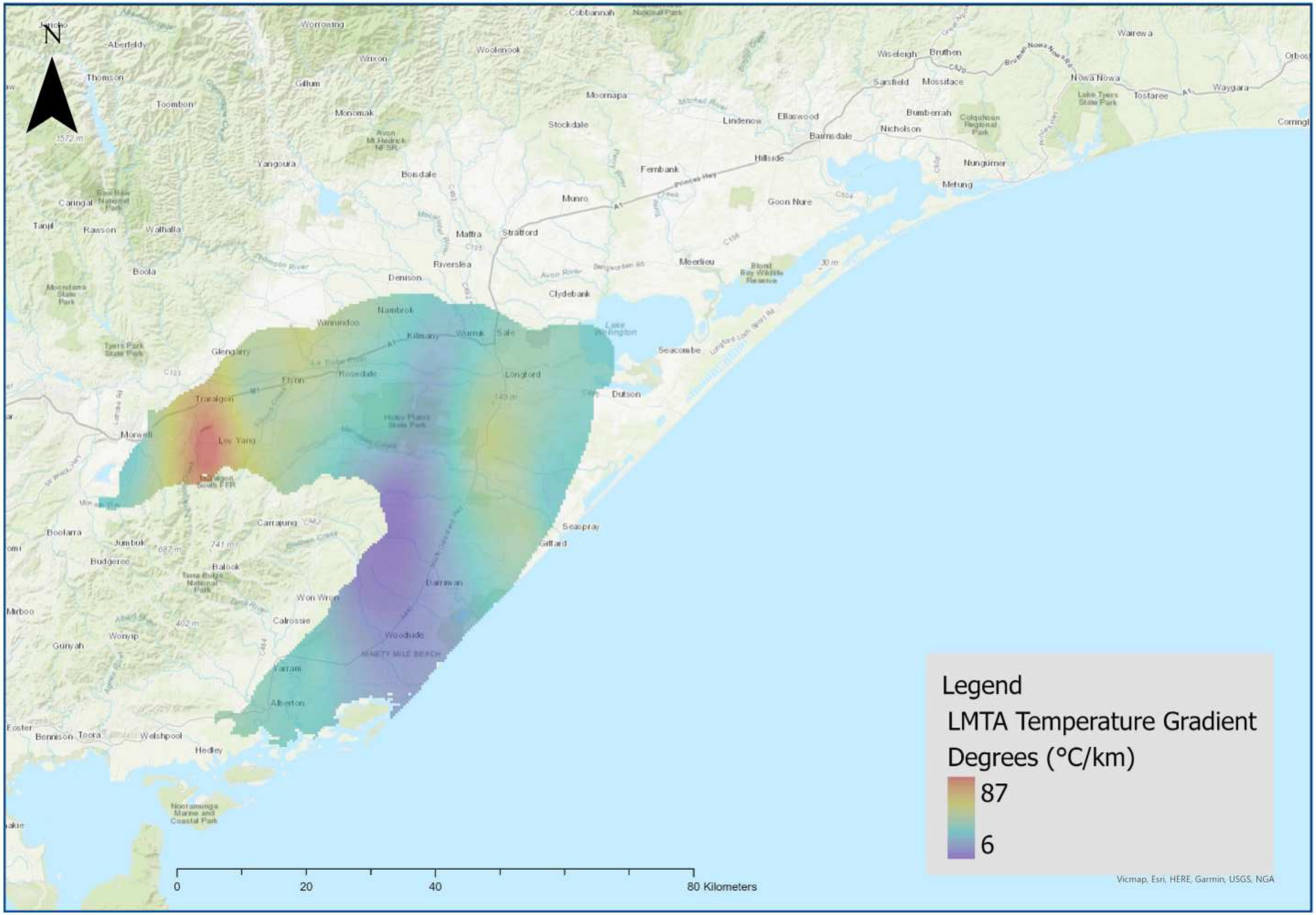

Figure 4.13 Temperature gradient in the Lower mid-Tertiary Aquifer (LMTA).

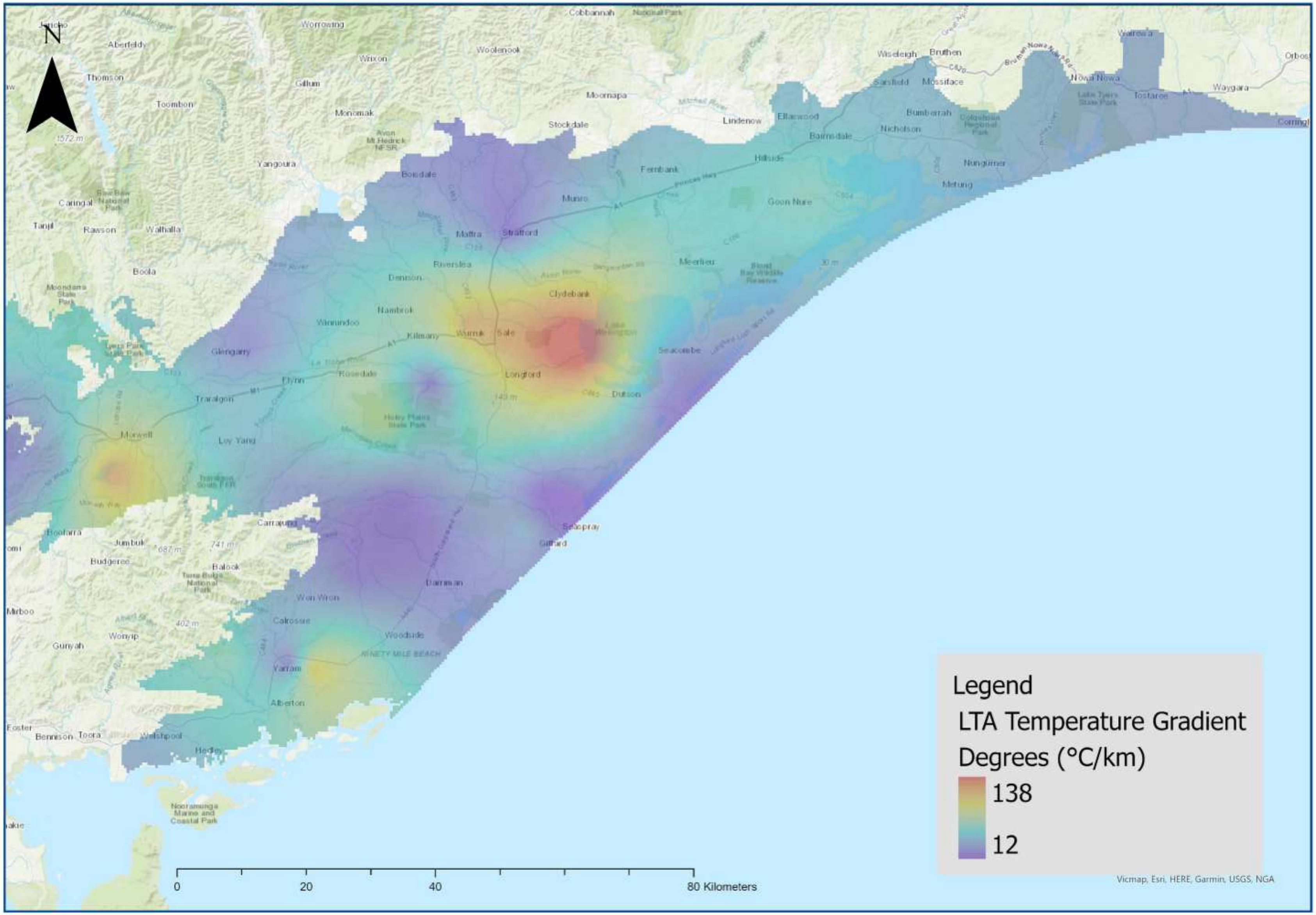

Figure 4.14 Temperature gradient in the Lower Tertiary Aquifer (LTA).

4.5. Depth to top of aquifers

Depth to the top of aquifer provides an estimate of the drilling depth required to intersect the top of each of the Gippsland aquifers (UTQA, UTAF, UMTA, LMTA, LTA). These have been produced because drilling comprises a significant portion of development cost associated with geothermal projects and depth is a major factor determining drilling cost. The depth grids were produced by subtracting the relevant top of aquifer grid from the digital elevation model. Smoothing has been applied to remove minor landscape artefacts. All grids used in their creation were sourced from the VAF (GHD, 2012 & SKM, 2009) through the subtraction of the aquifer top from the digital elevation model. .

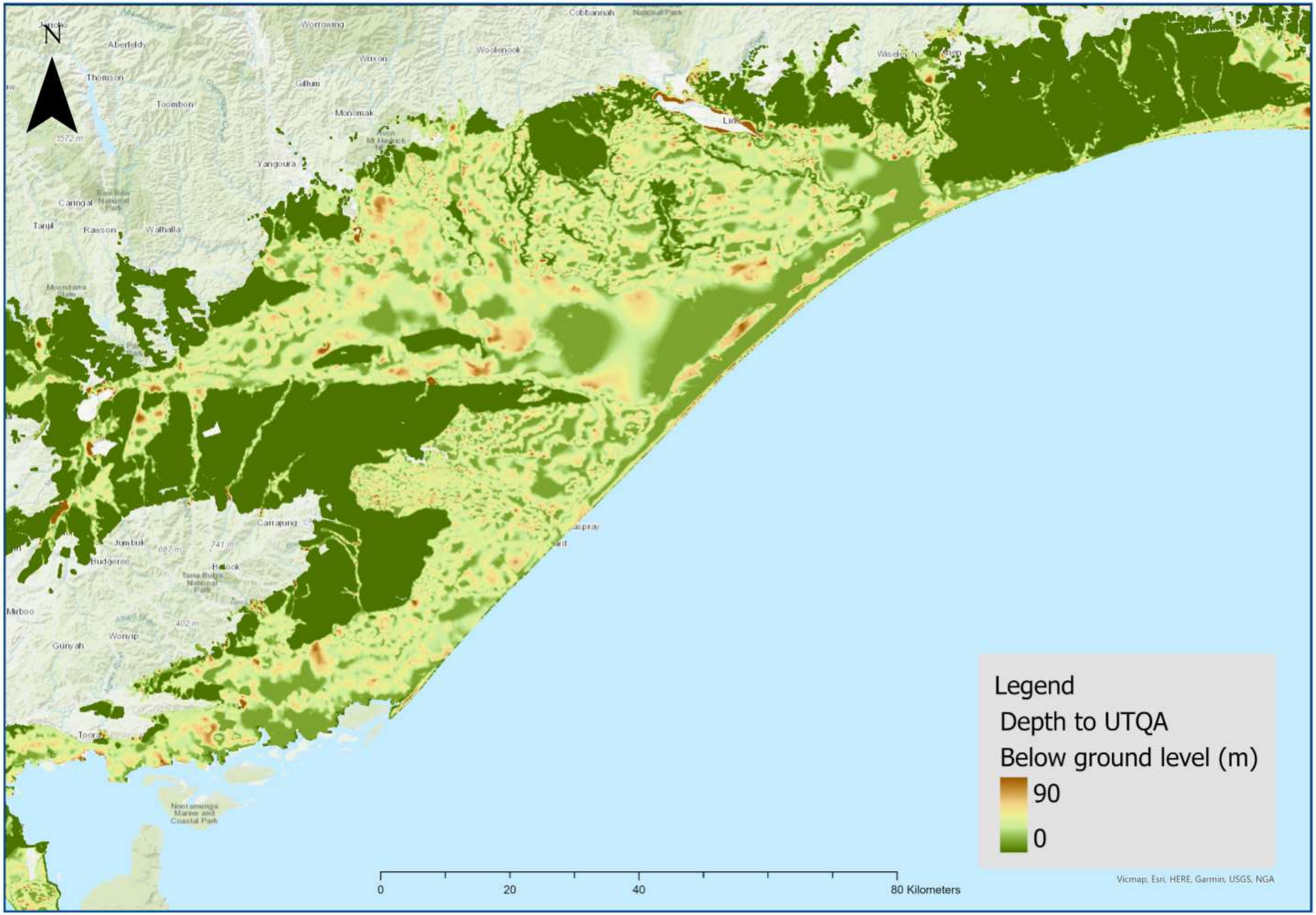

Figure 4.15 Depth to top of UTQA.

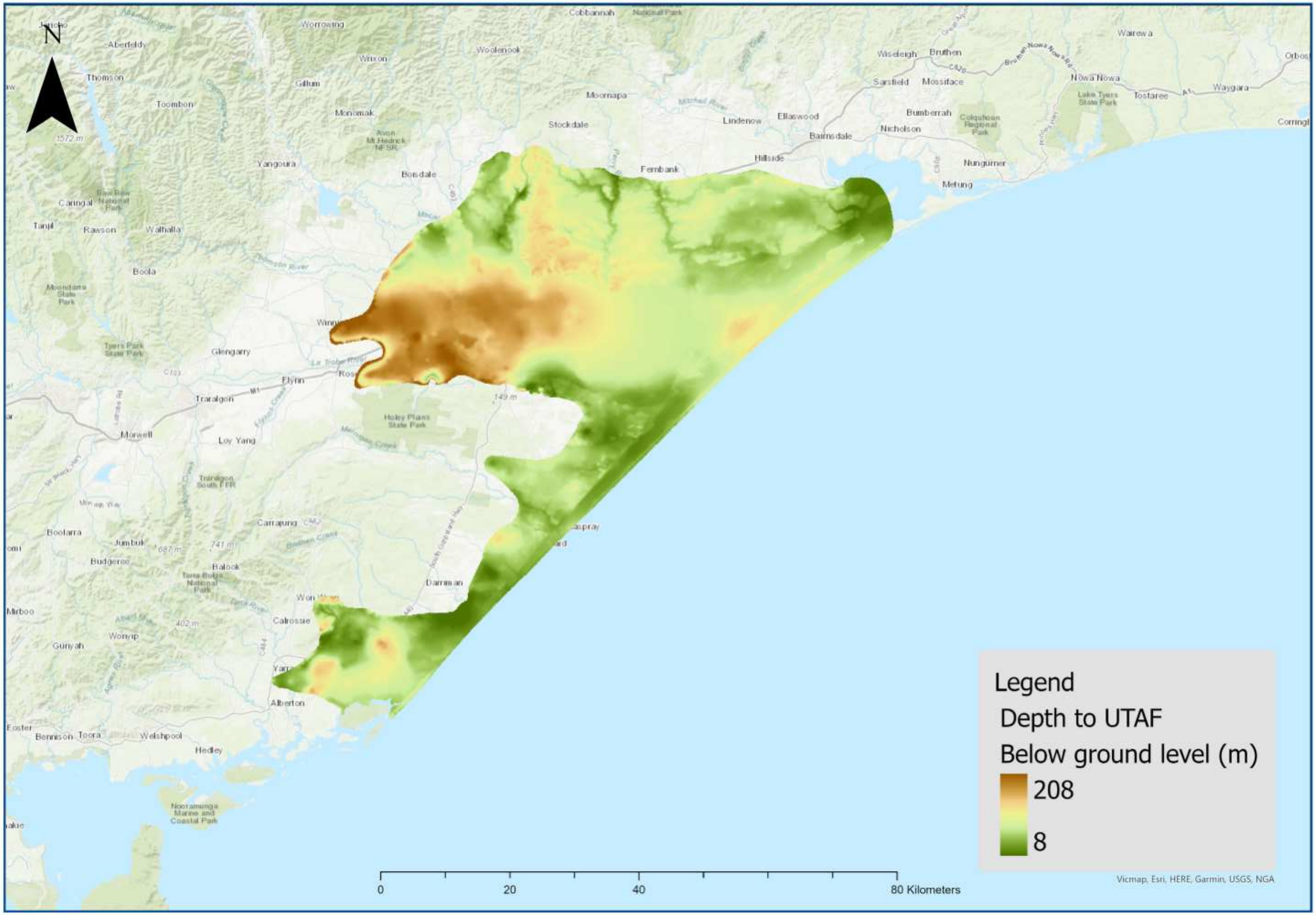

Figure 4.16 Depth to top of UTAF.

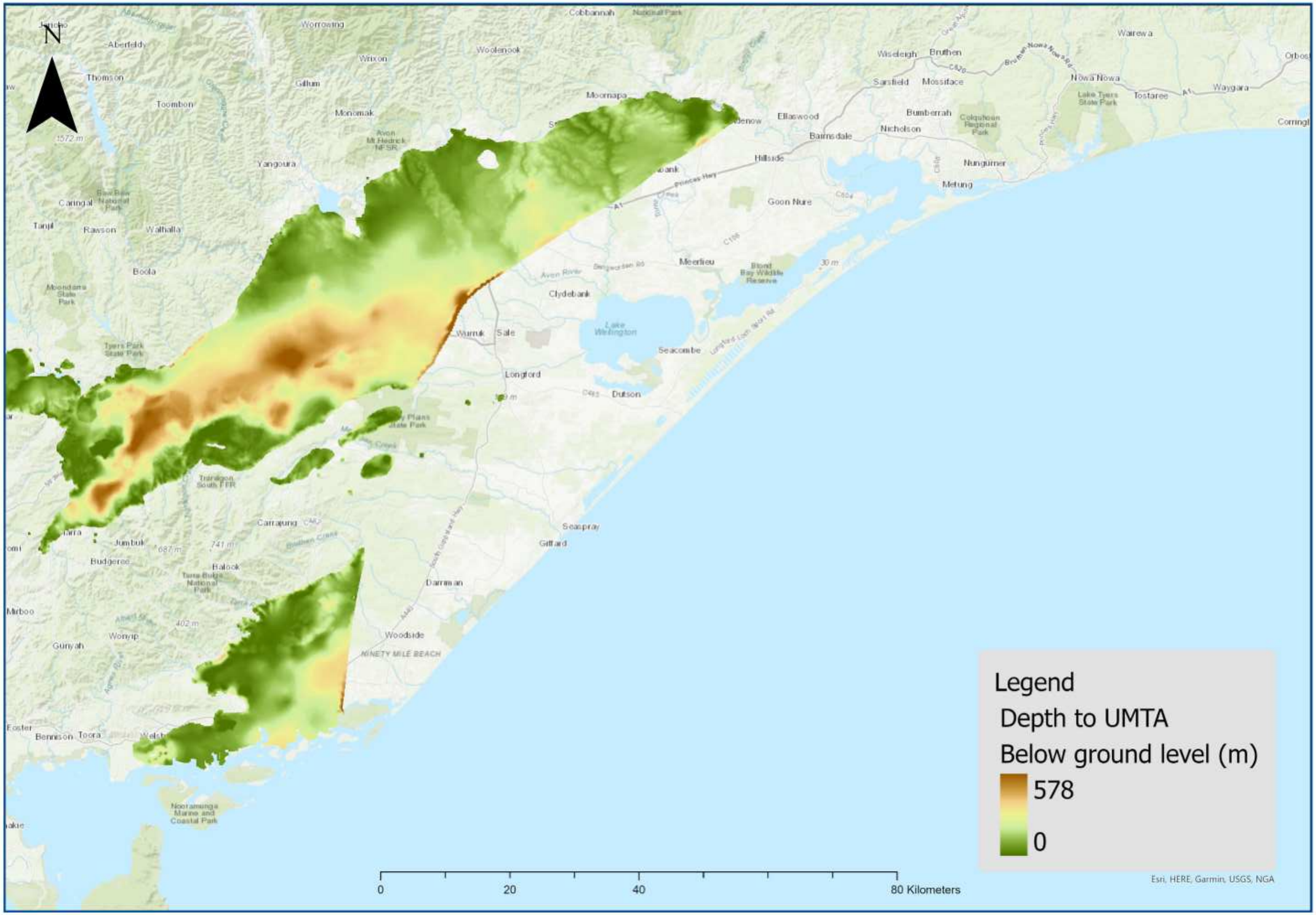

Figure 4.17 Depth to top of UMTA.

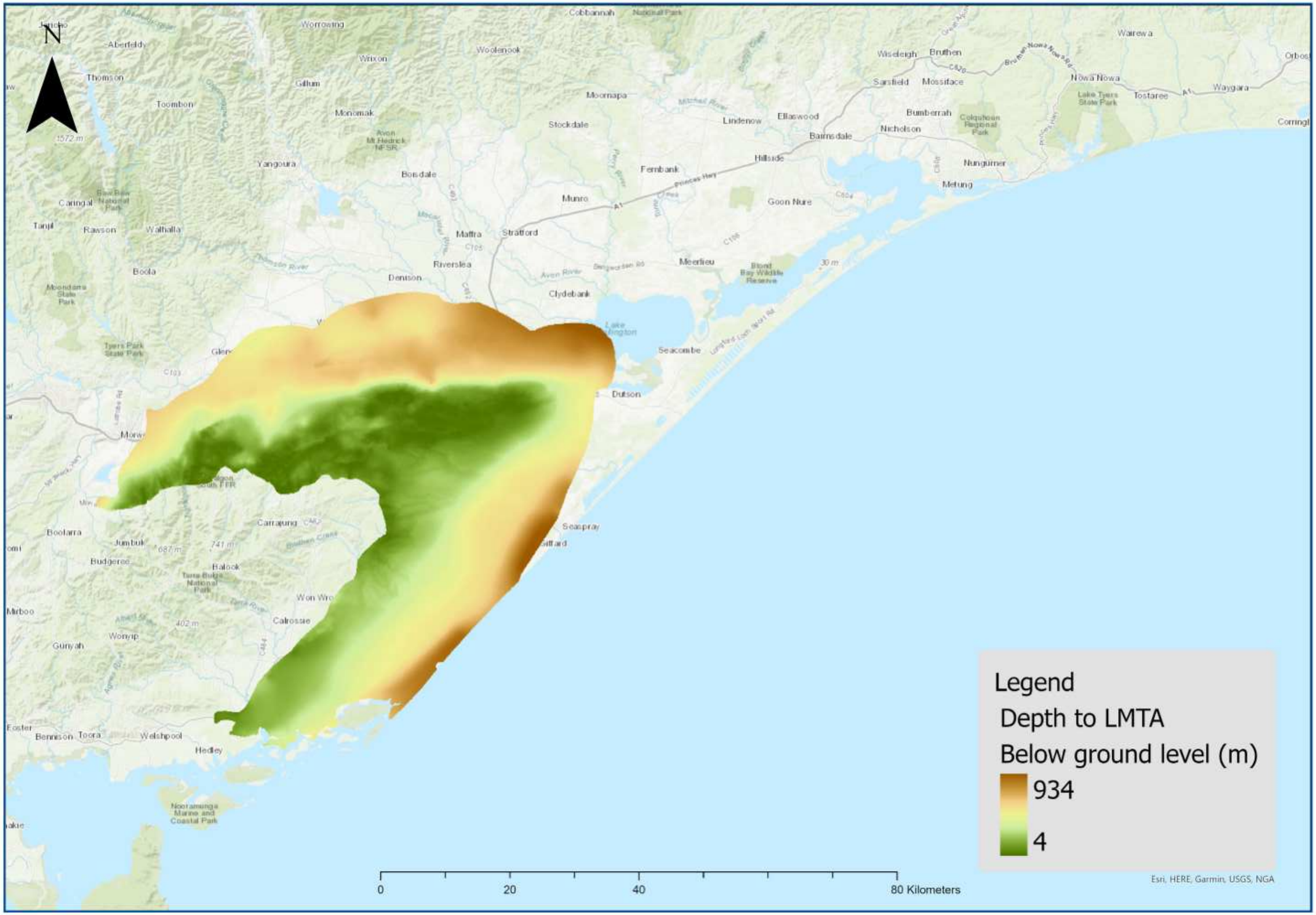

Figure 4.18 Depth to top of LMTA.

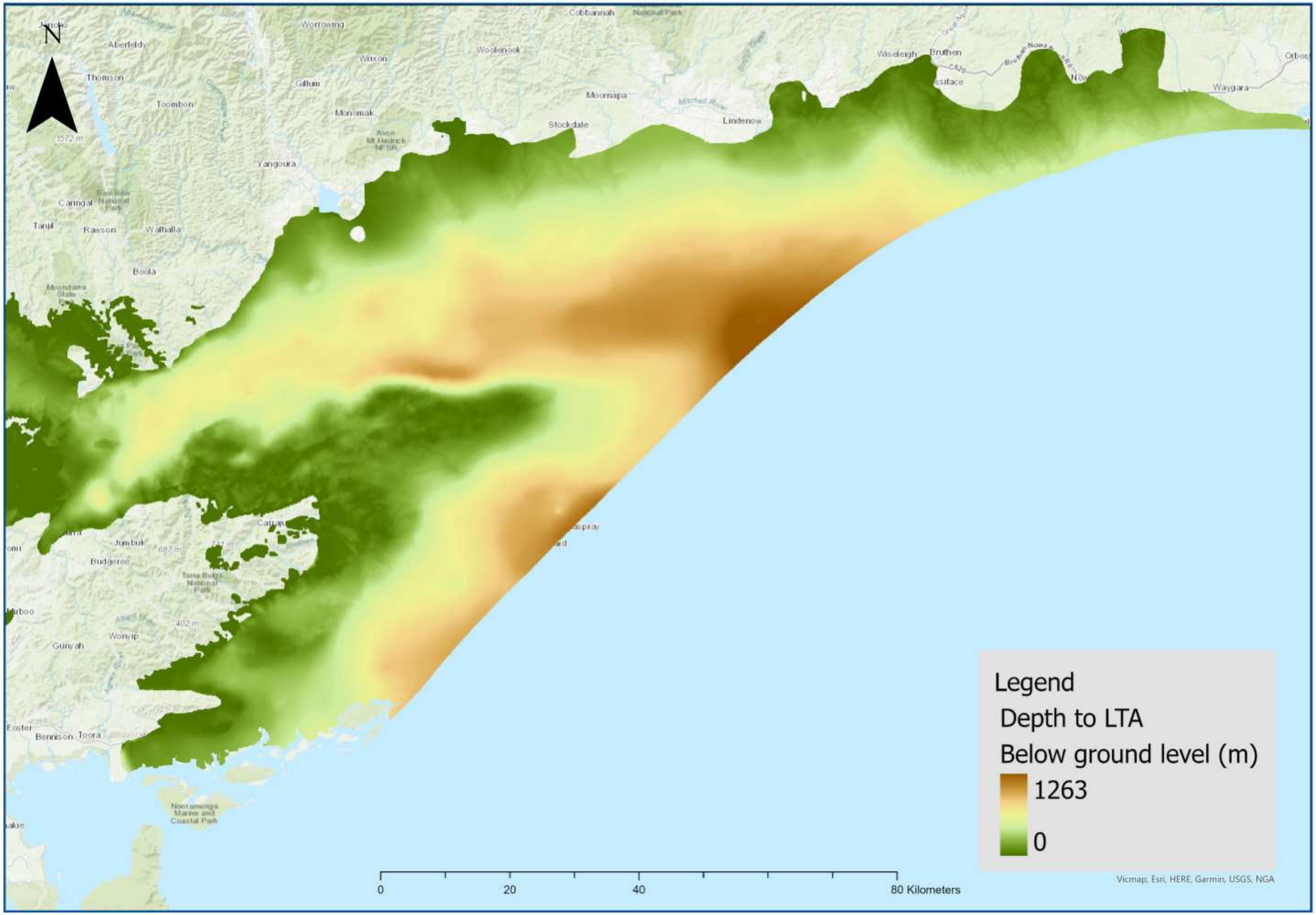

Figure 4.19 Depth to top of LTA.

4.6. Hydraulic conductivity

Hydraulic conductivity is an important parameter for calculating the potential yield of a geothermal well. Hydraulic conductivity can vary widely within aquifers due to changes in lithology, sorting and diagenesis. The values presented in Table 4.1 are summarised from Beverly et al. (2015) and Hocking et al. (2020) and represent a good estimate of the likely mid-point for each of the aquifers and aquitards. The range of potential hydraulic conductivity values are discussed in Hocking et al. (2020).

Table 4.1 Hydraulic conductivity for geothermal aquifers.

Aquifer/aquitard	Hydrogeological units	Hydraulic conductivity (m/day)
Upper Tertiary Quaternary Aquifer (UTQA)	Haunted Hill Formation, Eagle Point Sand	1
Upper Tertiary Quaternary Aquitard (UTQD)	Boisdale Formation (Nuntin Clay)	0.1
Upper Tertiary Aquifer Fluvial (UTAF)	Boisdale Formation (Wurruk Sand)	1
Upper Tertiary Aquitard (UTD)	Jemmy's Point Formation and upper Hazelwood Formation	1
	Yallourn coal seam	0.0001
	Yallourn aquifer	1
Upper mid-Tertiary Aquifer (UMTA)	Balook Formation, Tambo River Formation, Wuk Wuk Marl, Gippsland Limestone	1
	Morwell 1A coal	0.0001
	Morwell 1A interseam	5
	Morwell 1B coal	0.0001
	Morwell 1B interseam	5
	Morwell 2 coal seam	0.5
Upper mid-Tertiary Aquitard (UMTD)	Giffard Sandstone Member, Gippsland Limestone, Lakes Entrance Formation, Seaspray Group, Tambo River Formation	1
Lower mid-Tertiary Aquifer (LMTA)	Morwell 2 coal seam aquifer – (Rosedale, Lake Wellington Depression, Seaspray Depression, Traralgon Syncline) and Seaspray Group sands.	5
Lower Tertiary Aquifer (LTA)	Upper Latrobe Group, (Morwell 2 coal seam aquifer – when basal aquifer)	10
	Lower Latrobe T1 coal	0.005
	Lower Latrobe T1 aquifer	6.5
	Lower Latrobe T2 coal	0.005
	Lower Latrobe T2 aquifer	4.5

4.7. Transmissivity

From transmissivity values the potential flux of groundwater through an aquifer can be estimated. This enables calculation of aquifer yield and modelling of cold-water plumes. The transmissivity data presented in Figures 4.20 to 4.28 are based on the assumed hydraulic conductivity values presented in Table 4.1 and aquifer isopachs as modelled in Hocking et al. (2020). Aquifer isopachs are based on the VAF (GHD, 2012 & SKM, 2009) and the Latrobe Valley Coal Model (Jansen et al., 2003). These models were built from different datasets and as a result there is considerable uncertainty in places.

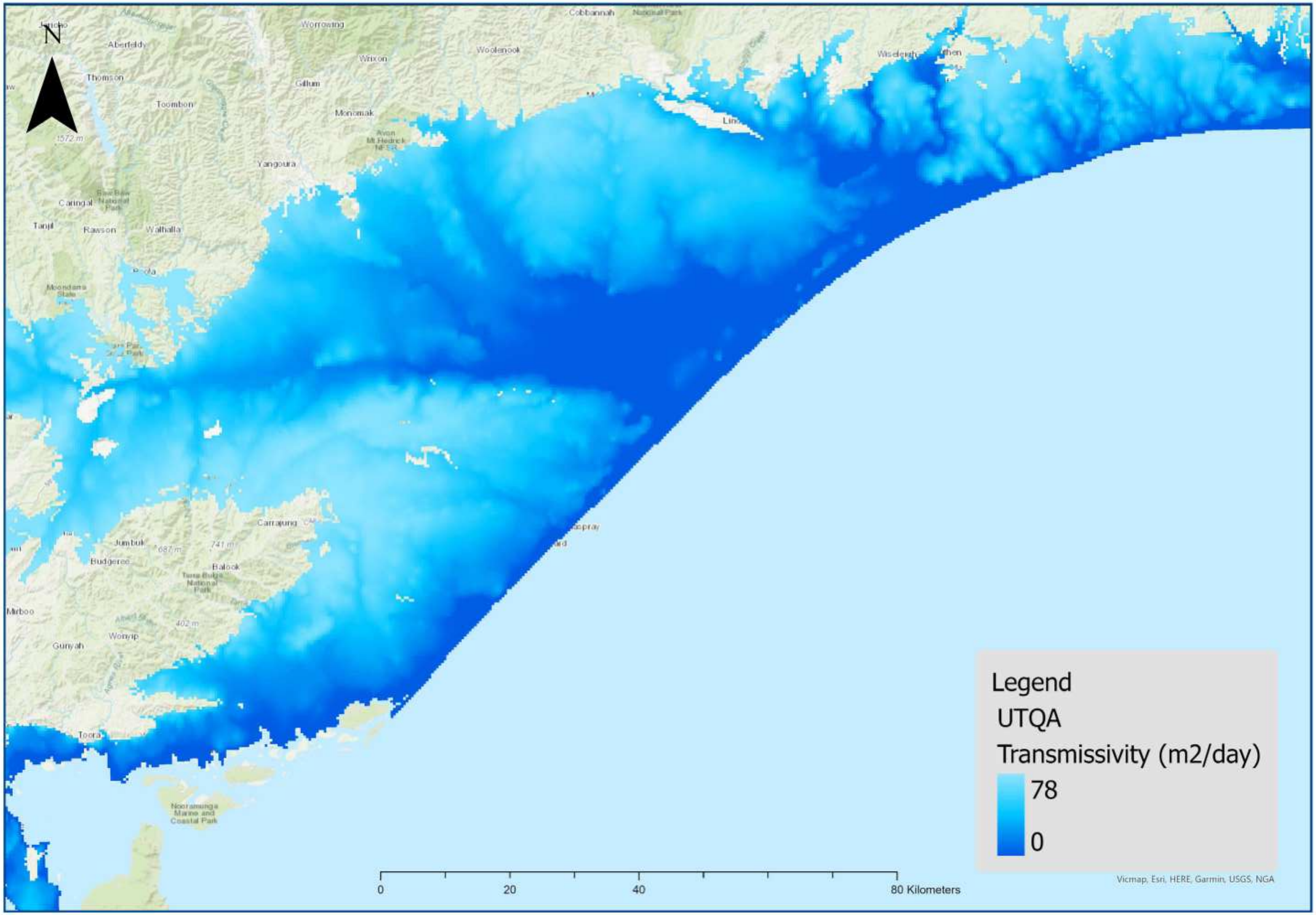

Figure 4.20 Transmissivity of the UTQA (Hocking et al., 2020).

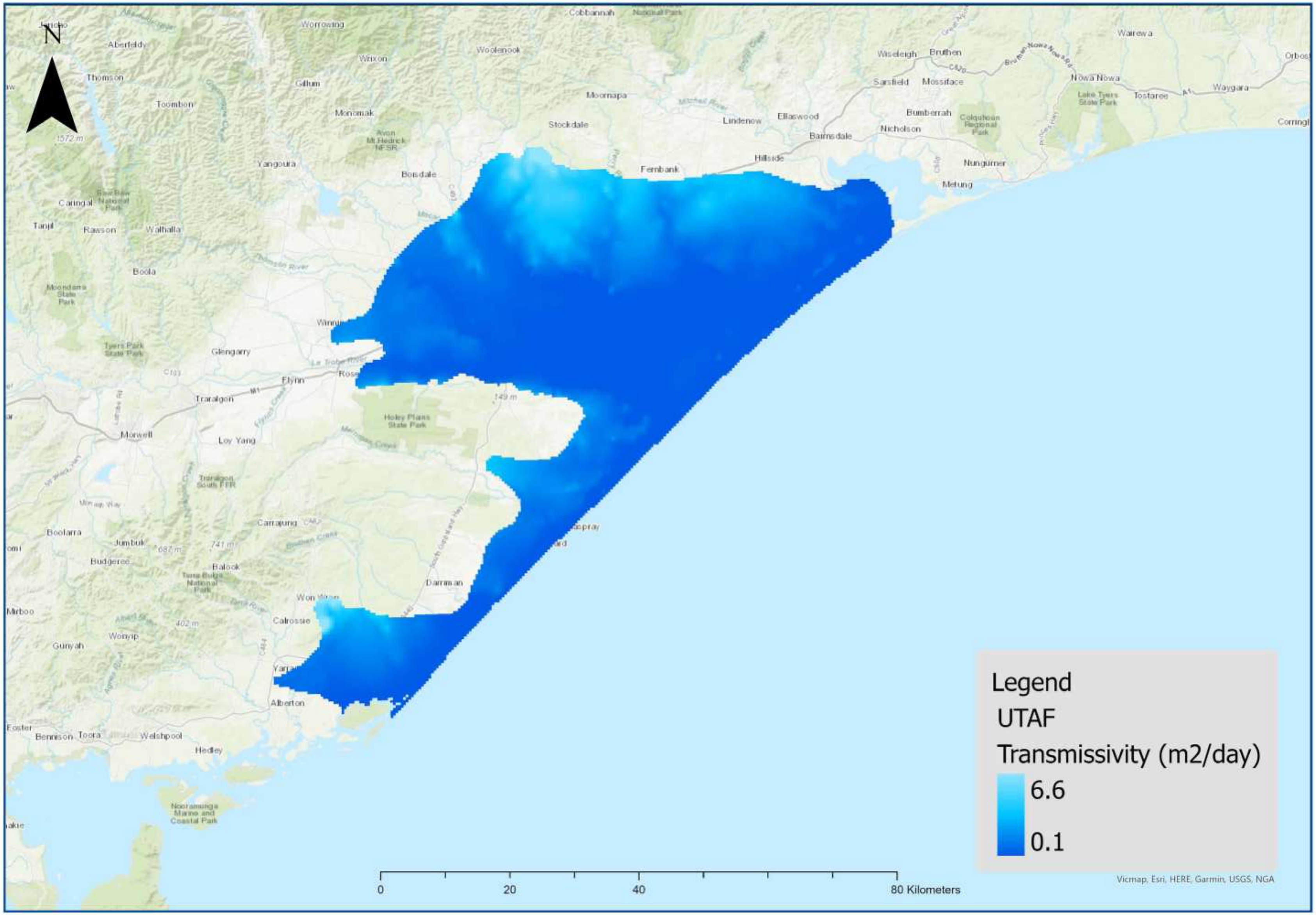

Figure 4.21 Transmissivity of the UTAF (Hocking et al., 2020).

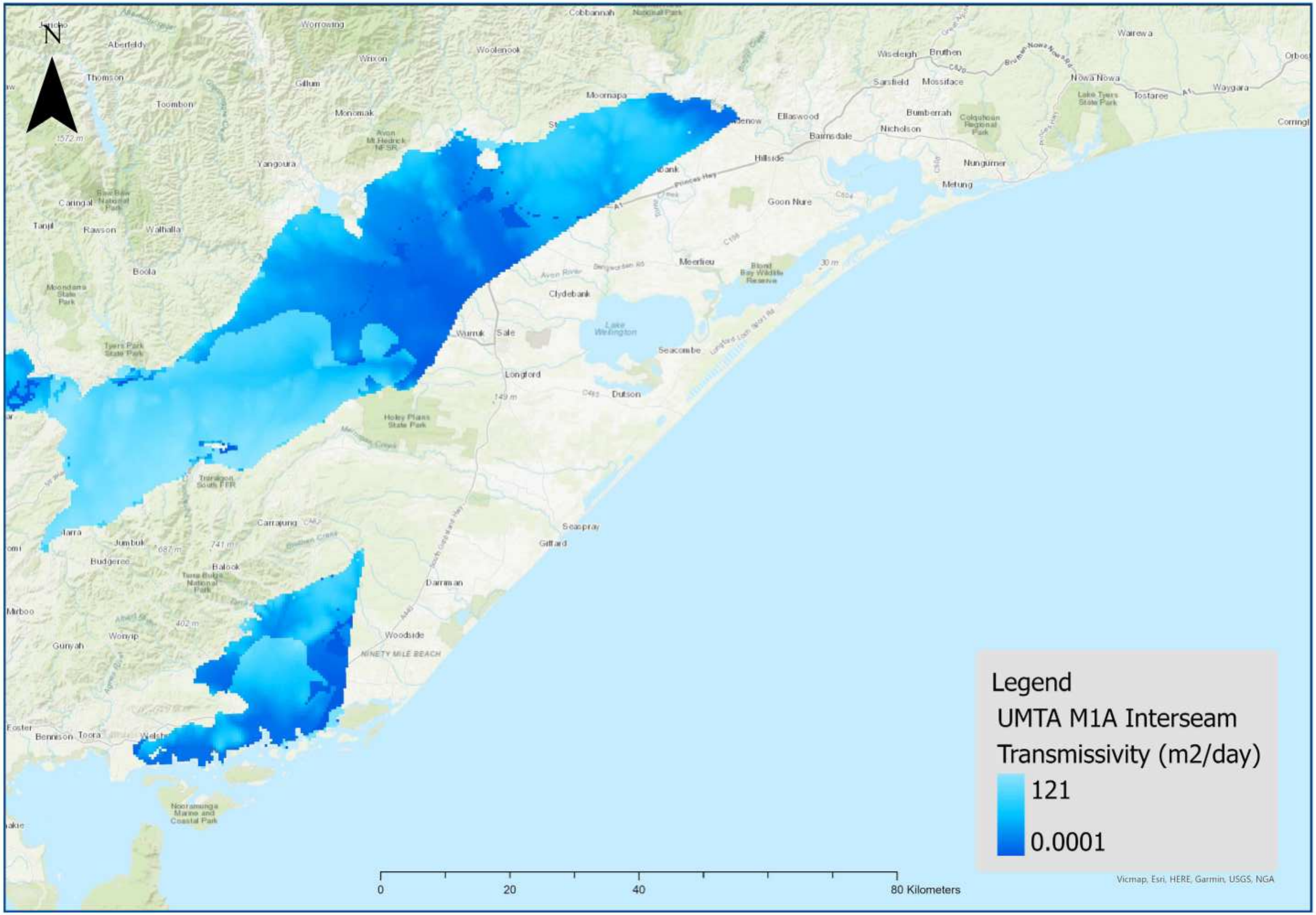

Figure 4.22 Transmissivity of the UMTA M1A aquifer (Hocking et al., 2020).

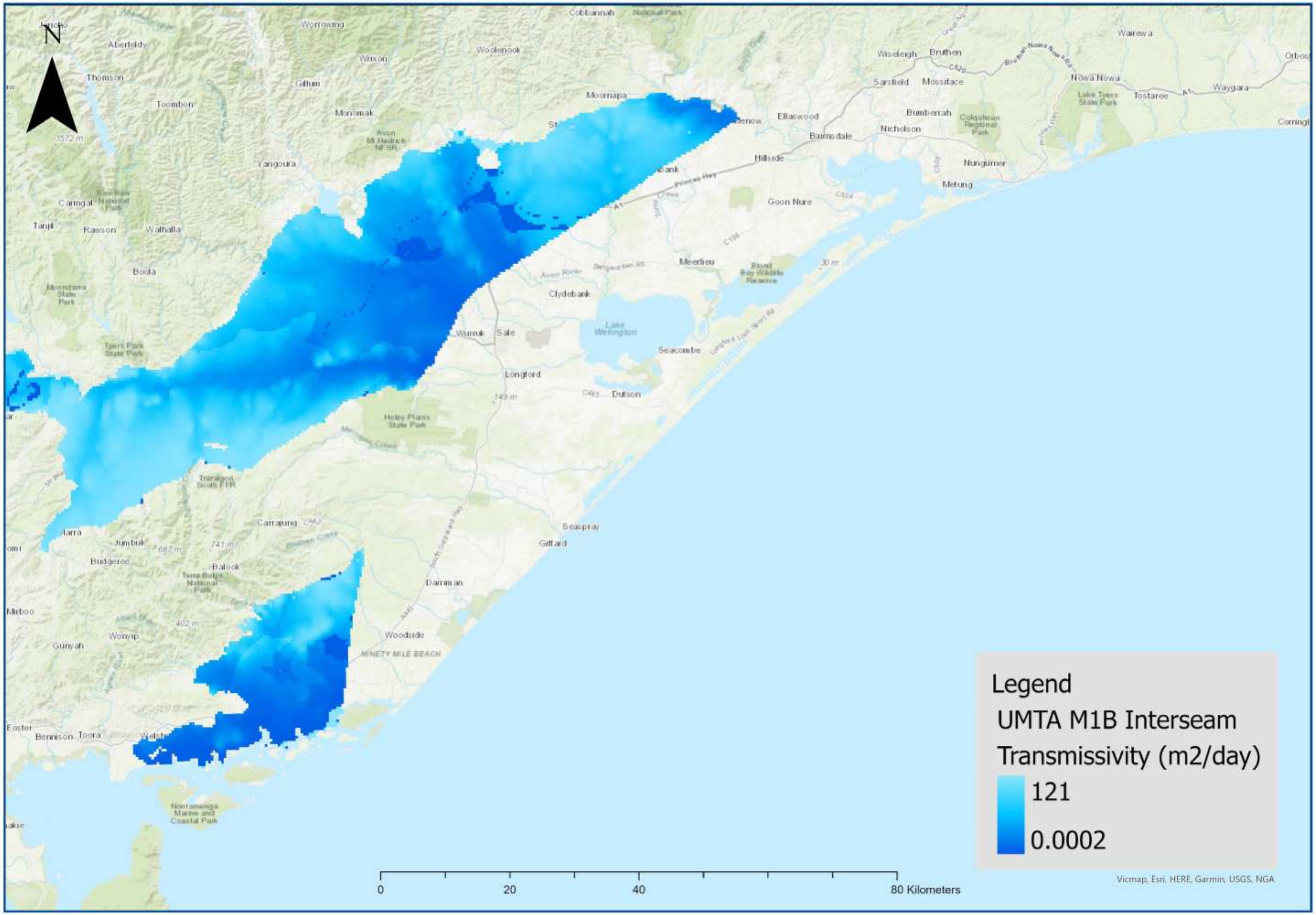

Figure 4.23 Transmissivity of the UMTA M1B aquifer (Hocking et al., 2020).

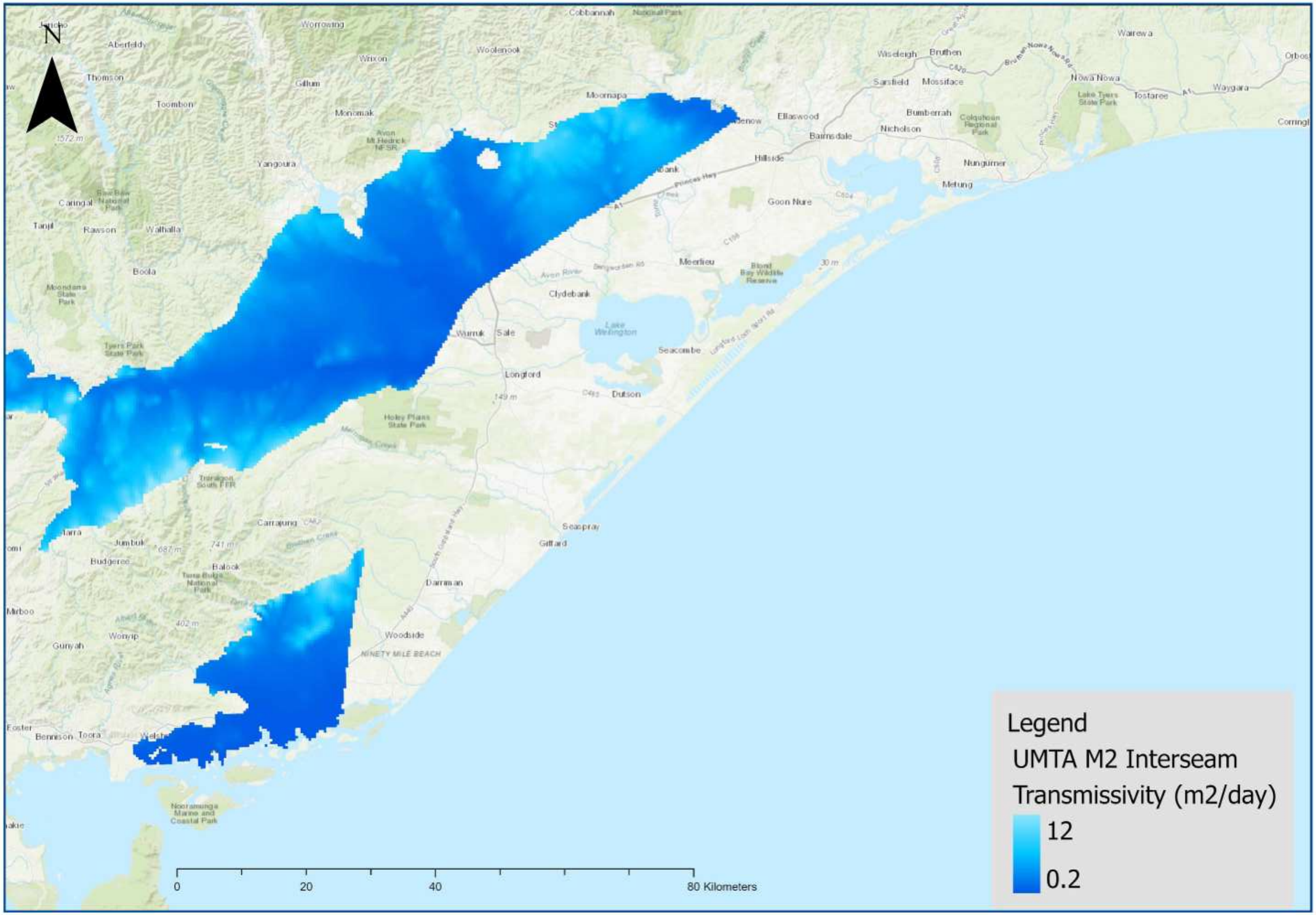

Figure 4.24 Transmissivity of the UMTA M2 aquifer (Hocking et al., 2020).

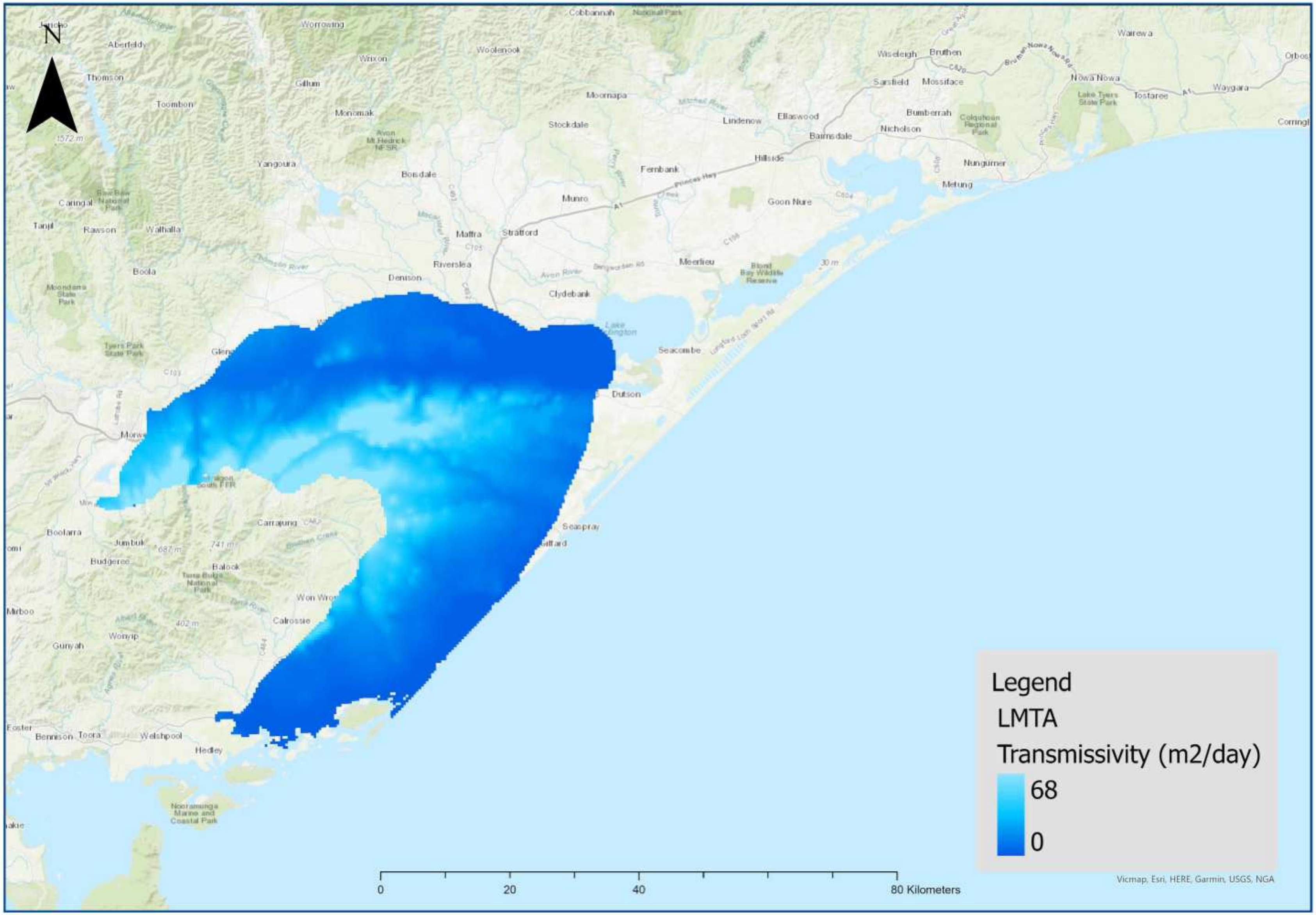

Figure 4.25 Transmissivity of the LMTA aquifer (Hocking et al., 2020).

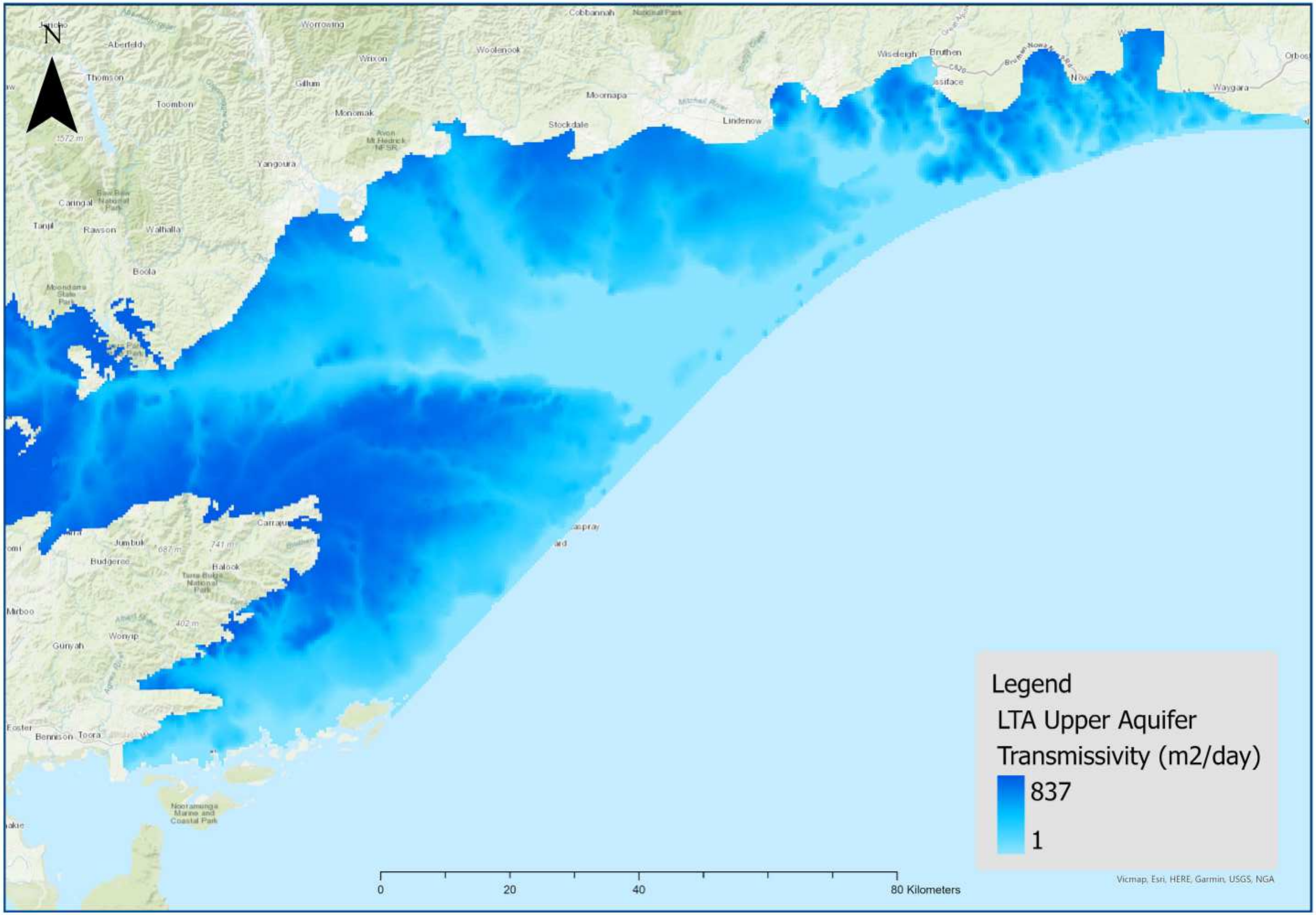

Figure 4.26 Transmissivity of the LTA upper aquifer (Hocking et al., 2020).

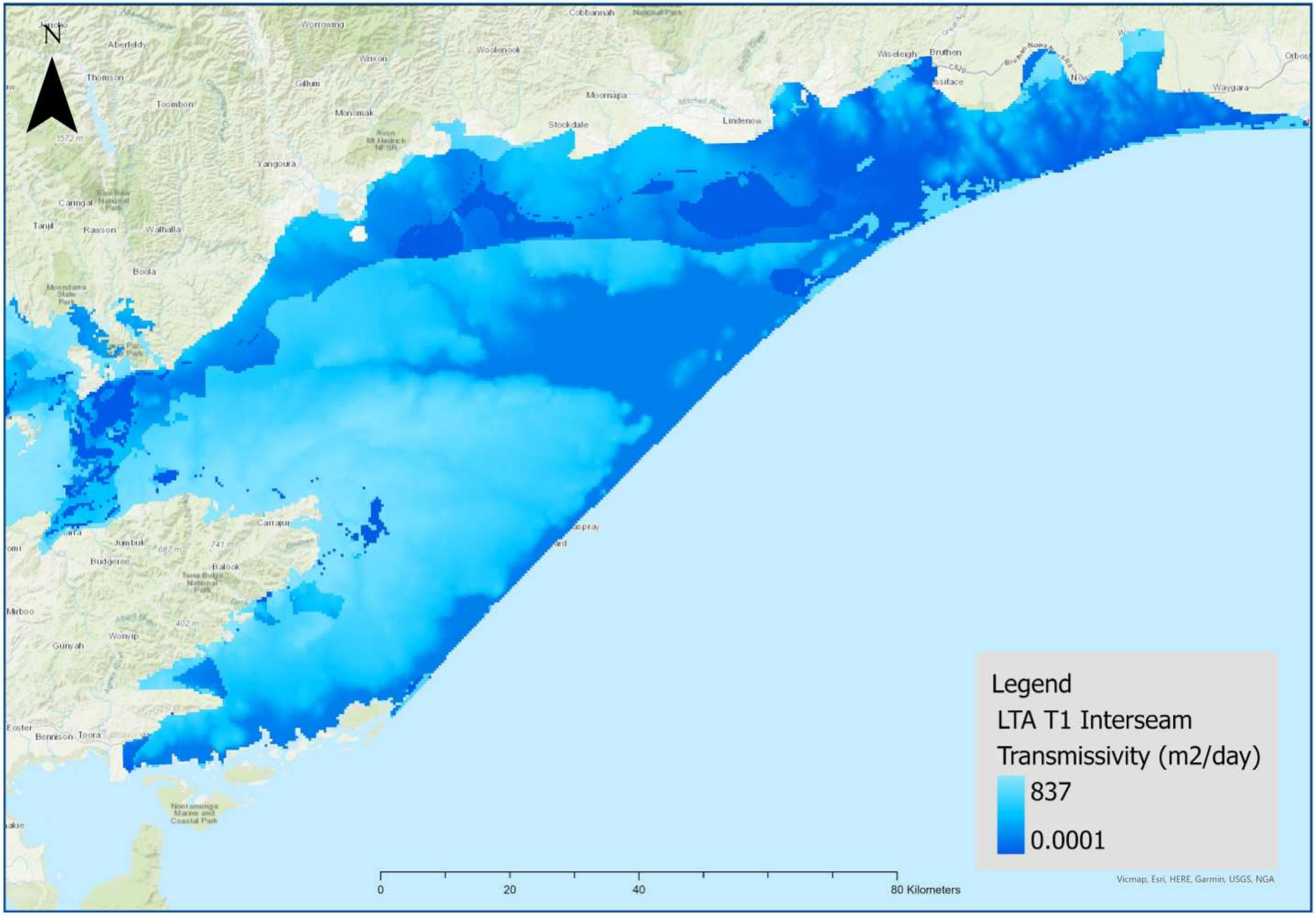

Figure 4.27 Transmissivity of the LTA T1 aquifer (Hocking et al., 2020).

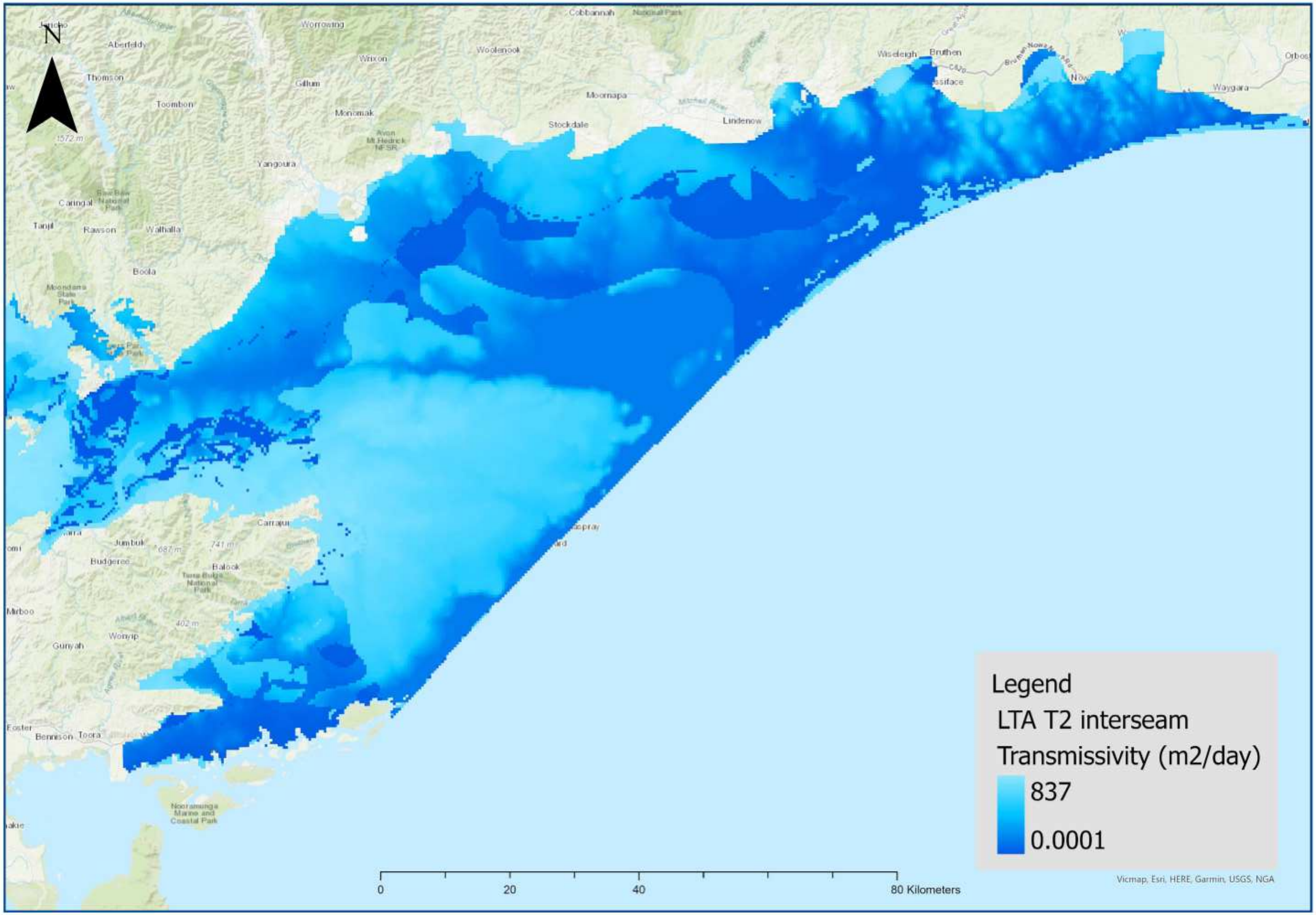

Figure 4.28 Transmissivity of the LTA T2 aquifer (Hocking et al., 2020).

4.8. Groundwater quality

Groundwater quality data was compiled by SKM (2014) for all the VAF aquifers in Gippsland. The data show groundwater quality is generally high for deeper aquifers but lower for shallower aquifers (Figures 4.29-4.33).

UTQA

Within the UTQA groundwater is of moderate quality with extensive areas having a of total dissolved solids (TDS) of 3,500 mg/l, although reaching 20,000 mg/l near Lake Wellington.

UTAF

Within the UTAF groundwater quality is generally high with the TDS generally ranging between 500 mg/l and 1,000 mg/l. Along the coast and near the western end of the basin, salinity frequently reaches 3,500 mg/L and occasionally 13,500 mg/l.

UMTA

Within the UMTA groundwater quality is generally high with TDS ranging between 500 mg/l and 1,000 mg/l. In shallow sections that are more exposed to modern recharge TDS increases to 3,500 mg/l. Near Alberton the TDS also increases to 3,500 mg/l.

LMTA

Within the LMTA groundwater quality is generally very high with TDS below 500 mg/l. In deeper sections along the northern margin the TDS increases to 1,000 mg/l.

LTA

Within the LTA groundwater quality improves from east to west with large volumes of water within the Latrobe Valley have TDS below 500 mg/l. A portion of the LTA near Alberton has considerably higher TDS.

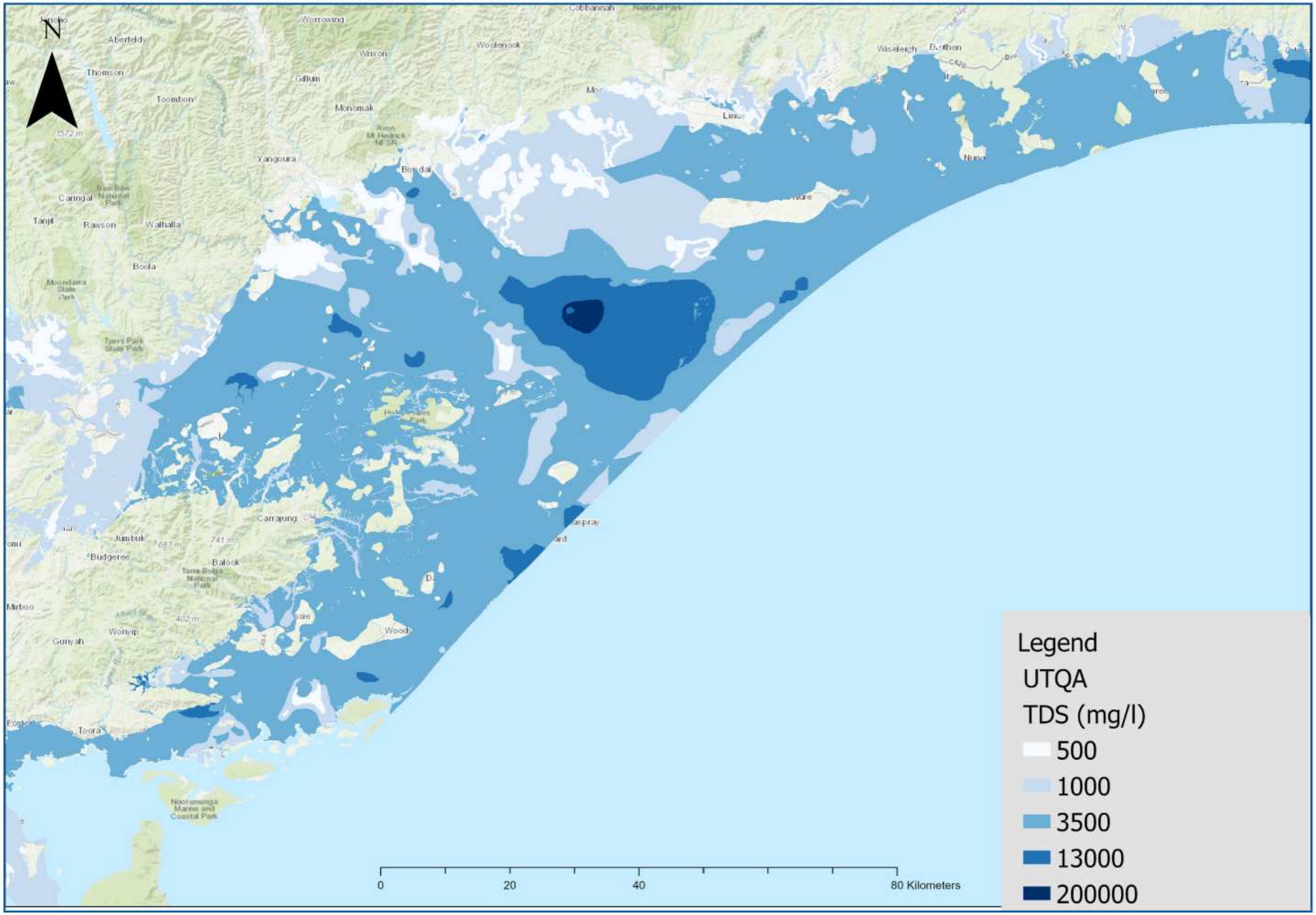

Figure 4.29 Total dissolved solids or groundwater in the UTQA (SKM, 2014).

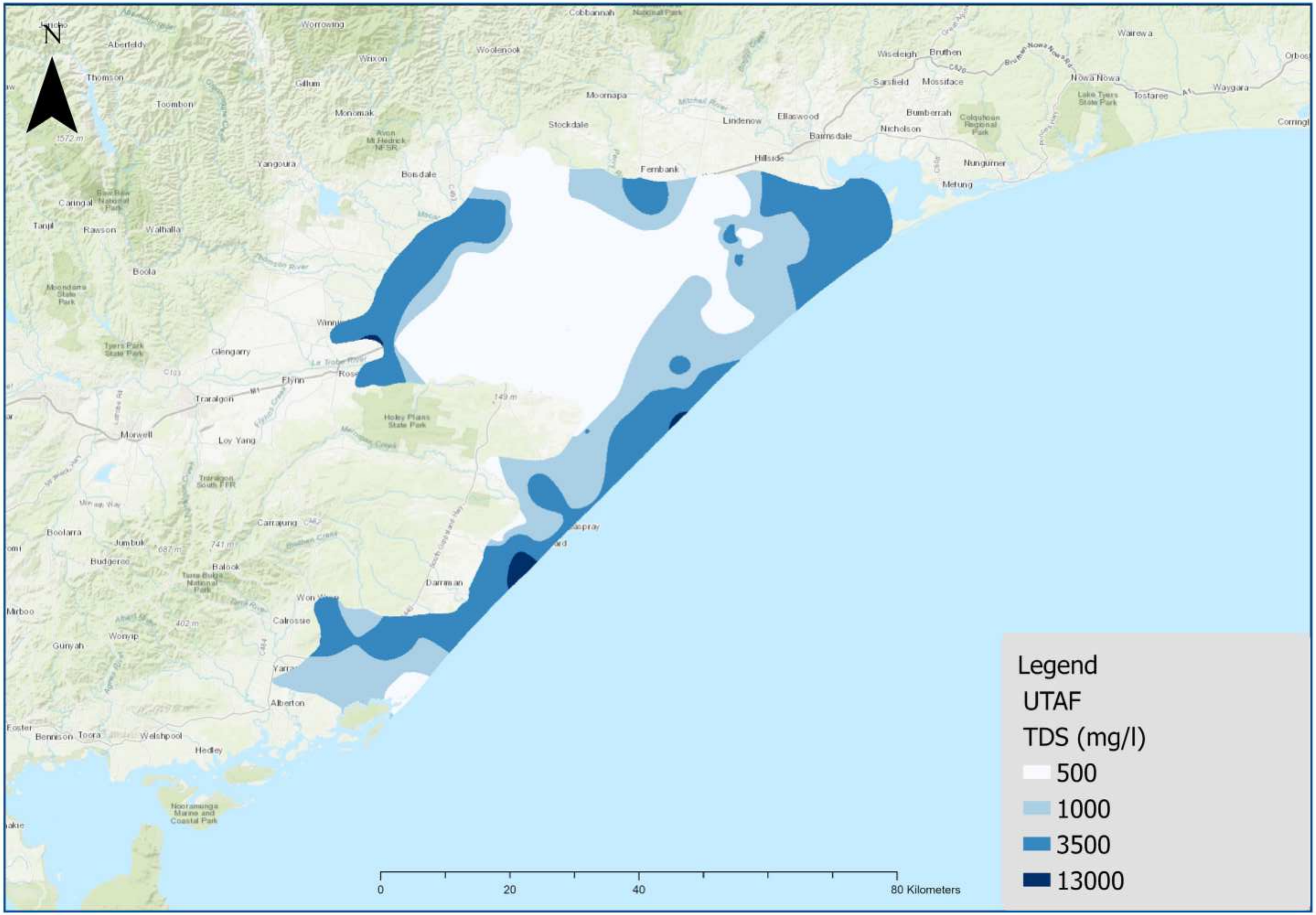

Figure 4.30 Total dissolved solids for groundwater in the UTAF (SKM, 2014).

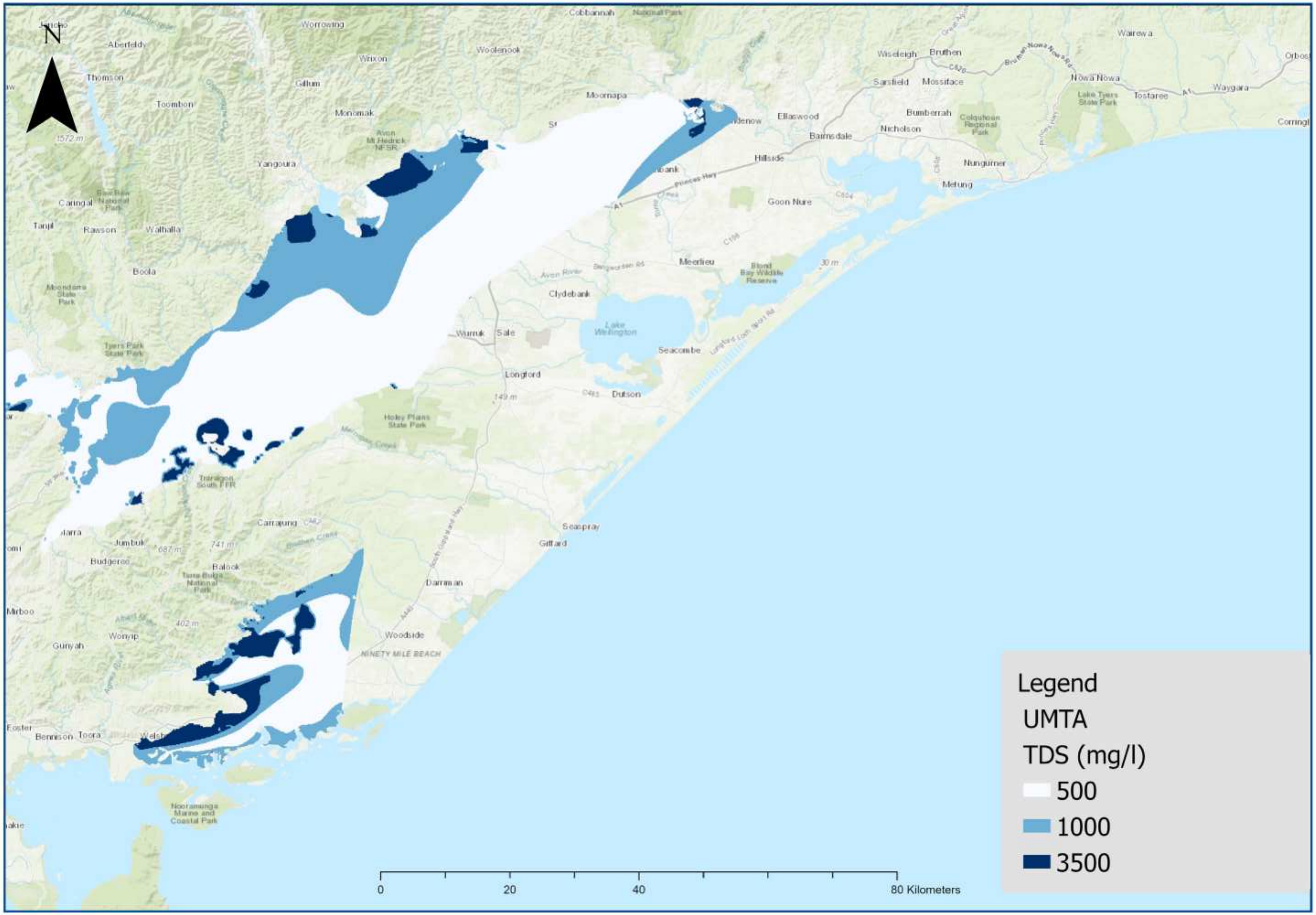

Figure 4.31 Total dissolved solids for groundwater in the UMTA (SKM, 2014).

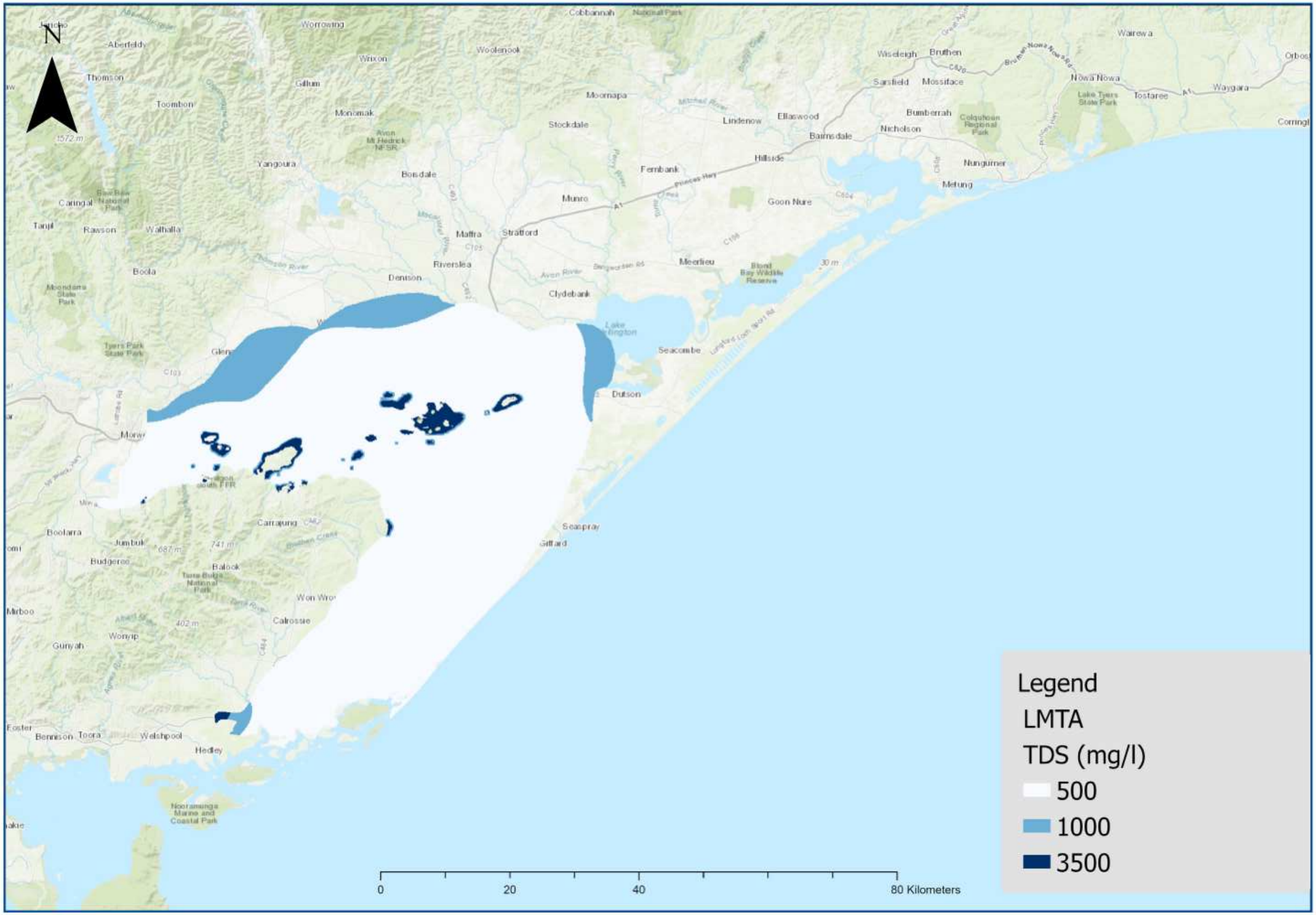

Figure 4.32 Total dissolved solids for groundwater in the LMTA (SKM, 2014).

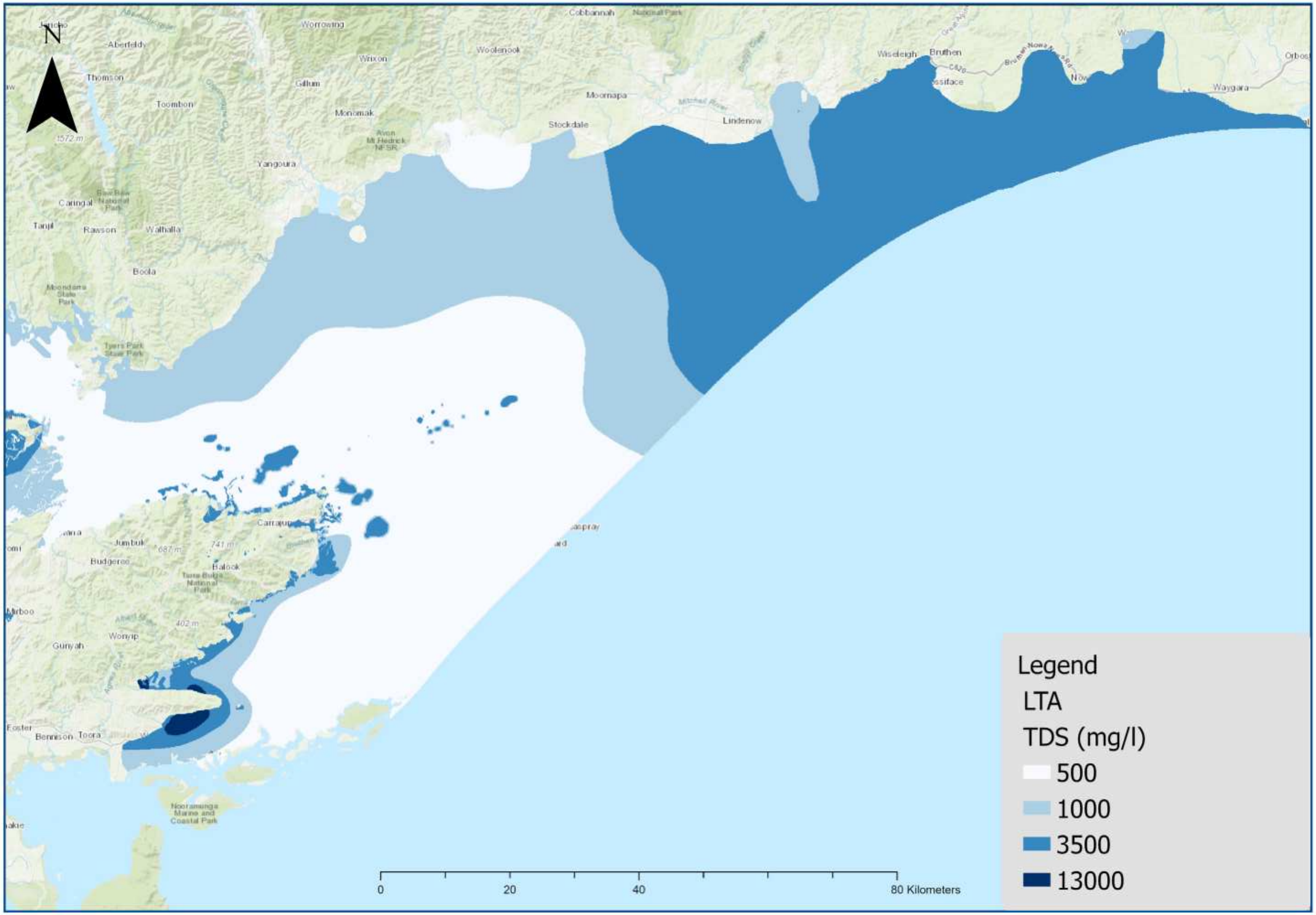

Figure 4.33 Total dissolved solids for groundwater in the LTA (SKM, 2014).

5. Discussion and conclusions

This study was undertaken to map the temperature, depth, and distribution of shallow geothermal resources in Gippsland and to underpin the development of a desktop-based tool for modelling the economics of potential uses.

The result is a series of maps detailing aquifer temperature, geothermal gradient, depth to the top of aquifers, transmissivity, and groundwater quality (dissolved solids). These maps provide a greater level of detail than previous publications and can be used to improve the understanding of the geothermal energy potential of the study area. By providing detail on aquifers that could be used for direct use geothermal energy production, stakeholders considering geothermal developments will be able to improve site selection and carry out initial feasibility studies.

The maps generated by this study conform to the aquifers and aquitards defined by the VAF (GHD, 2012 & SKM, 2009), which are used for licencing and groundwater management in Victoria. Insulating layers of coal and limestone trap the earth's heat, concentrating it in the groundwater beneath. This is demonstrated by temperature profiles (Appendix A2) that consistently show relatively rapid increases in temperature with depth as boreholes intersect coals or limestones. Coal is the better insulator with geothermal gradients reaching 119°C/km, or four times the global average geothermal gradient. Limestone is approximately twice the global average with a geothermal gradient reaching 63°C/km.

The deeper aquifers in the Latrobe Valley are insulated by the Morwell coal seams and are accessible at a relatively shallower depth (e.g., 600 m). Hot groundwater near Lake Wellington is insulated by the Gippsland Limestone, and is typically at greater depths (e.g., 900 m). Heat escapes more easily through the Balook sands between Sale and Rosedale where neither coal or limestone are present to provide insulation. Despite this, warm groundwater can still be accessed at this location, albeit at lower temperatures. Another insulating layer - the Traralgon coal seams, lies beneath the Morwell coal seam and the Gippsland Limestone. The hottest groundwater is located beneath the Traralgon coal seams both in the Latrobe Valley and near Lake Wellington. Where the Traralgon coal seams are overlain by either the Morwell Coal or the Gippsland Limestone there is increased insulation, and the groundwater temperature increases.

The most promising geothermal resource lies within the Lower Tertiary Aquifer (LTA) in both the Latrobe Valley and the Lake Wellington Depression. The hot LTA water is accessible at much shallower depths beneath the Latrobe Valley (typically around 600 m), with an area of 495 km^2 of land covering aquifers with groundwater temperatures above 50°C. The Lake Wellington Depression contains hot water at greater depths (typically around 900 m), with an area of 560 km^2 of land covering aquifers with groundwater temperatures above 50°C and significant potential for higher temperatures. Groundwater above 35°C is present over much larger areas including between Morwell and Stratford in the Latrobe Valley, and between Woodside and Lake Tyers along the coast.

Geothermal gradient maps can be used to estimate the rate of temperature increase with depth in an aquifer. If the temperature at the top of the aquifer is not warm enough for a particular purpose, the geothermal gradient can be used to estimate the depth required to reach the desired temperature. Geothermal gradient maps indicate that the Morwell coal seams, and the Gippsland Limestone are the most important insulators. These units are time-equivalent and form the UMTA in the Latrobe Valley and the UMTD in the Lake Wellington Depression. The LTA can also act as an important insulator; however, the resolution of the data is poor due to its depth and scarcity of precision temperature logs that fully penetrate it. Integrating detailed mapping of the Traralgon coal seams may aid in the understanding of the geothermal potential beneath these coal seams.

New precision temperature logs have increased data reliability throughout the Gippsland study area, particularly between Rosedale and Sale, and in the Seaspray Depression. However, significant data gaps and uncertainties remain. For example, where the Morwell coal seams become thinner adjacent to the margins of the Latrobe Valley, temperatures may be lower than interpolated by the gridding algorithm. Limited temperature data between Lake Wellington and Marlo ensures the geothermal energy potential of this area remains poorly understood. The presence of thick coal seams in the vicinity of Yarram suggests potential for geothermal resources in the area, but these are yet to be clearly identified due to limited data. Understanding of geothermal gradients in the LTA is very poor due to data gaps that has led to some very high and low estimates of geothermal gradient.

Temperature data collected in petroleum wells significantly expanded the available data in the LTA and deeper parts of the basin. There is potential for more temperature data to be gleaned from petroleum well completion reports that would allow deeper, higher temperature, geothermal resources to be characterised.

References

AKBARZADEH, A. & THOMPSON, B.R., 1984. An overview of the potential and applications of geothermal energy in Victoria and proposed future actions. Victorian Solar Energy Council and Department of Minerals and Energy, 1984. Unpublished.

ANTRIASIAN, A., TAYLOR, D., MATHER, B., HARRISON, B. & SANDIFORD, D., 2015. Thermal conductivity measurements of Victorian rocks. *Victorian Geothermal Atlas Report 2*. Geological Survey of Victoria Technical Record 2015/3. Geological Survey of Victoria.

BEARDSMORE, G.R. & CULL, J.P., 2001. Crustal Heat Flow. A guide to measurement and modelling. Cambridge, New York, Melbourne. ISBN 0-521-27289-4.

BEVERLY, C., HOCKING, M., CHENG, X., O'NEILL, C., SCHROERS, R. & BAKER, S. 2015. Gippsland Groundwater Model. Technical report. Onshore natural gas water science studies. Department of Economic Development, Jobs, Transport and Resources. Victoria. 409p.

CORRIGAN, J., 1997. Correcting bottom hole temperature data, AEPT Research Memo RM 97-0007.

CULL, J.P. & BEARDSMORE G.R., 1992. Statistical methods for estimates of heat flow in Australia. *Exploration Geophysics*, 23, pp. 83-86.

DRISCOLL, J., 2006. Geothermal Prospectivity of Onshore Victoria, Australia. *Victorian Institute for Minerals and Petroleum Report 85*, Department of Primary Industries. 2006.

EDWARDS, C.M., 2020. Petroleum systems modelling, Gippsland Basin, Victoria. *Victorian Gas Program Technical Report 49*. Geological Survey of Victoria. Department of Jobs, Precincts and Regions. Melbourne, Victoria. 147p.

GHD, 2012. Report on the development of state-wide 3D aquifer surfaces. Department of Sustainability and Environment.

GREENEARTH ENERGY LIMITED (GER) & HOT DRY ROCKS PTY LTD (HDR), 2008. Various precision down-hole temperature logs. Unpublished data.

GEOLOGICAL SURVEY OF VICTORIA (GSV) & HOT DRY ROCKS (HDR), 2005. Various precision down-hole temperature logs. Unpublished data.

GEOSCIENCE AUSTRALIA (GA), 2010. Various precision down-hole temperature logs. Unpublished data.

GNS SCIENCE, 2021. New Earth Energy, modified Lindal diagram. www.gns.cri.nz/Home/Learning/Science-Topics/Earth-Energy/Using-Earth-Energy/lindal-new-earth-energy Accessed 15th October 2021

HALLETT J., 2007. Investigation of heat flow in the onshore west Gippsland Basin. BSc Hons thesis, Monash University. Unpublished.

HARRISON, B., 2015. Measurement and modelling of heat flow in the Gippsland Basin, Victoria. Ph.D. Thesis. Melbourne University. Unpublished.

HOCKING, M., BEVERLY, C., BOLD, T.A. & IVERACH, C., 2020. Gippsland Groundwater Model (GGM v1.1) Groundwater impact assessment - Re calibration of numerical model, Onshore Gippsland Basin, Victoria. *Victorian Gas Program Technical Report 36*. Geological Survey of Victoria. Department of Jobs, Precincts and Regions. Melbourne, Victoria. 271p.

HORNER, D.R., 1951. Pressure build-up in wells, Proceedings of the Third World Petroleum Congress, 25-43. May 28–June 6, 1951, The Hague, the Netherlands.

INTERREG EUROPE, 2021. Smart Specialisation Strategy (S3): A policy brief from the policy learning platform on research and innovation, July, 2020. https://www.interregeurope.eu/fileadmin/user_upload/plp_uploads/policy_briefs/Smart_Specialisation_Strategy__S3___Policy_Brief.pdf#:~:text=Smart%20Specialisation%20strategy%20%28S3%29%20is%20a%20placebasedinnovation%20policy,in%20terms%20of%20its%20scientific%20and%20technological%20endowments Accessed 22nd December 2021.

JANSEN, B., SAY, P. & MAHER, S., 2003. Digital geological model of the Latrobe Valley coal resource. *Geological Survey of Victoria Unpublished Report 2003/2*.

JESSOP, A. M., 1990. Comparison of industrial and high-resolution thermal data in a sedimentary basin. *Pure and Applied Geophysics*,133, p. 251-267.

KEAREY, P., 2001. *The new Penguin Dictionary of Geology*. Secound Edition. Penguin Group, Victoria, Australia.

KING, R.L., FORD, A.J., STANLEY, D. R., KENLEY, P.R. & CECIL, M.K., 1987. Geothermal Resources of Victoria. Department of Industry, Technology and Resources and Victorian Solar Energy Council, Melbourne.

LEONARD, J.G. & KING, R.L., 1992. Low-enthalpy geothermal resources in the Gippsland Basin. In C.M. Barton, K. Hill, C. Abele, J. Foster & N. Kempton (eds), *Energy, Economics and Environment: Gippsland Basin Symposium, Melbourne, 22–23 June 1992*. Australasian Institute of Mining and Metallurgy, Melbourne. pp. 279-288.

MNGI (Petratherm) & Hot Dry Rocks Pty Ltd (HDR)., 2009. Various precision down-hole temperature logs. Unpublished data.

NAHM, G.Y. & REID, M.A., 1979. Potentiometric contour map and equi-geothermal gradient contour map of the Latrobe valley group basal aquifers. *GSV Unpublished Report No 1979/102*. Department of Minerals and Energy.

NATHENSON, M. & GUFFANTI, G., 1987. Compilation of geothermal-gradient data in the conterminous United States. Open-file report 87-592. U.S. Geological Survey.

RAWLING, T.J., SANDIFORD, M., BEARDSMORE, G.R., QUENETTE, S., GOYEN, S.H. & HARRISON, B. 2013. Thermal insulation and geothermal targeting, with specific reference to coal-bearing basins. *Australian Journal of Earth Sciences*. 60:8, 817-830, DOI: 10.1080/08120099.2013.864999

SKM, 2005. The geothermal resources of Victoria. Report by SKM in association with Monash university for the Sustainable Energy Authority of Victoria.

SKM, 2009. The Victorian aquifer framework – Summary Report. Report prepared by Sinclair Knight Merz for the Department of Sustainability and Environment.

SKM, 2014. Revision of Salinity Distributions - Deeper Aquifer Layers of the VAF. Version 4. Published by DEPI.

TAYLOR, D. & MATHER, B., 2015. Geothermal Heat Flow Map of Victoria. *Victorian Geothermal Atlas Report 1*. Geological Survey of Victoria Technical Record 2015/2. Geological Survey of Victoria.

TAYLOR, D., 2019. Unpublished spreadsheet of historical borehole temperatures records and Horner corrections compiled by Dave Taylor.

THE UNIVERSITY OF MELBOURNE, 2021. Gippsland Smart Specialisation Strategy. https://sustainable.unimelb.edu.au/research/research-projects/gippsland-smart-specialisation-strategy Accessed 20th December 2021.

THOMPSON, B., 1975. Thermal waters of the Gippsland Basin. GSV unpublished report 1975/81.

THOMPSON, B., 1979. Geothermal gradient maps of the Gippsland Basin. GSV unpublished report 1979/140.

THOMPSON, B., 1982. Geothermal investigations – a progress report. GSV unpublished report 1982/113.

WRIGHT, S., 2008. Heat flow in the Latrobe Valley: the role of thermal conductivity and lateral heat refraction. BSc honours thesis, University of Melbourne. Unpublished.

Glossary

Term	Explanation
Aquifer	A geological unit containing sufficient saturated permeable rock to yield significant amounts of water.
Aquitard	A formation allowing the through flow of water at much slower rates than an aquifer.
Basin	A topographic depression, containing or capable of receiving, sediments.
Geothermal	Concerning the flow of heat from the interior of the earth to the Earth to the surface.
Geothermal gradient	The rate of change in temperature with depth in the Earth.
Hydraulic conductivity	A measure of the ease with which a fluid flows and the ease with which a porous rock allows its passage.
Permeability	The coefficient linking groundwater flow rate to the pressure gradient in a rock medium.
Porosity	The ratio of the fraction of voids to the volume of rock in which they occur.
Transmissivity	The product of hydraulic conductivity and the thickness of a bed acting as an aquifer.

Source: Kearey (2001).

Abbreviations and units

AHD	Australian Height Datum
DST	Drill Stem Test
GER	GreenEarth Energy (Resources)
HDR	Hot Dry Rocks
GEDIS	Geological Exploration and Development Information System (GSV Oracle® database and systems).
MOC	Morwell Open Cut coal mine
SOBN	State Observation Bore Network
WMIS	Water Management Information System

Appendix A1 Precision temperature logs

SOBN	Log depth	Max temp °C	Log status	Date	Operator	Reference
47063	575	47.8	Existing	2015	Harrison	Harrison (2015)
110720	290	17.2	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
52752	140	24.61	Existing	2005	GSV/HDR (2005)	Taylor & Mather (2015)
58934	395	33.7	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
58935	272	29.7	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
58937	710	58.2	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
58937	719	54.3	Relogged	2020	Gaal	
60087	242	23.4	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
309164	365	47.2	Existing	2011	GER/HDR (2008)	Taylor & Mather (2015)
309177	557	53.3	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
309192	460	46.23	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
67441	783	36.5	Existing	2015	Harrison (2015)	Harrison (2015)
310063	292	29.1	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
76074	630	61.5	Existing	2015	Harrison	Harrison (2015)
Loy Yang 20002*	713	51.1	Existing	2008	Wright	Wright (2008)
314690	440	52.2	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
314691	245	35	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
76079	696	62.6	Existing	2005	GSV/HDR (2005)	Taylor & Mather (2015)
77436	143	18.7	Existing	2008	Wright	Wright (2008)
77351	447	60.9	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
77945	713	47	Existing	2005	GSV/HDR (2005)	Taylor & Mather (2015)
84156	172	23.3	Relogged	2020	Gaal	
89809	836	42.7	Extended	2019	Gaal	
90138	950	67.2	Existing	2009	MNGI/HDR (2009)	Taylor & Mather (2015)
92175	96	17.7	New	2020	Riley	
147174	158	23	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
95482	73	17.25	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
329701	612	61.4	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
329702	310	35.7	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
96560	542	62.7	Existing	2015	Harrison	Harrison (2015)
103583	664	66.2	Existing	2015	Harrison	Harrison (2015)
Wombat 4*	1714	70	Existing	2010	Geoscience Australia	Taylor & Mather (2015)

SOBN	Log depth	Max temp °C	Log status	Date	Operator	Reference
104536	728	26.9	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
104536	1009	33.7	Extended	2020	O'Neill/Hocking	
110726	528	44.7	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
105220	28	14.2	New	2020	O'Neill	
105222	324	24.1	Existing	2005	GSV/HDR (2005)	Taylor & Mather (2015)
105483	739	32.6	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
105548	168	22	Existing	2005	GSV/HDR (2005)	Taylor & Mather (2015)
105548	180	22	Relogged	2020	O'Neill/Riley	
107971	71	21	Existing	2007	Hallett	Hallett (2007)
90614	1023	60.3	New	2020	O'Neill/Hocking	
333927	221	23.3	Existing	2008	GER/HDR (2008)	Taylor & Mather (2015)
52754	882	55.2	New	2020	O'Neill/Riley	
64835	237	23.8	New	2020	Riley	
67442	146	23.04	New	2020	O'Neill/Riley	
90148	119	17.33	New	2020	O'Neill/Hocking	
90149	147	15.8	New	2020	O'Neill/Riley	
92118	214	14.18	New	2020	Riley	
105134	272	27.1	New	2020	O'Neill/Riley	
105728	140	23.6	New	2020	O'Neill/Hocking	
110729	110	19.2	New	2020	O'Neill/Riley	
110731	108	17.7	New	2020	O'Neill/Riley	
115732	31	15.1	New	2020	O'Neill/Hocking	
145092	50	14.6	New	2020	Riley	
147173	208	18.8	New	2020	Riley	
WRK059110	368	29.1	New	2020	O'Neill/Riley	
WRK059112	181	19.8	New	2020	Riley	
WRK059119	121	14.7	New	2020	O'Neill/Riley	
WRK059123	21	13.4	New	2020	Riley	
WRK059126	187	23.1	New	2020	Riley	

Appendix A2 Temperature profiles

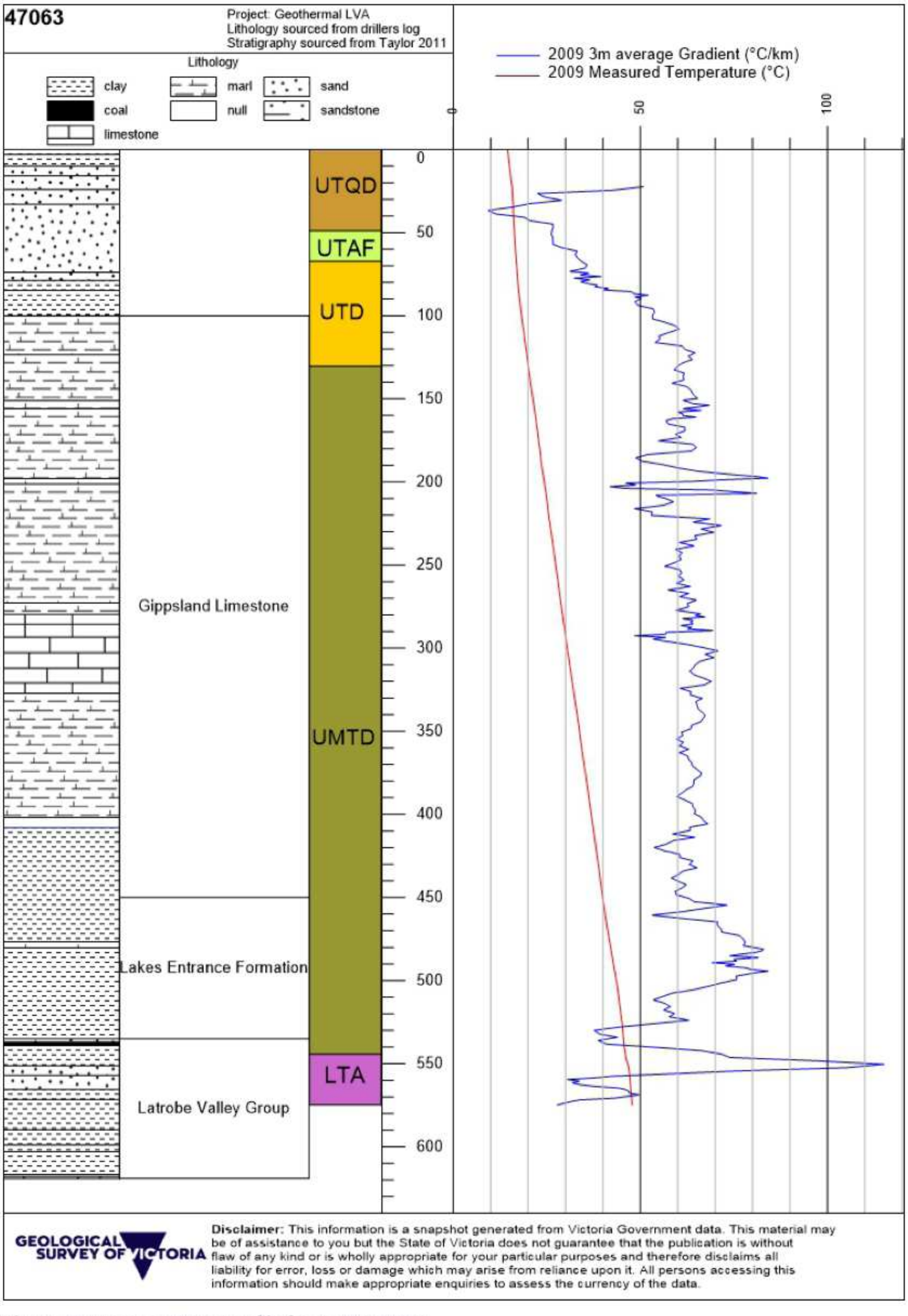

Figure A2.1 Temperature profile for SOBN 47063.

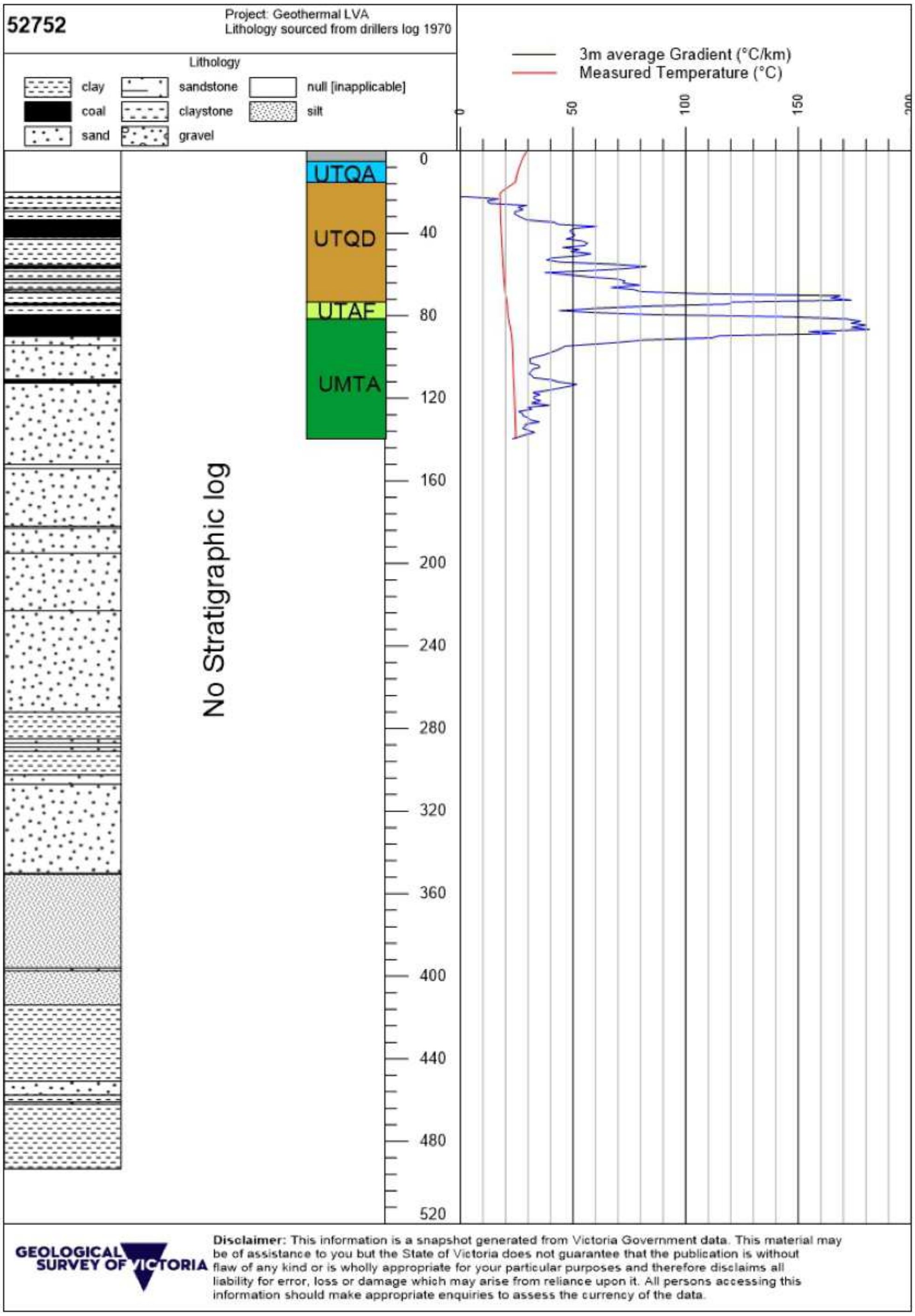

Figure A2.2 Temperature profile for SOBN 52752.

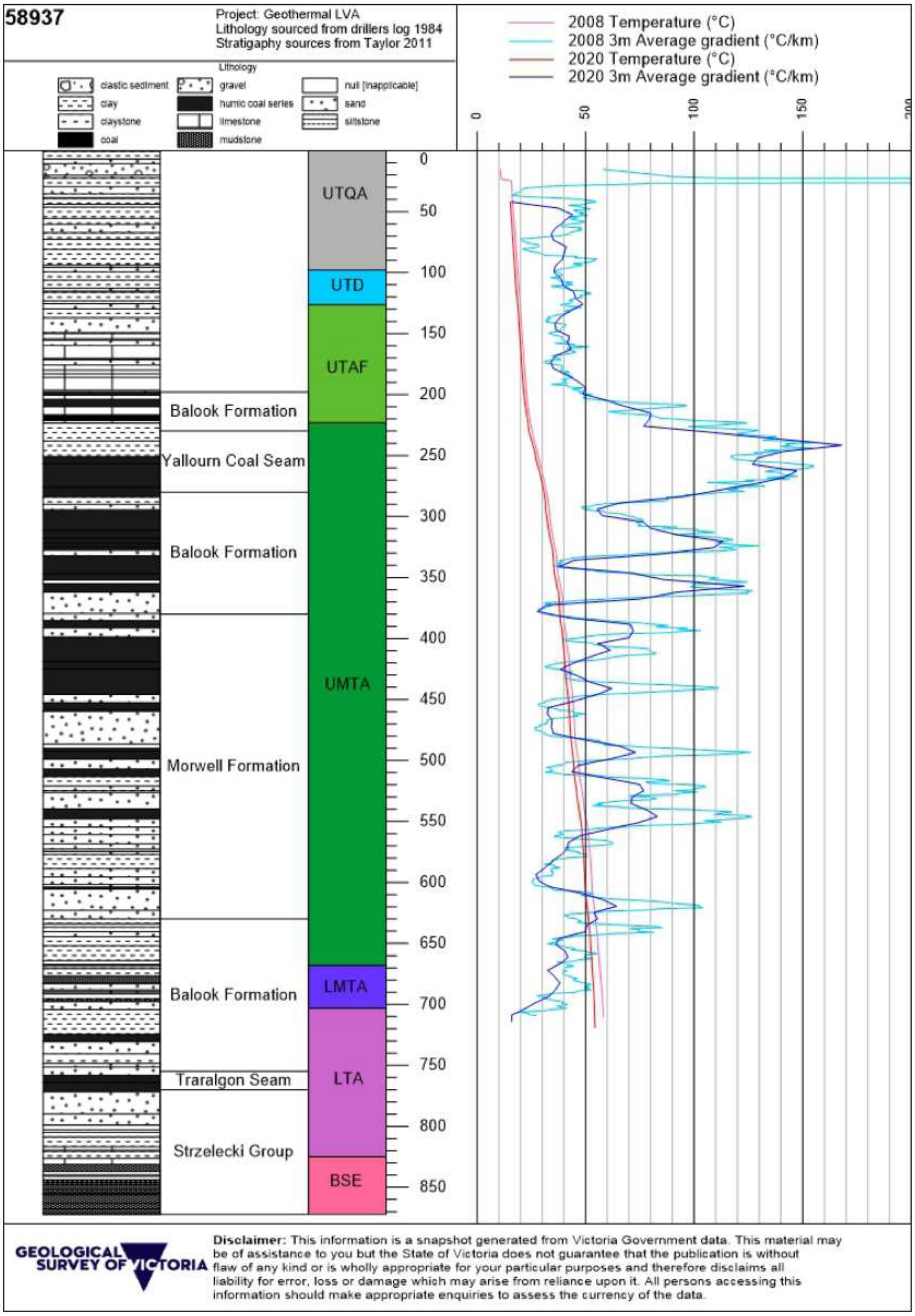

Figure A2.3 Temperature profile for Denison-57.

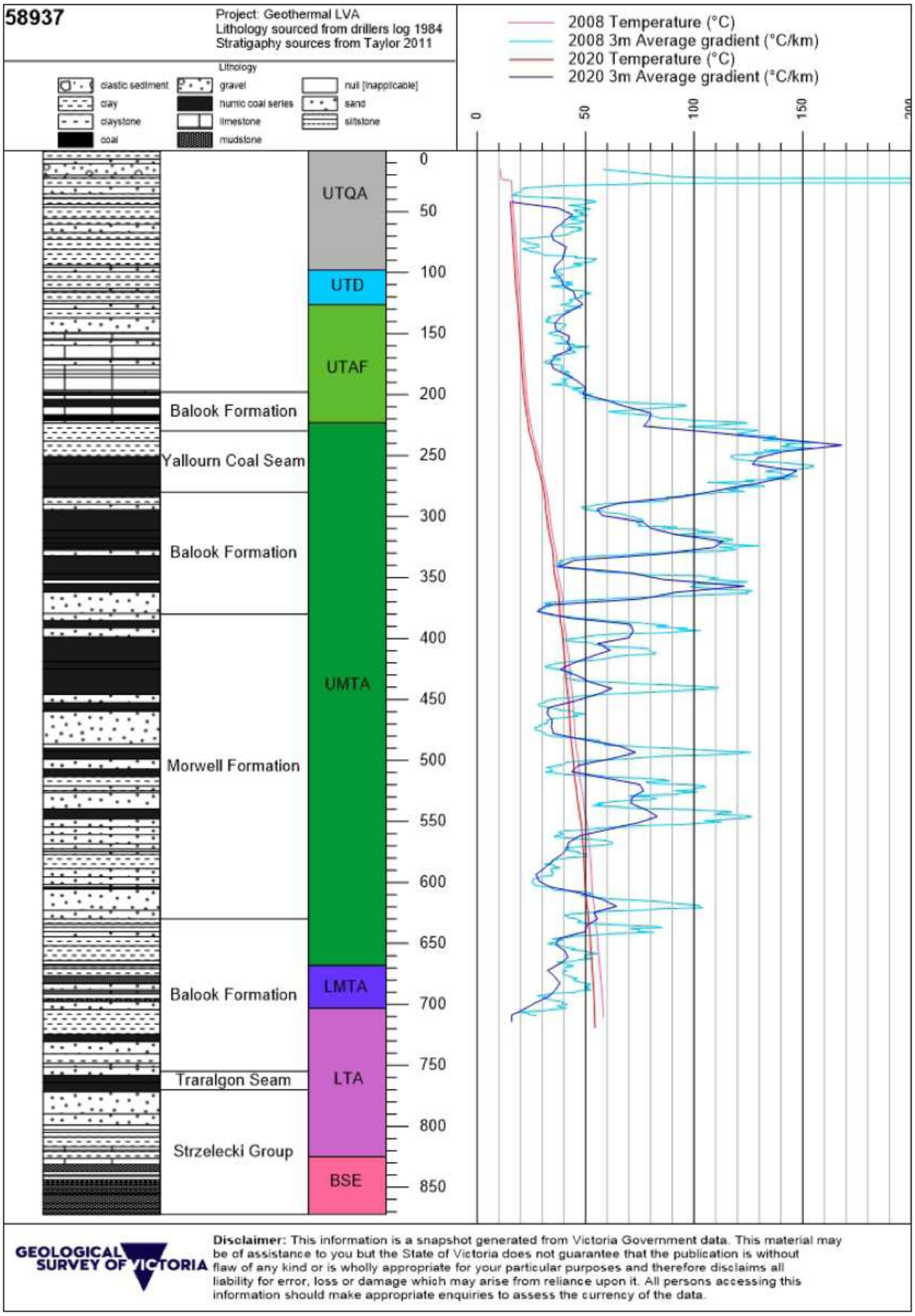

Figure A2.4 Temperature profile for Loy Yang 2390.

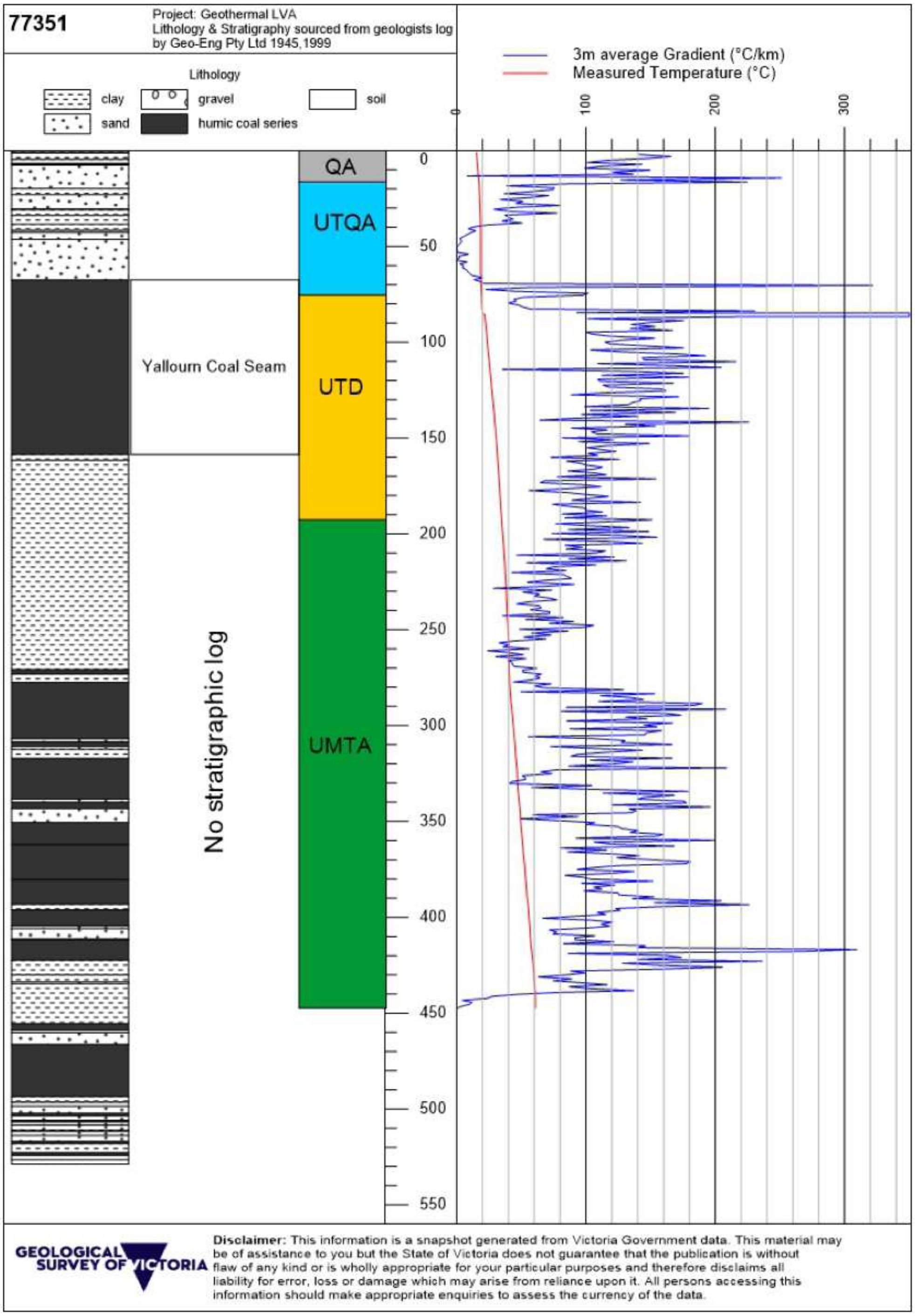

Figure A2.5 Temperature profile for SOBN 77351.

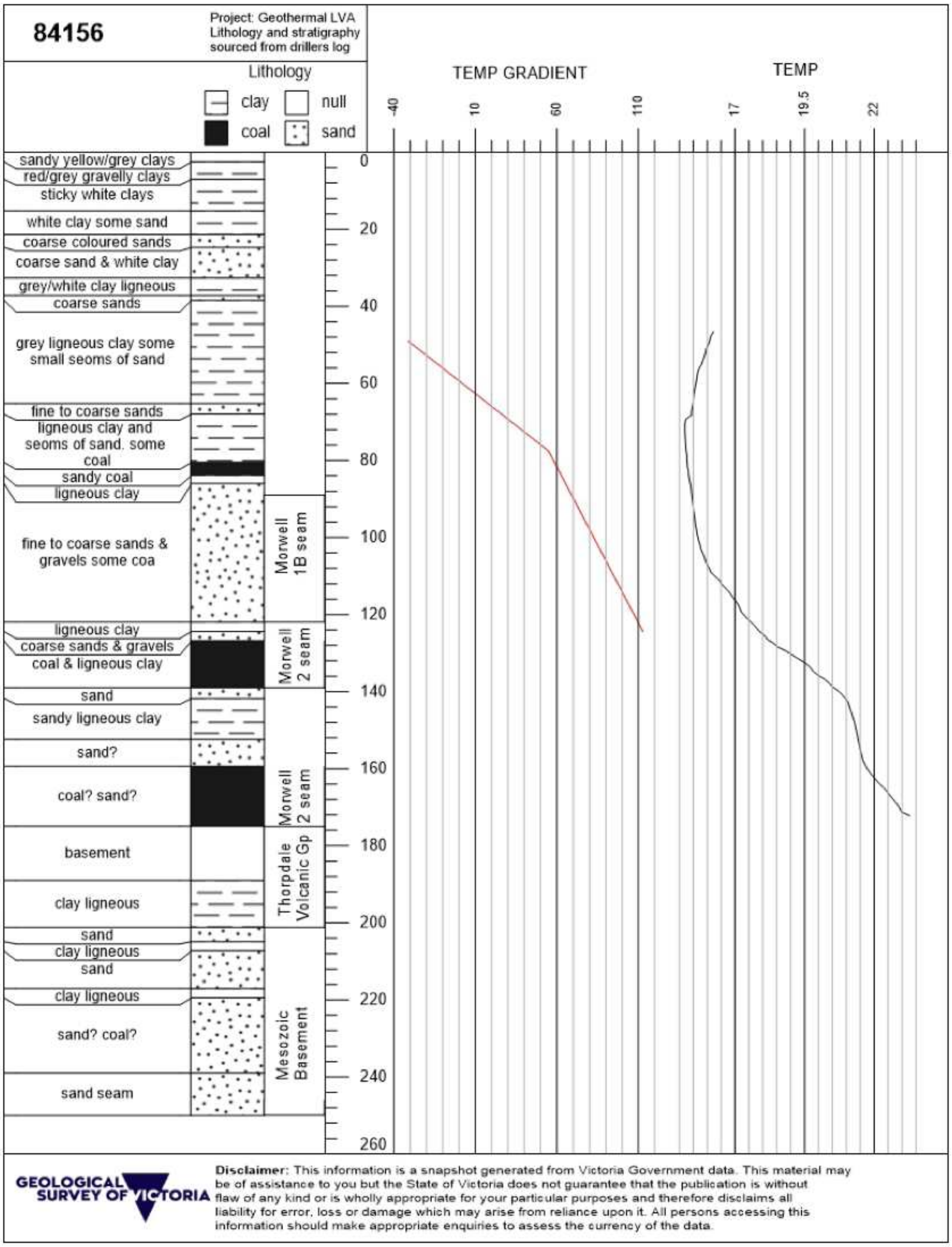

Figure A2.6 Temperature profile for Narracan-3284.

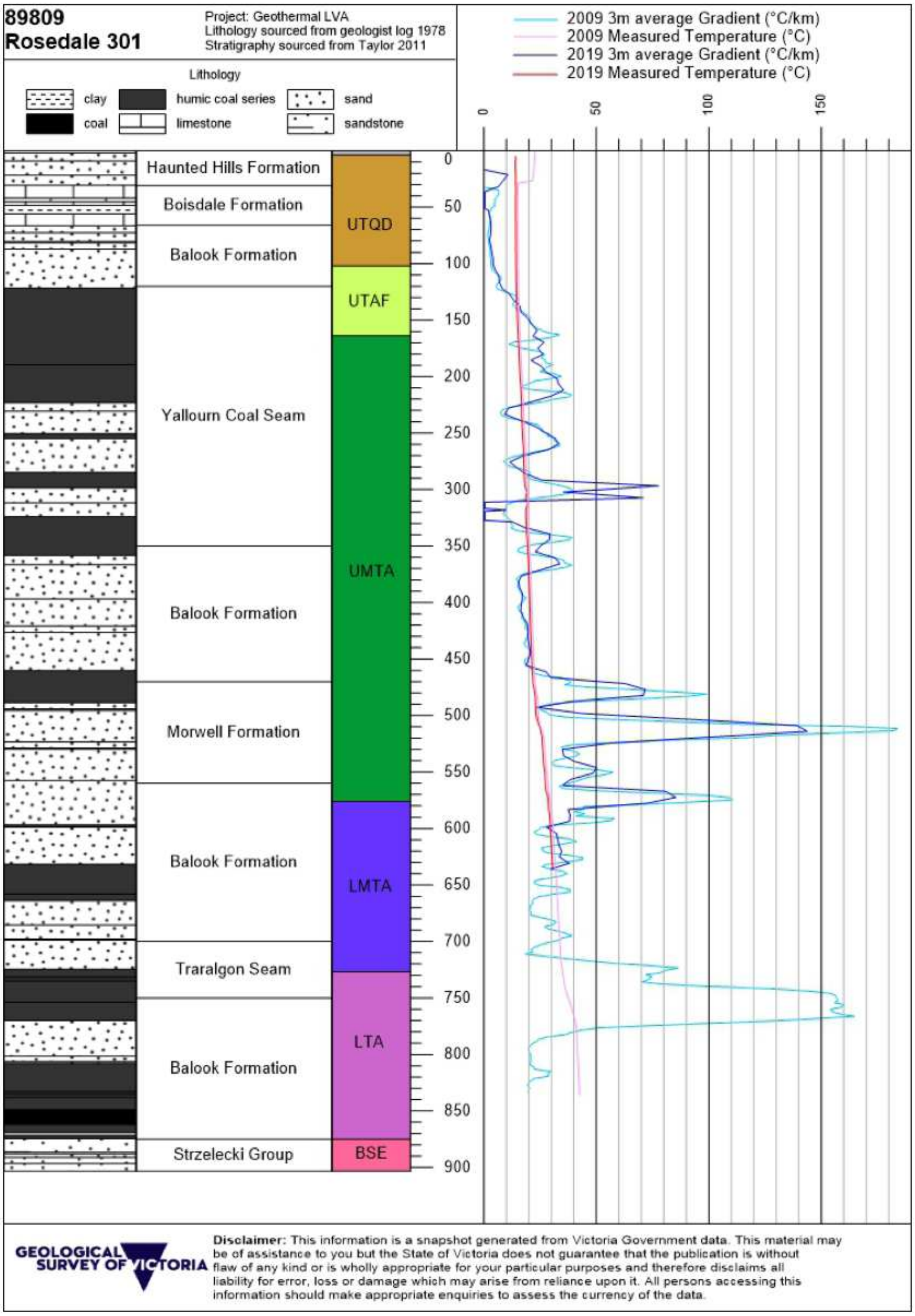

Figure A2.7 Temperature profile for Rosedale-301.

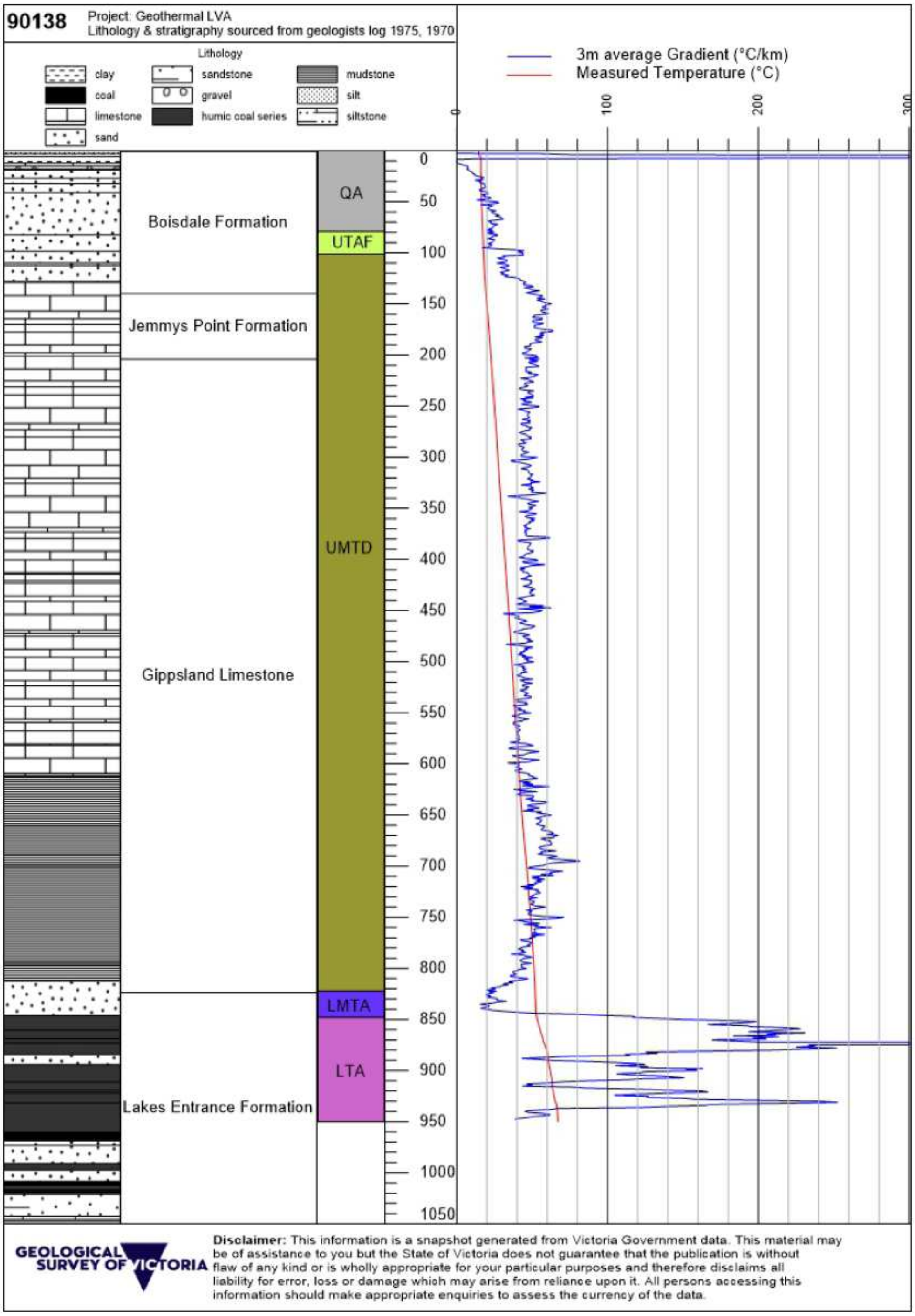

Figure A2.8 Temperature profile for Sale-13.

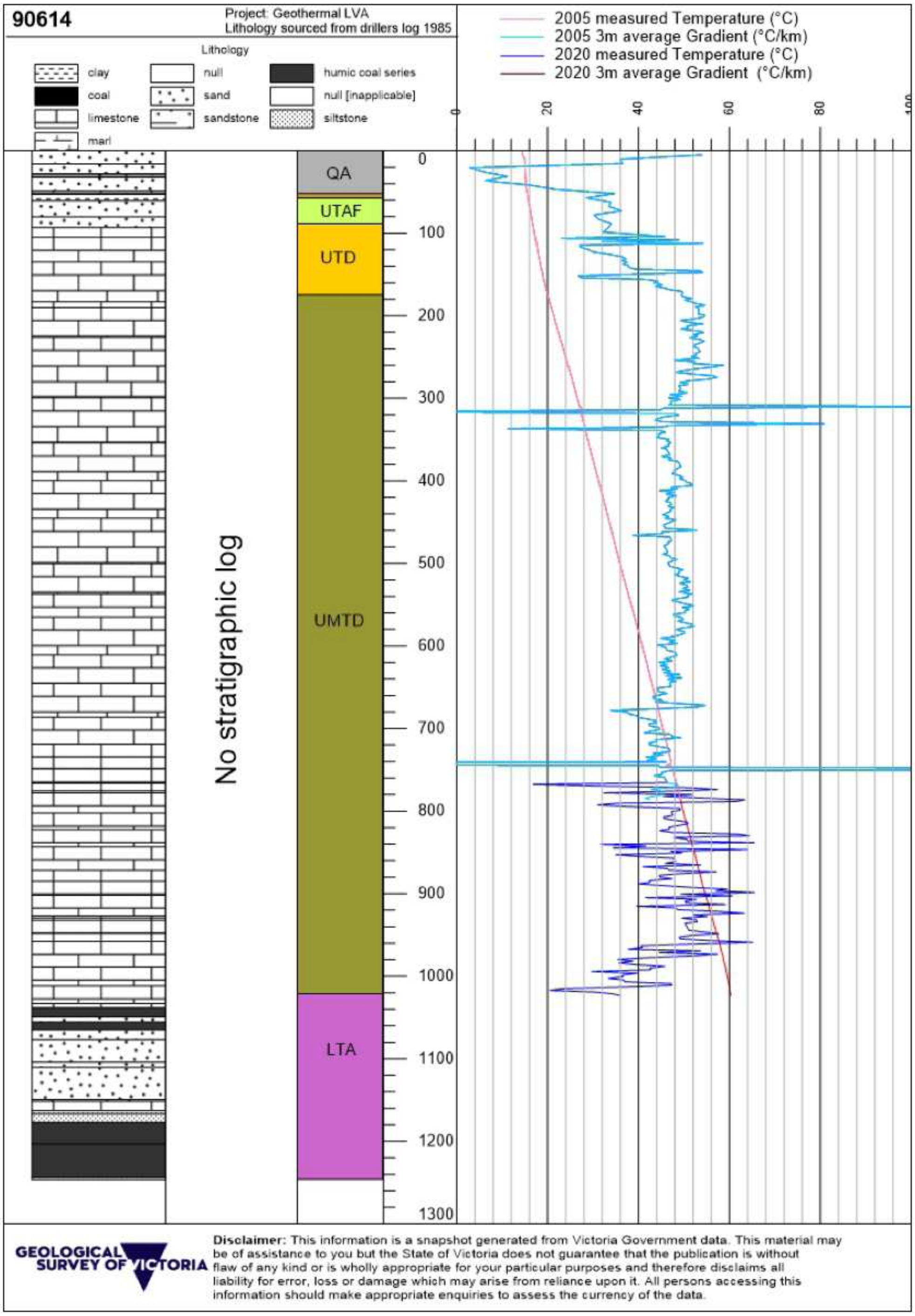

Figure A2.9 Temperature profile for Seacombe-7.

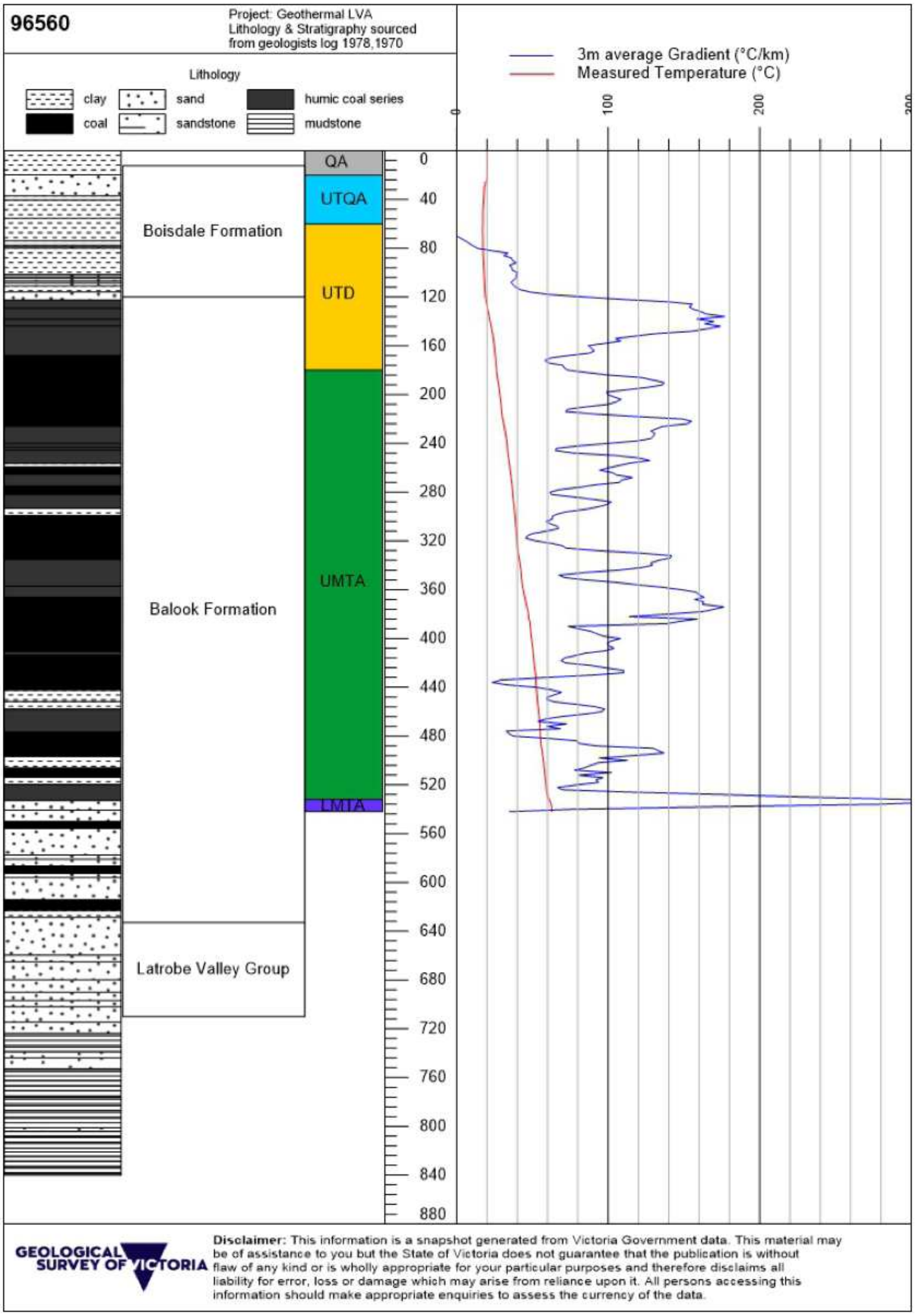

Figure A2.10 Temperature profile for Traralgon-286.

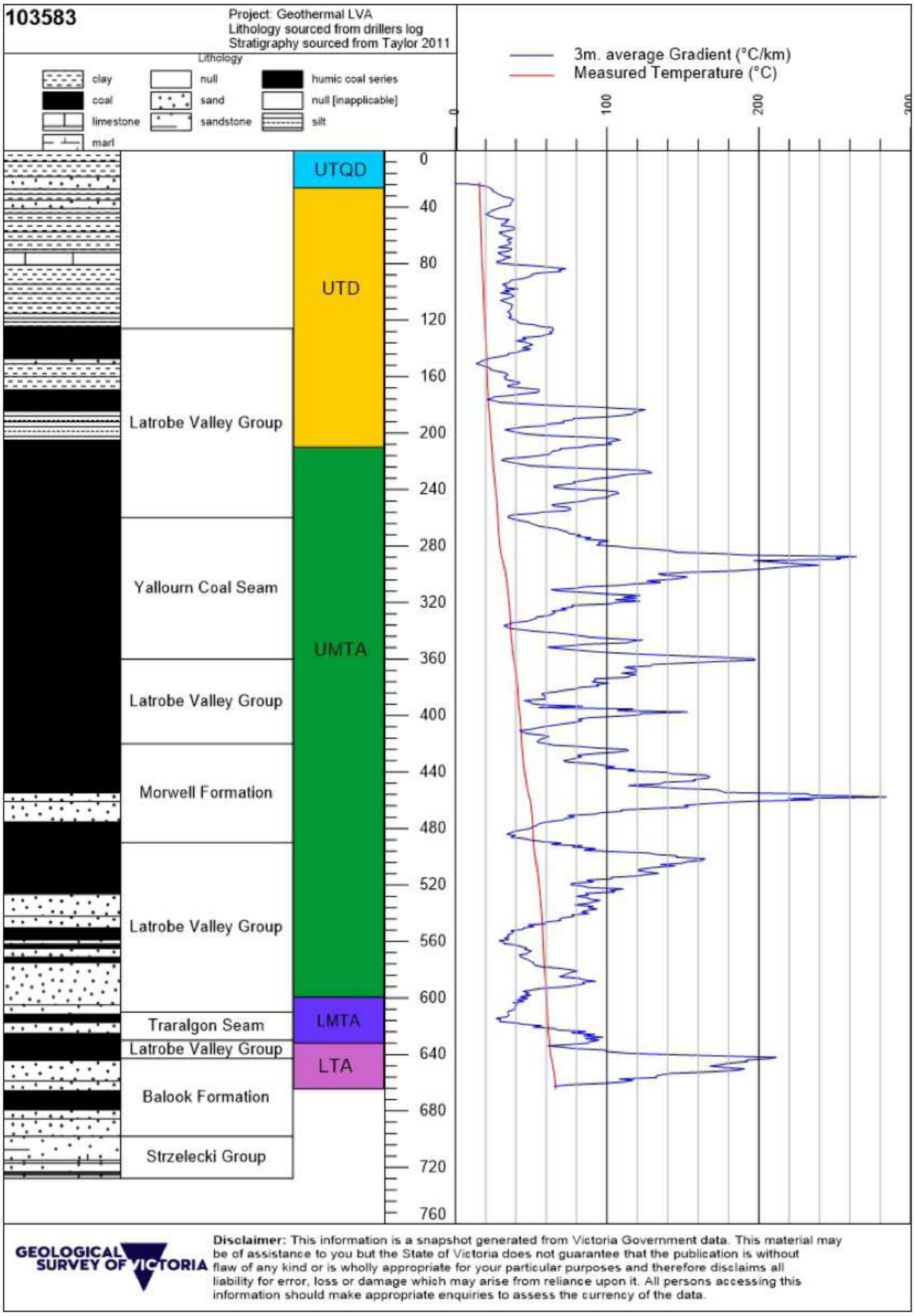

Figure A2.11 Temperature profile for Winnindoo-46

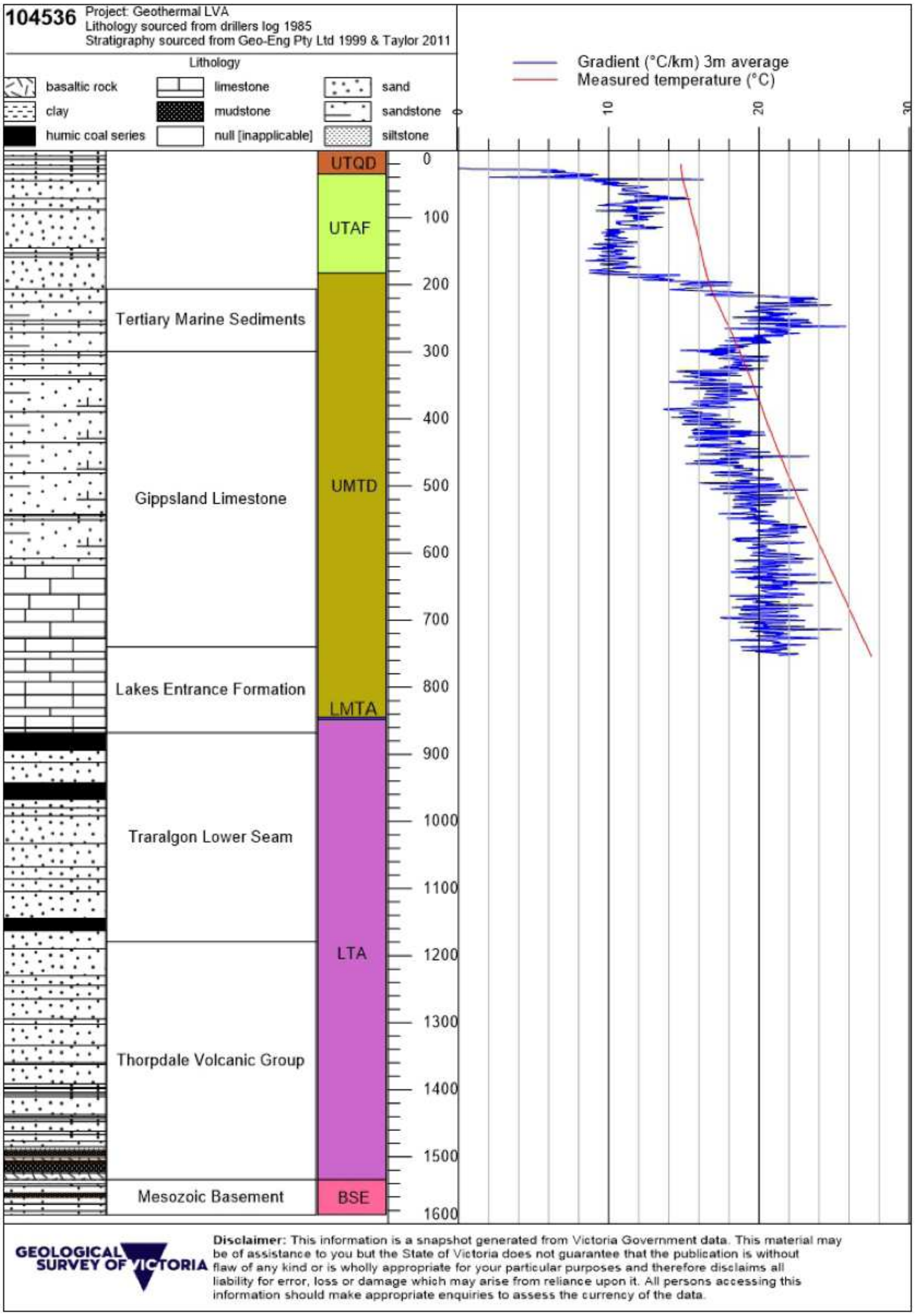

Figure A2.12 Temperature profile for Woodside-12.

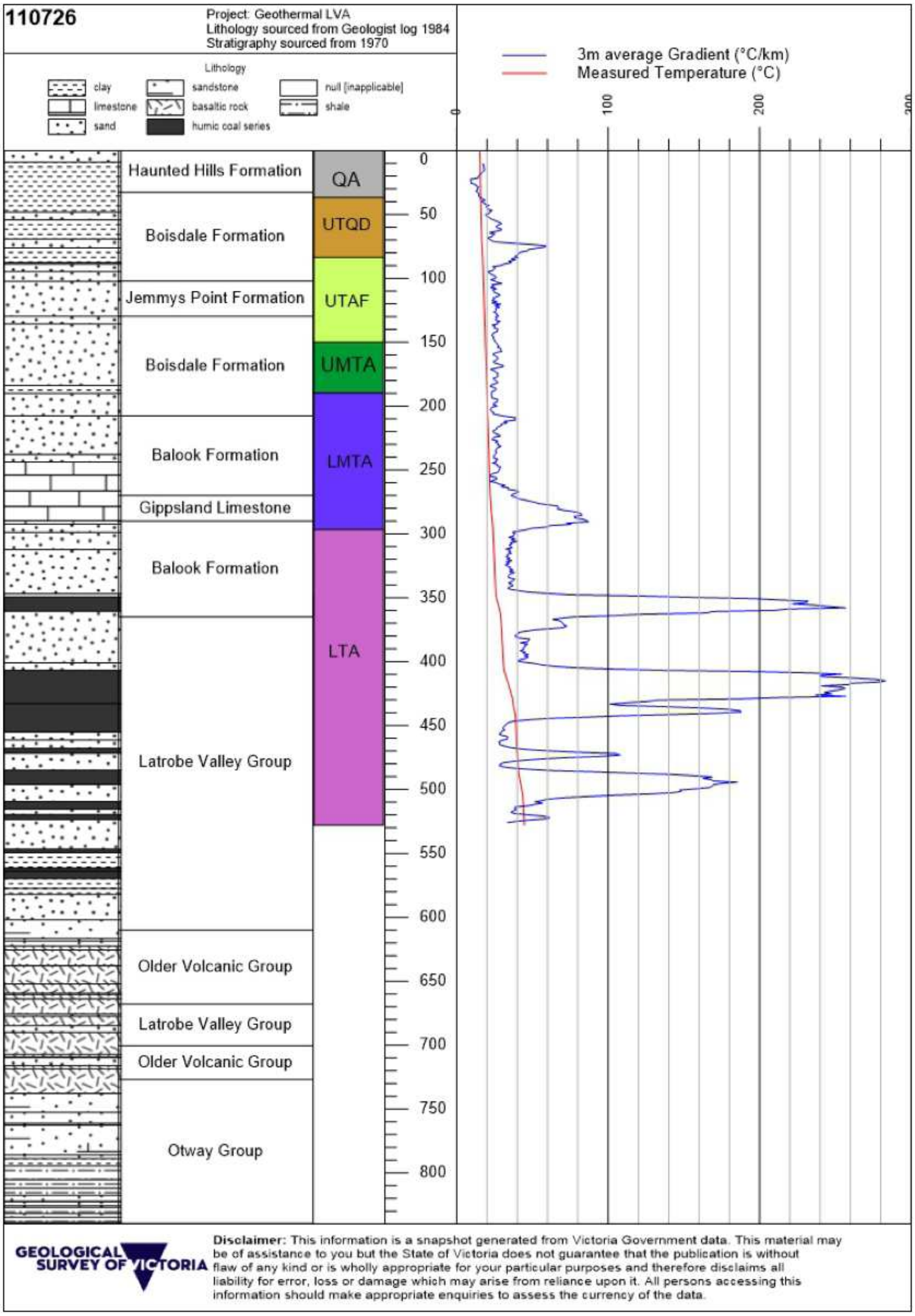

Figure A2.13 Temperature profile for Woranga-12.

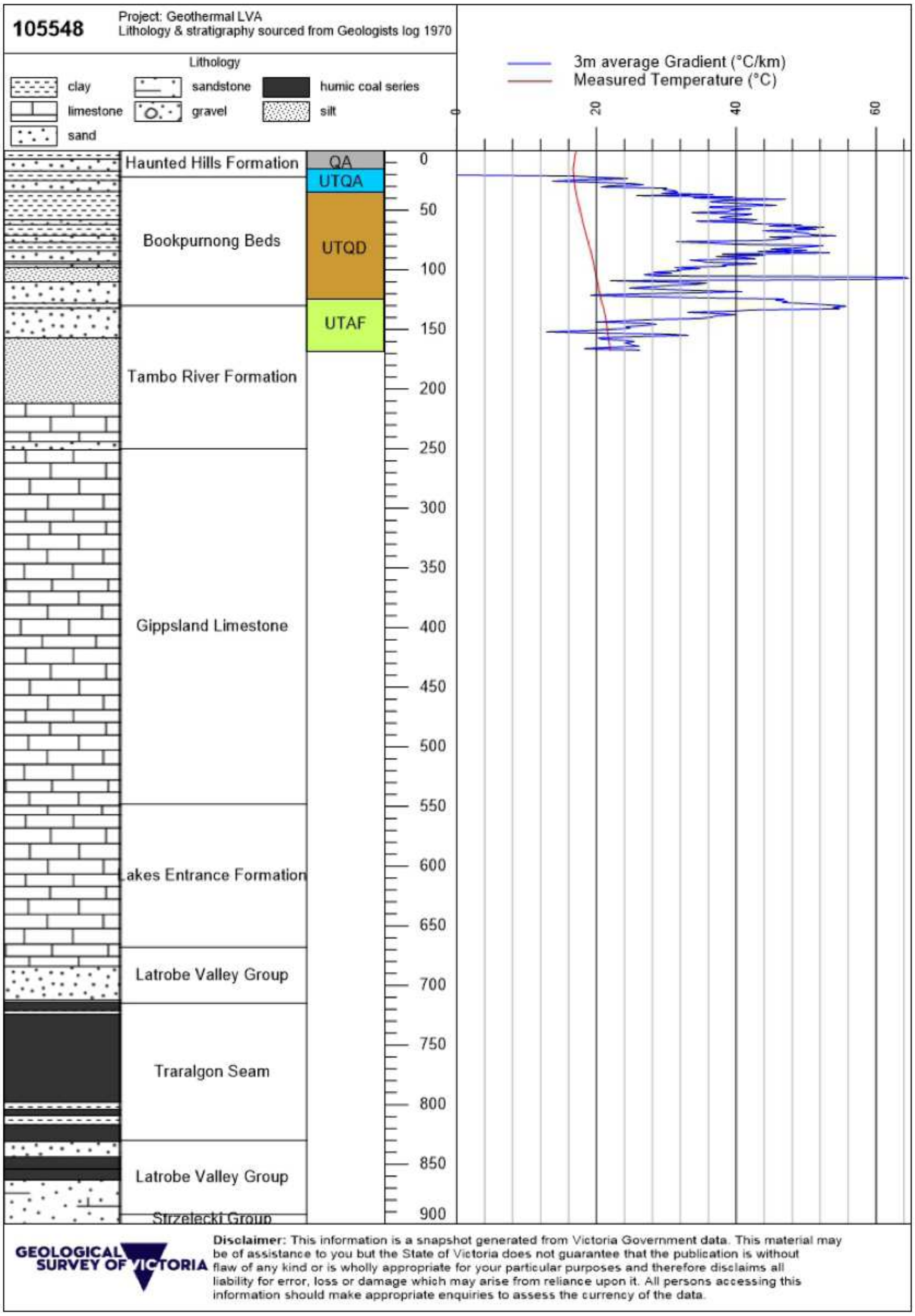

Figure A2.14 Temperature profile for Wurruk Wurruk-1

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