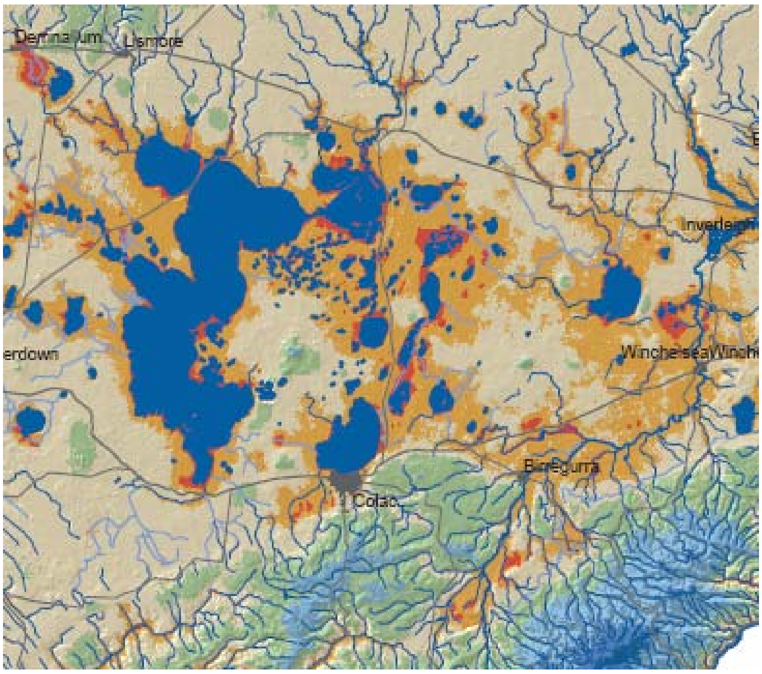
SINCLAIR KNIGHT MERZ
SKM

CORANGAMITE CMA

Groundwater Level Mapping



BORE DATA REVIEW AND MAPPING METHODOLOGY

- Final
- March 08

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1. Introduction

Salinity has been identified as Australia’s major natural resource management challenge and is one of two priorities for the National Action Plan for Salinity and Water Quality (NAP). The presence of shallow saline groundwater is one of the key threatening processes addressed by the NAP. Understanding the spatial distribution of shallow watertables across the landscape and their coincidence with ecological, agricultural and infrastructure assets is critical to the successful management of salinity.

Sinclair Knight Merz (SKM) was engaged by the Corangamite Catchment Management Authority (CCMA) to revise the watertable surfaces of the Corangamite CMA region produced under the NAP benchmarking Watertables project (SKM, 2006). The project utilises a suite of advanced geostatistical methods to determine watertable levels in a manner that is statistically robust and repeatable. The methods also provide a basis for evaluating and presenting the uncertainty in the watertable modelling in both qualitative and quantitative terms. The following mapping products have been produced in this project:

- A map illustrating the probability the watertable will be less than 2m below the land surface.
- A map illustrating the probability the watertable will be less than 5m below the land surface.
- A map illustrating the probability the watertable will be less than 10m below the land surface.
- A map showing the depth to the watertable based on the median watertable depth from the modelling process.
- A reliability map showing the uncertainty associated with the watertable surfaces.

This report documents the data collation and analysis process, provides a concise summary of the modelling methodology and limitations, and gives a brief commentary on the mapping products.

1.1 Background

In 2006, maps of watertable elevation and depth to watertable were prepared for the Corangamite CMA region as part of a NAP funded project covering six of Victoria’s CMAs (SKM, 2006). The maps provide a baseline for reporting future changes in watertable depth and accordingly have been developed in manner that can be replicated in future. Detailed assessment of individual areas and editing of the water level data sets to better reflect local knowledge was not attempted in this study. While these maps are a useful addition to the CMA’s groundwater data archive there are many areas where they can be improved. This project is aimed at improving the depth to water maps of the Corangamite CMA. Improvements on the SKM (2006) surfaces implemented in this project include:

- The development and use of a highly accurate digital elevation model of the region that was not available at the time of the original project.
- A refined calculation grid (the modelling grid has been reduced from $100m^2$ to $50m^2$ resulting in a fourfold increase in the horizontal resolution of the modelling).
- Careful review and editing of the input data sets to ensure that the measured water levels are consistent with current understanding of the hydrogeology of the region.
- Use of secondary information on watertable elevation (i.e. areas of mapped saline discharge and surface water hydrology) in the generation of the watertable surfaces.
- Involvement of hydrogeological knowledge in the modelling process through bore selection, development of constraint layers and sanity checking of results.
- Re-projection of watertable surfaces to summer 2007.
- Better presentation and communication of mapping products.

1.2 Objective of the Study

The objective of the study is to produce maps and supporting information/data, representing the groundwater level and water table depth across the area of the Corangamite CMA. It is anticipated that the data and maps can be used by water resource planners at the CCMA for salinity control as well as other groundwater investigations in the CMA.

2. Data Review

In SKM (2006) an automated bore filtering process was implemented to select the bores used in the watertable modelling process. The decision to automate the bore selection was driven by practical constraints – there are over 33, 000 bores in the Corangamite CMA alone, manual filtering of bores across all six NAP CMAs was not possible due to the scale of the mapping – and also by a requirement that the criteria for bore selection should be objective and transparent.

While we are confident that the original bore selection process captured the majority of watertable monitoring bores there are still local areas where bore data has been included or excluded erroneously. In some instances this has occurred because the selection criteria are not flexible enough to consider the variation in watertable depth driven by the local hydrogeology. In other instances bores with erroneous water level readings were included because there was insufficient time available to consider hydrograph records for each bore on an individual basis.

A key component of this project involved a closer examination of the bore data inputs to the modelling process. The review of the bore data involved the following steps:

- Review of the original SKM (2006) database and input dataset to examine the removal of “outlier” bores.
- Revision of the de-nesting routine.
- Consultation with Peter Dahlhaus to ensure that all available bore data was considered, including cross validation of the dataset against the CCMA groundwater Database.
- Re-projection of water levels to February 2007.

2.1 Review of Original SKM (2006) Input Data set

As a starting point the main bore filtering criteria used in SKM (2006) were applied to obtain a preliminary dataset. These criteria are described in Table 2-1. While there is a wealth of information available from stock, domestic and irrigation bores, water level readings from these bores are only recorded at the time of drilling and have a much lower reliability. For this reason, only the higher reliability monitoring bores were considered in the input data set.

A maximum depth criterion of 30m was applied as a cut off for watertable bores. In some instances deeper bores were included where there was additional information that indicated they were screening the watertable aquifer. The target date for the modelling was February 2007. Bores included in the input data set required either a water level reading over the summer 2007 period or a hydrograph record that allowed a reliable watertable depth for February 2007 to be estimated from a multiple regression model (see Section 2.5 for more detail).

- **Table 2-1 Starting Criteria for the Selection of the input bore list**

	Criteria	Comments
Location Coordinates	Required	If the bore was from the GMS, its location must be within 50m of the indicated parish. This helped to identify bores with coordinates that were clearly incorrect.
Minimum Bore Depth	>0	Bores without a bore depth were removed as there is no way of verifying what aquifer they are monitoring
Maximum Bore Depth	<=30	Bores less than 30m were considered to be monitoring the watertable. In a few instances bores >30m were included were there was additional information that indicated the bore was screening the watertable.
Bore Use	Monitoring bore	Only monitoring bores with multiple water level readings were considered in the analysis.
Water level record	Reading in Summer 2007 (Jan to March) OR Meets criteria for multiple regression estimate	Where bores did not have a reading taken in summer 2007 but did have a good hydrograph record readings were estimated using a multiple regression model (see Section 2.5 for more detail).
Multiple Regression Error r^2	>=0.6	Applied only if no observation existed for Summer 2007

2.2 Review of the Removal of “Outliers” in the Input Data set

A number of bores were removed from the SKM (2006) dataset because they were considered to be of poor reliability. These bores were classified as “outliers” in the input dataset. Bores were excluded for a number of reasons including: poor hydrograph records, inconsistency with the reduced water level in surrounding bores, uncertainty surrounding the location of the bore or suspicion that the bore was not monitoring the regional watertable. Part of the input data review in this project involved revisiting all bores that had been removed from the SKM (2006) modelling on an individual basis to confirm that their omission was justified.

2.3 Bore De-Nesting Check

Preliminary data analysis included the application of a de-nesting utility developed by SKM for the SKM (2006) project. Kriging and SGS allow only one data point per location. Nested sites are often included in the GMS data base with the same easting and northing. Alternatively some nested pairs of bores have unique coordinates. In this case the bores are close to one another and are probably monitoring different aquifers. If both bores are included in the geostatistical analysis they will cause an artificially high nugget in the variogram. A utility was developed to search through a data set and output only those bores with the shallowest bore depth for any cluster of bores within a designated buffer distance.

In the SKM (2006) project the de-nesting routine was run with a buffer distance of 500m. For the Corangamite watertable modelling the buffer distance was reduced to 75m. The 75m criteria ensures that only one bore per 50m^2 grid cell is accepted into the input data set while also maximising the number of bores included in the analysis. The reassessment of the de-nesting criteria resulted in the inclusion of an additional 39 bores and is expected to improve the accuracy of the watertable surfaces in areas where there is a high bore density.

2.4 Comparison of NAP Data Sets with Corangamite CMA Groundwater Database

A review of the SKM (2006) database was conducted to ensure that the original modelling process captured and used all of the available bore data. This was undertaken by comparing the bore data in the SKM (2006) database with the Corangamite CMA Groundwater database, which was supplied for use on this project by Peter Dahlhaus. The review process involved extracting all of the time series water level data from the database and running a query to identify the number of bores with multiple water level records, the date of the latest reading and the count of the number of readings for each bore. This bore set was then compared with a similar query run for the SKM (2006) database.

The results of this process are summarised in Table 2-2. A total of 32 new bores were identified. 21 of these bores were state observation bore network bores with good time series data, which had been overlooked in the original automated data selection process. The remaining 11 bores are located in the Morrisons - Sheoaks salinity action plan target area. These bores were installed in research programs undertaken by the University of Ballarat, detail on these bores was provided by Peter Dahlhaus.

- **Table 2-2 Summary of the comparison between the SKM (2006) database and the CCMA groundwater database**

	Corangamite Database	SKM 2006 Database
Number of Bores with times series water level data	976	1789*
Number of unique bores	32	-
Number of unique bores that satisfy the acceptance Criteria	32	N/A

*Note: The number of bores contained within the NAP database is substantially more that in the CCMA. This is due to the fact that the NAP database also captures bores within a 60km buffer zone around the CCMA.

2.5 Re-projection of time series bores to February 2007

The target date for the watertable modelling was February 2007. Updated water level monitoring data was extracted from the Groundwater Management System (GMS) for State Observation Bores

(SOB) and from the Corangamite CMA groundwater database for PIRVIC bores. Updated water level data was obtained for 267 of the bores used in the final input data set.[1]

In order to maximise the number of watertable observations and make best use of the available bore data multiple regression models were used to estimate the watertable depth where there was no reading available in summer 2007. Estimates were made using a modified HARRT method (Ferdowsian et al., 2000). HARTT is a simple multiple regression model that allows the separation of atypical rainfall periods from a linear time trend. The key inputs to the model are time series water level readings and monthly rainfall data for rainfall districts within the CMA. The process of generating a multiple regression model involved the following steps. Further detail on the method can be found in SKM (2006) and Ferdowsian et al. (2000).

1) Derivation of the cumulative monthly rainfall residual for all Bureau of Meteorology rainfall districts within the CMA;
2) Aggregation of the observed groundwater level to monthly average groundwater levels;
3) Optimisation of the r^2 correlation between the groundwater level and the cumulative rainfall residual by lagging the rainfall up to 24 months behind the groundwater level;
4) Building the multiple regression model for the above data. All models were built using the entire groundwater level record;

In order to be accepted in the final input datasets a bore was required to have a water level record >5 years, a multiple regression error $r^2 > 0.6$ and a strong model correlation between rainfall and groundwater level fluctuation. Multiple regression estimates for 106 bores satisfied these criteria and were included in the final input dataset.

2.6 Comparison of final datasets

A summary of the bores included in the NAP 2004 watertable surface and the revision of the surfaces undertaken in this project is provided in Table 2-3.

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[1] Five bores near Morrison (Mer1, Mer 2, Bal 1, 7128 and 7129) only had recent water levels available for May 2007. Although there may be some error due to seasonal fluctuation it was decided that there was still more value in including these bores than in excluding them.

- **Table 2-3 Comparison of bores, considered, removed and included in the NAP 2004 and Corangamite 2007 watertable surfaces.**

	NAP (2004)	Corangamite (2007)
All bores meeting initial selection criteria (see Section 2.1)	525	525
Bores removed in de-nesting routine	145	141
Bores removed as “outliers”	43	23
Bores acceptable in 2004 but not acceptable in 2007[2]	N/A	20
Additional bores identified in comparison with CCMA database	N/A	32
Total No. of bores used in the modelling	338	373

2.7 Digital Terrain Model

The DTM incorporated into the analysis was derived from the recently completed Victorian state-wide terrain model compiled by Sinclair Knight Merz for Department of Sustainability and Environment (DSE). Compilation of the DTM used modelling utilities developed by the Australian National University. These incorporate not only elevation data such as contours and spot heights but also hydrology features such as streams and lakes, to create a hydrologically correct terrain model that realistically represents surface drainage.

The model was compiled from a number of data sources. Within the project area, the two main data sources were the 1:25,000 topographic data series from DSE and airborne lazar scanning (ALS) data from the Corangamite Catchment Management Authority. The DSE 1:25,000 data has a stated accuracy of better than ± 5m, while the ALS data is generally considered to be of an accuracy better than ± 0.25m.

Figure 2-1 presents a comparison analysis over an area modelled using the 1:25,000 topographic data to the west and ALS data to the east. The white line is the border between the two data sets. As expected, in the west the mapped and derived contours are almost co-linear. In the east the difference between the mapped and ALS derived contours is apparent but well within the stated contour accuracy of ± half an interval (5m). It could be noted that in this area the ALS data tends to be lower that the mapped elevations.

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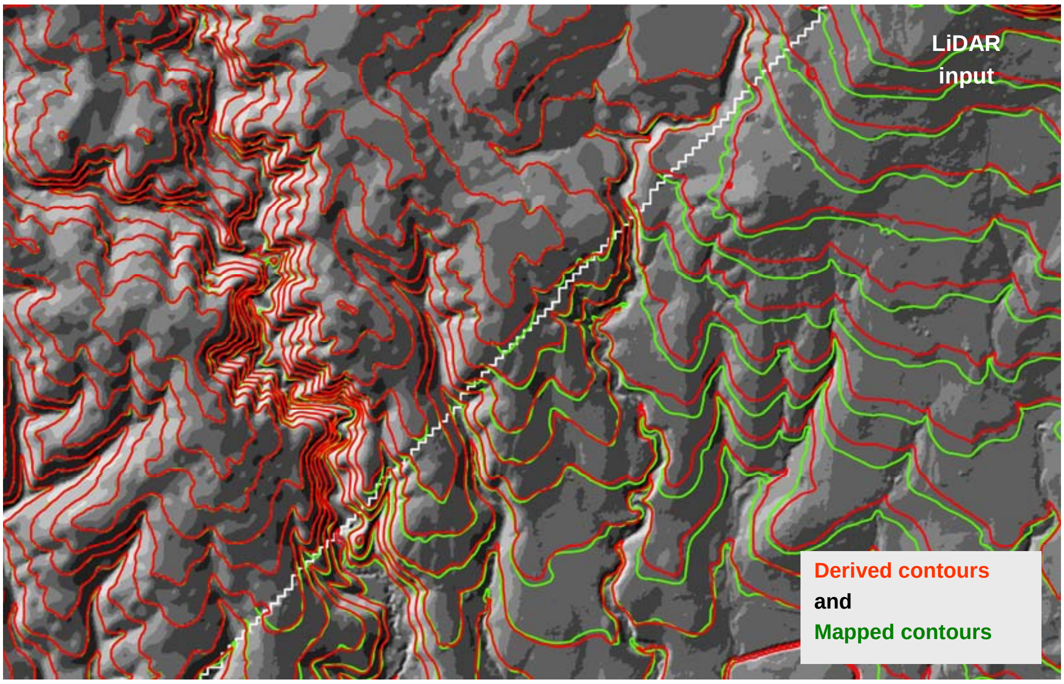
[2] These bores that were included in the NAP 2004 modelling but due to the cessation of salinity monitoring in the early 2000’s there were no readings available for 2007. The recommencement salinity monitoring by the CCMA promises to increase the availability and currency of monitoring bore data for future projects.

Figure 2-1 Comparison of 1:25,000 mapped contours (green) and contours derived from the state-wide 20m grid cell resolution DTM (red).



The DSE terrain model was compiled to a 20m grid resolution. Each grid cell represents the average elevation over a 20m by 20m area. To operate within the system limits of the kriging utilities, the grid size of the project DTM was increased to 50m. Averaging techniques were used to derive the project DTM grid values from the DSE model while retaining its hydrologically correct structure.

2.8 Surface Water Hydrology and Saline Discharge Mapping

GIS coverage of mapped saline discharge was provided for use on the project by the CCMA. This was used in concert with 1:25K VicMap Hydro coverage of hydrology to develop the watertable constraint layers used in the modelling process.

2.9 Development of Constraint Layers

A key advantage of the SGS modelling method is that it allows the incorporation of additional qualitative information; that is minimum and maximum water level criteria at certain grid cells. Where an SGS estimate does not meet the criteria it is rejected and another estimate is made.

The criteria applied in this project are in Table 2-4. The criteria ensure that implied or directly observed water table conditions are included in the predicted water level estimates. The criteria are based on the following assumptions:

- Rivers, streams and lakes are surface expressions of groundwater level and as such the water level in these features represent groundwater level,
- Saline discharge locations are a signature of shallow water table,

By applying these limiting criteria to the SGS analysis the resultant water table estimates are constrained to match observed or implied groundwater conditions and patently erroneous estimates (i.e. significant artesian heads) are eliminated. The resultant maps provide more realistic groundwater levels without invalidating the analysis.

It should be emphasised that these constraint layers do not prescribe watertable depths but rather provide bounds within which estimates must fall to be accepted. In areas where there are permanent surface water features or mapped saline discharge the constraint window is narrow. In areas where there is no secondary information (i.e. no surface water or saline discharge) the constraint window is very large. Since the SKM (2006) watertable maps the minimum depth to watertable constraint for the non-saline discharge has been reduced from >0.5m to >-2m. This change was made to allow the surface to go slightly artesian where surrounding bore data and topography suggests that groundwater discharge may be occurring. This ensures that the surfaces will not only reflect our existing knowledge of saline discharge but also have the potential to identify discharge that has not been identified in the saline discharge mapping process.

Table 2-4 SGS criteria for depth to watertable estimates

Type of Region Within CMA	Minimum Depth to Watertable	Maximum Depth to Watertable
Below streams and lakes that are receiving saline discharge	>= -5m (artesian)	<= 2m
Below streams and lakes **NOT** receiving saline discharge	>= -1m (artesian)	<= 2m
On the land surface and having saline discharge	>= -5m (artesian)	<= 2m
On the land surface and **NOT** having saline discharge	>= -1m	<= 500 m

Images showing the distribution and values applied to the maximum and minimum constraints for the SGS process can be found in **Appendix A**.

3. Methodology

3.1 Introduction

The depth to watertable map of the CCMA produced in SKM (2006) was formulated using kriging with external drift (KED), an interpolation method that draws on the land surface in its estimation of the watertable depth. A key component in the revision of the watertable surfaces was an evaluation of the accuracy and applicability of this method in the Corangamite CMA region. This evaluation and a discussion to determine the most appropriate modelling approach was conducted with Peter Dahlhaus.

The original intention was to sub-divide the CMA into different mapping units, based on an understanding of the regional hydrogeology and the relationship between the watertable and surface elevation. In each mapping unit an individual spatial model (correlogram) would be built and an appropriate modelling technique (KED or another form of kriging) selected.

After the data collation was completed it became apparent that this approach was not practical due to the limited number and the spatial distribution of observation bores, which tend to be concentrated in areas with known salinity problems. There were too few bores available to build statistically valid spatial models in each of the mapping units. The decision was taken to pursue an alternative geostatistical method, Sequential Gaussian Simulation (SGS), because this approach allows the incorporation of soft hydrogeological knowledge in the modelling process while still considering the bore data at a regional level. SGS also allowed secondary data such as saline discharge mapping and surface water hydrology to be considered in the modelling without biasing the modelling results towards these features.

3.2 Overview – Sequential Gaussian Simulation

Sequential Gaussian Simulation (SGS) is a geostatistical technique that is used to generate a series of possible watertable surfaces. This contrasts with more conventional spatial modelling methods (e.g. ordinary kriging, KED) which produce a single, best estimate watertable map.

In this project SGS was used to produce one hundred depth to watertable maps for the Corangamite CMA. A single water level map generated by the SGS method is termed a “realisation”. Each realisation honours both the observed data and any constraints that are applied. Mapping the water level one hundred times results in one hundred estimates for each grid cell and as such a statistical distribution of possible water level values at each grid cell is obtained.

An SGS realisation is generated by sequentially estimating the water table at single points within the measurement domain. An estimate of the watertable depth is made at a grid cell from surrounding observation bore data. Once estimated this grid cell is used as an additional data point in the subsequent estimation of all following grid cells. That is, it treats the previously estimated grid cell values as new groundwater observations. Each realisation differs from all others because the starting cell and the order in which the cells are estimated are randomly selected. Various user options exist to ensure the previously estimated cells do not dominate too heavily over the true observation data.

Presenting the statistical distribution of the hundred surfaces allows for a more explicit expression of the uncertainty involved with the interpolation method. Identifying the maximum and minimum watertable estimates from the hundred surfaces provides an uncertainty range at each grid cell in the modelling domain. This range is measured in metres and provides a measure of uncertainty

3.3 Application of the SGS Approach

The following section provides a generalised overview of the SGS modelling process as it was applied in this project. Specific detail on the methods can be found in SKM (2006), while theoretical background to the modelling technique is available in Goovaerts (1997), Deutsch et al. (1998), Peterson et al. (2004b) and SKM (2006). Detail of the spatial model applied (correlogram) and the parameter files used in the modelling in contained in Appendix B.

Figure 3-1 provides a simplified illustration of the steps involved in modelling the Corangamite CMA watertable surfaces. The method involves the following stages:

1. Input Data Sets

The following inputs data sets were generated:

- Bore Data - February 2007 watertable observations were obtained for a series of state observation network and salinity bores in and around the CMA. Detail on this process is provided in Section 2.
- Maximum Depth to Watertable Constraint – The maximum constraint layer was generated for every grid in the modelling domain based on surface water hydrology and saline discharge mapping (see Section 2 for more detail)
- Minimum Depth to Watertable Constraint - The minimum constraint layer was generated for every grid in the modelling domain based on surface water hydrology and saline discharge mapping (see Section 2 for more detail)
- RWL Residual Surface – A residual RWL surface is generated using the Kriging with External Drift (KED) Process. This surface is predominantly based on the RWL-RLNS residuals and so is not influenced by the artefacts that were apparent in the original NAP (2004) KED surfaces. The RWL residual surface is used in the post processing of the SGS results.
- Digital Elevation Model – The DEM is used to reference all modelling outputs back to the natural surface.

2a. SGS Modelling (Realisation 1)

The modelling routine randomly picks a grid cell within the modelling domain. It identifies neighbouring bore data and applies the correlogram to obtain an estimate of the watertable elevation at the grid cell. The routine then checks whether this estimate violates the minimum and maximum watertable constraints established for the grid cell. If the estimation is within the range defined by the constraints it is accepted. If the estimation is outside the constraint range it is discarded and a new estimate is made. This process is repeated until an estimate is obtained that meets the constraint criteria.

2b. SGS Modelling (Realisation 1)

The routine randomly selects a new grid cell to estimate. However, in estimating the watertable depth at this grid cell it not only uses bore data but also the watertable estimate made in step one.

2c. SGS Modelling (Realisation 1)

The process described in steps 1 and 2 is repeated until all grid cells in the modelling domain are estimated

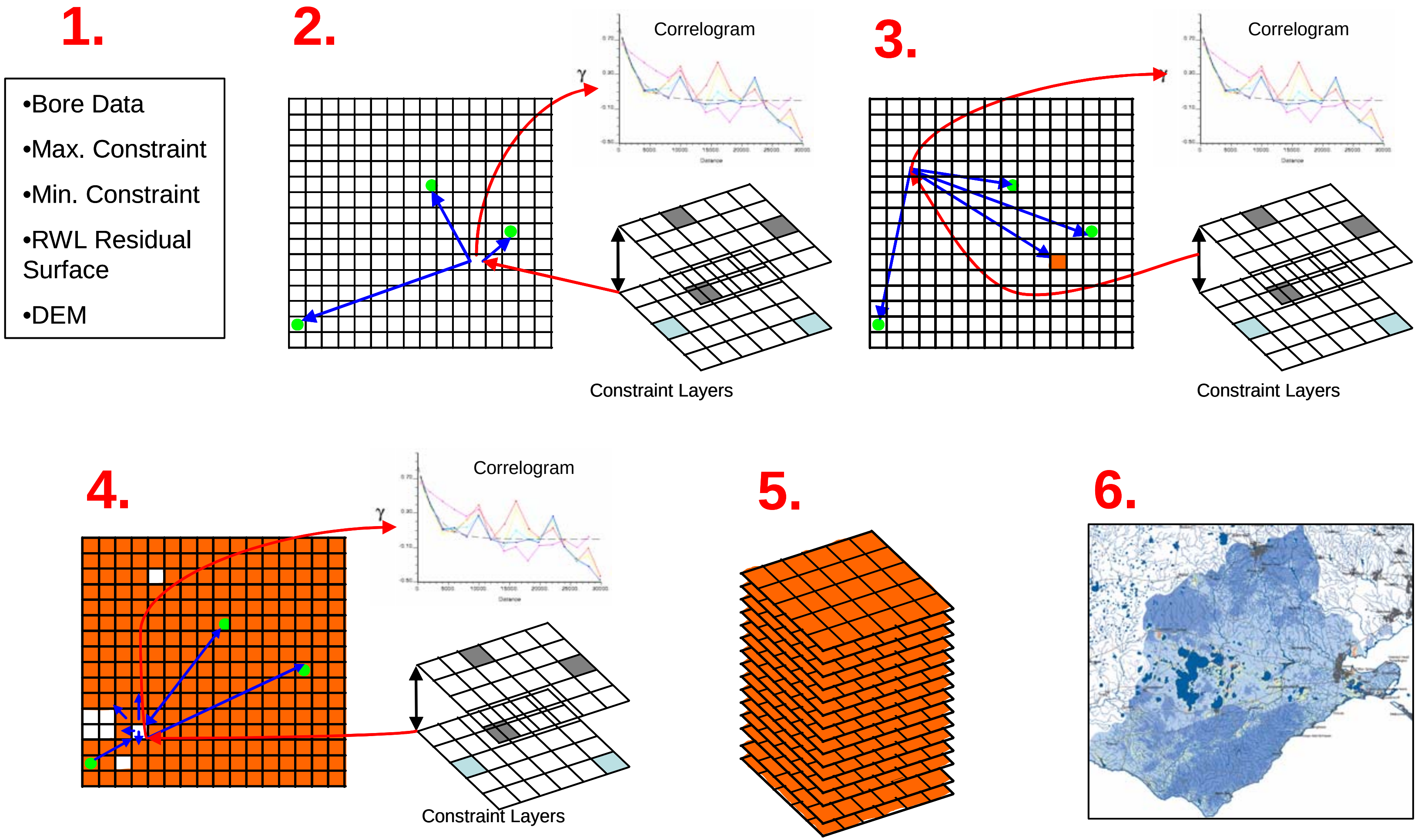
3. SGS Modelling (100 Realisations)

Once an estimate has been obtained at all grid cells the first realisation is completed. The modelling routine then starts on the second realisation selecting a new random grid cell to begin the watertable estimation process. Because estimated grid cells are subsequently used as observation points in the modelling process, the location of the starting grid cell and the order in which the grid cells are estimated influence the shape of the final watertable surface. The process is repeated 100 times and produces 100 watertable surfaces. All of the surfaces are consistent with the bore observations but vary slightly in their estimation of grid cells where there is no bore data.

4. Generation of SGS Watertable Products

The 100 watertable surfaces provide a statistical distribution that allows a range of probability products to be generated. In this project these include maps showing the probability that the watertable will be below a chosen depth (2m, 5m and 10m), a depth to watertable surface based on the median watertable depth taken from each grid cell and a reliability map that is based on the variation between the estimations at each cell.

- **Figure 3-1 Simplified diagrammatic representation of the SGS approach to modelling watertable surfaces.**



3.4 Assumptions and Limitations of SGS Method

- The constraint layers have been generated using the surface hydrology and saline discharge overlays. The approach assumes that all flowing water courses and lakes reflect the watertable surface and can be used as a proxy watertable measurement. While this is a commonly made assumption, it is possible that it may lead to an overestimation of the watertable depth in areas where lakes or streams are disconnected from the regional watertable surface.
- The constraint layers rely on the saline discharge overlay. They assume that this information is accurate and that the mapped saline discharge areas are associated with and caused by the occurrence of a shallow watertable. This assumption may lead to a less reliable estimate of the regional watertable where the saline discharge is related to other local processes such as water logging or a perched watertable.
- The saline discharge coverage has been compiled over a series of years and is not date specific. In contrast, the watertable estimations made in this project are current for February 2007. In some regions the area of land affected by saline discharge has decreased in the last decade due to the dry climatic conditions. The inconsistency between the currency of the saline discharge overlay and the watertable estimation date may reduce the reliability of the watertable predictions in some areas.
- The watertable products generated are regional maps and are not appropriate for the assessment of salinity at a small, sub-catchment scale. The size of the model grid size in this project has been refined from the original $100m^2$ to $50m^2$, increasing the resolution of the modelling by four times. However, the surfaces may not capture the topographic variation or subtle changes in watertable depth that manifest salinity in the break of slope in the transitional area between the highlands and the lower lying area within the CMA.

4. Results

4.1 Products

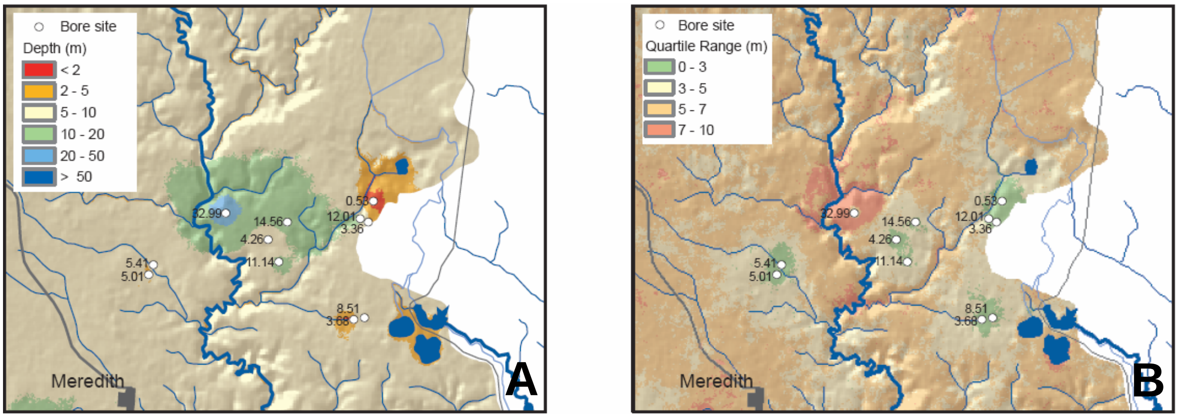
The SGS method produces numerous estimates of the watertable elevation. For every grid cell in the calculation domain there are multiple estimates of water table depth (one for every SGS realisation). For the SGS process 100 realisations were calculated for the CMA region. These estimates form a population of data that can be analysed to produce statistics at each grid cell. The statistics were used to derive the following products:

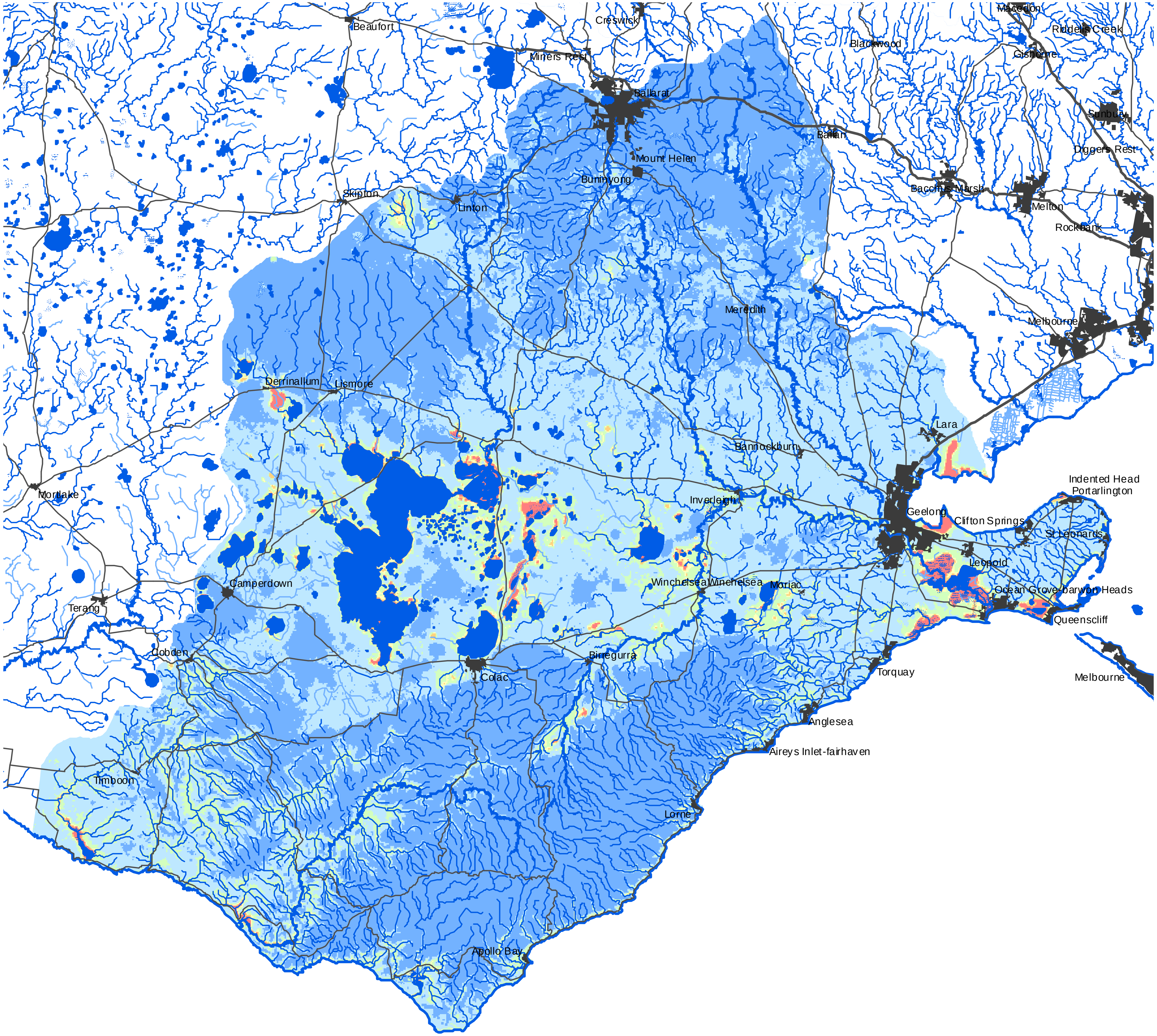
- **Watertable Depth Probability Maps -** Maps of the probability that the depth to the watertable was less than 2, 5 and 10m in 2007. The probability is determined by simply summing the number of realisations in which the criteria is met and expressing this as a ratio of the number of realisations.
- **Watertable Depth (Median) Map -** This was determined by taking the median watertable depth at each grid cell from the 100 realisations. The median depth is considered more appropriate than the mean or average depth because the distribution is not normal. Using the median depth minimises the influence that extreme or outlying realisations will have on the estimate of the watertable depth.
- **Reliability (Interquartile Range) -** Further analysis was carried out to illustrate the estimation uncertainty by quantifying the spread of data at each grid cell. This uncertainty is presented as the interquartile Range. The interquartile range is the range that contains 50% of the watertable estimates and is measured in metres. If the interquartile range is 3m then 50% of the realisations fall within a 3m range around the median watertable depth. Where the interquartile range is small the watertable probability and depth estimates have a high reliability. Where the interquartile range is large the watertable probability and depth estimates have a low reliability. Examination of the Reliability overlay will reveal that the interquartile range is generally smallest in areas where there is a high data density or the constraints are narrow (e.g. around Lake Corangamite).

  The reliability does not only reflect the bore density, it also identifies watertable observations that have a poor relationship with surrounding data. Figure 4-1 shows a cluster of bores located in the Morrisons - Sheoaks salinity action plan target area. The majority of bores have a shallow depth to watertable (less than five metres); however, there is one bore with a significantly deeper watertable of 33m. The depth to watertable surface honours the data point. However, the reliability map shows a halo of low reliability watertable estimations surrounding the observation point. This reflects the inconsistency between the bore with the deep watertable observation and the neighbouring bores which indicate the watertable surface should be shallower.

The reliability map should always be used in concert with the probability and the median depth to watertable maps. Uncertainty is inherent in the products due to the large spatial extent of the CMA and the scarce number and clustered distribution of watertable monitoring points. Understanding the reliability associated with a probability or watertable estimate is critical in judiciously using the information.

- **Figure 4-1 Inset A shows the watertable depth. Inset B shows the associated reliability (inter-quartile range). The watertable depth values at the bore locations is post plotted on both figures.**





CORANGAMITE CMA

Corangamite CMA Groundwater Level Mapping

Probability groundwater Is less than 2 metres deep

Kilometres

0 5 10 20 30 40

🟦 Surface water body

SGS less than 2m

🟥 > 0.95

🟧 0.75 - 0.95

🟨 0.75 - 0.50

🟩 0.50 - 0.25

🟦 0.05 - 0.25

🟦 < 0.05

This maps presents the probability that the watertable will be less than 2m beneath the land surface. Areas shown in red and orange have a high probability of being less than 2m in depth while areas shown in blue have a low probability of being less than 2m. The probability is based on 100 possible watertable surfaces that have been generated using a geostatistical modelling process called - Sequential Gaussian Simulations. To obtain an estimate of the reliability of the probability map see the accompanying map entitled "Reliability (Inter Quartile Range)"

SKM Refer to Sinclair Knight Merz document;
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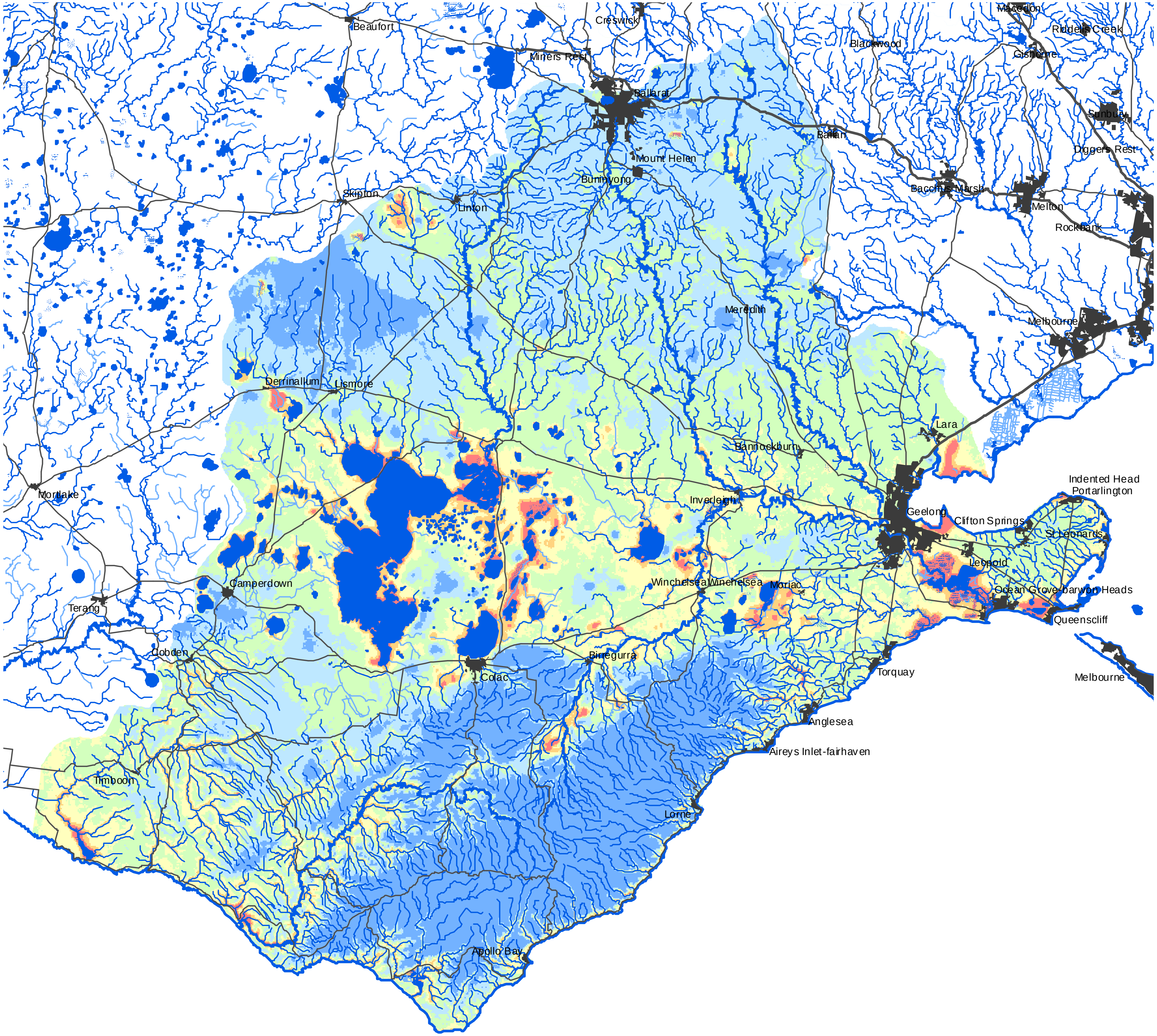
groundwater_le_02m.mxd Produced: 04/03/2008



CORANGAMITE CMA

Corangamite CMA Groundwater Level Mapping

Probability groundwater Is less than 5 metres deep

Kilometres
0 5 10 20 30 40

- 🟦 Surface water body

SGS less than 5m

- 🟥 > 0.95
- 🟧 0.75 - 0.95
- 🟨 0.75 - 0.50
- 🟩 0.50 - 0.25
- 🟦 0.05 - 0.25
- 🟦 < 0.05

This maps presents the probability that the watertable will be less than 5m beneath the land surface. Areas shown in red and orange have a high probability of being less than 5m in depth while areas shown in blue have a low probability of being less than 5m. The probability is based on 100 possible watertable surfaces that have been generated using a geostatistical modelling process called - Sequential Gaussian Simulations. To obtain an estimate of the reliability of the probability map see the accompanying map entitled "Reliability (Inter Quartile Range)"

SKM Refer to Sinclair Knight Merz document;
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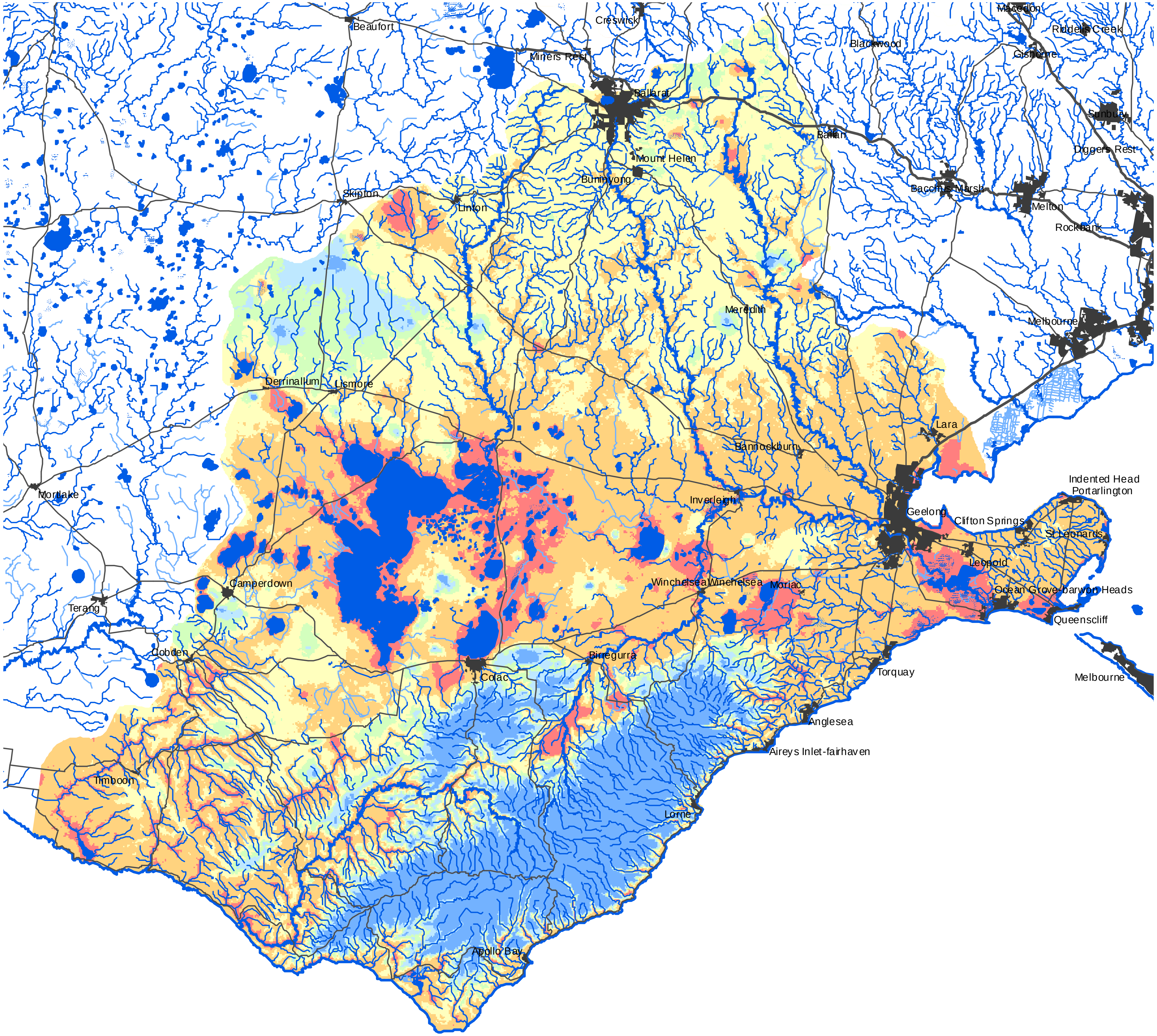

CORANGAMITE CMA

Corangamite CMA Groundwater Level Mapping

Probability groundwater Is less than 10 metres deep

Kilometres
0 5 10 20 30 40

🟦 Surface water body

SGS less than 10m

🟥 > 0.95
🟧 0.75 - 0.95
🟨 0.75 - 0.50
🟩 0.50 - 0.25
🟦 0.05 - 0.25
🟦 < 0.05

This maps presents the probability that the watertable will be less than 10m beneath the land surface. Areas shown in red and orange have a high probability of being less than 10m in depth while areas shown in blue have a low probability of being less than 10m. The probability is based on 100 possible watertable surfaces that have been generated using a geostatistical modelling process called - Sequential Gaussian Simulations. To obtain an estimate of the reliability of the probability map see the accompanying map entitled "Reliability (Inter Quartile Range)"

SKM
Refer to Sinclair Knight Merz document;
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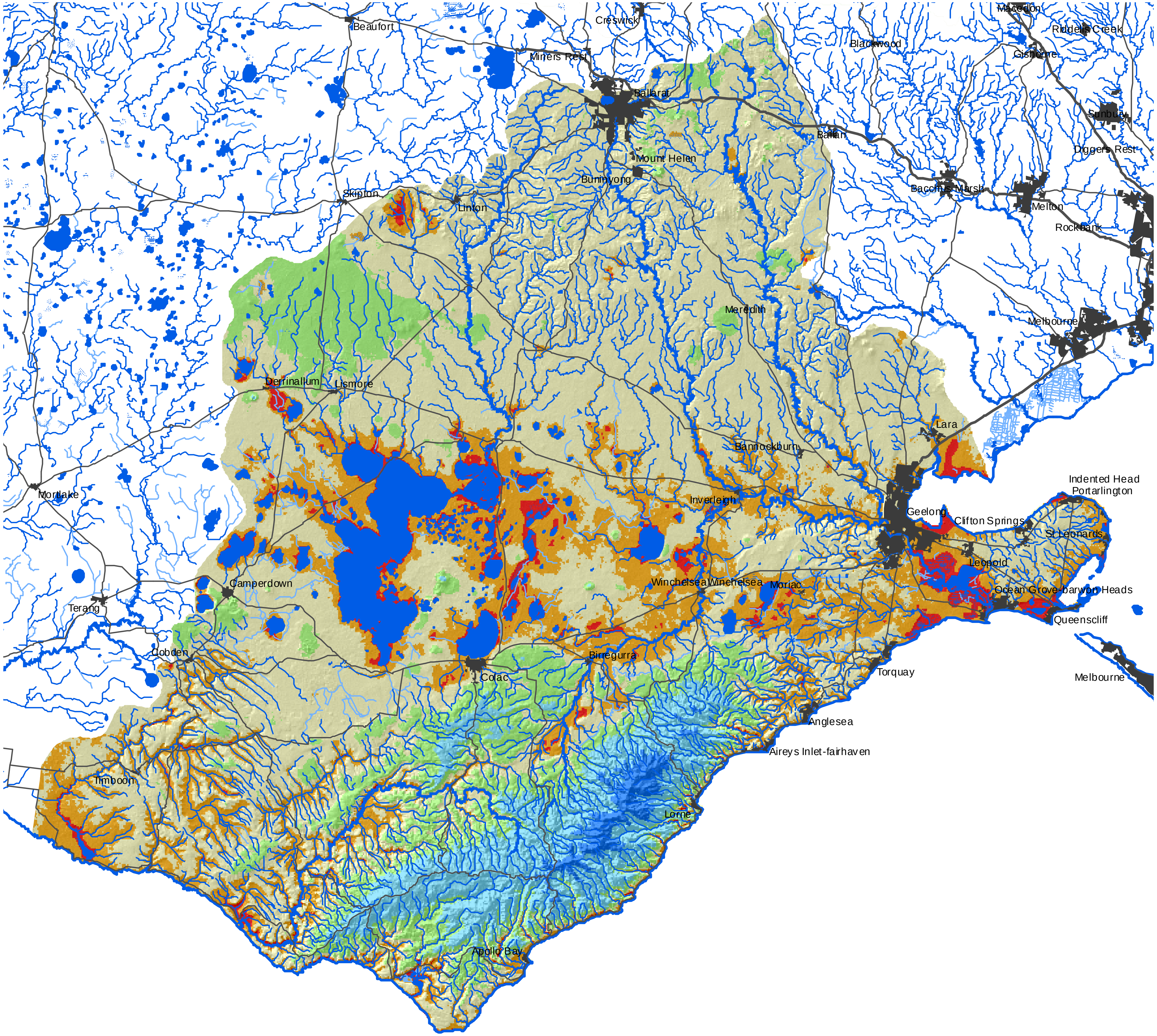
groundwater_le_10m.mxd Produced: 04/03/2008



CORANGAMITE CMA

Corangamite CMA Groundwater Level Mapping

Watertable Depth

Kilometres
0 5 10 20 30 40

🟦 Surface water body

Depth (m)

🟥 < 2
🟧 2 - 5
🟨 5 - 10
🟩 10 - 20
🟦 20 - 50
🟦 > 50

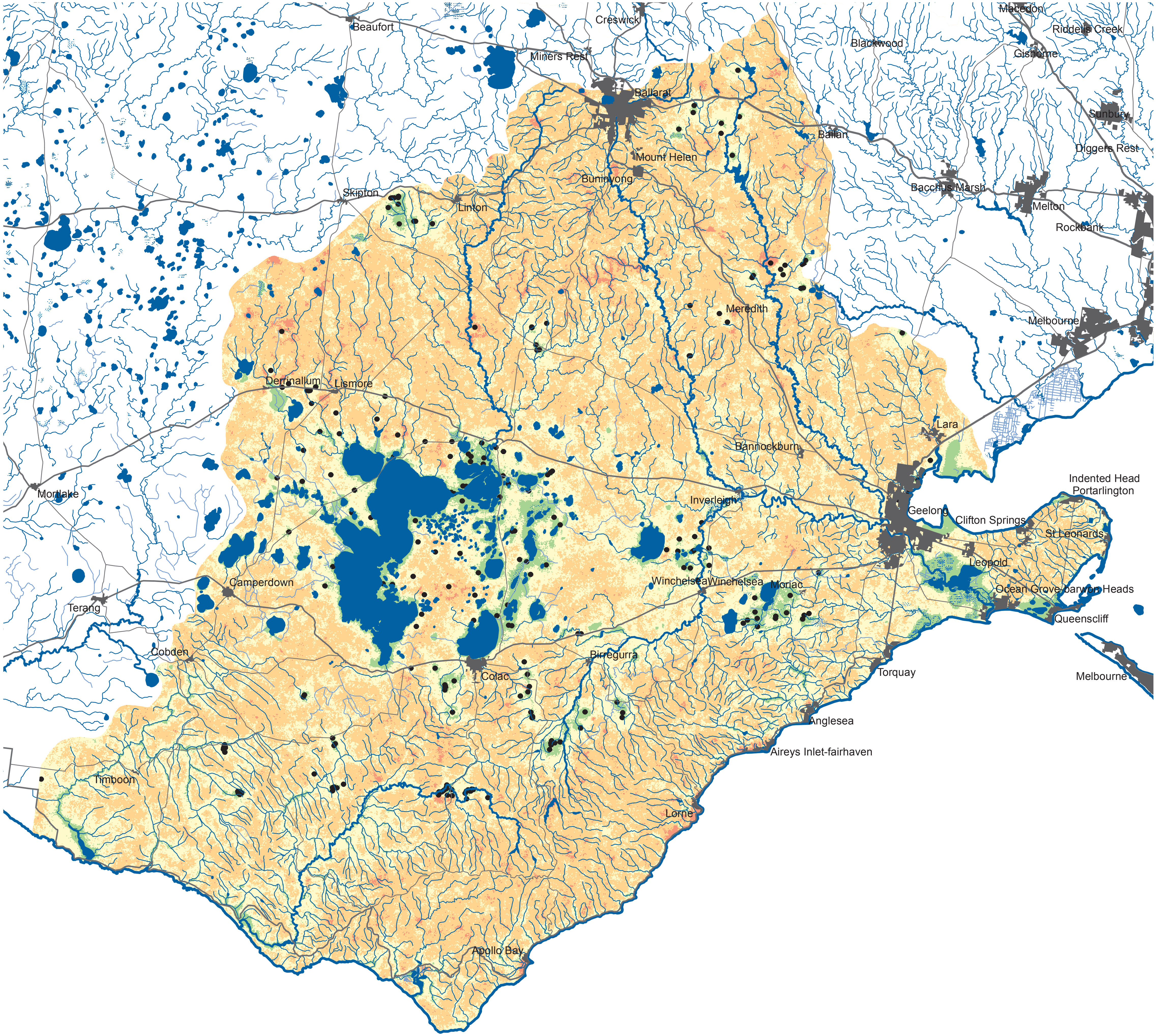
This map presents the depth to the watertable in metres below the land surface. The values displayed represent the median value taken from 100 possible watertable surfaces generated using a geostatistical modelling process called "Sequential Gaussian Simulations".
To obtain an estimate of the reliability of the Median depth to watertable map see the accompanying map entitled "Reliability (Interquartile Range)"

SKM
Refer to Sinclair Knight Merz document;
I:\VWES\Projects\VW03986\Technical\spatial\arcmap\
groundwater_median.mxd Produced: 04/03/2008

CORANGAMITE CMA

Corangamite CMA Groundwater Level Mapping

Reliability (Interquartile Range)



Kilometres

0 5 10 20 30 40

● Bore locations

🟦 Surface water body

Interquartile Range (m)

Reliability

High	🟩	0 - 3
	⬜	3 - 5
	🟧	5 - 7
Low	🟥	7 - 10

Reliability (Interquartile Range)
This map shows the reliability of the watertable depth and probability estimates produced in the Corangamite Region Depth to Watertable Mapping Project.

Reliability is presented as the Interquartile Range. It is based on the 100 possible watertable surfaces generated through a geostatistical modelling process called "Sequential Gaussian Simulations".

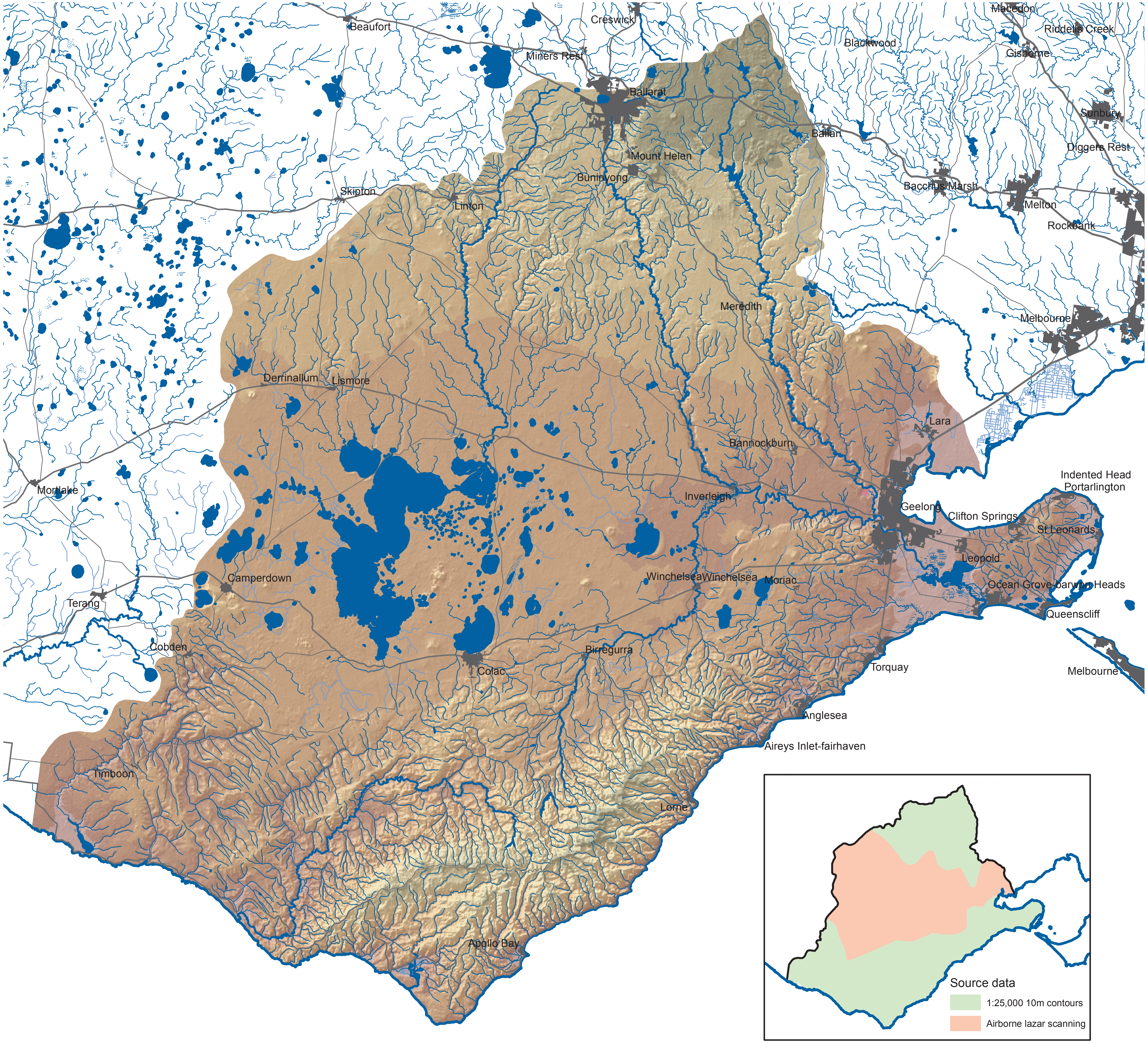
The interquartile range provides an estimate of reliability at each grid cell and is measured in metres. 50% of the modelled watertable surfaces will fall within the interquartile range (E.g. If the interquartile range is 3m then 50% of the watertable surfaces will be within a 3m band of the median). Where the interquartile range is small the watertable probability and depth estimates have a high reliability. Where the interquartile range is large the watertable probability and depth estimates have a low reliability.

SKM
Refer to Sinclair Knight Merz document;
I:\VWES\Projects\VW03986\Technical\spatial\arcmap\
Groundwater_quantile.mxd Produced: 04/03/2008

CORANGAMITE CMA

Corangamite CMA Groundwater Level Mapping

Digital Terrain Model



Kilometres

0 5 10 20 30 40

■ Surface water body

Elevation (mAHD)

- < 0
- 0 - 20
- 20 - 50
- 50.00000001 - 100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 500
- 500 - 750
- 750 - 1,000

The DTM incorporated into the analysis was derived from the recently completed Victorian state-wide terrain model compiled by Sinclair Knight Merz for Department of Sustainability and Environment (DSE). Compilation of the DTM utilised modelling utilities developed by the Australian National University. These incorporate not only elevation data such as contours and spot elevations but also hydrology features such as streams and lakes, to create a hydrologically correct terrain model that realistically represents surface drainage.

The model was compiled from a number of data sources. Within the project area, the two main data sources were the 1:25,000 topographic data series from DSE and airborne lazar scanning (ALS) data from the Corangamite Catchment Management Authority. The DSE 1:25,000 data has a stated accuracy of better than + 5m, while the ALS data is generally considered to be of an accuracy of better than + 0.25m.

Refer to Sinclair Knight Merz document;
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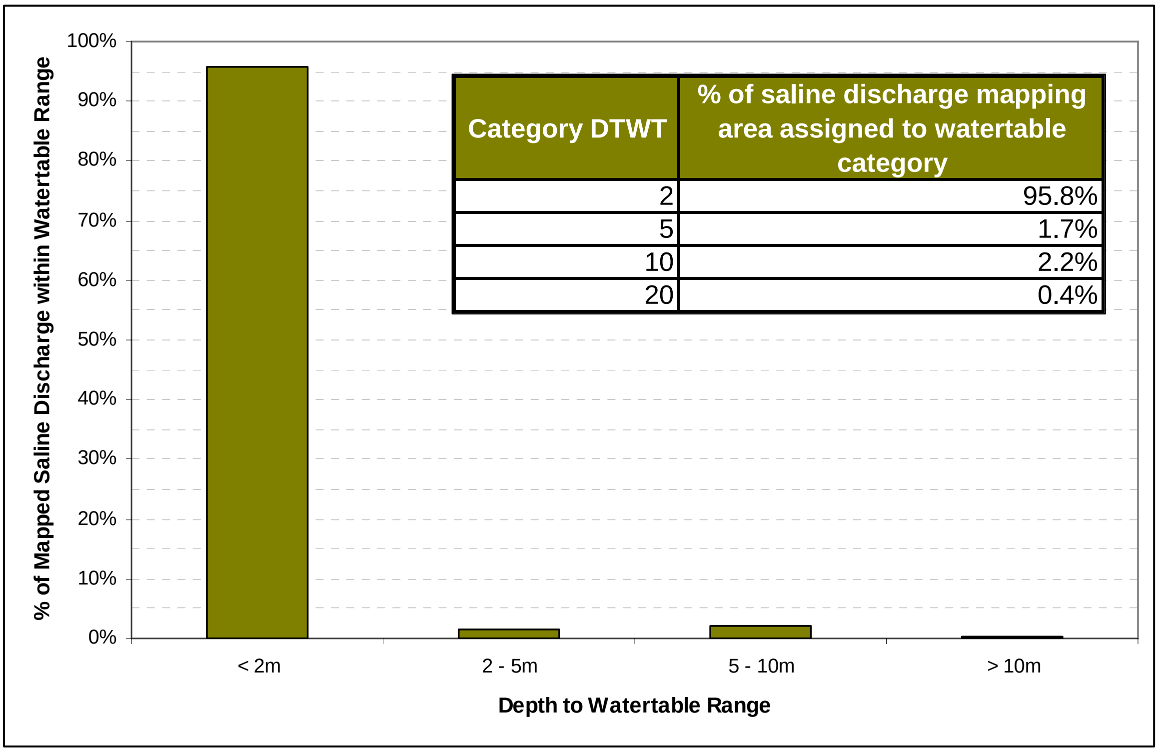
dtm.mxd Produced: 05/03/2008

4.2 Discussion

A preliminary examination has been undertaken to assess the accuracy of the modelled surface against the input bore data and the salinity discharge layer. In the GIS environment a grid of the watertable depth (derived from the median depth at each grid cell) was intersected with the polygons of mapped saline discharge. Each grid cell containing saline discharge was assigned with a water level. The sum of the areas for each watertable class (<2m, 2 – 5m, 5 – 10m, >10m) were divided by the total area of saline discharge to calculate a percentage coverage. Results are provided in Figure 4-2 and indicate that there is a strong correlation between the occurrence of shallow watertables and mapped saline discharge with 96% of saline discharge occurring in areas where the predicted watertable surface is less than 2m below the land surface.

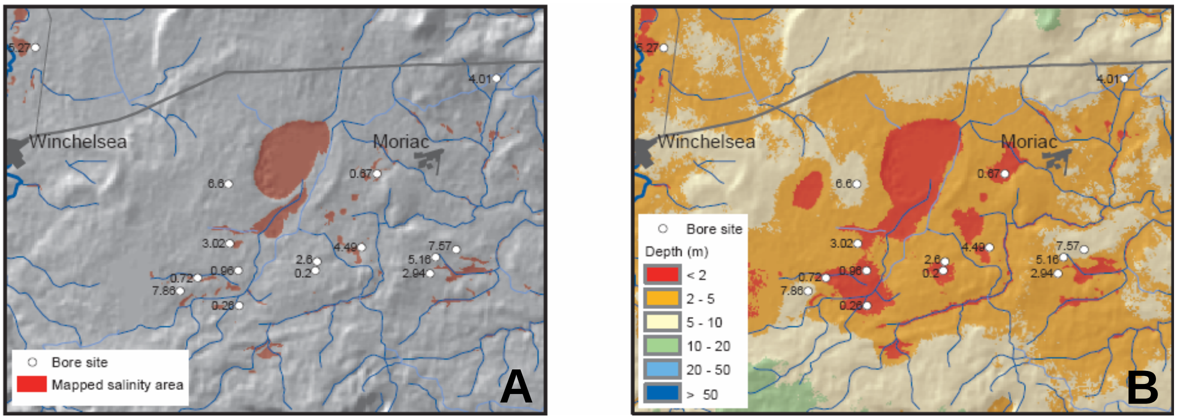
- **Figure 4-2 Predicted watertable beneath mapped saline discharge as a percentage of the total area of saline discharge.**



Category DTWT	% of saline discharge mapping area assigned to watertable category
2	95.8%
5	1.7%
10	2.2%
20	0.4%

This correlation is also apparent when the spatial distribution of the saline discharge is compared with the occurrence of shallow watertables. An example from the area between Moriac and Winchelsea is provided in Figure 4-3. Inset A shows the mapped saline discharge and the observed water level depths from the bores used in the modelling, Inset B shows the predicted depth to watertable.

- **Figure 4-3 Inset A shows the mapped saline discharge area. Inset B shows the watertable depth derived from the median estimate at each grid cell.**



5. Conclusions and Recommendations

5.1 Conclusions

Sinclair Knight Merz was engaged by the Corangamite CMA to revise watertable maps for the CMA region produced under the National Action Plan for Salinity and Water Quality "Benchmarking Watertables" project (SKM, 2006). Since the completion of the NAP project a number of significant advancements have been made to both the geostatistical modelling method and the accuracy of the input datasets. The key improvements implemented in this project include:

- Use of a significantly more accurate Digital Terrain Model (DTM), resulting in a four fold increase in the resolution of the model grid and a significant increase in the vertical accuracy of the DTM.
- An extensive review of the available bore data in the Corangamite region. Including a review of the bores included and removed from the SKM (2006) surfaces, cross referencing the CCMA Groundwater database and salinity monitoring bores.
- Re-projection of watertable surfaces to February 2007 and use of the most up to date version of the saline discharge mapping.
- Incorporation of hydrogeological knowledge through consultation with P Dahlhaus at following key stages of the project: review of available bore data, selection of the most appropriate modelling technique for the CMA region and review of the final mapping products.
- Adoption of Sequential Gaussian Simulation as the primary geostatistical modelling method (in the place of kriging with external drift which was used as the primary method in the NAP project). SGS allows the incorporation of saline discharge, surface water hydrology and land surface elevation in the watertable modelling process.
- Better presentation and communication of the SGS mapping products. This included the production of a depth to watertable surface from the SGS which was not undertaken in the NAP project, and a more considered presentation of reliability.

Results of the watertable modelling show marked improvement on the original NAP depth to watertable and probability surfaces. The revised depth to watertable map shows a strong correlation between saline discharge and shallow watertables, such that >95% of mapped saline discharge has a watertable depth of less than two metres. The watertable depth strongly honours the input watertable observations and contains negligible artefacts (such as artesian watertables, which undermined confidence in the original NAP depth to watertable maps).

5.2 Recommendations

The following recommendations are made for the continued development of this work in the Corangamite CMA region:

- Improving Constraint layers

Constraint layers are based on saline discharge mapping and the surface water network. Uniform constraints have been applied across the whole CMA region. There is an opportunity to build in more local knowledge of salinity and groundwater processes by refining the constraint layers on a sub-catchment scale.

- Individual selection of watertable bores

Consultation was undertaken to ensure that a greater number of bores were used and all readily available information accessed. However, CMA wide rules were still applied to screen the inclusion/exclusion of bores based on a depth criteria. There is an opportunity to review these rules and revise them on a catchment scale to provide better characterisation and a better input dataset. This would involve workshopping specific areas with local hydrogeological experts to ensure that all watertable bores are included in the modelling process.

- Identification, refinement and calibration of “problem areas”

The watertable modelling is a “regional” tool. There are still some areas where the reliability is lower. Investigation of these areas at a smaller scale and interrogation of the modelling may help understand the reliability of the modelling better at the smaller scale and enable to the methods to be refined to better characterise the watertable in these areas.

- Re-modelling of watertable surfaces using greater availability of water level data

In the current surfaces there are a number of key salinity bores that were not available for use in the input dataset due to the cessation of monitoring by PIRVIC in the early 2000s. A number of watertable observations also rely on predictions from multiple regression models due to sporadic monitoring over the last five years. Monitoring of salinity bores has since been recommenced by the CCMA. An opportunity exists to revise the watertable modelling in the future when the number of monitoring bores available has increased and certainty in the watertable observations has improved.

- Forecasting of future watertable surfaces by using climate scenarios.

The 2007 surfaces represent a very “dry” scenario, coming off a decade of lower than average rainfall. While this may be more characteristic of future climates it is unlikely this cycle of dry years will continue. Projections for other CMAs are currently being undertaken that use projected climate trends based that consider climate variability. Stochastic rainfall sequences are produced and can be used to inform groundwater trends and provide a higher and lower prediction of future depth to watertable surfaces.

6. References

SKM (2006) *National Action Plan for Salinity and Water - Benchmarking Regional Water Table and Trends – Project Report.* Report for the National Action Plan for Salinity. WC02661.

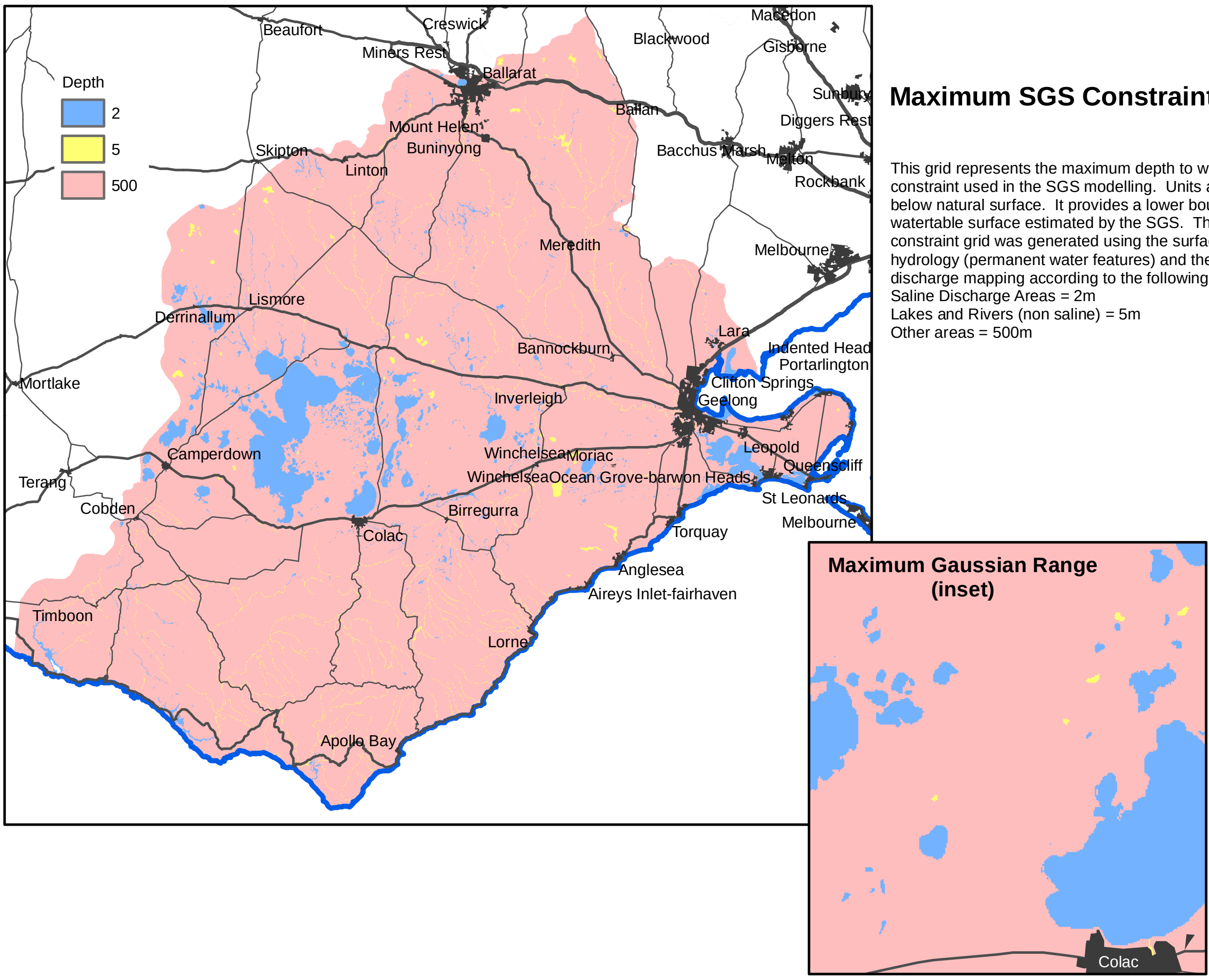
Ferdowsian, R., D. Pannell, C. McCarron, A. Ryder, L., 2000, Crossing, Explaining groundwater hydrographs: separating atypical rainfall events from time trends, *SEA Working Paper 00/12*;

Goovaerts, P., (1997) *Geostatistics for Natural Resources Evaluation*, Oxford University Press, New York, 1997.

Deutsch, C. V. and Journel, A. G. (1998), GSLIB *Geostatistical Software Library and User's Guide*, 2nd Edition. Oxford University Press, New York, 1998.

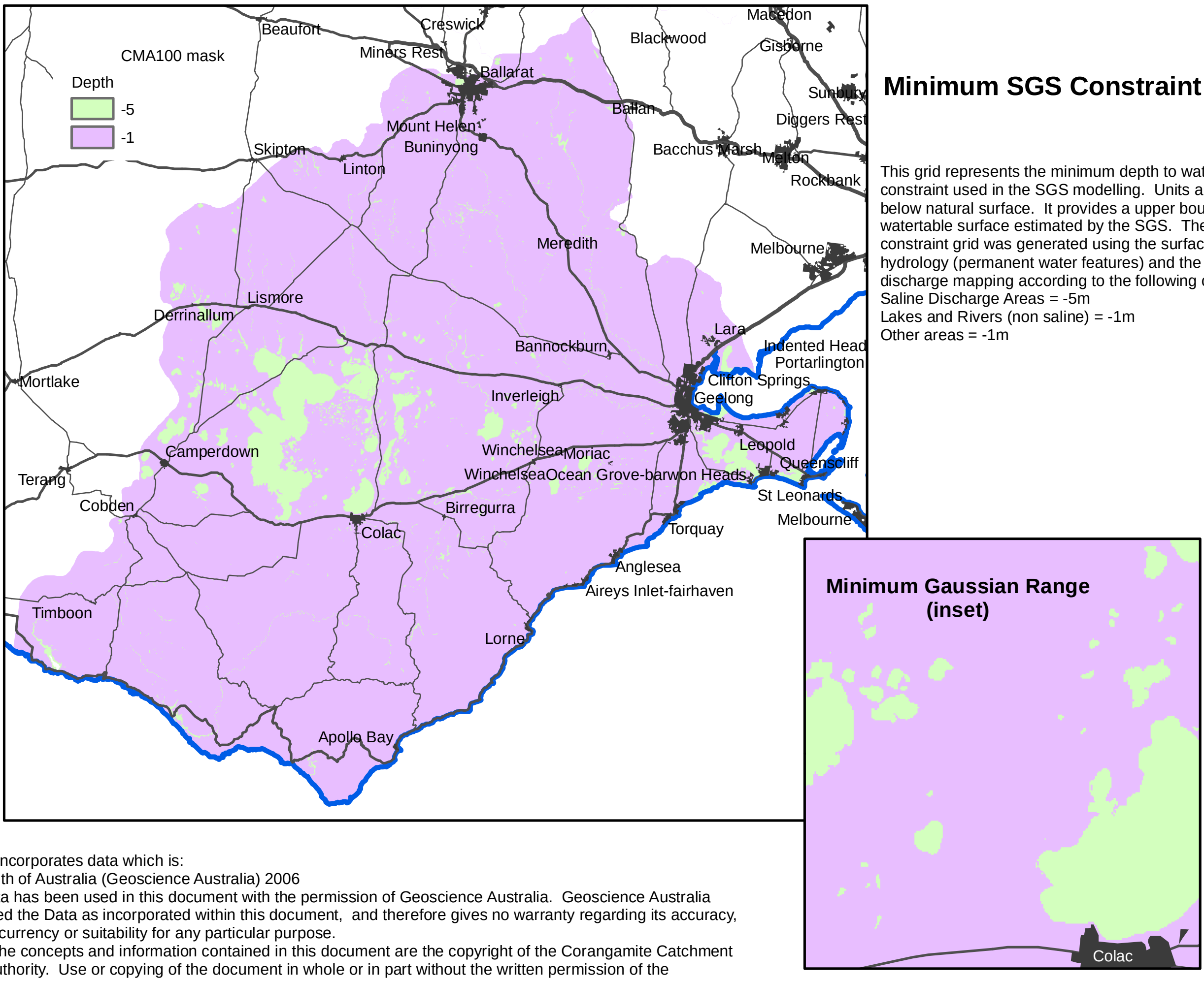
Peterson, T. J. and B. Barnett. 2004b. Spatially Quantifying the Uncertainty of Salinity Risk Assessments. S. Dogramaci and A. Waterhouse. 1st National Salinity Engineering Conference, Perth, Australia., Institute of Engineers.

Appendix A Constraint Layers



Maximum SGS Constraint

This grid represents the maximum depth to watertable constraint used in the SGS modelling. Units are metres below natural surface. It provides a lower bound for the watertable surface estimated by the SGS. The maximum constraint grid was generated using the surface water hydrology (permanent water features) and the saline discharge mapping according to the following criteria:
Saline Discharge Areas = 2m
Lakes and Rivers (non saline) = 5m
Other areas = 500m



Minimum SGS Constraint

This grid represents the minimum depth to watertable constraint used in the SGS modelling. Units are metres below natural surface. It provides a upper bound for the watertable surface estimated by the SGS. The minimum constraint grid was generated using the surface water hydrology (permanent water features) and the saline discharge mapping according to the following criteria:
Saline Discharge Areas = -5m
Lakes and Rivers (non saline) = -1m
Other areas = -1m

Refer to Sinclair Knight Merz document;
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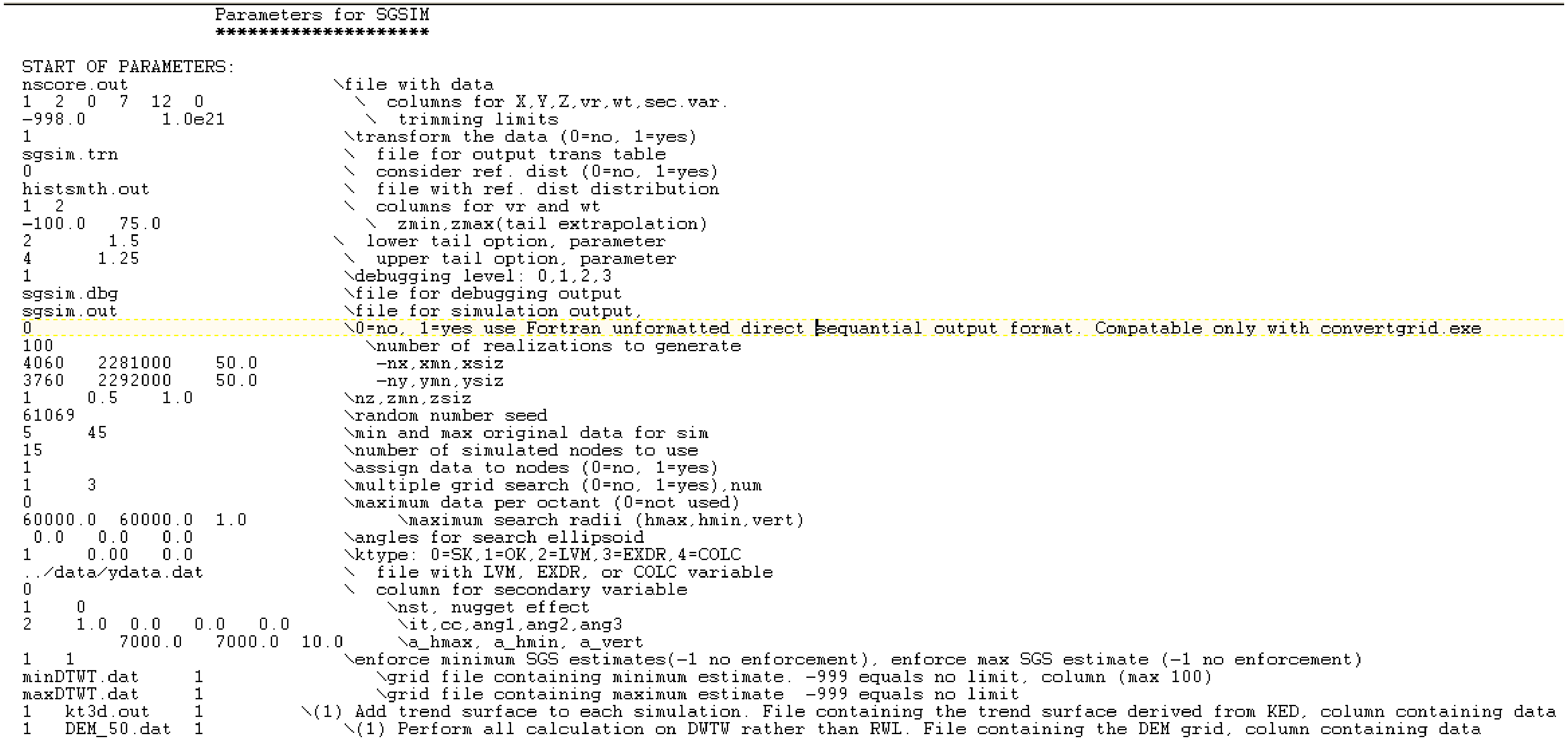
constraints.mxd.mxd Produced: 13/03/2008

Appendix B Input Files for Modelling Process

Figure 6-1 Input Parameter file for SGS modelling



```
                  Parameters for SGSIM
                  ********************

START OF PARAMETERS:
nscore.out                   \file with data
1  2  0  7  12  0              \ columns for X,Y,Z,vr,wt,sec.var.
-998.0       1.0e21             \ trimming limits
1                             \transform the data (0=no, 1=yes)
sgsim.trn                     \ file for output trans table
0                             \ consider ref. dist (0=no, 1=yes)
histsmth.out                  \ file with ref. dist distribution
1  2                          \ columns for vr and wt
-100.0   75.0                   \ zmin,zmax(tail extrapolation)
2       1.5                  \ lower tail option, parameter
4      1.25                   \ upper tail option, parameter
1                             \debugging level: 0,1,2,3
sgsim.dbg                     \file for debugging output
sgsim.out                     \file for simulation output,
0                             \0=no, 1=yes use Fortran unformatted direct sequantial output format. Compatable only with convertgrid.exe
100                             \number of realizations to generate
4060   2281000    50.0           -nx,xmn,xsiz
3760   2292000    50.0           -ny,ymn,ysiz
1     0.5    1.0              \nz,zmn,zsiz
61069                         \random number seed
5     45                      \min and max original data for sim
15                            \number of simulated nodes to use
1                             \assign data to nodes (0=no, 1=yes)
1     3                       \multiple grid search (0=no, 1=yes),num
0                             \maximum data per octant (0=not used)
60000.0  60000.0  1.0              \maximum search radii (hmax,hmin,vert)
 0.0   0.0   0.0              \angles for search ellipsoid
1     0.00   0.0              \ktype: 0=SK,1=OK,2=LVM,3=EXDR,4=COLC
../data/ydata.dat             \  file with LVM, EXDR, or COLC variable
0                             \  column for secondary variable
1    0                           \nst, nugget effect
2    1.0  0.0   0.0   0.0          \it,cc,ang1,ang2,ang3
         7000.0   7000.0  10.0     \a_hmax, a_hmin, a_vert
1   1                         \enforce minimum SGS estimates(-1 no enforcement), enforce max SGS estimate (-1 no enforcement)
minDTWT.dat     1                \grid file containing minimum estimate. -999 equals no limit, column (max 100)
maxDTWT.dat     1                \grid file containing maximum estimate  -999 equals no limit
1   kt3d.out    1         \(1) Add trend surface to each simulation. File containing the trend surface derived from KED, column containing data
1   DEM_50.dat  1             \(1) Perform all calculation on DWTW rather than RWL. File containing the DEM grid, column containing data
```

- **Figure 6-2 Experimental and Modelled Correlogram used in the SGS modelling**