Construction and Calibration Of the Perth Regional Aquifer Model

PRAMS 3.5.2

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Prepared For

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EXECUTIVE SUMMARY

The Department of Water (DoW), as part of their groundwater abstraction resource management planning, have previously and continue to use groundwater flow modelling. In response to environmental constraints on the Swan Coastal Plain, the DoW are developing more sophisticated models to simulate both the saturated and unsaturated zones in the superficial aquifer and the saturated zone in the artesian aquifers. The objective of the Perth Regional Aquifer Model (PRAMS) coupled flow model is to provide a quantitative tool that can be used to assess alternative resource management strategies on the Swan Coastal Plain. In this context, the PRAMS 3.5 model has the same objectives as PRAMS 3.0 (PRAMS), with some additions:

- Estimate the impact of public and private abstraction on water levels in all aquifers;
- Provide quantitative estimates of the water resource on the Swan Coastal Plain;
- Evaluate the effects of future landuse management on groundwater levels on the Swan Coastal Plain;
- Evaluate the impacts of climate change;
- Evaluate the impacts of large artificial recharge and recovery schemes in both confined and unconfined aquifers;
- Determination of well field protection boundaries for public drinking water supply areas using particle tracking; and
- Preparing historic annual water accounts.

A coupled flow model of the Swan Coastal Plain was constructed and calibrated using available water level monitoring data. The construction of the model is consistent with, and based on PRAMS 3.4, as developed by the DoW and includes the VFM, as developed by CSIRO and the Water Corporation. The PRAMS 3.5 model is based on an updated geological interpretation of the Swan Coastal Plain, which includes block faulting (De Silva 2012). The model was constructed using available geological and hydrogeological information, and consists of a 13-layer model, covering approximately 10,000 square kilometres.

The PRAMS 3.5 model was calibrated and verified over the period 2000 to 2012 and 1980 to 2000, respectively. The present calibration of the model is consistent with previous calibrations (e.g. PRAMS 3.0) with average absolute error less than 5% for all of the aquifers. This error is consistent areas south of Gingin Brook, and hence the model is suitable for the relative assessment of changes in water levels in the central area of the model (i.e. Mandurah to Gingin Brook).

Due to the different approaches to calibration in 3.5 compared to other versions of PRAMS it is not relevant to compare model error as an inferred measure of which model is better. The datasets and geology in PRAMS 3.5 are improved; hence most of the error in this model reflects the limits of both spatial and temporal resolution rather than errors in the conceptual model.

The model calibration error has been calculated for the 4 major aquifers in the model and is summarised below.

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	1.7	2.4	2.0	14.3	-13.9
Mirrabooka	2.1	2.1	1.4	17.4	-2.9
Leederville	4.4	5.7	3.1	16.7	-18.4
Yarragadee	4.0	5.3	3.6	20.4	-22.8

Most of the simulated heads at monitor bores in the aquifer systems have a response consistent with measured data. The monitor bores maintain correct trends and the magnitude of the error is constant.

The largest errors are in the north of the model, where there are limited measurements, complex geology and some uncertainty as to aquifer characteristics. Other areas of significant error are:

- At the interface of the Tamala Limestone and the Bassendean Sand, north of the Swan River; and
- Along the Darling Fault, south of the Swan River, where water levels tend to influenced by the Serpentine Fault;
- In the block faulted area in the confined aquifers.

In addition, the other major constraints on improving the calibration of the model are:

- An insufficiently detailed conceptual hydrogeological model that does not address localised conditions at the scale used in the model (i.e. 25 ha); and
- Generalised parameter distributions that lack the spatial resolution to account for changes in aquifer characteristics.

Verification of a model is best described as assessing whether the model has any predictive capability by testing it against data that is independent from the calibration data. PRAMS 3.5 is verified using different temporal datasets. The temporal verification is from January 1980 to December 2000.

A review of verification hydrographs, show that while there is some offset error in most bores, water level trends and responses to stresses are consistent with measured data in the superficial, Mirrabooka and Leederville aquifers. Specifically, the increase in error from 1980 to 2000, compared to the calibration period (2000 to 2013) is not large in the Mirrabooka, Leederville and superficial aquifers, with distribution in error similar to that during calibration.

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	2.3	3.4	2.8	16.1	-28.7
Mirrabooka	1.7	1.8	3.7	6.8	-2.6
Leederville	4.6	5.6	3.5	23.8	-13.8
Yarragadee	3.3	4.6	4.7	9.3	-29.7

The largest increase in model error in the verification period is in the superficial aquifer.

Recommendations

The mode is amendable to additional calibration. This effort should address those areas showing significant calibration error (i.e. more than 3 metres). The additional calibration should be undertaken by the DoW and based on their organisational priorities.

Any updated model of PRAMS 3.5 should include the following changes:

- Improve the conceptualisation of the offshore boundary in the confined aquifers;
- Refinement of the model grid in areas on rapid changes in elevation in the confined aquifers.
- Refinement of the grid and parameterisation in the area of the interface between the Tamala and Spearwood units in the superficial aquifer.

Significant improvement in model calibration can be achieved if completed and validated water level and piezometric surfaces are established for all the aquifers, at selected times (i.e. every 5 years), over the entire domain of the model. This data will eliminate a significant amount of uncertainty with respect to initial conditions and provide spatial head distributions at regular intervals for the calibration of transient models.

The quality of the present calibration is primarily constrained by available resources and data quality, as well model grid spacing. To further improve the model, independent calibration of the model should be undertaken in sections consisting of the area:

a. North of Gingin Brook;
b. Between Gingin Brook and the Jandakot Mound; and
c. South of the Jandakot Mound to Mandurah.

These areas can be calibrated separately and the results used to update the PRAMS 3.5 model. Future calibration of the model should use automated processes.

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1 INTRODUCTION

The Department of Water (DoW), as part of their groundwater resource management and planning role, have previously and continue to use groundwater flow modelling. In response to environmental constraints on the Swan Coastal Plain, the DoW are developing more sophisticated models to simulate both the saturated and unsaturated zones in the superficial aquifer and the saturated zone in the artesian aquifers. As part of this development, the coupled saturated/unsaturated groundwater flow model PRAMS 3.0 was constructed in 2004, and used extensively to assess groundwater impacts. Subsequently, and as part of the DoW's ongoing development, PRAMS 3.2 to 3.4 were released based on an improved conceptual hydrogeological model of the Swan Coastal Plain and other datasets.

Since the release of these previous versions, a significant amount of work has been done to enhance the abstraction datasets, refine climate inputs, improve the conceptual hydrogeological model, and improve the overall quality assurance of geological inputs. These improved datasets warranted the construction of a new version of PRAMS, designated 3.5. This report presents the construction and calibration of the PRAMS 3.5 model, which incorporates these new datasets.

2 MODELLING APPROACH

The objective of the Perth Regional Aquifer Modelling System (PRAMS) coupled groundwater flow model is to provide a quantitative tool that can be used to assess alternative resource management strategies on the Swan Coastal Plain. PRAMS 3.5 has the same objectives as PRAMS 3.0 to 3.4, with some additions. The model is required to simulate the responses of the superficial and artesian aquifers to changes in climate, landuse and abstraction in the context of:

- Estimating the impact of public and private abstraction on water levels in all aquifers;
- Provide quantitative estimates of the water resource on the Swan Coastal Plain;
- Evaluate the effects of future landuse management on groundwater levels on the Swan Coastal Plain;
- Evaluate the impacts of climate change;
- Evaluate the impacts of large artificial recharge and recovery schemes in both the confined and unconfined aquifers; and
- Preparing historic annual water accounts.

To meet the above objectives, PRAMS 3.5 consists of a saturated flow model, an unsaturated flow model and ancillary programs and supporting databases. The model, with respect to applicable modelling guidelines is characterised as Class 3. This report has been written to conform to client requested guidelines (Barnett et al., 20121). These guidelines should be consulted for the application of and use of definitions specific to meeting those guidelines.

2.1 Modelling System

PRAMS 3.5 continues to use the same approach as the PRAMS 3.0 groundwater modelling system (CyMod Systems, 2004), but with some changes to workflow. PRAMS 3.5 is an updated version of the PRAMS 3.0 saturated model, coupled to a vertical flux model (VFM), based on the WAVES model developed by CSIRO, which was primarily developed to improve the simulation of the superficial aquifer. PRAMS 3.5 supersedes all previous versions and should be used in preference to any of the earlier models.

The development of the PRAMS modelling system is documented via version numbers of major releases of the aquifer simulator. Table 2-1 summarises the development tree.

Saturated Model	Unsaturated Model	Status	Description
PRAMS 1.0	None	Not released	Used to test data sets and geometry.
PRAMS 2.0	None	Not released	First complete implementation of the saturated flow model.
PRAMS 2.1	None	Released April 2002	First released version. Used by Water Corporation for drought contingency planning.
PRAMS 2.2	None	Not released	Superseded by PRAMS 3.0.
PRAMS 3.0	VFM 2.1.3-2.1.5	Released October 2003	Coupled model using 500 x 500 metre grid.
PRAMS 3.0	VFM 2.1.6	Released August 2004	Change to root truncation algorithm in the VFM and MODFLOW 2000 version.
PRAMS 3.1	VFM 2.1.6	Not released	Superseded by PRAMS 3.2.
PRAMS 3.2	VFM 2.1.6	Released August 2008	13-layer model with an additional layer in the superficial aquifer. Updated superficial aquifer calibration. Updated landuse and monitor data to 2008. Updated allocation database to 2007.
PRAMS 3.3	VFM 2.1.6	Not released	Updated Artesian calibration of PRAMS 3.2.
PRAMS 3.4	VFM 2.1.6	Not released	Reinterpreted geology. Improved private allocation estimates. Updated climate zonation. Improved VFM. Recalibrated and validated.
PRAMS 3.5	VFM 2.1.6	Pending	Improved geology. Re-interpreted block fault model

Table 2-1: PRAMS Development

The versioning of PRAMS uses a decimal system consisting of a major version, minor version, and revision number. The numbering system follows the rules as indicated below:

1. Major version – uses a different horizontal grid, and modelling platform;
2. Minor version – uses different vertical discretisation and geological model; and
3. Revision – changes to input data sets, or recalibrated.

Based on the versioning system, the model described in this report is PRAMS 3.5.2, but will be referred to as PRAMS 3.5.

The PRAMS 3.5 modelling system consists of a PRAMS database containing abstraction, monitoring and environmental data, a MODFLOW 2000 groundwater model with pre and post processors, the Vertical Flux Manager (VFM 2.1.6) and the VFM 2.1.6 datasets. The construction, validation and updating of the PRAMS database is done by the DoW and Water Corporation, and consists of databases and Excel spreadsheets that contain abstraction, monitoring, climate data and landuse coverages. The monitoring data was updated to December 2012 using data supplied by the DoW. The private allocation data was updated and modified by the DoW to January 2013 and then pre-processed by CyMod Systems for use in the model as described later in this report. The Water Corporation production data was updated to July 2013.

The major changes to PRAMS 3.5, compared to previous versions are:

- All layer surfaces have been regenerated using the most recent hydrogeological interpretation and data;
- Updated conceptual model of the Leederville aquifer, using a block faulting approach, where applicable;
- Update of 8 climate zones, using interpolated gridded data;
- Conversion of most algebraic landuse codes to WAVES simulations, except for lakes and public open spaces;
- Addition of an additional native vegetation landuse code;
- Use of Visual MODFLOW as the pre-processor;
- A modified VFM that improves convergence for rapidly changing landuse;
- Updated abstraction estimates for unlicensed use;
- Calibration period from 2000 to 2013, and the validation period from 1980 to 2000. This recognizes the model guidelines recommendation to sue the most recent data for calibration.

In addition to the above datasets, the Water Corporation constructed landuse coverage’s for input into the VFM for 2004 through 2013. These datasets are based on available data from the Department of Land Administration (DOLA), the Department of Conservation and Land Management (DCLM) and other ministries, which was processed onto a regular grid covering the model area (Canci 2003).

The climatic coverage is based on a cluster analysis undertaken for PRAMS 3.4, which was modified to better account for rainfall in the Serpentine and Gingin areas in PRAMS 3.5.2. The climatic coverage consists of eight zones and describes the spatial rainfall pattern on the Swan Coastal Plain. The soil and landuse coverage's are based on extensive spatial information that has been collated and synthesised in to viable VFM datasets. The physical properties of the soil classifications have been estimated using in-situ and laboratory measurements, to develop unsaturated-hydraulic conductivity and water retention curves as a function of pore pressure for each soil type (Xu et al, 2003) and are the same as in previous versions of PRAMS.

2.1.1 System of Units

The system of units used in PRAMS is shown in Table 2-2, by model component.

Model	Length	Time	Mass	Energy	Temperature
MODFLOW	metres (m)	Day (d)	-	-	-
WAVES	metres (m)	Day (d)	Kilogram (kg)	Kilojoules (kJ)	Celsius (C)
VFM	metres (m)	Day (d)	-	-	-

Table 2-2: Systems of Units

3 MODEL CONSTRUCTION

The design and construction of the numerical groundwater model component of PRAMS 3.5 are described below in terms of the MODFLOW and VFM datasets used, the approximations made with respect to the saturated/unsaturated numerical model and changes made to the saturated model. A more detailed description of the hydrogeology and construction of the PRAMS 3.5 conceptual model can be found in De Silva et al, 2013.

3.1 Spatial Discretisation

3.1.1 Horizontal Discretisation

The model domain and horizontal discretisation of PRAMS 3.5 remains the same as in the PRAMS 3.0 model, with the model extending approximately 217 kilometres north-south and 107 kilometres east-west, as shown in Figure 1. The active model area is about 10,000 square kilometres. Horizontally, the finite-difference grid is the same as used in previous versions, consisting of a uniform grid having square elements 500 by 500 metres, which provides sufficient resolution at a regional scale to allow for the relative assessment of quantitative effects of changes in abstraction, landuse and climate.

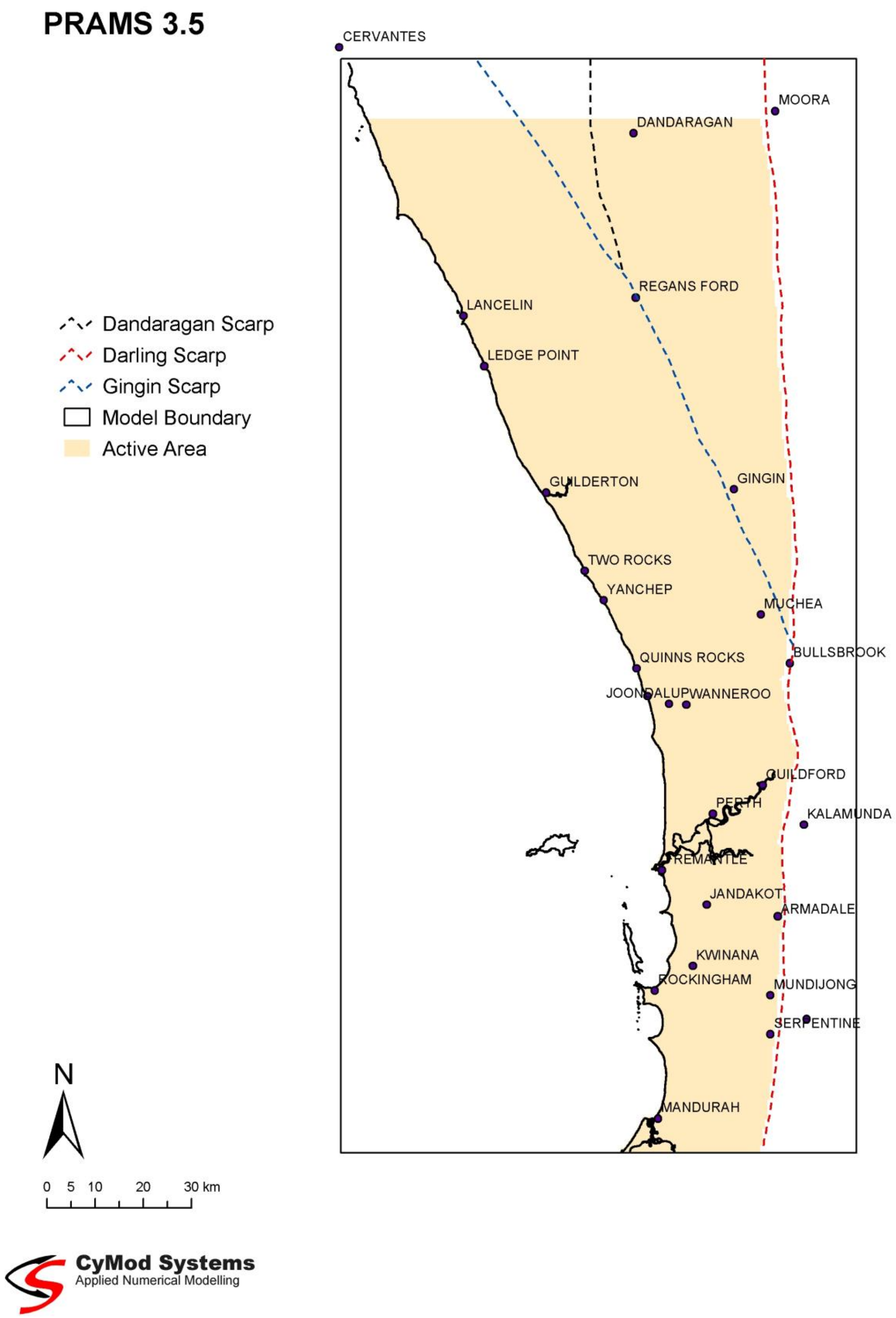

Figure 1: PRAMS 3.5 Model Extent

Figure 2 shows the active area of model for all layers. The model domain is referenced to the north-west corner of the model at 315000E mGDA94, 6621000N mGDA94.

The spatial resolution of 500 by 500 m is not sufficient to model features less than 1 kilometre, such as small wetlands, urban drainage issues, local perched conditions associated with surface water or individual production bore test.

The VFM unsaturated flow model uses the same domain and grid geometry as the saturated model and is characterized as layer 0 of the model.

3.1.2 Vertical Discretisation

Table 3-1 and 3-2 lists the geological formations and corresponding layers that make up the PRAMS 3.5 aquifer system. The hydrogeological basis for the layers in PRAMS 3.5 is given in De Silva et al, 2013. This report details the geological and hydrogeological model used in PRAMS 3.5. Figure 2 shows a schematic illustration of the conceptual hydrogeological model used in developing the numerical model, and is provided to demonstrate the relative connections between aquifers.

The model layers are defined by digital terrain models (DTMs) of the upper surface of each aquifer or aquitard and isopachs for the aquifer/aquitard represented by each layer. The digital terrain model of each layer elevation in PRAMS 3.5 was constructed and quality assured by the DoW, based on available geological logs and drilling information. Appendix A and B presents the top surface and isopachs for each layer as supplied by the Department of Water (DoW), respectively.

All the DTMs are bounded by the active area of the model domain. Note that the active area of the model changes with depth. The active area for the superficial aquifer, Layers 1 through 3 and for Layers 4 through 13 is shown in in Figure 3. The active area for Layers 1 through 3 (superficial aquifer) differs from the active area for the remaining layers 4 through 13, in that it does not extend beyond the coast.

None of the geological formations fully extend over an entire model layer. While the model layering is based on aquifers and aquitards, in areas where a formation is absent, the hydrogeological properties of the layer are changed to reflect the formation occupying the layer at that depth. In the event that underlying formations subcrop or outcrop, layer thicknesses are adjusted to a minimum thickness of 1 metre and the layers assigned the properties of the subcropping formation. This modified layering of aquifers based on formations is required, as MODFLOW does not allow the pinching out or the absence of a layer. The interpolation from the DTMs onto the model grid was performed using ArcGIS.

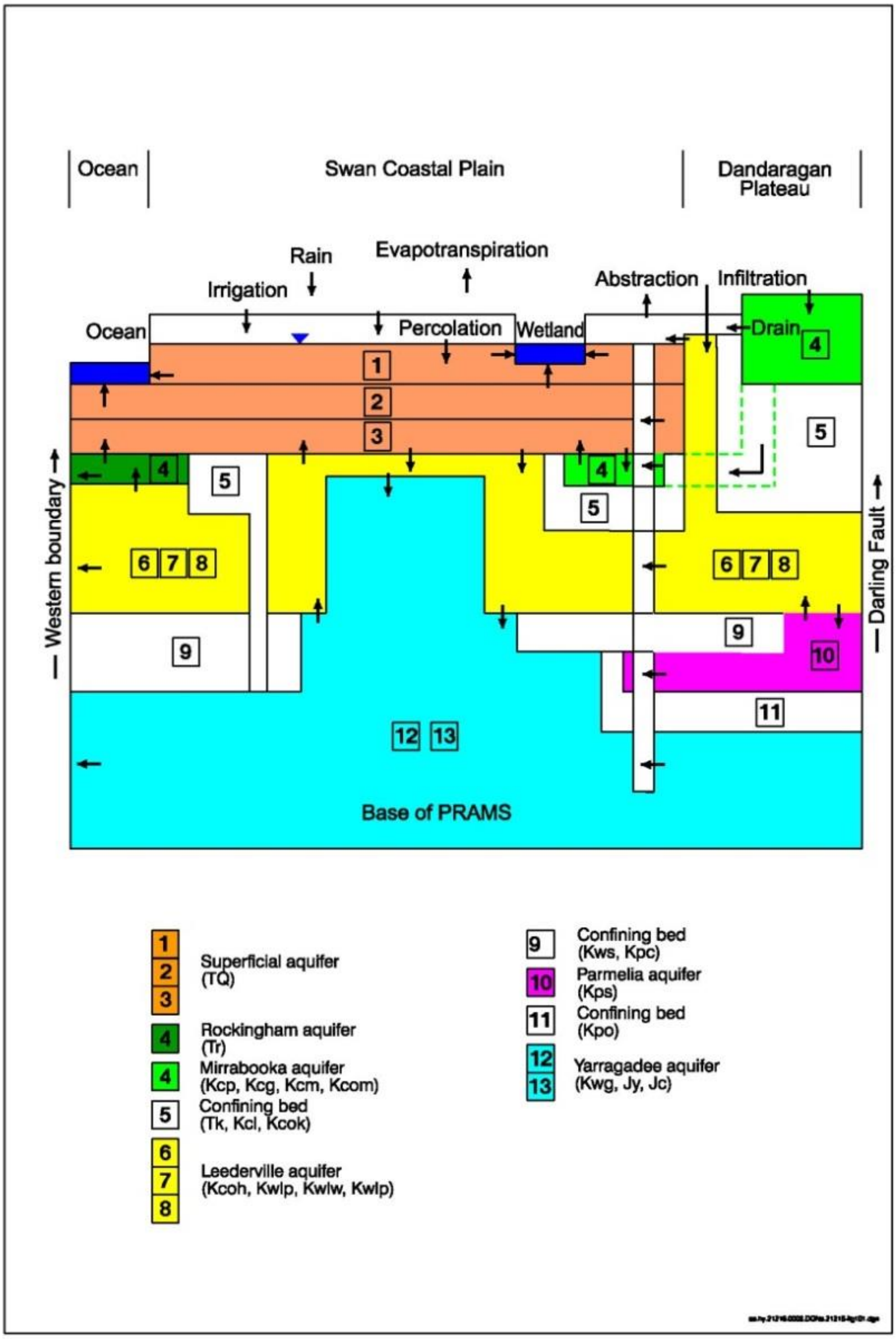

Figure 2: Conceptual Hydrogeological Model

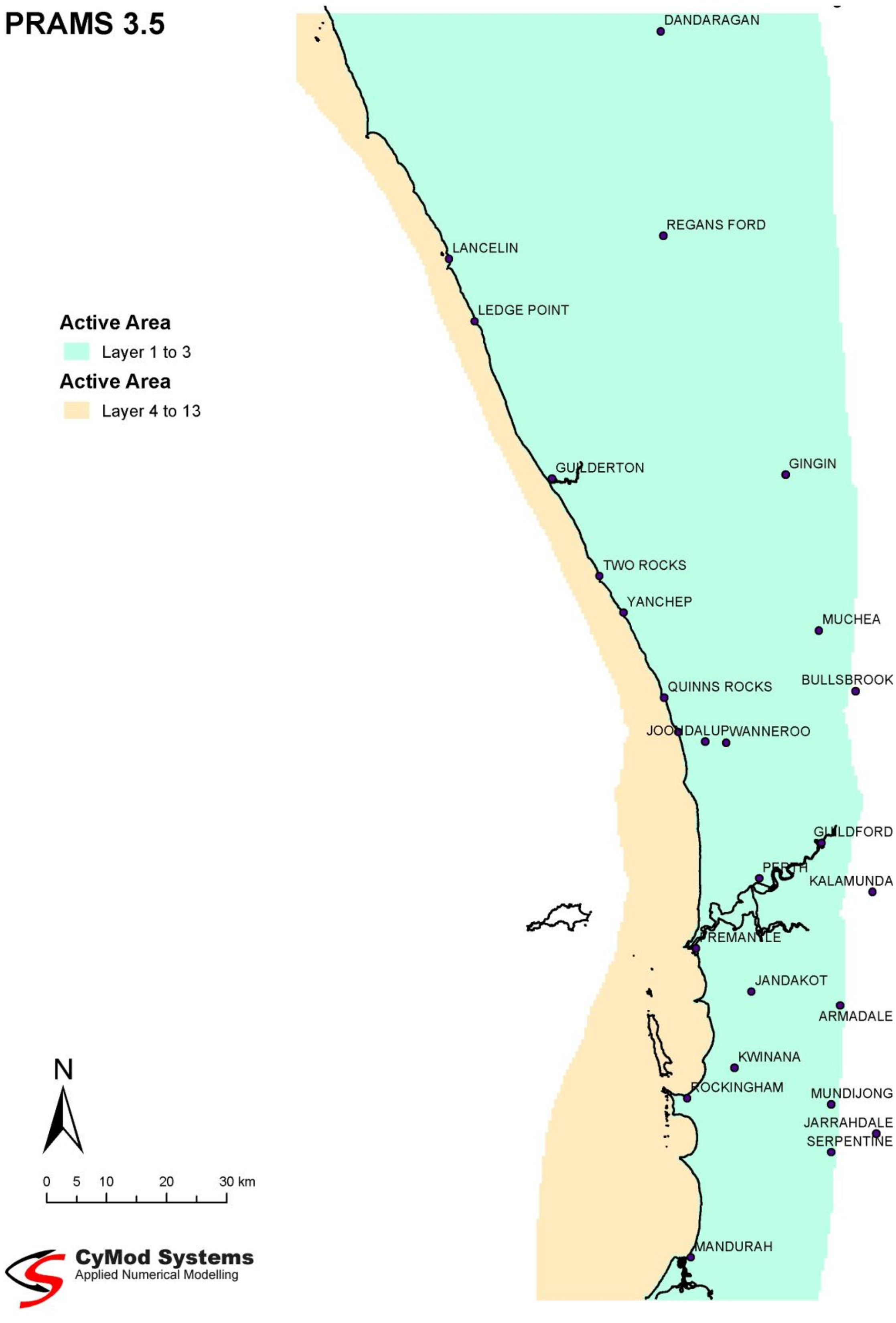

Figure 3: Active Area for Layers 1 through 13

3.1.3 Layer 1 Thickness

The top of layer 2 is unique in that it does not define a geological formation, but rather a hydrogeological unit that represents the water table. The top of layer 2 is defined as the bottom of the unsaturated zone (i.e. the depth to the water table) plus one third of the saturated thickness of the superficial aquifer. Consequently, using this definition, layer 1 will be saturated over the entire active area of layer 1, excluding the Dandaragan Plateau (where the superficial aquifer is absent). The advantages of this definition for the top of layer 2 are:

- All cells in layer 1 are initially saturated allowing for a continuous water table;
- Prevents the occurrence of dry of cells, which in MODFLOW, means they are no longer active in the model

If a large number of dry cells were to occur, it would require using the wetting and dry feature of MODFLOW to allow resaturation of dry cells, which tends to be computationally difficult.

The construction of the top of layer 2 used following procedure:

1. High resolution topography was interpolated on to the active area of the grid, using Akima's bilinear interpolation (Akima, 1978).
2. An interpolated water table for 2012 was constructed using Akima interpolation for the active area of the grid. The interpolation used data supplied by the DoW, and topographic control points (i.e. ocean and Swan River) to constrain the interpolated elevation of the water table.
3. The inferred water table was subtracted from the topography, with the difference being the inferred unsaturated zone thickness. Areas of negative thickness are interpreted as the water table being above ground level and removed, using raster algebra, by setting their thickness to zero.
4. The modified unsaturated zone thickness is subtracted from the topography to define the top of saturated zone (i.e. the water table surface), constrained by ground surface (i.e. it excludes surface water features).
5. The top of layer 4 (as supplied by the DoW, 09/04/2014) is then subtracted from the constrained water table surface, to give an estimate of the saturated thickness of the superficial aquifer.
6. The saturated thickness of the superficial aquifer is adjusted to ensure a minimum thickness of three metres, including areas on the Dandaragan Plataea. This constraint results in some small areas south of Jandakot having their thickness increased to three metres. Note that this thickness is inconsistent with the saturated thickness of the superficial aquifer as estimated by Davidson, 1994. The thin saturated thickness may reflect errors in the estimate of the elevation of the top of layer 4, which was not generated by subtraction of the thickness of the superficial aquifer from topography.

7. The resulting constrained superficial aquifer saturated thickness was then divided in to three equal thicknesses, that represent; the saturated thickness in layer 1; the thicknesses of layer 2; and layer 3.
8. The subdivided saturated thickness of the superficial aquifer was successively subtracted from the overlying layer elevations to generate the three layers making up the superficial aquifer.

Due to the application of the three metre minimum thickness constraint, the successive subtraction of these thicknesses from the unsaturated zone elevation results in a discrepancy between the top of layer 4 elevation as supplied by the DoW, which is then propagated to underlying layers until an aquifer thickness of more than 1 m is encountered.

Note that the small changes in the top of layer 4 elevation will not impact the numerical model performance. However, it should be recognized that the numerical model layers are not quantitatively the same as the conceptual model geology and should not be used in that role. More importantly, the thin saturated thicknesses in some areas south of Jandakot may be inconsistent with the conceptual hydrogeology.

The VFM can be considered an additional layer lying above the water table. Within this report, the VFM model may be referred to as Layer 0. Note that within Layer 0, the VFM models only vertical unsaturated flow – there is no lateral flow modelled.

As indicated above model Layer 1 is not based on a geological formation, but referenced to the water table. Where there is no superficial aquifer, as on the Dandaragan Plateau, and the water table resides in layers below layer 1 (in some cases in layer 4 for example), all layers above the water table are given a minimum thickness of 1 metre and are effectively dry and not in the model.

A detailed geological description of the layers used in PRAMS 3.5 is given in De Silva et al, 2013.

Layer	Top Surface	Thickness	Bottom Surface	Hydrogeology	Geological units
1	Topography	1/3 saturated thickness of superficial aquifer	Layer 2 top	superficial aquifer	TQ
2	Layer 2 top	As above	Layer 3 top	superficial aquifer	TQ
3	Layer 3 top	As above	Layer 4 top	superficial aquifer	TQ
4	Layer 4 top	Layer 4 thickness	Layer 5 top	Mirrabooka aquifer	Kcp, Kcg, Kcm & Kcom
				Rockingham aquifer	Tr
5	Layer 5 top	Layer 5 thickness	Layer 6 top	King's Park formation	Tk
				Lancelin aquitard	Kcl
				Kardinya Shale confining bed	Kcok
6	Layer 6 top	Layer 6 thickness	Layer 7 top	Henley Sandstone aquifer	Kcoh
				Leederville (Pinjar Member) aquifer	Kwlp
7	Layer 7 top	Layer 7 thickness	Layer 8 top	Leederville (Wanneroo Member) aquifer	Kwlw
8	Layer 8 top	Layer 8 thickness	Layer 9 top	Leederville (Mariginiup Member) aquifer	Kwlm
9	Layer 9 top	Layer 9 thickness	Layer 10 top	South Perth Shale confining bed	Kws
				Carnac Member confining bed	Kpc
10	Layer 10 top	Layer 10 thickness	Layer 11 top	Parmelia Sand aquifer	Kps
11	Layer 11 top	Layer 11 thickness	layer 12 top	Otorowiri Member confining bed	Kpo
12	Layer 12 top	230 metre thickness	Layer 13 top	Yarragadee aquifer	Kwg, Jy, Jc
13	Layer 13 top	Layer 13 thickness	Bottom of the model	Yarragadee aquifer	Kwg, Jy, Jc

Table 3-1: PRAMS 3.5 Model Layer Geometry

Formation	Model Layer	Comments
Unsaturated Zone	0	Modelled by the VFM 0 to 50 metres thick
Water Table	1	1/3 of saturated thickness of the superficial aquifer
Superficial	2, 3	2/3 of the saturated thickness of the superficial aquifer
Mirrabooka, Osborne, Kardinya Shale, Leederville and Yarragadee	4	Where present
Kardinya Shale, Leederville and Yarragadee	5	Where present
Pinjar	6	Where present
Wanneroo	7	Where present
Mariginiup	8	Where present
South Perth Shale	9	Where present
Carnac	9	Where present
Parmelia	10	Where present
Otorowiri	11	Where present
Yarragadee Cattamarra Coal Measures	12	Top 230 metres of Yarragadee formation
Yarragadee Cattamarra Coal Measures	13	Remaining saturated thickness of the Yarragadee aquifer

Table 3-2: Summary of Model Layering

3.1.4 Ground Surface

PRAMS 3.5 uses a high-resolution topographic dataset LIDAR with a spatial horizontal resolution of 1 metre and a horizontal accuracy of 0.6 metres. Vertically, the Lidar dataset has accuracy of 0.15 metres for the Swan Coastal Plain, south of Gingin. North of Gingin, the PRAMS 3.4 topography is based on a Land Monitor DEM, which has a spatial resolution of 10 metres and a vertical resolution accuracy of 1.5 metres. The PRAMS 3.5 surface topography is shown in Figure 4.

The topographic data is used to define, in some areas, the drain invert levels for drain boundary conditions. The surface topography is also used to reference the VFM model to the depth to water. The depth to water is used in the VFM model to determine vertical node spacing for the solution of the Richard's equation, and to sort rectangular elements into appropriate RRUs (Representative Recharge Units, (Silberstein et al, 2003). The VFM obtains the top elevation of the model from the VFM data input file.

The accuracy of the interpolated upper model surface is not the same as the digital elevation data. The interpolated model surface is based on bilinear interpolation of the digital data onto the centroid of grid nodes, which are 500 x 500 m flat planes. This interpolation results in elevations that are not necessarily representative of the predominant ground elevation within an element. Any variables that depend on this topographic elevation may introduce errors into the model on the same order of magnitude as the error in interpolated elevation.

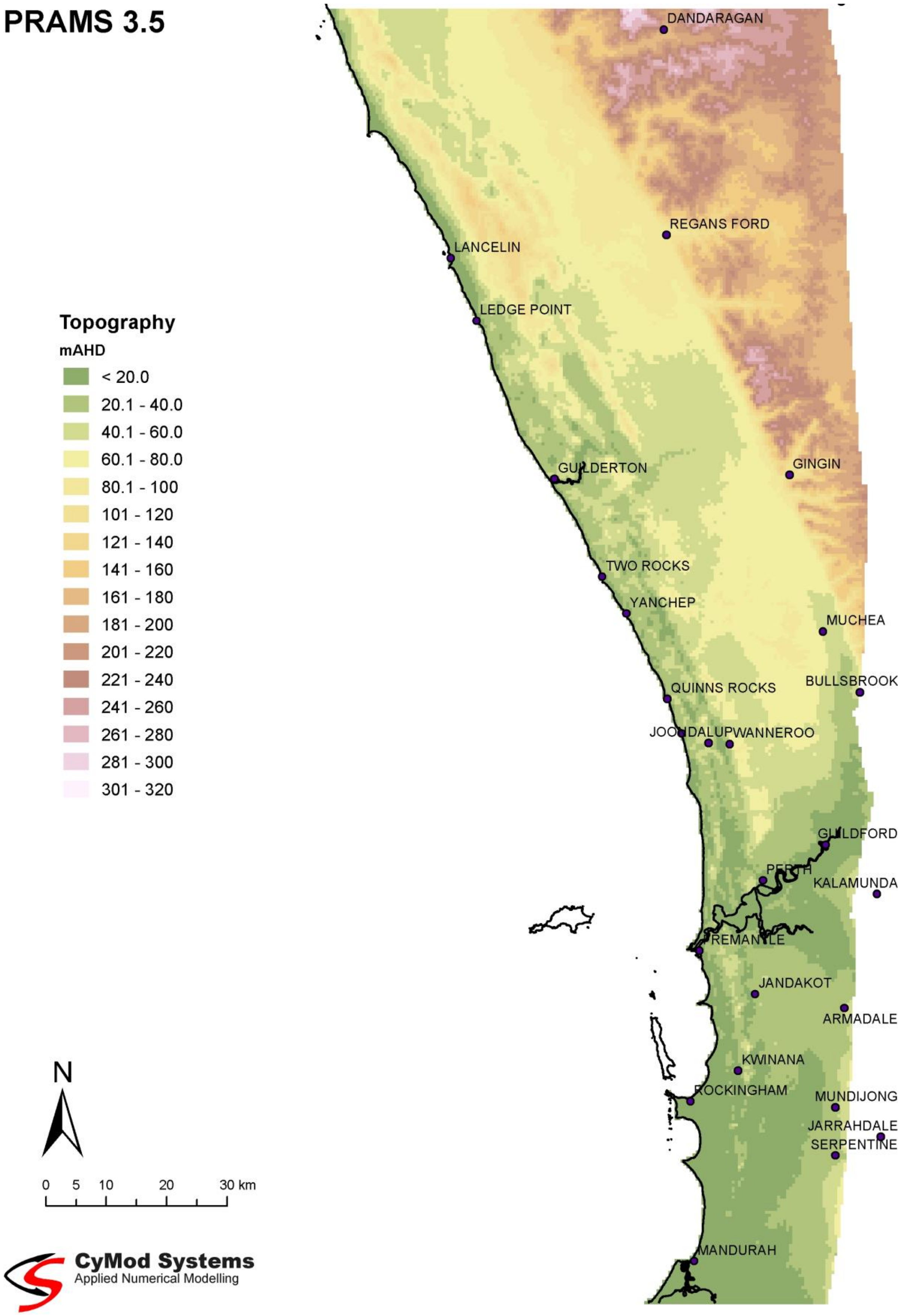

Figure 4: Topography

3.2 Model Parameters

3.2.1 Aquifer Parameters

The DoW has reviewed the available data for the formations making up the aquifer system on the Swan Coastal Plain and estimated ranges for selected aquifer parameters. Table 3.3 summarises the range of hydraulic conductivity and specific yield for selected formations (De Silva et al, 2013) for the superficial aquifer. Table 3.4 summarises the range of hydraulic conductivity and storativity for confined aquifers and aquitards. These ranges represent best estimates of the upper and lower bounds for aquifer properties that may be assigned during calibration. Spatially, aquifer parameter distributions were initially based on the formation's geological boundaries. The spatial distribution of the aquifer parameters may be subsequently modified as part of the calibration of the model.

Aquifer	Stratigraphy		Aquifer Thickness (m)	Average Specific Yield	Hydraulic Conductivity (horizontal) (m/day)
Superficial aquifer	Superficial Formations		110		
		Safety Bay Sand	24	0.2	15
		Becher Sand	20	0.2	8
		Tamala Limestone	110	0.2-0.3	100-1000
		Bassendean Sand	80	0.2	10-50
		Gnangara Sand	30	0.2	20
Aquitard	Guildford Clay		35	0.05	0.1-1
Superficial aquifer		Yoganup Formation	10		10
		Ascot Formation	25		8
Rockingham aquifer	Rockingham Sand		110	0.2	20

Table 3-3: Estimated Aquifer Properties – Superficial Aquifer

Aquifer	Stratigraphy		Maximum thickness (m)	Storativity	Hydraulic Conductivity (horizontal) (m/day)
Kings Park aquifers	Kings Park Formation		530		
		Mullaloo Sandstone Member	200	$10^{-3(1)}$	10–15
		Como Sandstone Member	57	$10^{-3(1)}$	10–15
Aquitard	Lancelin Formation		120		0.1
Mirrabooka aquifer	Poison Hill Greensand		90	10^{-3}	10
Aquitard	Gingin Chalk		40		0.001–0.1
Mirrabooka aquifer	Molecap Greensand		80	$10^{-3(1)}$	?1
	Osborne Formation				
		Mirrabooka Member	160	$10^{-3(1)}$	4–5
Aquitard		Kardinya Shale Member	260		$10^{-4} – 10^{-6}$
Leederville aquifer		Henley Sandstone Member	80	$10^{-3} – 10^{-4}$	2–3
	Leederville Formation		600		
		Pinjar Member	150	$10^{-3} – 10^{-4}$	1
		Wanneroo Member	450	$10^{-3} – 10^{-4}$	1–10
		Mariginiup member	250	$10^{-3} – 10^{-4}$	0.1–1
Aquitard	South Perth Shale		300		$10^{-4} – 10^{-6}$
Yarragadee aquifer	Gage Formation		350	10^{-4}	2–10
Aquitard	Parmelia Formation		>287		
		Carnac Member	450		10^{-6}
Parmelia aquifer		Parmelia Sand Member	750	10^{-4}?	0.5–2
Aquitard		Otorowiri Siltstone Member	200		10^{-6}
Yarragadee aquifer	Yarragadee Formation		>2000	10^{-4}	1–3
	Cadda Formation		290	10^{-4}	1-3
	Cattamarra Coal Measures or Cadda Formation		>500	10^{-4}	1–3

(after De Silva et al, 2013)

Table 3-4: Estimated Aquifer Parameters - Confined Aquifer

Initial estimates of vertical hydraulic conductivity assume a ratio of 10:1, K_h to k_v, but were modified based on available data, such as estimates made by Davidson for the Leederville aquifer (Davidson, 1994), the occurrence of downward hydraulic gradients, and lithological descriptions from bores indicating clay, shale, coffee rock and other descriptions that tend to correlate with reduced vertical hydraulic conductivity.

Specific storage was based on an average storativity of 5 x 10^{-4} and adjusted during calibration to improve model response to seasonal variation in aquifer response to abstraction and recharge.

3.3 Faults

The Swan Coastal Plain has several major faults, which in some cases affect groundwater flow. In previous versions of PRAMS the modelling of faults was limited to the Serpentine Fault, in the south-east corner of the model domain and limited faulting in the Leederville and Yarragadee aquifers. In PRAMS 3.5 faulting has been modelled to a much greater extent due the acceptance of block faulting as part of the depositional environment. Consequently, block faulting is explicitly modelled to improve the geological model fidelity with respect to drilled results.

However, due to the importance of faulting in controlling groundwater flow, and the uncertainty in characterising the effects of faulting, PRAMS 3.5 has both a faulted model (PRAMS 3.5A) and a limited faulted model (PRAMS 3.5B). Note that in this report PRAMS 3.5 always refers to faulted model (PRAMS 3.5A).

All the faults in both models are implemented using the horizontal flow barrier package from MODFLOW 2000. This package provides a convenient mechanism for imposing faults on the model, without requiring refinement of the grid, or the modification of horizontal hydraulic conductivity.

3.3.1 Faulting - PRAMS 3.5A

The faulting in version 3.5A is based on the analysis presented in De Silva et al, 2013. Faults were added to the model for Layers 6 through 13, as indicated in Figures 5 and 6. Each fault was assessed in terms of its likely impact on groundwater flow and given a relative fault hydraulic conductivity.

3.3.2 Faulting - PRAMS 3.5B

The faulting in PRAMS 3.5B is the same as that used in PRAMS 3.0. In the absence of any measured data, fault conductance was assumed to be the same as that determined from the calibration of PRAMS 3.3, and is variable in the PRAMS 3.5B model with values ranging from 0.002 to 2×10^{-7} 1/day. In practice, a fault with a conductance of 0.002 1/day has very little influence on the hydrogeological environment. A fault with a value of 2×10^{-7} 1/day however, will cause significant head differences (i.e. more than 20 metres) across the fault, if it is perpendicular to the direction of flow. Figures 7 and 8 shows the faulting that is used in the PRAMS 3.5B model for Layers 6 through 8 and Layers 9 through 13.

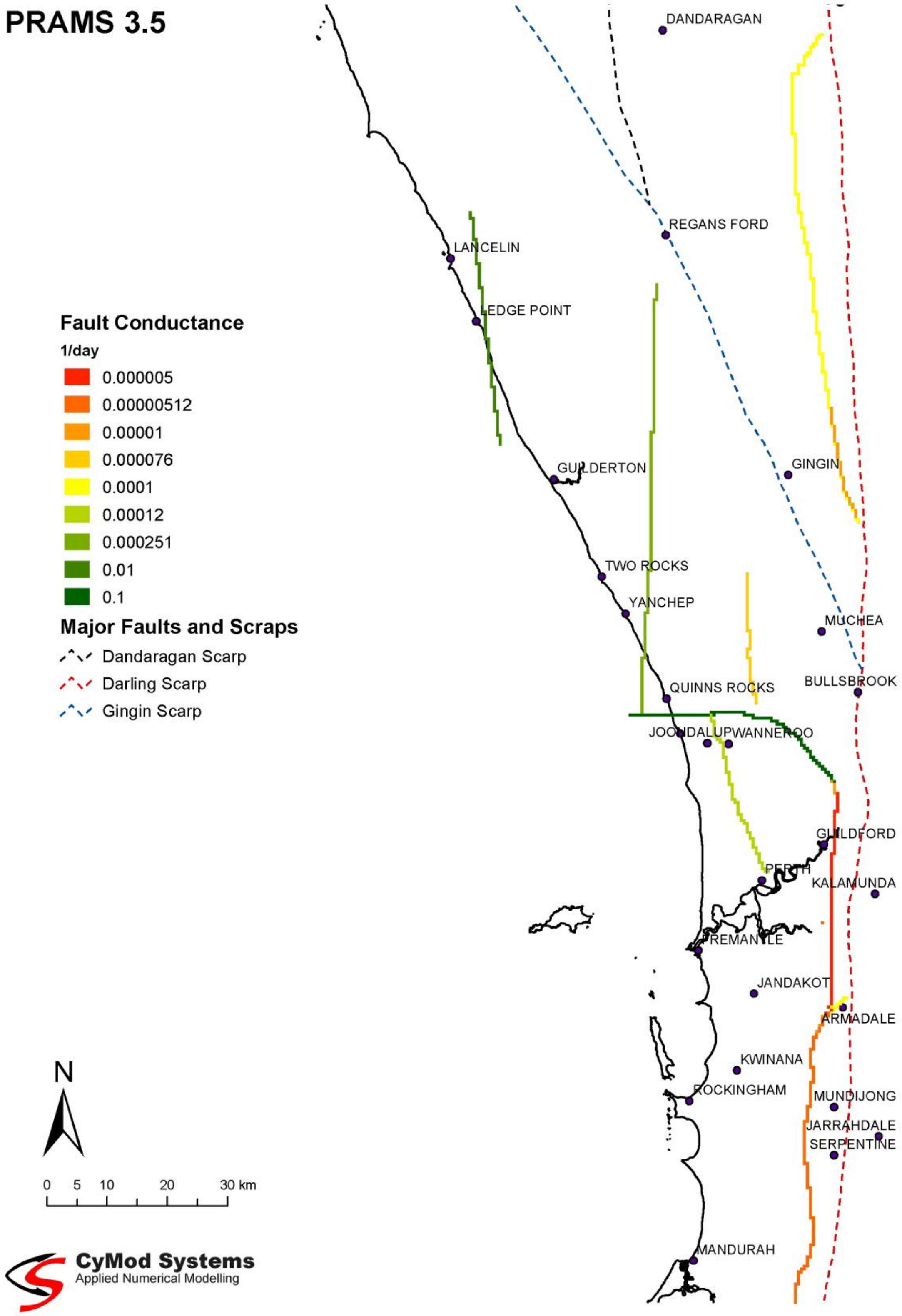

Figure 5: PRAMS 3.5A Faulting - Layers 6 through 8

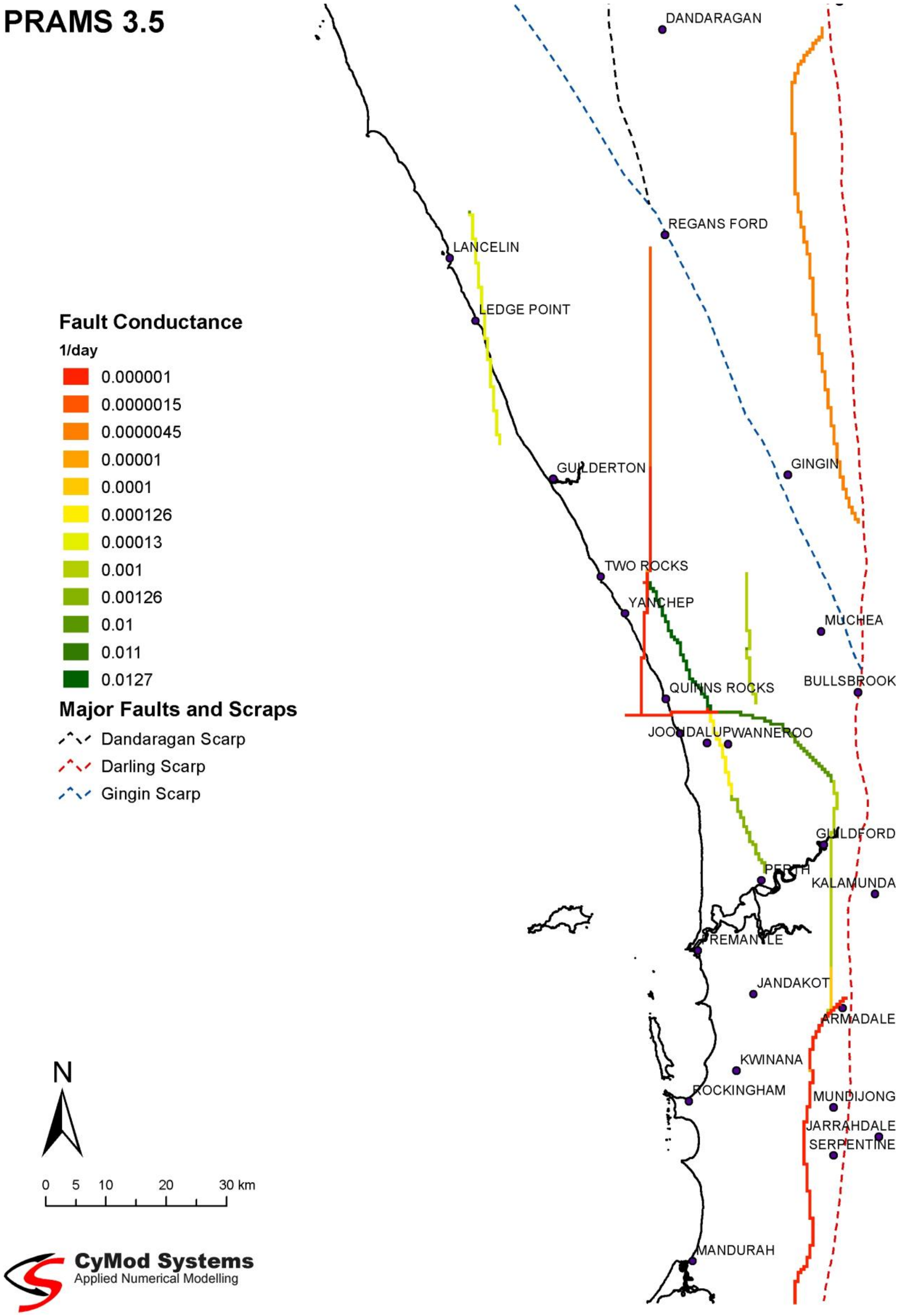

Figure 6: PRAMS 3.5A Faulting - Layer 9 through 13

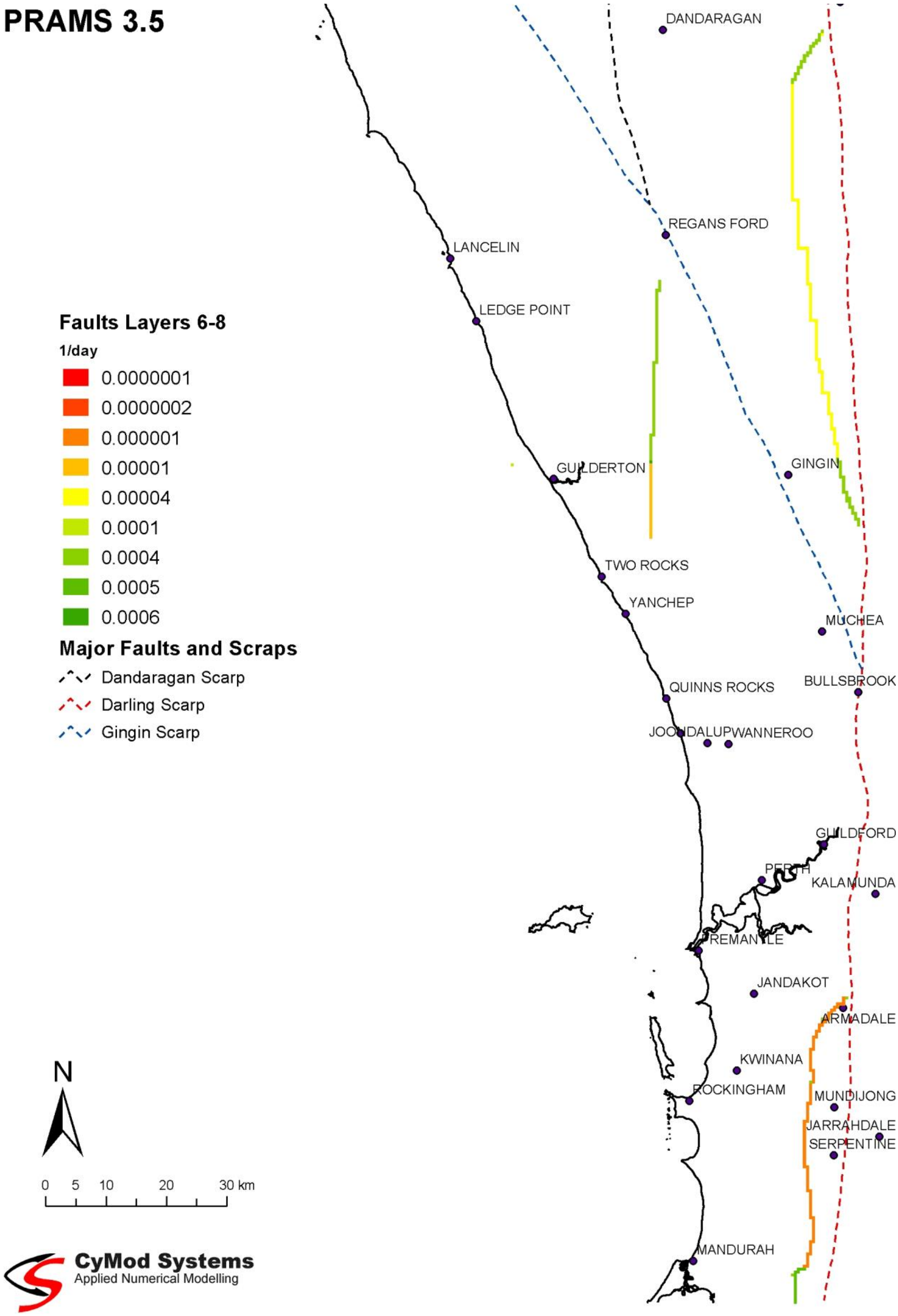

Figure 7: PRAMS 3.5B Faulting – Layer 6 through 8

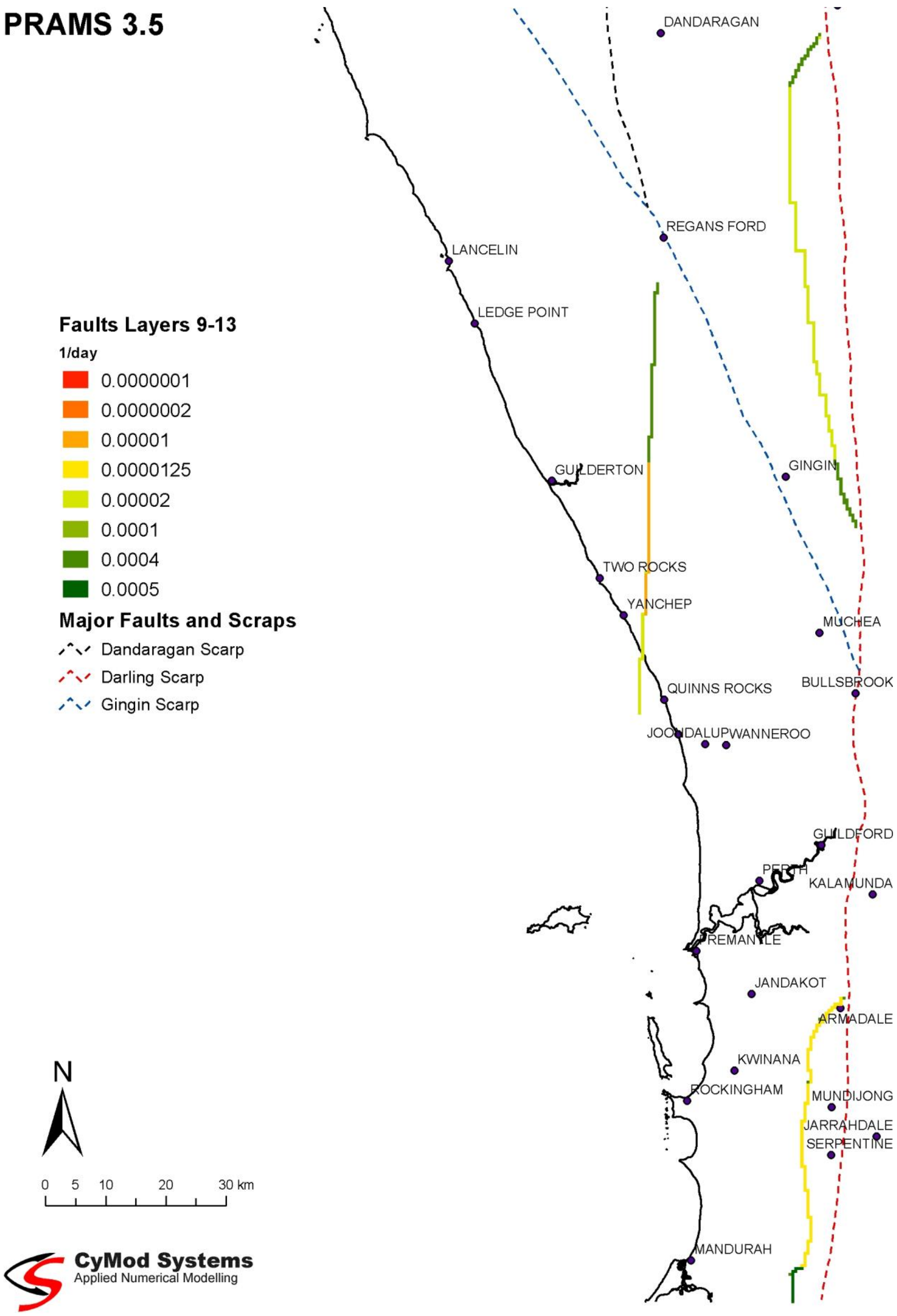

Figure 8: PRAMS 3.5B Faulting – Layers 9 through 13

3.4 Boundary Conditions

PRAMS 3.5 only uses 2 time-invariant boundary conditions: time varying specified heads (TVSH), which are effectively constant head boundaries, and general head boundaries (GHB), which allows the simulation of variable flow across a boundary. These two boundary conditions are new to PRAMS 3.5 and have been used to improve the operational aspects of the model as well as fidelity with the conceptual hydrogeological model. The TVSH boundary is also used to conform to how Visual Modflow implements constant head boundaries.

3.4.1 Constant Heads

In the superficial aquifer, (Layer 1 and 2), the western boundary has been modelled as a TVSH coincident with the shoreline of the Indian Ocean, having a head of 0.5 metres which reflects the difference in fresh water head between the ocean and the superficial aquifer, assuming an average aquifer thickness of 40 metres at the coast. However, rather than modelling the ocean as a constant head (which are not used in Visual MODFLOW), it has been modelled using a time varying specified head module.

Placing the TVSH boundary in Layer 1 and 2 at the coastline recognises the existence of a salt water interface and models it as stationary. Groundwater flow in Layers 3 and 4 preferentially flows upwards and is discharged from the model in Layers 1 and 2, which is consistent with a stationary saltwater interface (Anderson, 1997).

Calibration of the Leederville aquifer, south of Jandakot, required placing a constant head boundary in the area of the Rockingham Sand, to effectively model its connection with the ocean.

3.4.2 Off Shore Boundary – Leederville Aquifer

In PRAMS 3.0 to PRAMS 3.4 a constant head boundary was assigned to the first set of faults lying off the Western Australian coast, within Layer 5 of the model. These constant heads in Layer 5 modelled freshwater discharge to the ocean as upward vertical flow via vertical faults from lower aquifers. The calibration of the model required the adjustment of the vertical hydraulic conductivity of the fault zone (modelled as thin areas of increased vertical hydraulic conductivity) in Layers 5, 9, 10 and 11 to obtain the correct flow from the confined aquifers.

The truncation of the Leederville aquifer offshore is inconsistent with the conceptual hydrogeology of the aquifer, which drilling shows extends offshore beyond the first set of faults. Consequently, to improve the model fidelity within the conceptual hydrogeology of the Leederville, the constant head boundary in layer 5, was replaced with general head boundaries (GHB) in layers 6 and 7. These general head boundaries simulate the offshore flow of water beyond the first set of offshore faults, by allowing a conductance term to be specified which simulates the head loss due to flow offshore. The offshore head and conductance term simulated in the GHB are determined during calibration, but were initially based on the fresh water equivalent head due to the depth of seawater overlying the fault. Figure 10 shows the GHB boundary condition for Layer 6 and 7 of the model.

3.4.3 No-flow Boundaries

No-flow boundary conditions are assigned to Layers 3 through 5, 8 and 9 through 13. Outflows from these aquifers occur as vertical flow via the offshore faults, or into Layers 2 and 6 through 7, respectively. This vertical leakage occurs due to natural head differences between the Yarragadee, Leederville and the ocean and is determined during model simulation.

The eastern boundary of the model for all layers is the Darling Fault, and is impermeable (i.e. no-flow boundary). The southern boundary is coincident with a streamline in the superficial aquifer and considered a no-flow boundary for all layers.

The northern boundary is modelled as a no-flow boundary in all layers. However, in practice there is a flux entering the model, which is estimated at 250 m^3/day•km in the Yarragadee and 250 m^3/day•km in the Leederville aquifers (Davidson, pers. comm.). The estimated length of the flux along the northern boundary is 20 kilometres, resulting in a total inflow of 5,000 m^3/day, or 1.83 GL/annum, from each of the Leederville and Yarragadee aquifers. Due to the volume of groundwater associated with these fluxes versus recharge to these aquifers from other sources, the boundary was approximated as no-flow.

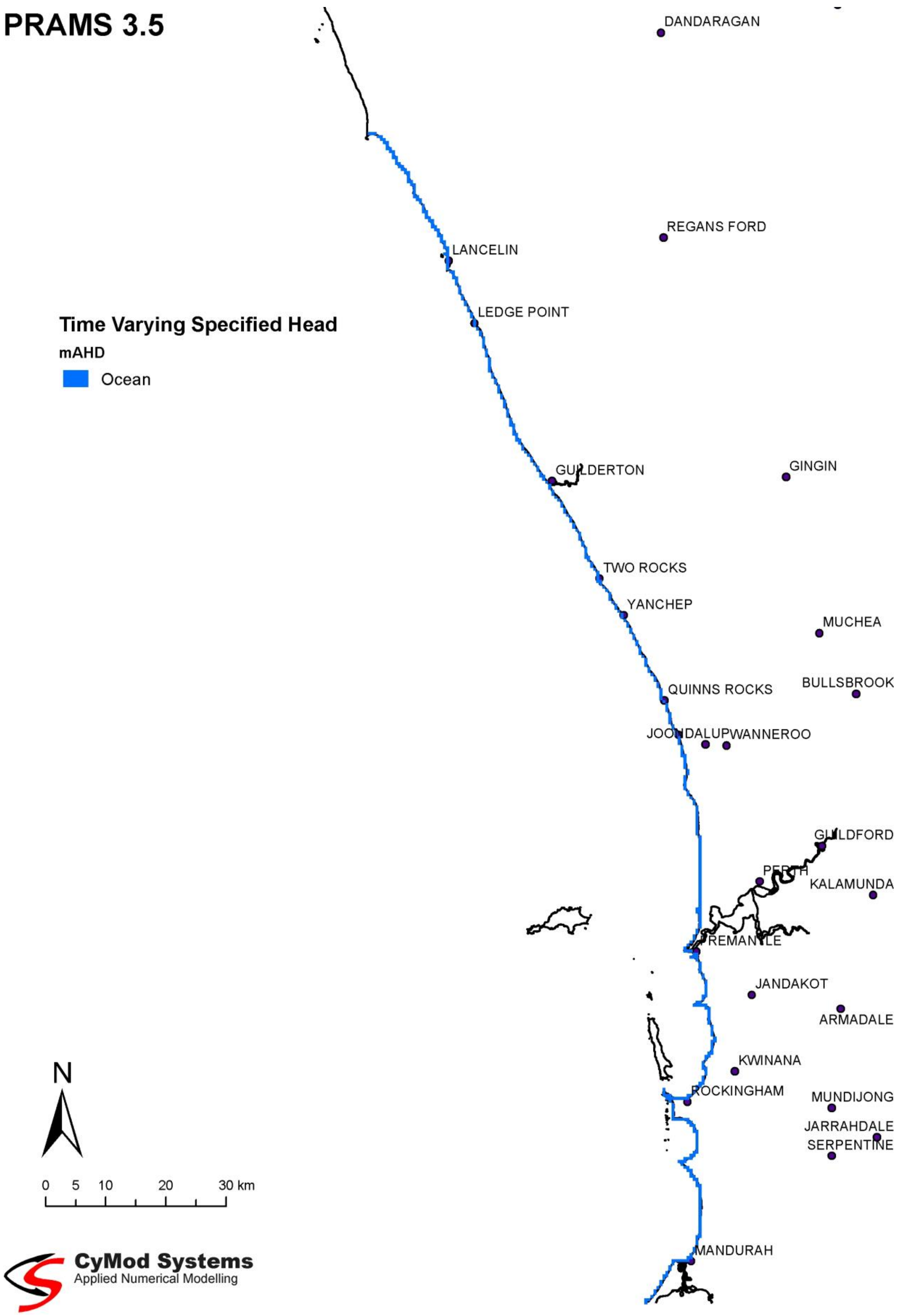

Figure 9: TVSH Boundary – Layer 1 and 2

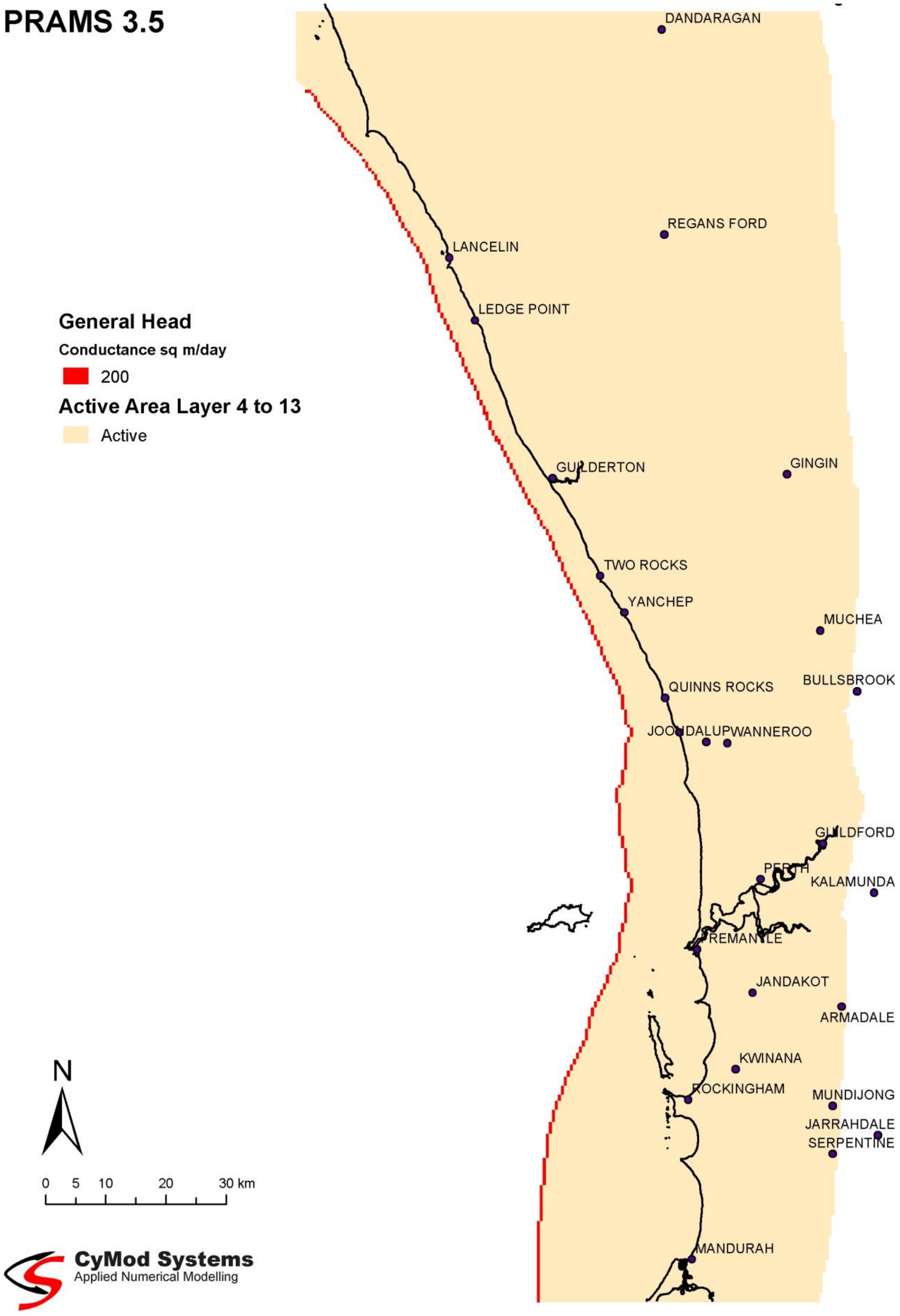

Figure 10: GBH Boundary – Layers 6 and 7

3.5 Drainage

There are only a few significant natural drainages or creeks (i.e. Gingin Brook, Moore River, Serpentine River), within the PRAMS 3.5 model domain, other than the Swan River and Ellen Brook. Figure 11 shows the major drainage features that have been modelled. A review of these drainage features indicates that most are acting to discharge groundwater, and are consequently modelled as drains with MODFLOW.

In addition to natural drainages, some areas of the Swan Coastal Plain have extensive networks of man-made drains. Some of these drains have been included in the model and are based on data compiled by the Water Corporation. However, not all drainages have been included, and no calibration of measured drain discharges to simulated discharges has been undertaken in PRAMS 3.5. Consequently, it is recommended that available spatial and flow data be acquired (if available) and included in future versions of PRAMS, as a way of extending the calibration to flow components.

Drains, as implemented in MODFLOW, are elements where water discharges once the water table rises above the specified drain invert level. Groundwater discharged into a drain permanently leaves the model via that drain node. There are 2 parameters used to define drains: drain conductance and drain bed level. The first parameter, drain conductance is the bed resistance to flow into the drain. Drain conductance is used to scale the drain area relative to the area of the element used to model the drain. Drain conductance was set at a maximum of 25,000 m^2/day. The second parameter, bed level, specifies the level at which water will begin to discharge into the drain. The bed level for active drains in the model is defined as the topographic surface, or if specified, the drain invert level as interpolated onto the closest node.

As indicated above, using an interpolated ground surface as the basis for estimating the drain bed level may introduce errors into the calculation of head at elements having the drain boundary condition. For elements with water levels above the drain bed level, the drain boundary conditions will act to discharge water at a rate proportional to the head differences and bed conductance, such that the head in the aquifer will be controlled by the bed elevation. Consequently, any error in the drain bed level will be directly reflected in the calculated head. This error will be directly proportional to the error between the actual creek or riverbed level and the model drain invert level. The drain elevations in PRAMS 3.5 could be improved by using a weighted-estimate drain elevation for the model node, to get a more representative elevation. However, this could result in a spatial shift in the location of the drain that will also impact model fidelity. The only effective way to improve the representation of drains in the model is to increase the spatial resolution.

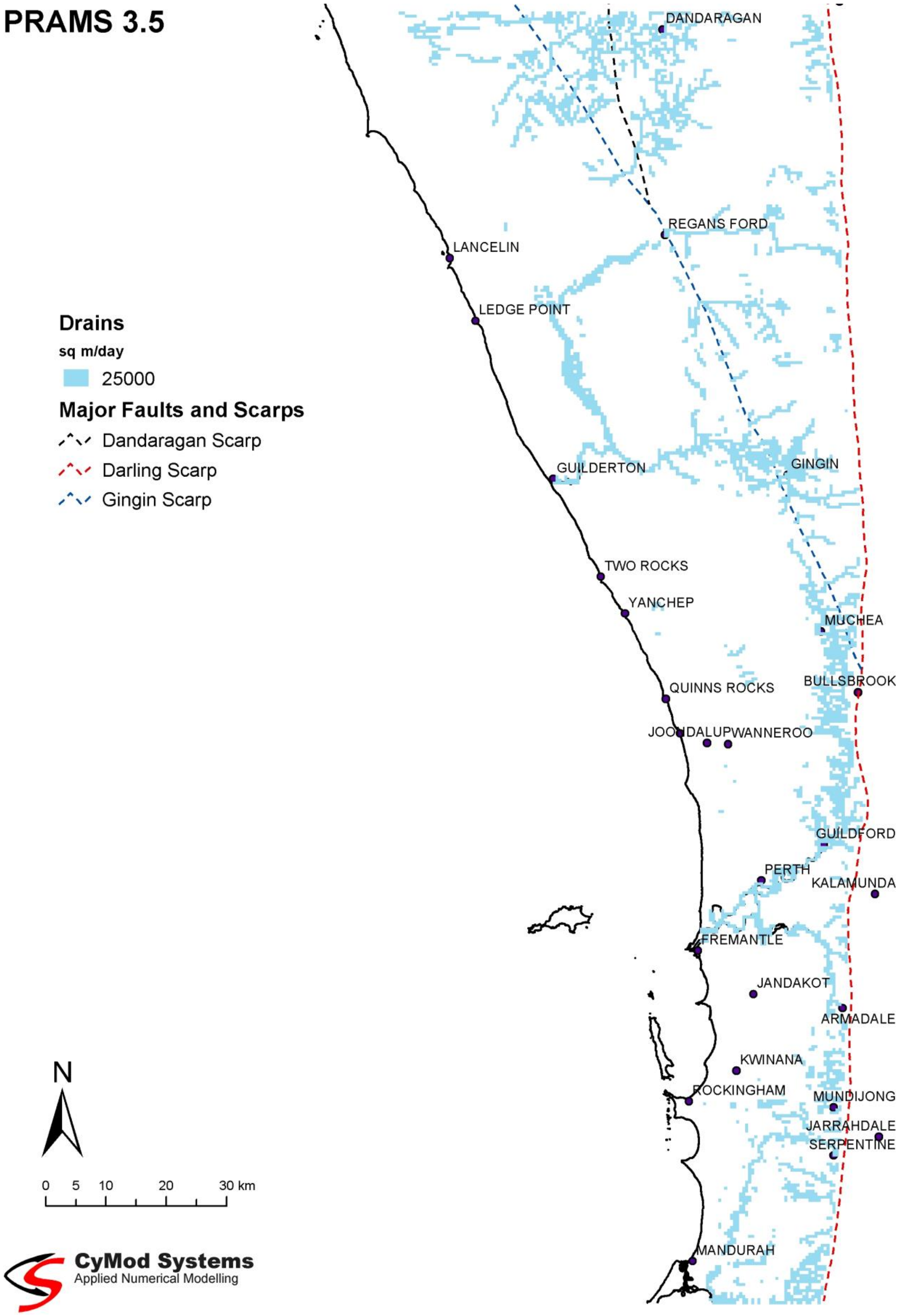

Figure 11: Drains

3.6 Recharge and Evapotranspiration

The upper surface of the model is defined in the VFM, as the top of Layer 1. The VFM has two boundaries, the ground surface and the water table. At ground surface, the VFM models a variety of processes including rainfall, insolation, wind and plant growth which generates a net recharge to the saturated component of the model, modelled as Layer 1 in MODFLOW. The conditions on this boundary are specified as part of the input to the VFM model.

3.6.1 VFM Model

In PRAMS 3.5, the VFM is used to determine net rainfall recharge without plant growth. The only significant change in the VFM with respect to the saturated zones, is that recharge from the VFM is applied to a specified layer, via a recharge layer array, similar to option 2 of the standard recharge MODFLOW package (USGS 1988).

The VFM calculates the daily net recharge to a 500 by 500 metre soil column, ranging in depth from 1 to 50 metres. This daily recharge is aggregated over the MODFLOW stress period, to provide a net recharge to the saturated aquifer model for that stress period. A complete description of the algorithms used in the VFM is given in Barr *et al* 2003. The VFM is integrated into the MODFLOW program and effectively replaces the EVT module. The net recharge as generated by the VFM is included in the MODFLOW global water balance as well as output as a source component in the cell-by-cell water budget file.

The net rainfall recharge as calculated by the VFM is the major source of water into the model. The other boundary conditions, such as constant heads on the coast and drains along the Swan River and Ellen Brook typically discharge water from the model.

The VFM calculates net vertical flux (recharge) to the saturated aquifer, while MODFLOW 2000 calculates the regional horizontal flow due to this vertical flux and other groundwater flow sources and sinks. The VFM model solves vertical flow only for sub-regions of the MODFLOW model. These sub-regions consist of Representative Recharge Units (RRUs) covering from 1 to several thousand MODFLOW cells, that are grouped based on depth to water, climate, landuse, soil and vegetation characteristics (Silberstein et al, 2003). The approach is based on recognising that net recharge will be similar for regions that have similar hydrologic and landuse characteristics. This approach results in having to solve recharge for a smaller set of nodes, but without the equivalent loss in spatial resolution. The maximum number of RRU’s in PRAMS 3.5 is on the order of 5,000 compared to about 40,000 active elements. However, not all RRU’s are actually used: in the calibration model, for example, less than 2,000 RRU’s are used.

The VFM uses four major parameters to define internally allocated and calculated RRUs. These parameters are:

- Landuse;
- Soil type;
- Climatic zones; and
- Depth to the water table.

Typically, landuse is spatially variable and time-variant, while soil type and climatic zones are spatially variable and time-invariant datasets. Each of these parameters is defined as an integer value for every active node in Layer 1 (as defined by the saturated flow finite-difference grid). Defining the appropriate integer values spatially and temporally is done using grid-based GIS datasets that are combined by the VFM to generate the finally integer-valued RRUs. Depth to water is calculated by MODFLOW, and hence is spatially variable and time dependent, and is not defined prior to model simulations. However, the number of available integer codes used to define depth to water is predefined and typically is limited to 10-14 categories, accounting for depth to water from 0.01 m to 50 metres. Complete details of the linkage of the VFM to MODFLOW, including the incorporation of WAVES is given in Silberstein et al (2003).

3.6.1.1 Landuse Coverage

The landuse coverage specifies 15 landuse codes, ranging from 1 to 23, based on the dominant vegetation type or economic activity occurring within a cell. The 15 different landuses presently defined in PRAMS 3.5, are shown in Table 3-5.

Unlike PRAMS 3.0 to 3.3, all Landuse Codes (LUC), except lakes and parkland use the WAVES subroutine. Previously, only LUCs involving banksia, pines, and pasture used the WAVES subroutine (physical-based model) to calculate recharge and changes in soil moisture (Silberstein et al, 2003). The use of physical-based landuse codes has significantly improved the performance of the VFM, particularly in areas having low hydraulic conductivity that were previously modelled using algebraic equations.

The distribution of these landuse classifications has been determined from satellite imagery, air photographs and other cadastral and spatial information. The distribution of landuse is considered to be an independently derived input to the PRAMS model, having low uncertainty and is not changed during calibration. However, the properties of each landuse (i.e. LAI, leaf litter, root depth, the amount of EVT, and gross recharge) are changed during calibration to reduce observed error in the model. A detailed description of the data, processing algorithms and GIS data structures is given in Canci, 2003.

Land Use Code	Description	Suggested Ranges
1	Banksia – high density	Leaf area index > 1.2
2	Banksia – low density	Leaf area index < 0.70
3	Pasture	Leaf area index = 0 - 3.0
4	Market Garden	Leaf area index = 0 - 3.0
5	Parkland	
6	Pine – high density	Leaf area index = 2.5 – 3.5
7	Pine – medium low density	Leaf area index = 1.5 – 2.0
8	Pine – low density	Leaf area index = 0.5 – 1.0
9	Urban	Leaf area index = 1.2
10	Lakes	
11	Commercial/Industrial	Leaf area index = 0.48
17	Pine – medium high density	Leaf area index = 2.0 – 2.5
18	Pine – medium low density	Leaf area index = 1.0 –1.5
22	Banksia – medium density	Leaf area index = 0.70 to 1.2
23	Banksia – low density shallow roots	Leaf area index < 0.70

Table 3-5: Landuse Codes

The LUCs also account for temporal changes in vegetation, wetland distribution and urbanisation. The temporal changes in landuse are modelled by constructing coverage's over the model area, at 1 or 2-year intervals, starting in 1988. Prior to 1988, landuse coverage's have been constructed for 1980 and 1985. However, differences in remote sensing technology prior to 1988 cause inconsistencies with later coverage's, that result in some inconsistencies in leaf area index (LAI) estimates prior to 1988. Annual coverage's are used after 2002. Appendix C shows the distribution of LUCs used from 1980 to 2013 as used in PRAMS 3.5.

3.6.2 Landuse Code 23

PRAMS 3.5 includes one additional LUC compared to PRAMS 3.0/3.3. LUC 23 is a modified low density banksia landuse that has a limited root depth of 6 metres, compared to the other banksia LUC's which have a root depth of 10 metres. This code was introduced to eliminate the rapid drawdown of the water table in areas of banksia woodland that have a shallow depth to water (i.e. less than 4 metres). The process for creating this landuse is:

1. A mask was constructed for areas of shallow groundwater (<4 m) and spatially joined to the landuse coverages;
2. All the cells of medium and high density banksia that also had shallow depth to groundwater where set to landuse code 23; and
3. The new landuse coverages were then applied to the model, having a 6m rooting depth.

Note that in this case only one depth to water coverage was used (i.e. 2000) in the spatial join. Best practice would suggest doing the spatial join using the yearly maximum water level coverages to account for a declining water table.

3.6.3 Soil Type

Six different soil profiles are specified for the model domain, as shown in Table 3-6. Each soil profile is characterised by vertical hydraulic conductivity and moisture retention curves, defined as a function of pore pressure. These saturation curves are used to solve the Richard's equation in WAVES, given the preceding moisture conditions, the depth to groundwater and net recharge. The six soil types have been defined based on the surface soil geology of the Swan Coastal Plain and are the same as used in previous versions of PRAMS.

Soil Type	Description	Comment
1	Quindalup	
2	Spearwood	Includes Tamala Limestone and Sand
3	Bassendean	
4	Guildford Clay	
5	Mesozoic	Area between Gingin and Darling Scarp
6	Lacustrine deposits	Associated with lakes and wetlands

Table 3-6: VFM Soil Types

The characteristics of these soils are based on the Brooks-Corey model for estimating hydraulic properties as a function of pore pressure. In general, the properties of these soils are considered independently determined and were not subject to change during calibration, except for saturated vertical hydraulic conductivity, which was changed in the calibration of PRAMS 3.0, in some cases to improve hydrograph responses to recharge. Xu gives a complete description of the soil property classification approach used (Xu et al, 2003), including a sensitivity analysis of estimated recharge to changes in model parameters.

3.6.4 Climatic Data

A k-means cluster analysis, based on measured climate data from 442 climate stations on the Swan Coastal Plain, was used to identify the spatial distribution of 8 different climatic zones. The cluster analysis was based on 5 kilometres of gridded data as provided by the DoW and used 6 clustering parameters:

1. Distance between climate stations;
2. Variance in daily rainfall at each station;
3. Mean daily rainfall at each station;
4. Mean daily evaporation at each station;
5. Maximum daily rainfall at each station: and
6. Coherency between time series for each station.

The first 5 parameters are statistical parameters, while the coherence is a measure of the similarity of the rainfall time series between stations. Coherence uses the cross-correlation coefficient between rainfall time series, and by comparing the frequency component of rainfall time series determines how similar they are in terms of frequency and phase.

If the precipitation time series is caused by the same rainfall, as recorded at different locations, the coherency for them shows a strong correlation. Therefore, the similarity of rainfall series can be ascertained by the value of coherency and be used to group stations that are influenced by similar rainfall events.

The 8 climatic zones identified by the clustering procedure, define areas that have similar climatic characteristics, and which can be represented by measured time series of daily rainfall and other environmental parameters at a single station. The 8 rainfall zones used in PRAMS 3.5 are summarised in Table 3-7. Appendix C shows the distribution of the 8 zones with respect to the PRAMS 3.5 model domain. The rainfall sequences corresponding to the eight climate zones are shown in Appendix D.

Zone	Average Rain (2000-2013) (mm/annum)	Average total evaporation (mm/annum)
1	432	2144
2	524	2106
3	606	2020
4	614	2014
5	697	1966
6	717	1940
7	679	2024
8	1006	1635

Table 3-7: Climate Zones Used in PRAMS 3.5

3.6.5 Recharge Layer

Previous versions of PRAMS have used an option in the VFM that automatically assigns recharge and evapotranspiration (EVT), as calculated by the VFM to the highest active (saturated) layer for each active node. Due to the different approach used to construct the layering in PRAMS 3.5, this automatic assigning of layers resulted in anomalous recharge/EVT to confined layers, which is inconsistent with the conceptual hydrogeological model. Consequently, a specified layer approach was used, where recharge/EVT is specified prior to model execution, and remains constant during the simulation. The limitation of this approach is that if the specified layer goes dry at a node, then no recharge or EVT can occur at that location.

The specified recharge layer array has values ranging from Layer 1 on the Swan Coastal Plain to Layer 4 on the Dandaragan Plateau. The recharge distribution was determined iteratively during model calibration, and is shown in Appendix C.

3.7 Abstraction

Abstraction from the PRAMS 3.5 model area occurs from the superficial and artesian aquifers. There are 3 major types of abstraction from these aquifers:

1. Water Corporation abstraction (public licensed abstraction);
2. Licensed abstraction by private users (private allocations); and
3. Unlicensed abstraction by private users.

Each of these abstractions was quantified both spatially and temporally, on a monthly basis over the model calibration (2000 – 2013) and verification (1980 – 2000) periods.

The Water Corporation typically measures and reports abstraction as monthly volumes, for each of their operating bores. The licensed abstraction by private users is based on an annual allocation assigned to a legal property, after a successful application by the landowner for a licence from the DoW. The allocation promulgated by the DoW specifies the volume of water that may be extracted via specified wells during a twelve-month period. Unlicensed abstraction (i.e. garden bores) is permitted from bores that abstract less than 1,500 kilolitres per year.

3.7.1 Water Corporation Abstraction

The Water Corporation provided raw data of abstraction volumes for their bore fields beginning in 1972 until June 2013. This data was collated, validated and stored in the PRAMS 3.5 database.

The data was processed for input into PRAMS 3.5 by:

- Extracting monthly volumes for each bore for the model period;
- Integrating the monthly volumes into a cumulative production curve for the simulation period;
- Calculating the average bore production rate for each model stress period by taking the difference between cumulative production at the beginning and end of a stress period and dividing by the length of the stress period; and
- Saving the estimated monthly bore abstraction rate for each stress period for each bore in a MODFLOW compliant format.

The above procedure results in some smoothing of production data but guarantees that the abstraction from the aquifer as modelled by PRAMS 3.5 will be similar to the abstraction as measured by the Water Corporation.

Table 3-8 summarises the annual Water Corporation abstraction used in the PRAMS 3.5 model from 1980 to 2013. Figure 12 shows the total abstraction from all public water supply bores for 1980 to 2013. Figures 13 and 14 shows the spatial distribution of the Water Corporation abstraction.

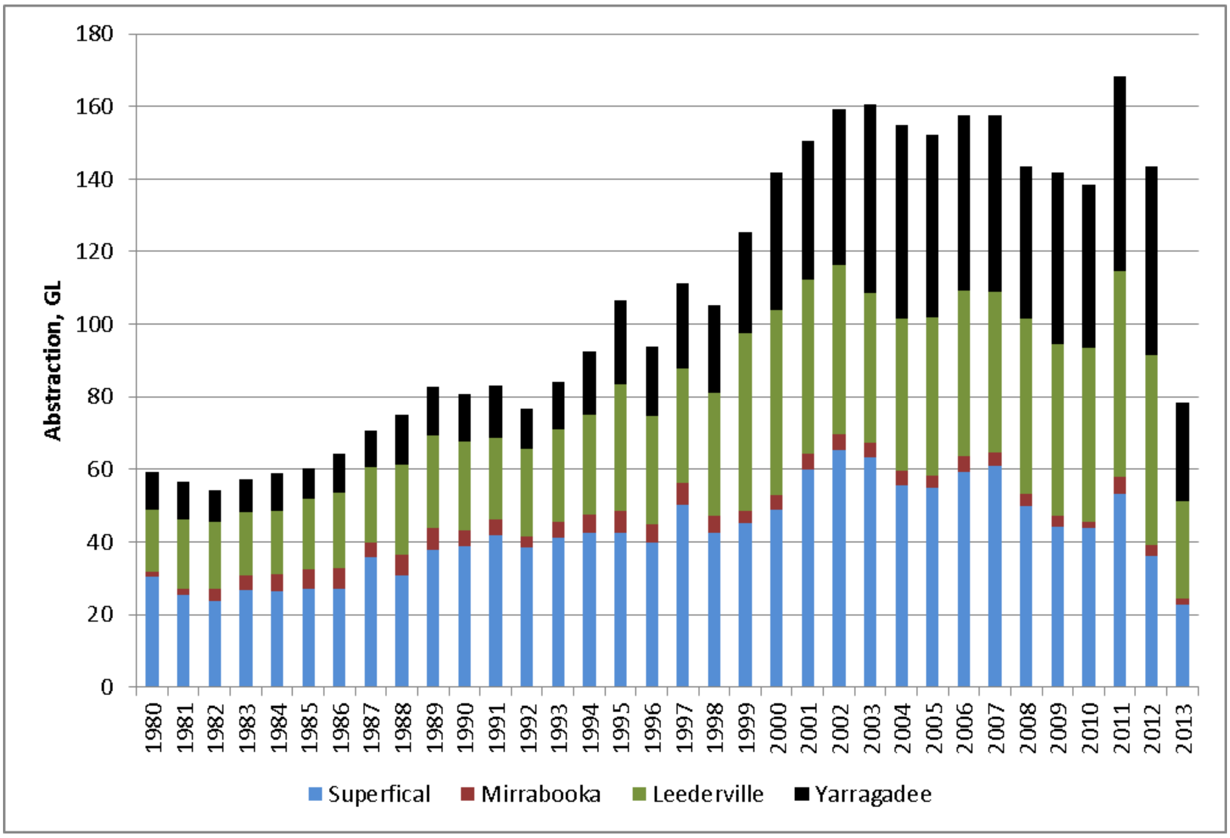

Figure 12: Water Corporation Abstraction 1980 – 2013

Year	Superficial (GL)	Mirrabooka (GL)	Leederville (GL)	Yarragadee (GL)	Total (GL)
1980	30.6	1.4	17.3	10.2	59.1
1981	25.6	1.9	19.1	10.4	56.8
1982	24.1	3.3	18.7	8.6	54.3
1983	26.9	4.1	17.4	9.3	57.3
1984	26.7	4.8	17.3	10.6	59.1
1985	27.2	5.2	19.3	8.4	60.1
1986	26.9	5.9	20.7	10.8	64.3
1987	35.9	4.0	20.7	10.1	70.7
1988	30.6	5.8	24.9	13.7	75.1
1989	37.8	6.0	25.6	13.2	82.6
1990	38.7	4.4	24.5	13.0	80.7
1991	41.9	4.4	22.4	14.3	83.0
1992	38.5	3.0	24.2	11.1	76.8
1993	41.3	4.1	25.5	13.1	84.0
1994	42.4	5.2	27.3	17.7	92.6
1995	42.5	6.1	34.7	23.0	106.4
1996	39.8	5.2	29.8	18.9	93.7
1997	50.1	6.1	31.6	23.4	111.2
1998	42.7	4.4	33.9	24.3	105.2
1999	45.2	3.2	49.2	27.7	125.4
2000	48.8	4.2	50.7	38.1	141.9
2001	60.5	4.1	48.1	38.7	150.6
2002	66.3	4.2	46.5	40.5	159.2
2003	66.3	3.9	41.3	55.2	160.6
2004	63.9	4.1	41.8	45.6	155.0
2005	63.5	3.6	43.5	45.2	152.2
2006	59.4	4.1	45.6	48.4	157.5
2007	61.1	3.7	44.2	48.7	157.6
2008	49.8	3.2	48.3	41.6	143.4
2009	44.3	2.8	47.4	47.3	141.9
2010	43.7	1.9	47.8	45.0	138.4
2011	53.2	4.6	56.8	53.6	168.2
2012	35.8	3.1	52.1	52.1	143.1
2013[1]	22.7	1.6	26.8	27.5	78.2

1. To July 2013

Table 3-8: Water Corporation Abstraction

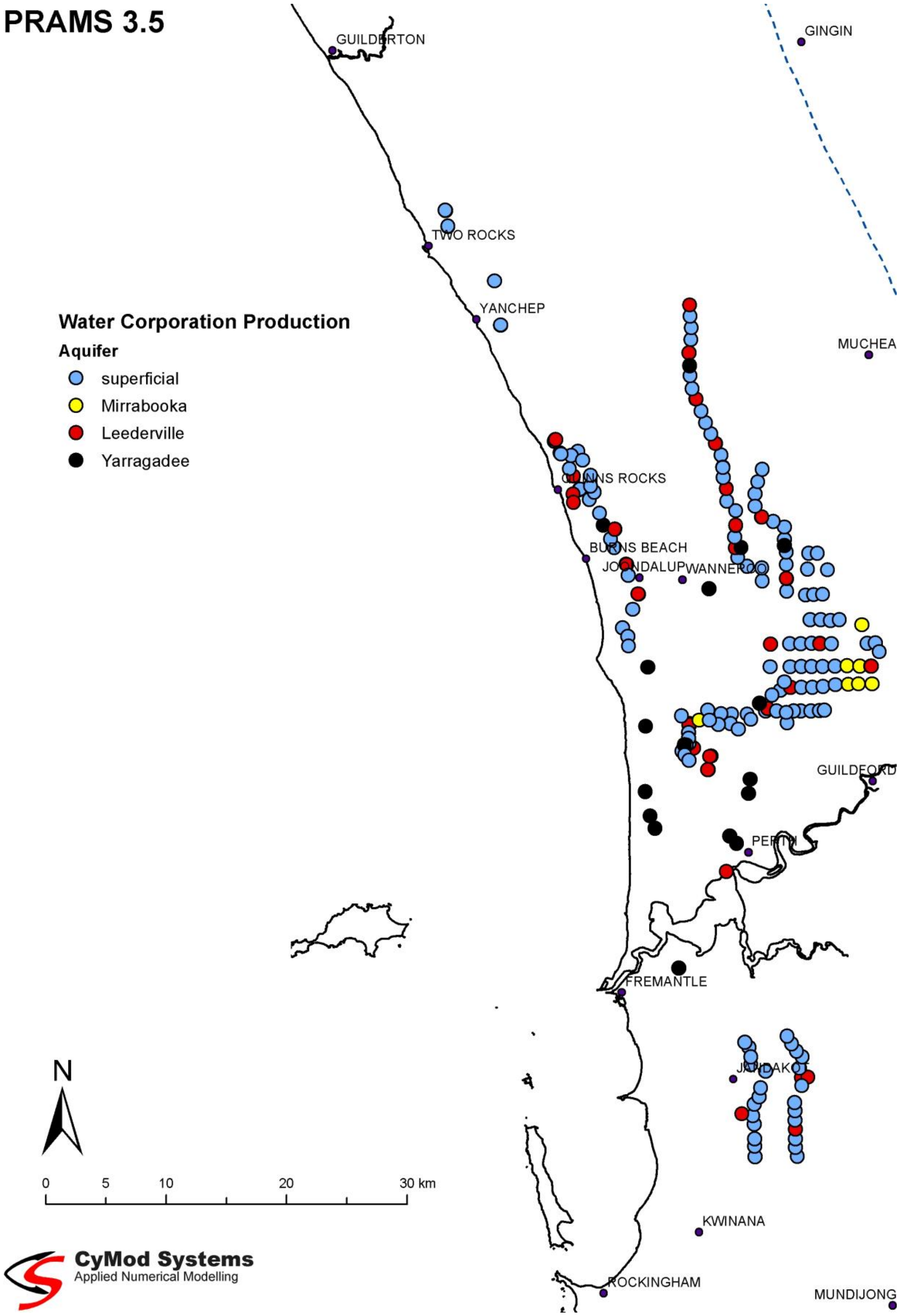

Figure 13: Water Corporation Bores by Aquifer

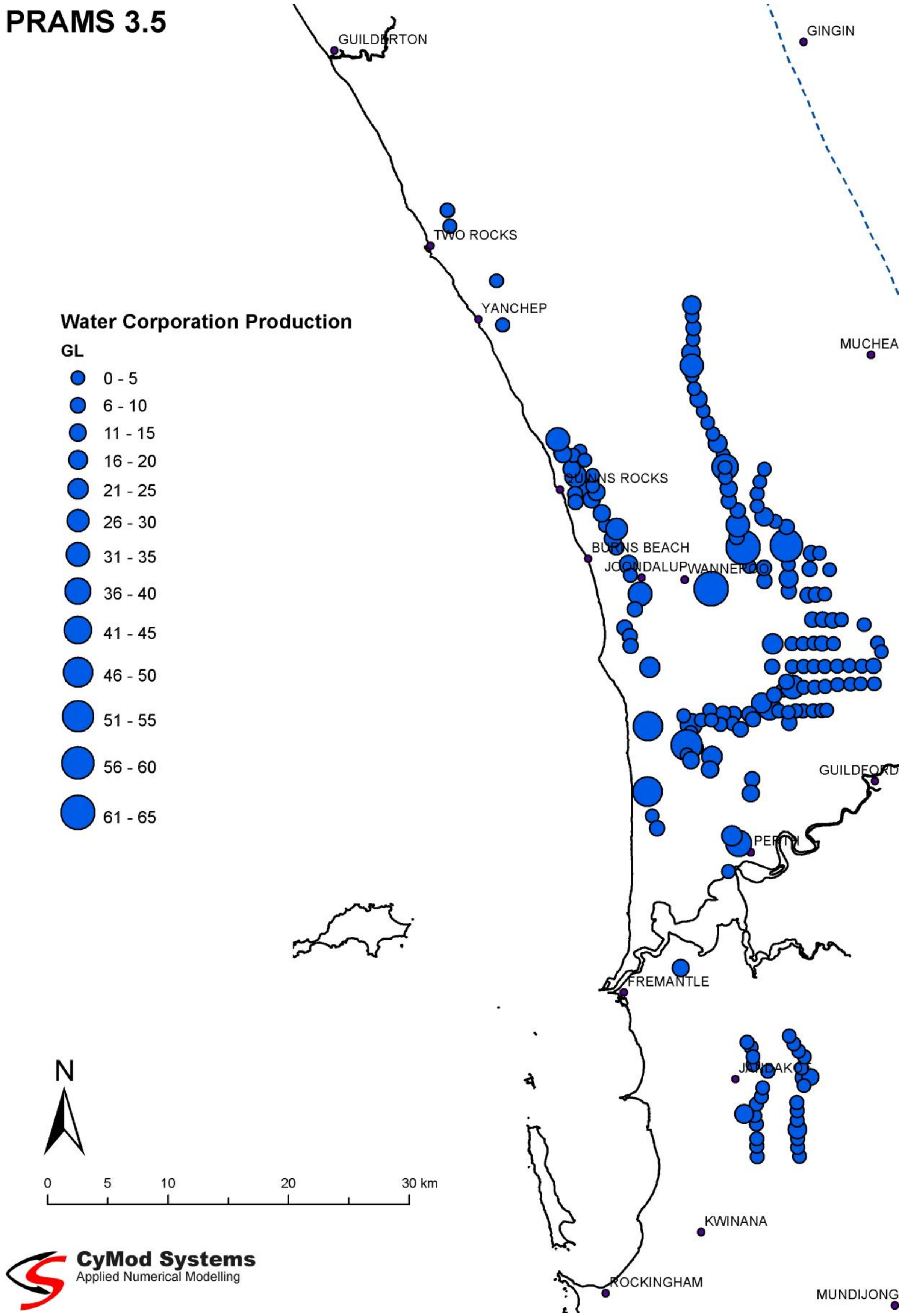

Figure 14: Water Corporation Total Production by Bore 2000 - 2012

3.7.2 Licensed Private Bores

The DoW has developed a database containing all existing licensed allocations for private users. This database records current and expired licenses as of 2013. However, no historical record of license allocations prior to 1997 is available, while data prior to 2006 is considered to be unreliable. The database records annual allocation, the location of the property or bore that has been assigned the allocation, the aquifer to which abstraction is licensed, and the use to which the groundwater is applied.

The allocation database prior to 1997 represents a single point measurement of allocation in time. It is likely that the spatial distribution and total volume of annual abstraction has changed in response to economic and urban development in Perth over the model calibration/validation period from 1980 to 2013. In the absence of specific data showing the trends and changes in spatial distribution and volume of licensed allocation, the historical licensed allocation distribution required for input to PRAMS 3.5, beginning in 1980 until 2006 must be generated synthetically, based on accepted growth rates in water usage.

Previous studies of licensed allocation on the Swan Coastal Plain have suggested that groundwater abstraction has increased on average by 3% per year since 1970 (Davidson, 1994). In practice this 3% increase was found to lead to problems with model calibration indicating this estimated rate might be too high. Monthly abstraction from 1980 to 1997 was calculated using a 2.5% growth rate over the period based on the abstraction in 1997. Note that changes in the spatial distribution of licensed abstraction before 1997 were ignored, as there is no easily accessible information on the spatial distribution of allocation with respect to the expiry and issuing of licences prior to 1997.

From 1980 to 1997 licensed allocation from PRAMS 3.0 is used to model private abstraction, as there is limited information prior to 1997 on actual usage. The records of licensed allocations between 1997 and 2005 are deemed to be unreliable due to the way data is stored in the DoW database. Instead of using the recorded licensed allocations for this period, the licensed abstraction was modelled using a linear growth factor based on the difference between the 1997 and 2005 allocations. The spatial distribution of the allocations is constant and identical to the distribution in 2005.

After 2006, the annual abstraction has been generated from the analysis of enforced licensed abstraction, for each financial year. These abstractions are derived from the allocation for each licence from the WRL database. All abstraction data for a calendar year is derived from a different snapshot of the WRL database, usually taken sometime in the middle of that calendar year. The dates of the snapshots are as shown in Table 3-10.

Date of WRL Data	Allocation Year
2005, 2006, 2007	July 2006
2008	July 2008
2009	July 2009
2010	June 2010
2011	June 2011
2012	June 2012
2013	June 2012

Table 3-9: Available Allocation Data

From 2006 onwards, the licensed abstraction is modelled from the data supplied from the DoW database and varies both spatially and temporally. Table 3-10 summarises the current licensed abstraction excluding Water Corporation allocations for the entire Swan Coastal Plain. The yearly licensed abstraction is also shown in Figure 15.

The licensed allocation database does not have data for screened intervals or bore depth. Consequently, in extracting the licensed allocations from the database and converting them into MODFLOW wells the following algorithm is used:

a) Current licensed allocations are extracted from the database, sorted by aquifer and assigned to specified model layers:
    a. Superficial Layer 3
    b. Mirrabooka Layer 4;
    c. Leederville Layer 7;
    d. Parmelia Layer 10; and
    e. Yarragadee Layer 12.
b) The total licensed abstraction in each element is divided by 365 to give the average daily abstraction in m^3/day;
c) The average daily licensed abstraction for each layer is scaled for each stress period in the model, using a time series containing a growth factor and a seasonal irrigation factor (i.e. as per figure 16); and

The licensed allocation database does not provide any information as to the monthly pattern of abstraction for individual licensed bores. However, groundwater monitoring suggests that licensed and unlicensed abstraction from private bores has a strong seasonal component. A review of water usage for licensed bores suggests that the majority provide irrigation water for parks and gardens, market gardens and lawn reticulation. Irrigation abstraction has a strong seasonal pattern with maximum volumes occurring in January and February and no abstraction occurring in May, June and July. Using recommended irrigation schedules for turf the annual abstraction for licensed bores was scaled on a monthly basis to seasonal water requirements from 0 to 2.1 times annual average abstraction, as shown in Figure 16.

In general, the licensed abstraction is consistent with measured water level responses and historical water balances of the Swan Coastal Plain. However, the limitations in the present licence database constrain the accuracy of the calibration as indicated below:

1. The constant spatial distribution of licensed allocation before 1997 may result in historical abstraction (before 1997) from areas that had none (i.e. rural areas which underwent urban development during the 1980s and 1990s). The same goes for the constant distribution of abstraction between 1997 and 2007;
2. The assumption of a uniform growth in abstraction may result in over and under estimates of abstraction, in particular in periods where growth rates were not constant; and
3. The inferred seasonal pumping schedules based on irrigation requirements results in a seasonal variation in abstraction that may not occur in practice.

Year	Licensed Abstraction (GL)	Superficial	Mirrabooka	Leederville	Yarragadee
2000	254.8	192.8	10.5	42.3	9.2
2001	267.5	208.5	11.0	39.5	8.6
2002	286.5	223.2	11.8	42.3	9.2
2003	305.6	238.1	12.6	45.1	9.8
2004	322.9	251.6	13.3	47.7	10.4
2005	343.7	263.8	16.2	52.9	10.9
2006	344.2	262.9	19	51	11.1
2007	344.2	262.9	19	51	11.1
2008	336.2	270.2	7.9	48.2	9.9
2009	345.4	270.3	7.7	51	16.3
2010	358.1	272.3	18.2	51.8	15.7
2011	344.4	261.3	17.2	53.4	12.4
2012	351.5	267.8	17.4	53.5	12.8
2013	352.3	264.2	20	55.3	12.8

Table 3-10: Annual Licensed Private Abstraction 2000 – 2013

Figure 15: Annual Licensed Private Allocation 1980 – 2013

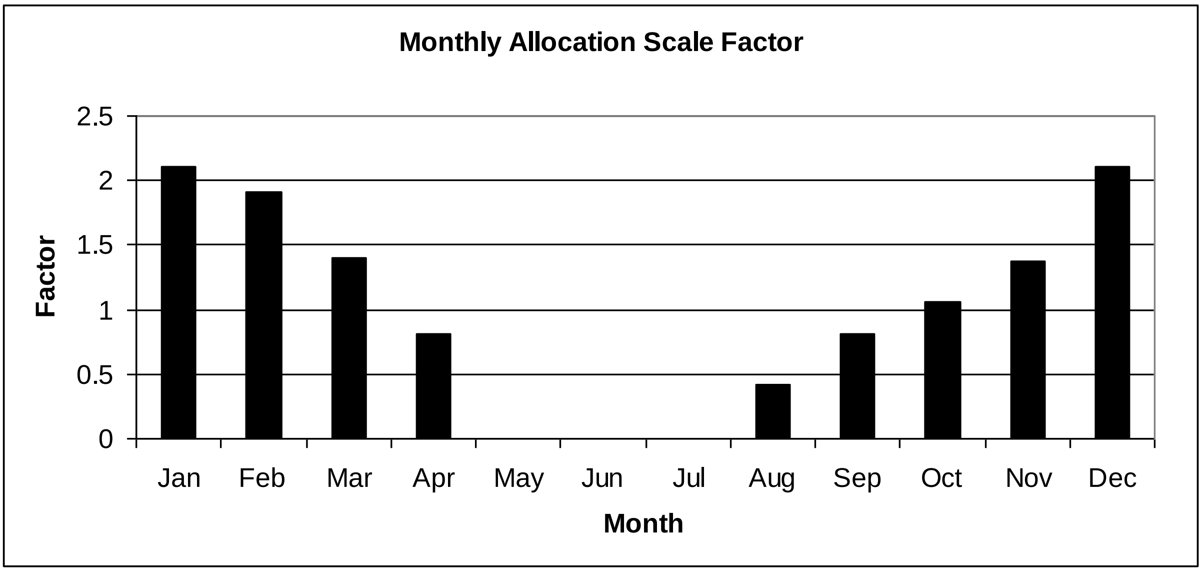

Figure 16: Monthly Allocation Scale Factor

3.7.3 Unlicensed bores

The estimates of unlicensed abstraction in PRAMS 3.0 to 3.4 used a study commissioned by the DoW in 2001 that identified the extent and distribution of unlicensed bores in the superficial aquifer, for most areas of the Swan Coastal Plain (Aquaterra, 2001). Using this data, unlicensed abstraction was modelled as a net negative recharge from the superficial aquifer. The net negative recharge varied seasonally based on irrigation requirements, as in the case of licensed allocation bores. Figure 16 shows the monthly scaling factors used to scale unlicensed abstraction.

During the calibration period, 30% of abstraction is estimated to flow back to the superficial aquifer, giving a net abstraction due to unlicensed bores of 73 GL/annum in 2009. The use of 30% return to the aquifer was considered to be a conservative assumption that implies the measured changes in water levels occur for a smaller volume of abstraction. The volume of annual abstraction for unlicensed bores was assumed to grow at 3% per year over the calibration period.

Recent studies by the DoW suggest that water is efficiently used and it is unlikely that 30% of abstraction returns to the superficial aquifer. In addition, the studies also reduced the estimated water usage of unlicensed bores. This suggests that after 2009 the net amount of abstracted water is similar to gross abstraction. The DoW estimated gross abstraction for 2009 and 2012, as shown in Figure 17, based on this improved understanding of unlicensed water use and the updated average bore consumption. The estimated gross abstraction in 2009 and 2012 is similar to the estimate obtained in the PRAMS 3.0 model net abstraction approach. Consequently, in the absence of data prior to 2009 to estimate gross abstraction, net abstraction volumes were used instead of gross volumes in combination with a 30% return factor for both the calibration period and the validation period.

The distribution of unlicensed abstraction is based on the DoW’s (2001) classification of the Swan Coastal Plain groundwater subareas. For each groundwater subarea the number of households, percentage of ownership and average bore usage were estimated to give the total annual abstraction for each region. These total abstractions were then divided by the area of each region and converted to a daily flux, for input into MODFLOW. Table 3-11 summarises the annual garden bore abstraction as used in PRAMS 3.5.

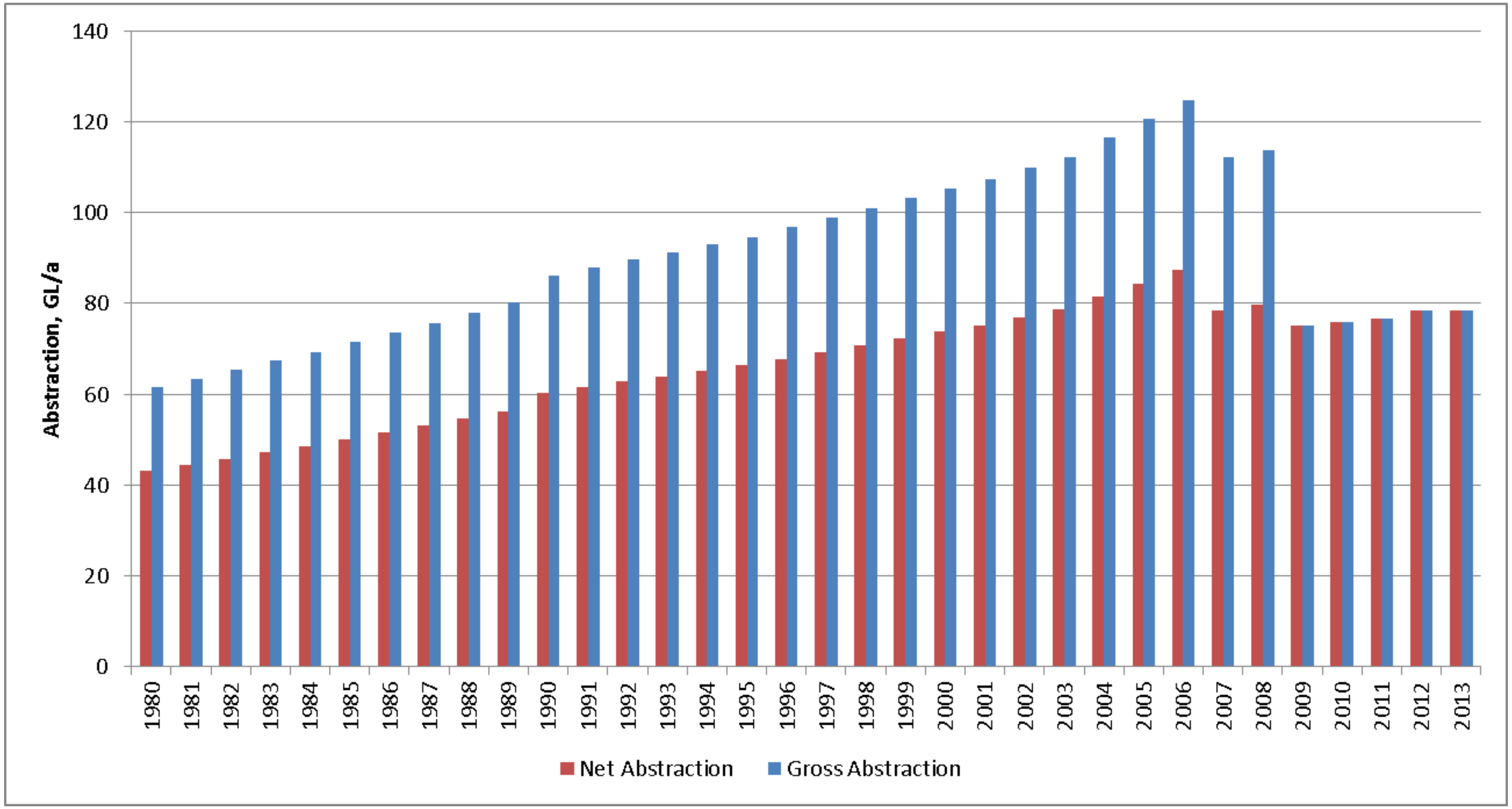

Figure 17: Annual Unlicensed Abstraction 1980 – 2013

Year	Net Abstraction (GL)	Gross Abstraction (GL)
1980	43.1	61.6
1981	44.4	63.4
1982	45.7	65.3
1983	47.1	67.3
1984	48.5	69.3
1985	50	71.4
1986	51.5	73.5
1987	53	75.7
1988	54.6	78
1989	56.2	80.3
1990	60.3	86.2
1991	61.5	87.9
1992	62.7	89.6
1993	63.9	91.2
1994	65.1	92.9
1995	66.3	94.6
1996	67.7	96.8
1997	69.2	98.9
1998	70.7	101.0
1999	72.2	103.1
2000	73.7	105.2
2001	75.1	107.3
2002	76.9	109.8
2003	78.6	112.2
2004	81.5	116.4
2005	84.4	120.6
2006	87.4	124.8
2007	78.5	112.2
2008	79.7	113.8
2009	75.1	75.1
2010	75.9	75.9
2011	76.7	76.7
2012	78.5	78.5
2013	78.5	78.5

Table 3-11: Annual Unlicensed Bore Abstraction 1980 - 2013

4 MODEL CALIBRATION AND VERIFICATION

The calibration of a groundwater model involves the iterative adjustment of selected aquifer parameters to minimise the error between measured and simulated heads in all aquifers. Two types of calibration can be undertaken; steady state (or quasi steady-state) where input variables and boundary conditions are constant with time (or periodic); and transient where predicted hydrographs are compared to measured hydrographs over a selected period, and input variables vary with time. PRAMS 3.5 was calibrated under transient conditions.

Two models were constructed and calibrated as part of PRAMS 3.5 development:

a. PRAMS 3.5A uses the block faulted model of the Leederville and Yarragadee; and
b. PRAMS 3.5B uses the faulting as described in PRAMS 3.0.

Note that the same aquifer geometry is used in both models, which implies a block faulted depositional environment. This deposition model is different from PRAMS 3.0-3.3 and hence the PRAMS 3.5B model is not comparable to these previous versions of PRAMS. The description and calibration approach are identical for the two models, with only calibration statistics and some aquifer parameters in the Leederville and Yarragadee different between the models.

4.1 Calibration Approach

The approach to the calibration of PRAMS 3.5A was based on the model guidelines Guiding Principle 5.2:

The calibration process should be used to find model parameters that prepare a model for use during predictions of future behaviour, rather than finding model parameters that explain past behaviour.

Using this guideline implied using data from a recent period (i.e. 2000 to 2013), and simplifying the model parameterisation, which had become complicated during the development of PRAMS 3.0 to 3.4.

4.1.1 Steady State

In the case of PRAMS 3.5 there is insufficient data and no identifiable period that can be considered in steady state. Consequently, the model was not calibrated in steady state.

4.1.2 Dynamic Calibration

The transient calibration of the model, without an initial steady state condition is problematic in that model artifices may exist due to non-representative conditions at the beginning of the model. Initial conditions based interpolated water levels as measured in 2000 were used as the initial head in each aquifer in PRAMS 3.5. The model was then dynamically calibrated using a manual iterative technique to conditions in July 2000 by adjusting hydraulic conductivity, given average recharge and abstraction conditions. The resulting head distribution was used as the initial condition of the transient calibration which runs from 2000 to 2013.

In the case of the verification model, which runs from 1980 to 2000, a similar procedure was undertaken. Initial conditions from the PRAMS 3.4 model were used as the initial head in each aquifer in the PRAMS 3.5 verification model. The model was then dynamically calibrated to conditions in January 1980 by adjusting hydraulic conductivity to get stable water levels, using average abstraction and recharge from 1980. The resulting head distribution was used as the initial condition of the transient calibration which runs from 1980 to 2000.

4.1.3 Transient Calibration

The model was manually iteratively calibrated by adjusting selected parameters in both MODFLOW and the VFM for the period July 2000 to July 213. Typically the following process was used:

- Adjust the LAI ranges and rooting depth for the landuses in the VFM to establish net recharge to the superficial aquifer;
- Review the error in predicted water levels in the Superficial aquifer and adjust horizontal and vertical hydraulic conductivity;
- Review the error in the Mirrabooka, Leederville and Yarragadee aquifers and adjust horizontal and vertical hydraulic conductivity and fault conductance to reduce the error; and
- Re-run the simulation and compare new predicted heads to begin another iteration.

This procedure was augmented with qualitative sensitivity analysis and localised improvements in the conceptual hydrogeological model to address areas of apparent intractable error.

4.2 Run Parameters

The transient calibration model was run for 156 stress periods, beginning in July 2000 and running to June 2012. Stress periods were defined as calendar months. Each stress period had 6 time steps. Model output was monthly.

The VFM runs on a daily basis. Rainfall and other meteorological data begin on the 30th of June 2000 (i.e. one day before the model run start date). However, to condition the soil moisture distribution prior to the start of a model run, the VFM is run for 2 years, from the 1st of July 1998 to the 30th of June 2000. Sensitivity analysis of the VFM suggests that 2 years conditioning is sufficient to establish a representative moisture profile in the unsaturated zone in most areas of the model (Cheng, 2003).

Convergence criteria for the VFM is set at $1x10^{-13}$ but is allowed to be adjusted to $7x10^{-6}$ mm/day if convergence is difficult to achieve. However, solutions that use a convergence criterion of less than $1x10^{-10}$ may have significant water balance error and should not be used for analysis. A review of the VFM water balance error indicated that for most RRU's the error is less than $1x10^{-5}$ mm/day. However, for some RRU's that have perched conditions, or large depth to groundwater the error can be as high as 25 mm/day. Since RRU's represent a number of cells in the model, these errors may represent an important source of error in the recharge estimate to the saturated flow model.

The reporting of the water balance error in the VFM is limited and difficult to analysis given the number of RRU's in the model. It is recommended that improved diagnostics be output to allow better assessment of the water balance error in the VFM.

The VFM requires MODFLOW 2000 to run. The solver used in for solving the saturated flow component of the model is the pre-conjugate gradient solver, with a head error criterion of 0.001 metres and has a residual error of 10 m^3/day. Total iterations were limited to 1000 outer iterations and 10 inner iterations.

A review of the calibration runs showed that the maximum water balance error for the saturated model was less than 0.5% in any one time step and less than 0.01% for the entire model run.

4.3 PRAMS 3.5 Calibration

4.3.1 Re-Parameterisation

Prior to the calibration of PRAMS 3.5A, horizontal and vertical hydraulic conductivity and the storage parameters were re-parameterised by aggregating zones of similar values into larger zones. For example, zones with similar values (e.g. 10 and 12 m/day) were combined into one zone. In addition, the zones were based on geology instead of the hydraulic responses at monitor bores, as used in previous versions of PRAMS. During the calibration process the zones were subdivided as necessary to reduce error, but on a reasonable large scale while adhering to geological constraints.

During this re-parameterisation, the zones for both horizontal and vertical hydraulic conductivity were made identical. This is required to allow calibration to be performed using Visual MODFLOW. This approach assumes a spatial correlation between k_h and k_v that does not necessarily reflect the actual distribution, and may result in some additional error in the model. The larger scale of zones in PRAMS 3.5A makes this more of a problem than in previous model, but is the trade-off inherent in using a model generalized parameter distribution. The result may be realized as some monitor bores reporting higher error as opposed to previous versions of PRAMS.

The aquifer parameters in PRAMS 3.5A were also rationalised to be consistent with the ranges set out in Tables 3-3 and 3-4. These tables do not specify a vertical hydraulic conductivity, hence initial estimates of this parameter where based on applying the arbitrary rule, that k_v is 10 times less than k_h. During calibration this ratio was relaxed as required to achieve a viable calibration, supported by conditions in the aquifer.

4.3.2 Calibrated Model Parameters

The following parameters were adjusted as part of the model calibration: horizontal hydraulic conductivity, k_h, vertical hydraulic conductivity, k_v, specific storage, S_s and fault conductance. Based on a recommendation from PRAMS 3.4, an area of constant heads was added to Layer 4, to simulate upward leakage of groundwater offshore to the ocean in the Serpentine area. Other than this change, no other adjustments of boundary conditions were made during calibration.

The ranges of the calibrated aquifer parameters are consistent with those suggested in the conceptual hydrogeological model (Tables 3-3 and 3-4). The distribution of aquifer parameters is given in Appendix E.

In terms of the VFM the following changes were made:

- Addition of a new LUC, to account for low density Banksia in areas of shallow groundwater; and
- Adjustment of the LAI and root depth for the different landuses as described in Section 3.6.1.1

Other than these changes, the VFM is the same as that used in PRAMS 3.4. Note that the VFM used the same calibration values for both the 3.5A and 3.5B models.

Calibrated aquifer parameters are given in Appendix E. Table

4.4 Monitor Bores

PRAMS 3.5 has been calibrated to the monitor bore dataset as supplied by the DoW. This dataset uses different bores than those used in previous versions of PRAMS, and reflects recent drilling and the results of a review of monitoring bores as undertaken in 2012.

The DoW selected and provided data on 1,123 monitoring bores that were considered suitable for calibration. These bores were selected based on the quality and quantity of water level data, the depth at which the bores were completed and an assessment of whether the bores adequately reflect regional water levels.

Of the bores with a reported screen interval, 633 were completed in the superficial aquifer with the remaining bores completed in the Mirrabooka (40 bores), Leederville (134 bores) and Yarragadee (88 bores) aquifers, respectively. The distribution of calibration bores, by aquifer, is given in Appendix F.

4.5 PRAMS 3.5A Calibration - Discussion

Table 4-1 summarises the calibration error in the PRAMS 3.5A model. Below is a discussion of the calibration for each aquifer. The evaluation of calibration error provides a basis on which to modify the conceptual hydrogeological model, improve data fidelity and optimise available resources to efficiently minimise model error.

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	1.7	2.4	2.0	14.3	-13.9
Mirrabooka	2.1	2.1	1.4	17.4	-2.9
Leederville	4.4	5.7	3.1	16.7	-18.4
Yarragadee	4.0	5.3	3.6	20.4	-22.8

Table 4-1: PRAMS 3.5A-Summary of Transient Calibration Error

4.5.1 Superficial Aquifer

Figure 18 shows a comparison of predicted and measured water levels for the calibration bores completed in the superficial aquifer. Appendix F shows the calibration hydrographs for the same set of monitor bores. From Figure 18, the model predicted water levels in general show a random distribution around the unity slope line, with little or no systematic deviation. However, the width of the distribution suggests that some significant differences between measured and predicted water levels do exist.

The relative absolute error in the calibration, over this period is 2.3%, suggesting a reasonable calibration has been achieved. The average absolute error in PRAMS 3.0 was 1.6 metres, and in PRAMS 3.2 it was 1.5 metres, indicating that PRAMS 3.5A is consistent with previous models, in terms of accuracy of the calibration. However, the distribution of the error is more uniform compared to the other models.

The calibration of water levels in the superficial aquifer was achieved by:

- Adjusting the LAI of urban and commercial landuse to reflect high recharge;
- Adjusting horizontal hydraulic conductivity spatially in selected areas, particularly along the coast at the interface between the Tamala Limestone and the Bassendean Sand; and
- Adjusting vertical hydraulic conductivity spatially in selected areas to account for vertical gradients.

The superficial aquifer was also rezoned, based on hydraulic gradient and soil types adjacent to the Indian Ocean. This allowed the interface between the Tamala Limestone and Bassendean Sand to be more accurately calibrated.

The average absolute error is 1.6 metres and is defined as the difference between the predicted and measured water levels. The maximum positive error in the superficial aquifer in predicted head is 16 metres at GB16B, while the maximum negative error is –9.8 metres at RGB3, both of which are on the Dnangargan Plateau. Most of the simulated heads at monitor bores in the superficial aquifer have a response consistent with measured data. The monitor bores maintain correct trends and the magnitude of the error is constant, indicating that some of the error stems from initial conditions. Figure 19 shows the spatial distribution of the average calibration error, for the superficial aquifer in 2009. Spatially, the calibration error is typically less than 2 metres over most of the model area. However, there are several areas where some systematic error is present. These areas are:

a) In the vicinity of GB20, and GB21 where simulated water levels are seen to be more than 6 metres lower than measured;
b) In urban areas north of the Swan River near the ocean, water levels are consistently over predicted by 2 metres, which tends to correlate with the interface between the Tamala Limestone and the Bassendean Sand; and
c) Areas associated with shallow depth to water where the water table is consistently low (e.g. WM7 and WM8).

Some of the error in the model may also be attributed to the vertical discretisation of the superficial aquifer. The upper layer (Layer 1) of the superficial aquifer is defined as the top one third of saturated thickness of the aquifer. This definition results in Layer 1 having no correlation with the geological structure of the superficial aquifer. This lack of correlation to geology is typically not significant in areas where the superficial aquifer consists of a continuous sequence of permeable sand. However, in areas where the superficial aquifer has lenses of Guilford Clay and coffee rock, the lack of fidelity between the model layers and the actual geology of the superficial aquifer makes it difficult to simulate vertical gradients accurately. Significant error is also caused by local perched conditions, where there are 2 water table aquifers (e.g. Yeal). PRAMS 3.5A is unable to simulate perched conditions and will only predict water levels in the lower water table aquifer.

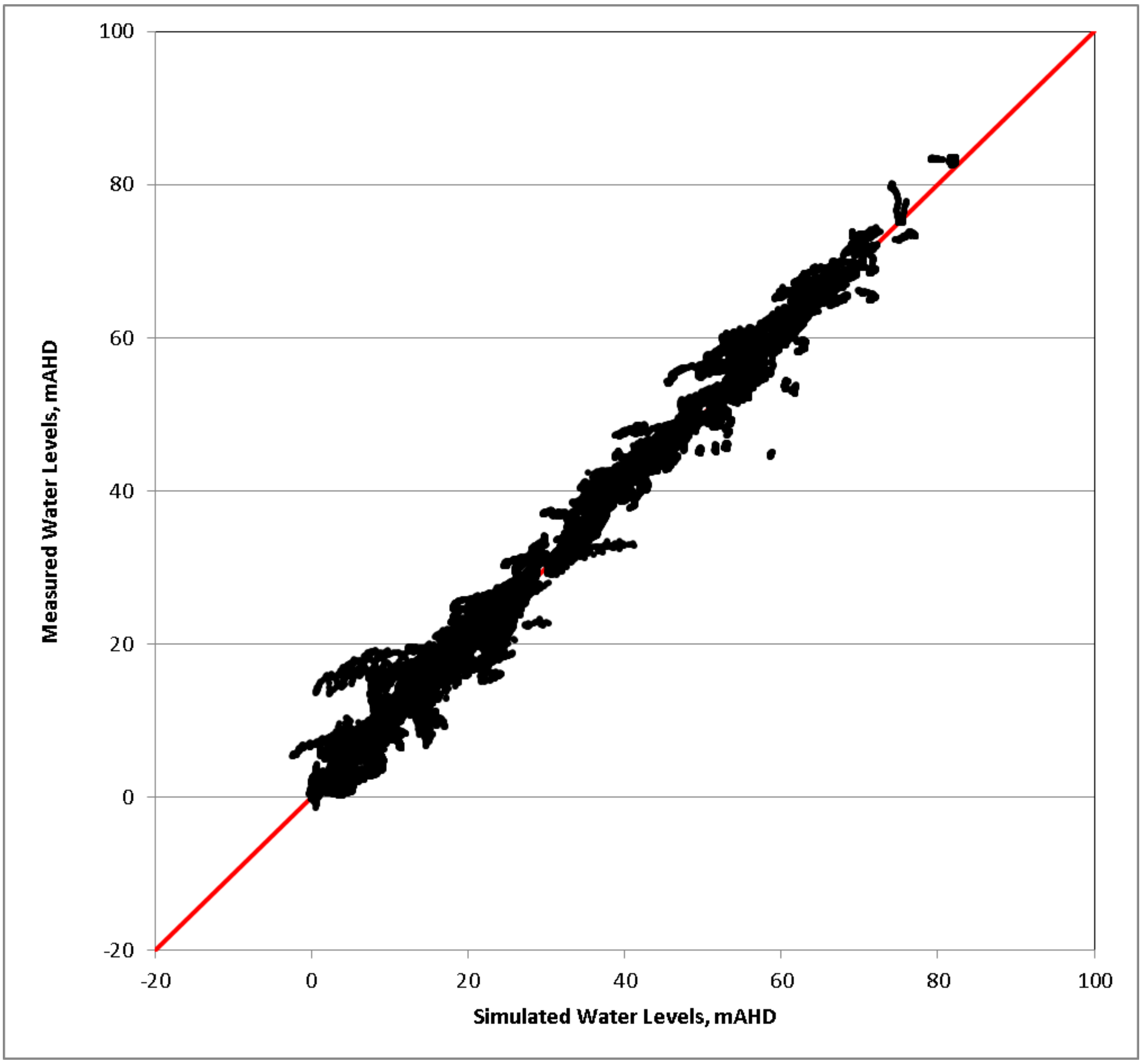

Figure 18: Calibration Error – Superficial Aquifer 3.5A

The present model error in the superficial aquifer is amenable to additional calibration, through increasing the number of zones, and thereby increasing spatial resolution of the distribution of hydraulic conductivity. The most sensitive area is the interface between the Bassendean Sand and the Tamala Limestone.

4.5.2 Mirrabooka Aquifer

Figure 20 shows a comparison of predicted and measured water levels for the calibration bores completed in the Mirrabooka aquifer. Appendix F shows the calibration hydrographs for all Mirrabooka monitor bores used in the calibration of PRAMS 3.5A. From Figure 20, the model predicted water levels are similar in quality to the superficial aquifer, but tend to be systematically high. The simulated piezometric levels in the Mirrabooka aquifer are not randomly distributed, but tend to be high for most bores, where the piezometric surface is below 50 mAHD. The relative absolute error in the calibration, over this period is 3.0%, suggesting the calibration is adequate but needs to be improved. Some of this error is ascribed to prevailing water levels in the superficial, as well as some error in matching the vertical gradient between the superficial and Mirrabooka and the Mirrabooka and Leederville aquifers, respectively.

The spatial distribution of error is not shown for the Mirrabooka aquifer, as most of the calibration bores are located in a relatively small area, on the extreme eastern edge of the model.

Some of the error in the Mirrabooka aquifer is due to the error in the superficial aquifer, in areas of the Guildford clay. The majority of the Mirrabooka calibration bores are in areas where the Mirrabooka aquifer is overlain by the Guildford clay. The modelling of the Guildford clay presently simplifies both the vertical and horizontal variation in aquifer parameters, resulting in water level errors in the superficial aquifer. This error propagates downwards into the Mirrabooka aquifer. Correcting the error in the superficial aquifer will significantly reduce the error in the Mirrabooka aquifer. This is seen on the hydrographs where the modelled Mirrabooka bores show a recharge response similar to climate that is not seen in measured data which suggests too much vertical leakage from the superficial aquifer.

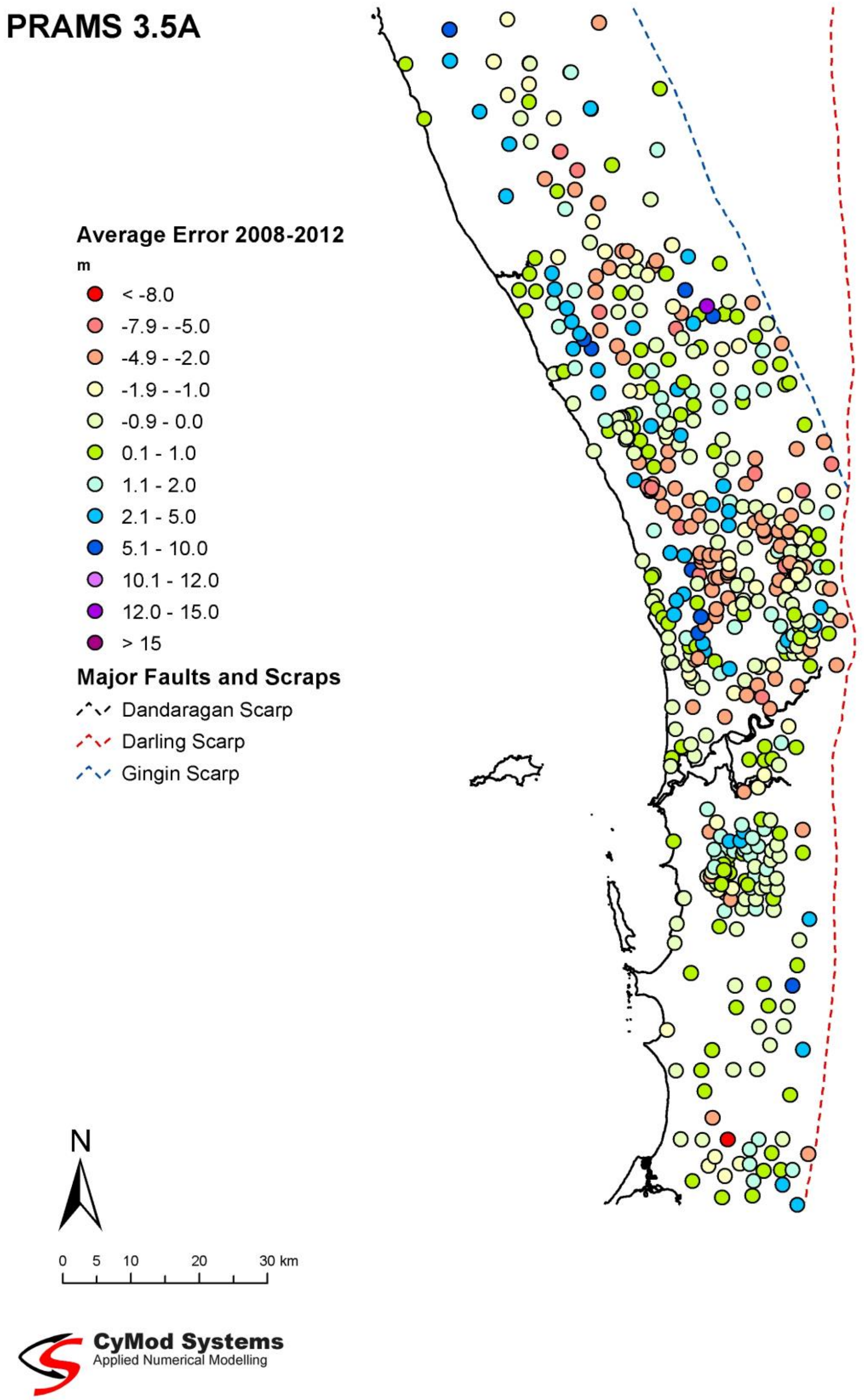

Figure 19: Error Distribution 2008-2013 – Superficial Aquifer 3.5A

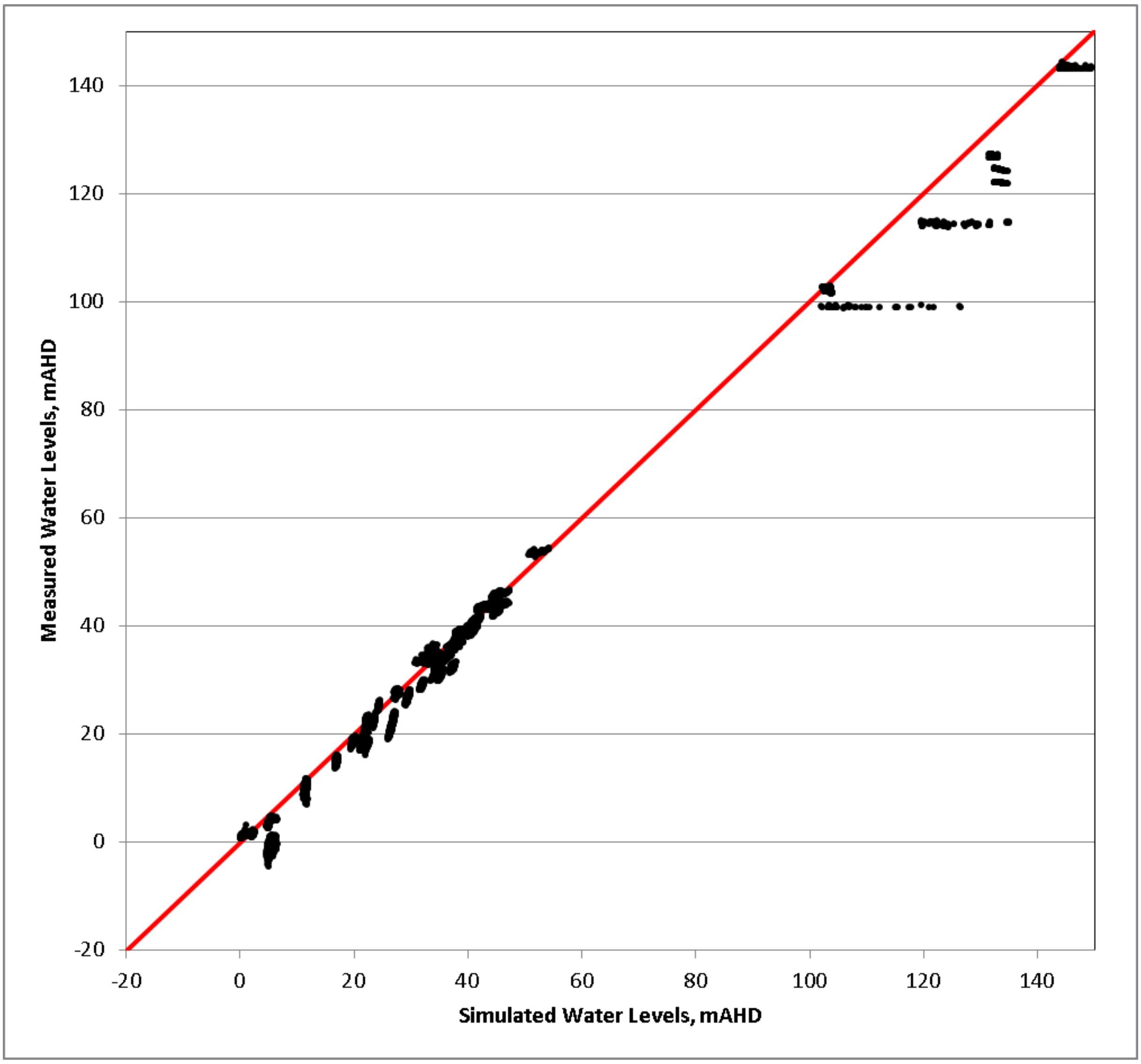

Figure 20: Calibration Error – Mirrabooka Aquifer

4.5.3 Leederville Aquifer

Figure 21 shows a comparison of predicted and measured water levels for the calibration bores completed in the Leederville aquifer. Appendix F shows the calibration hydrographs for all Leederville monitor bores used in the calibration of the PRAMS 3.5A model. From Figure 21, the model predicted water levels are not that well correlated to measured data. However, the relative absolute error in the Leederville calibration, over this period, is 3.9%, suggesting a reasonable calibration has been achieved, albeit with some systematic error. The modelled piezometric levels in the Leederville are not randomly distributed, but tend to be low for most bores, where the piezometric surface is between 0 and 20 mAHD. Since most of these bores are on the western side of the model and influenced by local abstraction, this suggests the influence of the hydraulic conductivity, faulting and the Kings Park Formation are important in these areas. The under prediction of water levels in these areas suggests there is more flow into the area than presently modelled.

For bores with water levels between 0 and 20 mAHD, modelled levels tend to be too low, suggesting that average hydraulic conductivity of the aquifers is too low, or that the influence of block faulting on flow into areas of abstraction is too large. The error in these areas was reduced by increasing the interaction of the Leederville with the Kings Park Formation, by explicitly modelling the sandy aquifers in this formation.

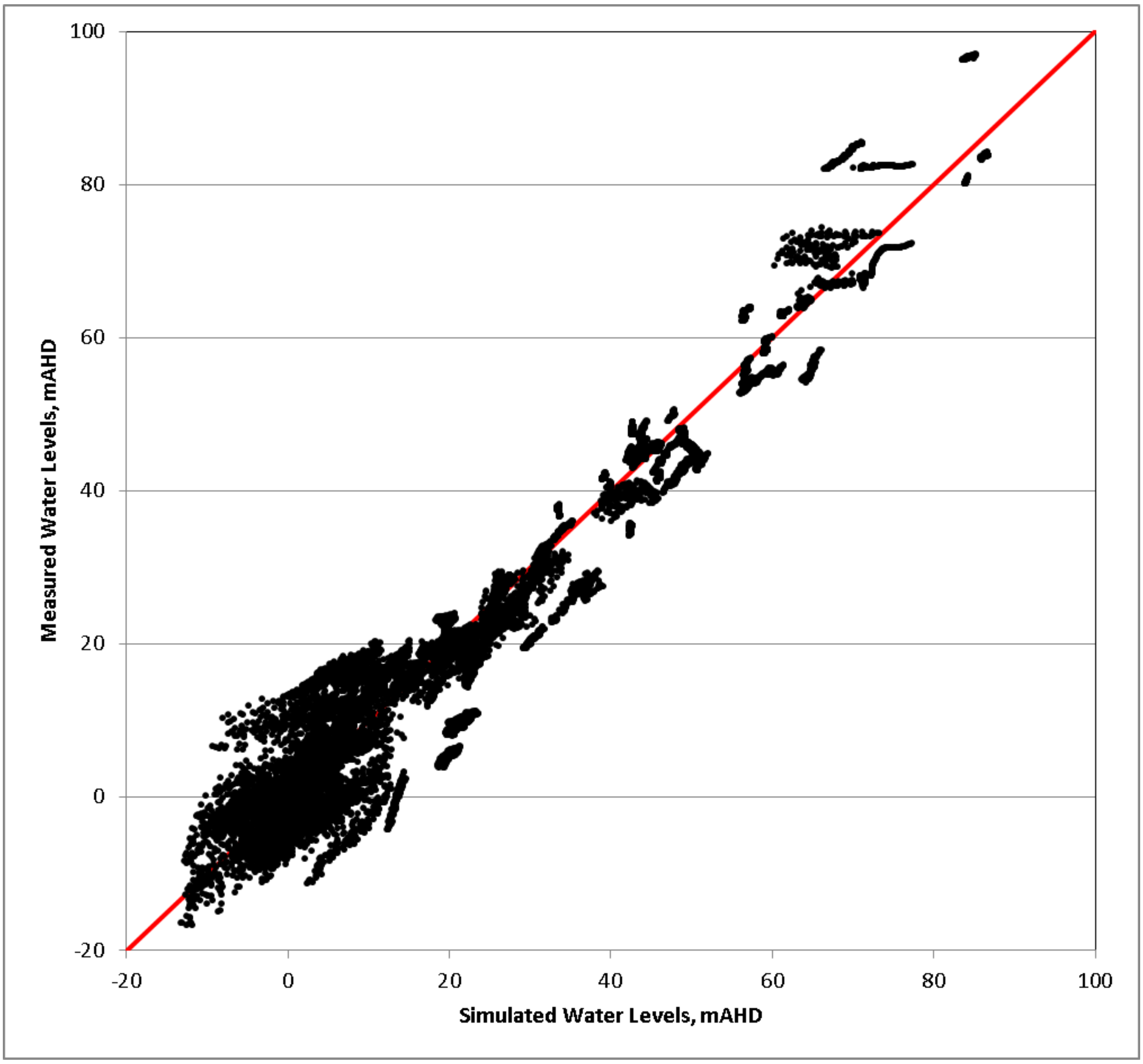

Figure 21: Calibration Error – Leederville Aquifer

Figure 22 shows the spatial distribution of the average calibration error at the calibration bores, for the Leederville aquifer in 2008.

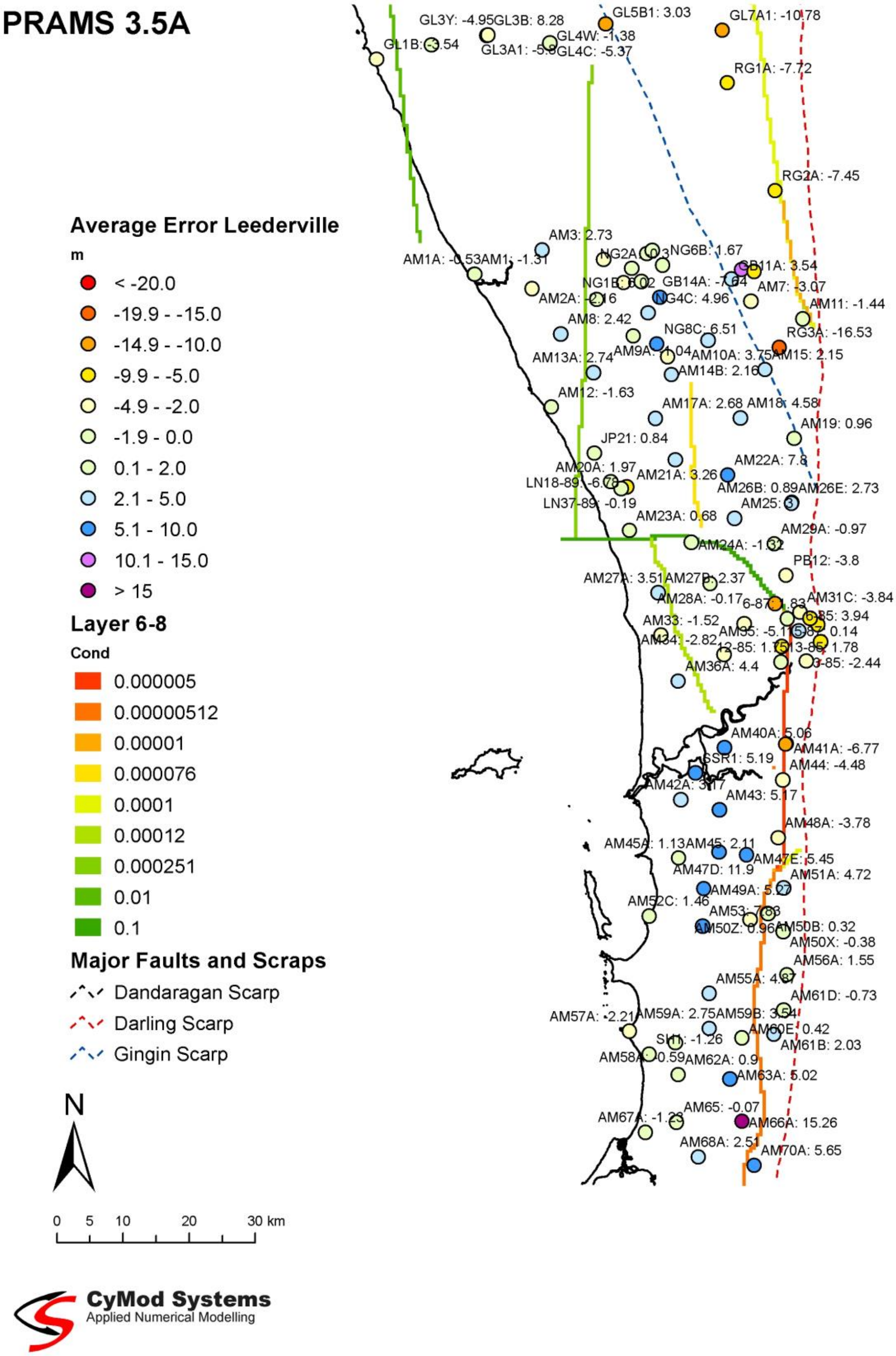

Figure 22: Average Error Distribution 2008-2013 – Leederville Aquifer

Some of the error in PRAMS 3.5 in the Leederville is similar to that found in PRAMS 3.0/3.4. For example:

- Calibration bores AM34, AM35 and AM36 all show lower simulated piezometric levels compared to measured levels. This error suggests that additional vertical leakage or horizontal flow is required to increase piezometric levels in the model. This area is close to the incised Kings Park Formation, which is now modelled as a source of vertical leakage from overlying aquifers. A review of the conceptual hydrogeology and calibrated aquifer parameters in this area should be undertaken to identify sources of groundwater that could increase piezometric levels in the vicinity of these bores; and

- Bore AM6A has an error of approximately 5 metres above the measured piezometric level, but unlike PRAMS 3.0, this error is due to error in the superficial water level which is 6 metres too high in the area. The Water Corporation drilled near this bore, and found a thin ~ 6 metres thick perched aquifer on top of the Guilford Clay, then intersected a thin dry sand bed in Guilford Clay, below a saturated sand.

The similarity in model error with previous models suggests deficiencies in the conceptual model and data, given the differences between the models.

The calibration error in the south is consistent with the average, but bore AM66A shows simulated heads more than 12 metres higher than measured values. Bore AM66A may be influenced by structures associated with the Serpentine Fault. Alternatively, AM60B and AM63A are too low, suggesting higher hydraulic conductivity or increased influence from areas to the east of the Serpentine Fault. A review of the conceptual hydrogeology in these areas should identify the basis for reducing error at these locations.

4.5.4 Yarragadee Aquifer

Figure 23 shows a comparison of predicted and measured water levels for the calibration bores completed in the Yarragadee aquifer. Appendix F shows the calibration hydrographs for all Yarragadee monitor bores used in the calibration of the PRAMS 3.5A model. From Figure 23, the model predicted water levels are reasonably correlated to measured data above 0 mAHD. The piezometric levels in the Yarragadee are randomly distributed. The width of the distribution is large, suggesting that abstraction and the effects of faulting may not be modelled 4accurately.

Figure 24 shows the spatial distribution of the average error between model prediction and measured water levels in 2008.

The error distribution shows widely scattered, punctuated by localised high/low spots typically associated with error at one bore, as in the case of AM23 and AM24 for example.

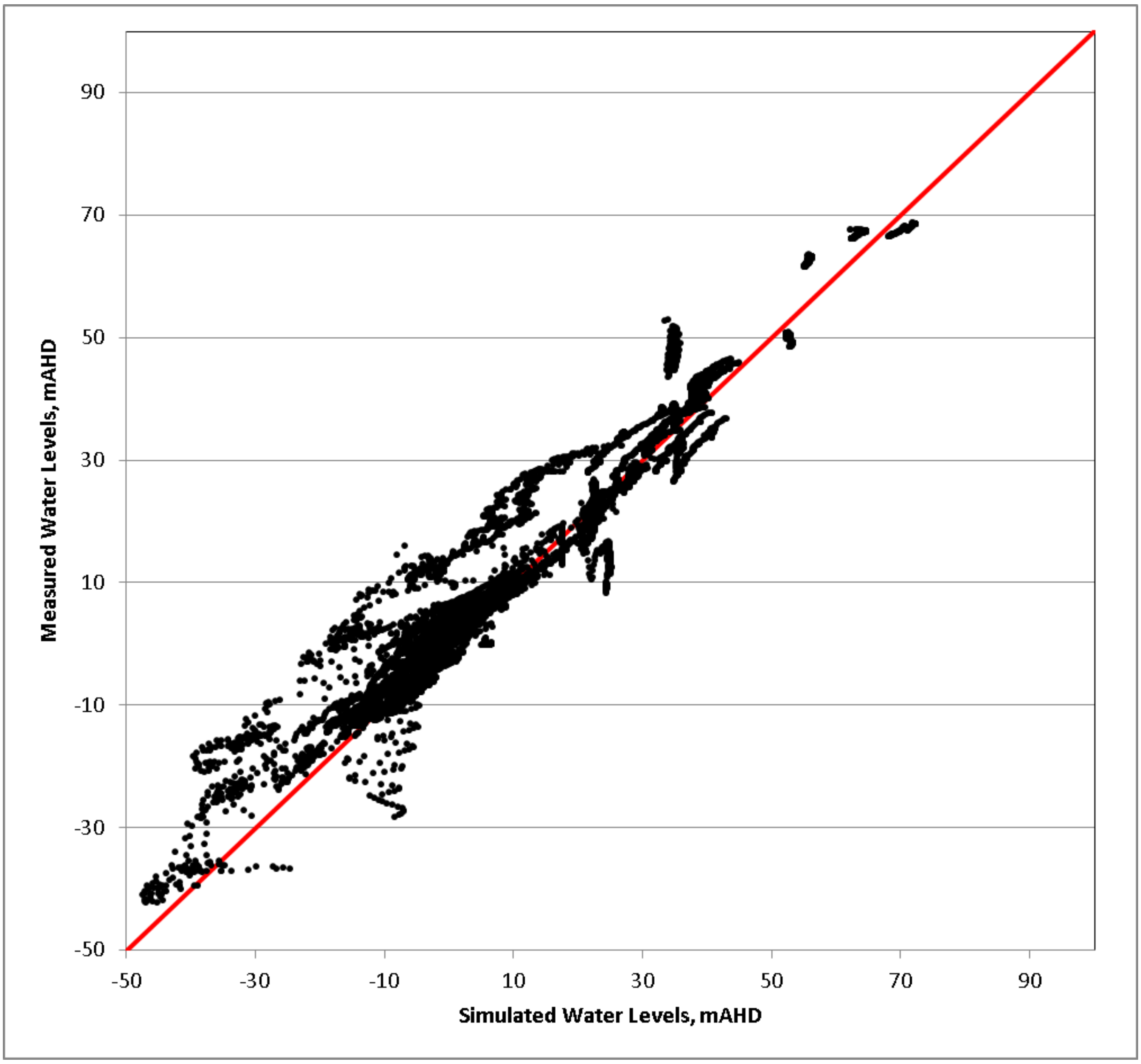

Figure 23: Calibration Residuals – Yarragadee

Bore AM23 has an error of approximately 10 to 14 metres, with the simulated piezometric level lower than measured. Similarly, AM24 had an error of -24 to 12 metres. The measured piezometric level at AM23/AM24 suggests the effects of block faulting, but that other effects are occurring as well. Sensitivity analysis of vertical and horizontal hydraulic conductivity and fault conductance showed that it was improbable that the piezometric level at AM23/AM24 can be simulated more accurately using aquifer parameter values consistent with accepted ranges for the Yarragadee aquifer. These bores are near faults and changing aquifer thickness and hence the error may be due to model limitations or hydrogeological conditions at depth.

Calibration of bores in areas of abstraction required upward leakage from Layer 13, inferring that water is being sourced from depth, rather than horizontally or vertically from downward leakage.

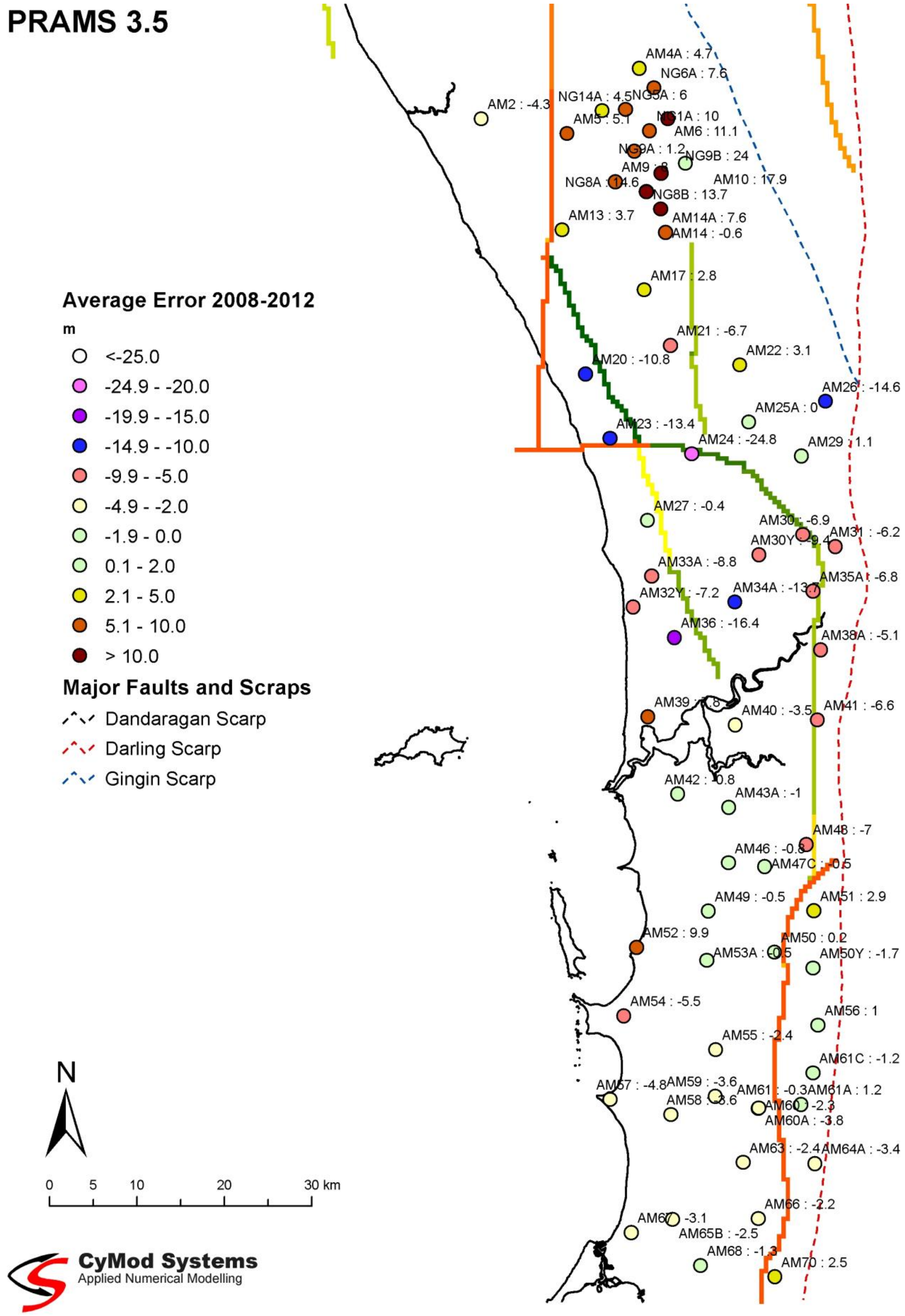

Figure 24: Average Error Distribution 2008-2013 – Yarragadee Aquifer

4.6 Model Verification

The verification of a numerical model is difficult and suffers from the same limitations as demonstrating that a groundwater model is unique. Verification of a model is best described as assessing whether the model has any predictive capability, by testing it against data that is independent from the calibration data. Based on the model guidelines Guiding Principle 5.6:

> *A formal verification process should only be attempted where a large quantity of calibration data is available and it is possible to set aside a number of key observations that could otherwise be used for calibration;*

there is sufficient data to verify PRAMS 3.5.

PRAMS 3.5A was verified using different temporal datasets. It has also been implicitly verified spatially in the superficial aquifer, in that not all bores that are presented in the calibration dataset were necessarily used in the calibration and consequently those bores represent an independent dataset. The use of temporal verification reflects the availability of more than 25 years of monthly and quarterly monitoring data in the four major aquifers on the swan coastal plain. While there are numerous bores in the superficial aquifer, a subset of which could have been used for spatial verification, the number of available bores in the confined aquifers is too limited spatially to allow for an effective spatial verification.

The temporal verification is from July 1990 to July 2000. This period is characterised by increasing public and private abstraction, significant landuse changes in terms of bush fires, urbanisation and variable rainfall. Consequently, the period provides significant variation in aquifer stresses from the calibration period. The period from 1980 to 1990, while viable in terms of monitoring data, is not well characterized in terms of licensed abstraction or landuse change. Hence, this period is deemed to have too much uncertainty with respect to input data to offer a viable verification dataset.

The verification is evaluated by qualitatively assessing selected hydrographs to compare simulated and measured response, and by summarising model versus measured water levels at selected bores, to determine model error statistics for the period. A summary of the error in the model during the verification period is shown in Table 4-2. Appendix H presents the verification hydrographs for each aquifer. In general, the error has not increased in the model during the verification period, but is consistent with the magnitude of the absolute average error during calibration. The increase in error ranges from 2-8% in the superficial and Yarragadee aquifers. The error in the Mirrabooka and Leederville aquifer has declined in the verification period compared to the calibration period.

A review of hydrographs show that while there is some offset error in most bores, water level trends and responses to stress are consistent with measured data. Specifically, the increase in error is not large in the superficial and Mirrabooka aquifers, with distribution in error similar to that during calibration. The largest increase in model error in the verification period is in the Leederville and superficial aquifers. These errors are related to an increase in error at bores in areas of abstraction, and the addition of a zone of 100 m/day in the superficial aquifer. In addition, the simulated heads in the Yarragadee are systematically low, suggesting poor initial conditions and errors in abstraction for areas south of the Swan River.

Water levels in the superficial aquifer at most bores show consistent trends and qualitatively good correlation with changes in aquifer stresses. This suggests that the impacts of aquifer stresses are reasonably predicted in the model and represents a significant improvement over PRAMS 3.0/3.4.

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	2.3	3.4	2.8	16.1	-28.7
Mirrabooka	1.7	1.8	3.7	6.8	-2.6
Leederville	4.6	5.6	3.5	23.8	-13.8
Yarragadee	3.3	4.6	4.7	9.3	-29.7

Table 4-2: Summary of Transient Verification Error

Figures 25 through 28 show the error distribution for each aquifer during the verification period. Figures 29 through 31 show the spatial distribution of error for the superficial, Leederville and Yarragadee aquifers.

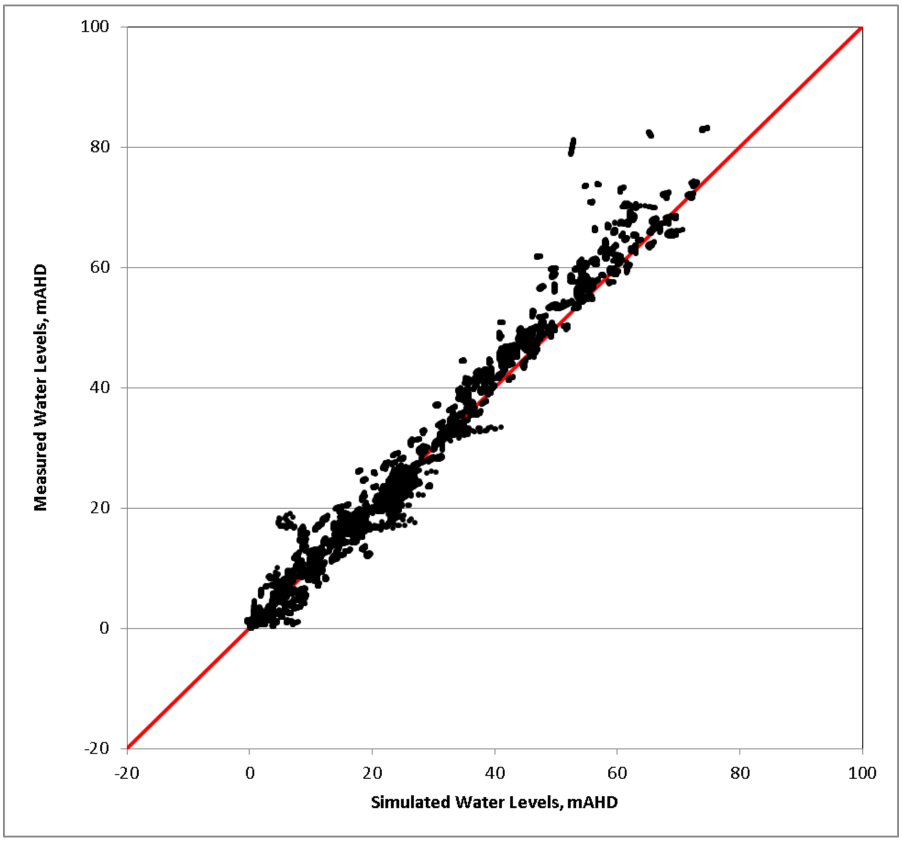

Figure 25: Verification Error – Superficial Aquifer

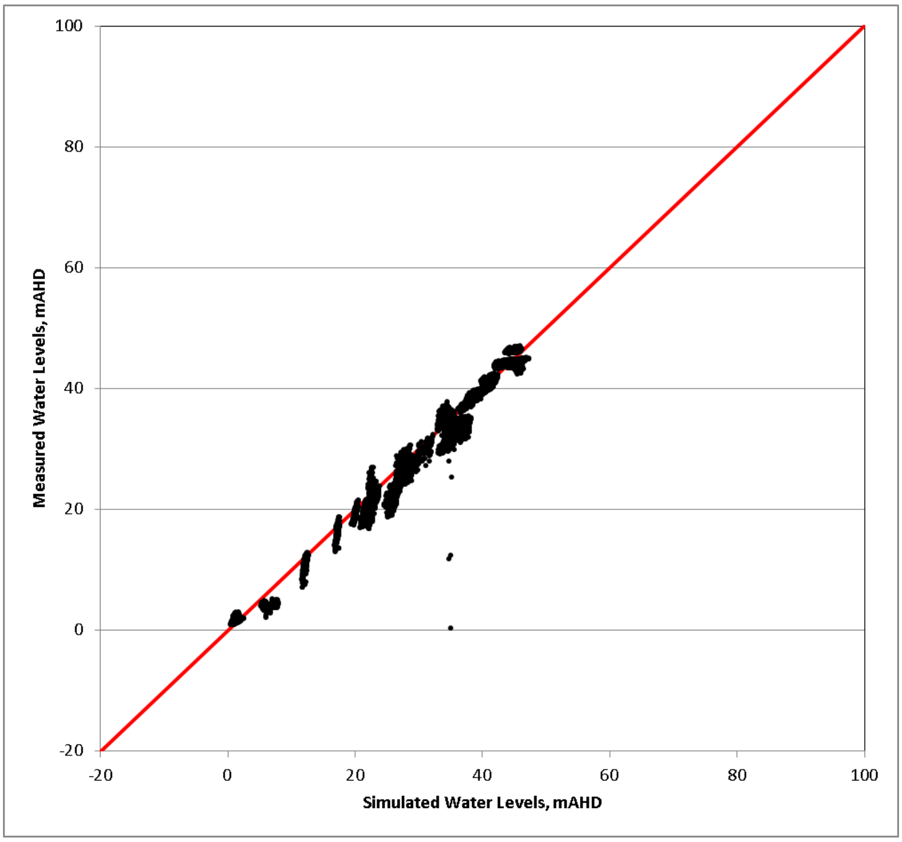

Figure 26: Verification Error – Mirrabooka

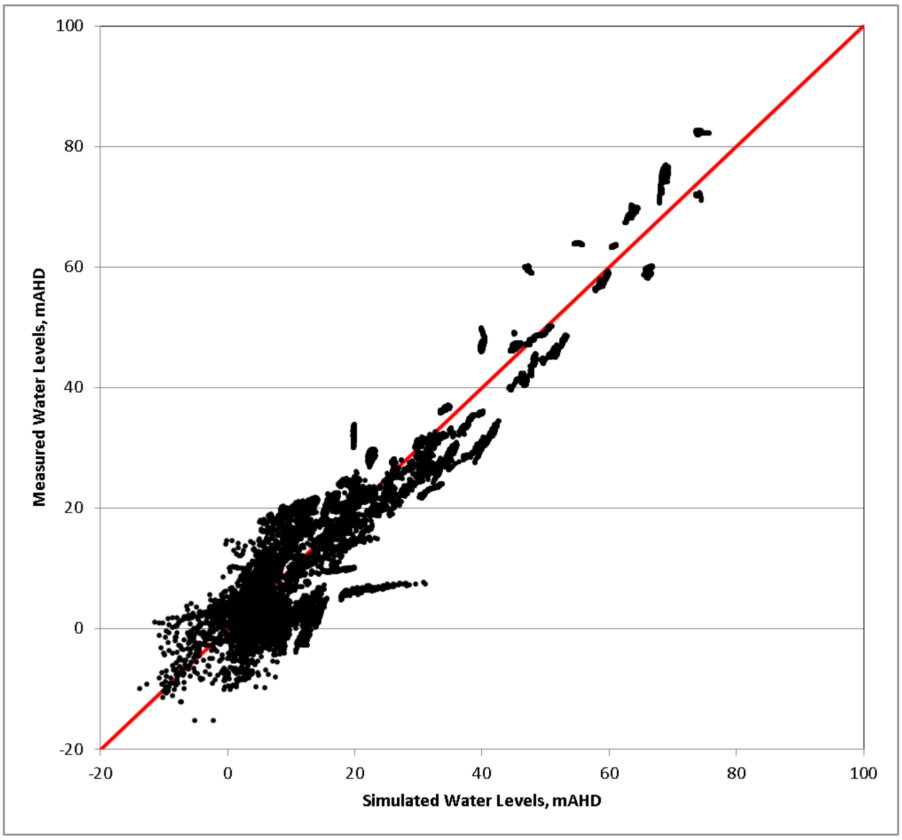

Figure 27: Verification Error – Leederville

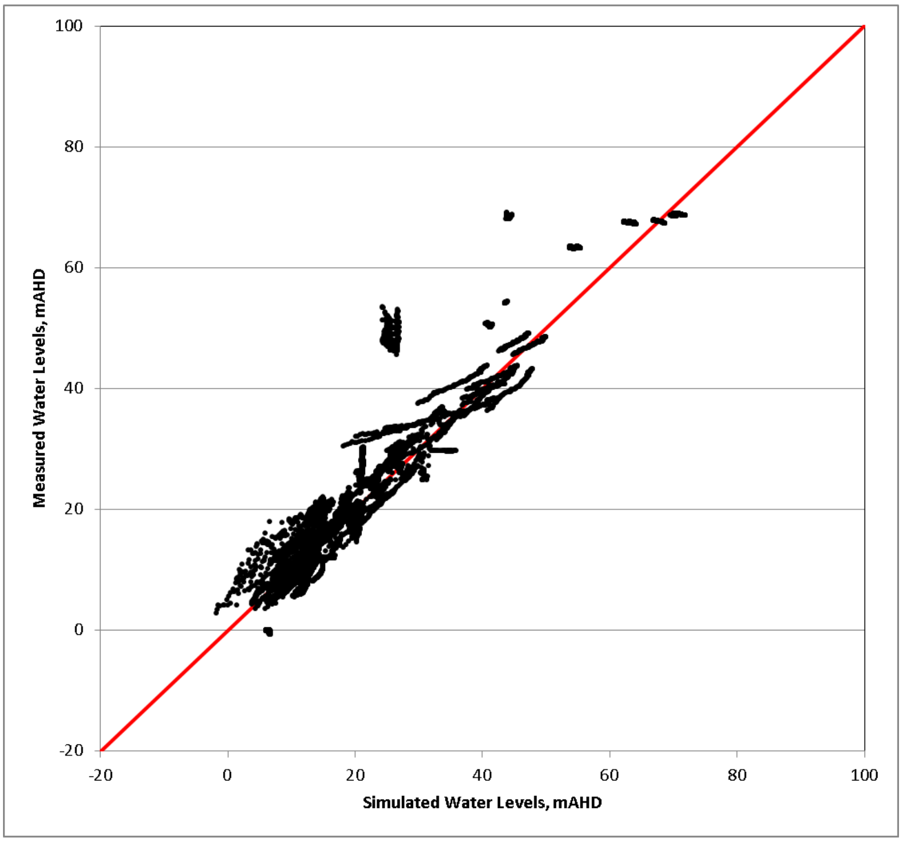

Figure 28: Verification Error - Yarragadee

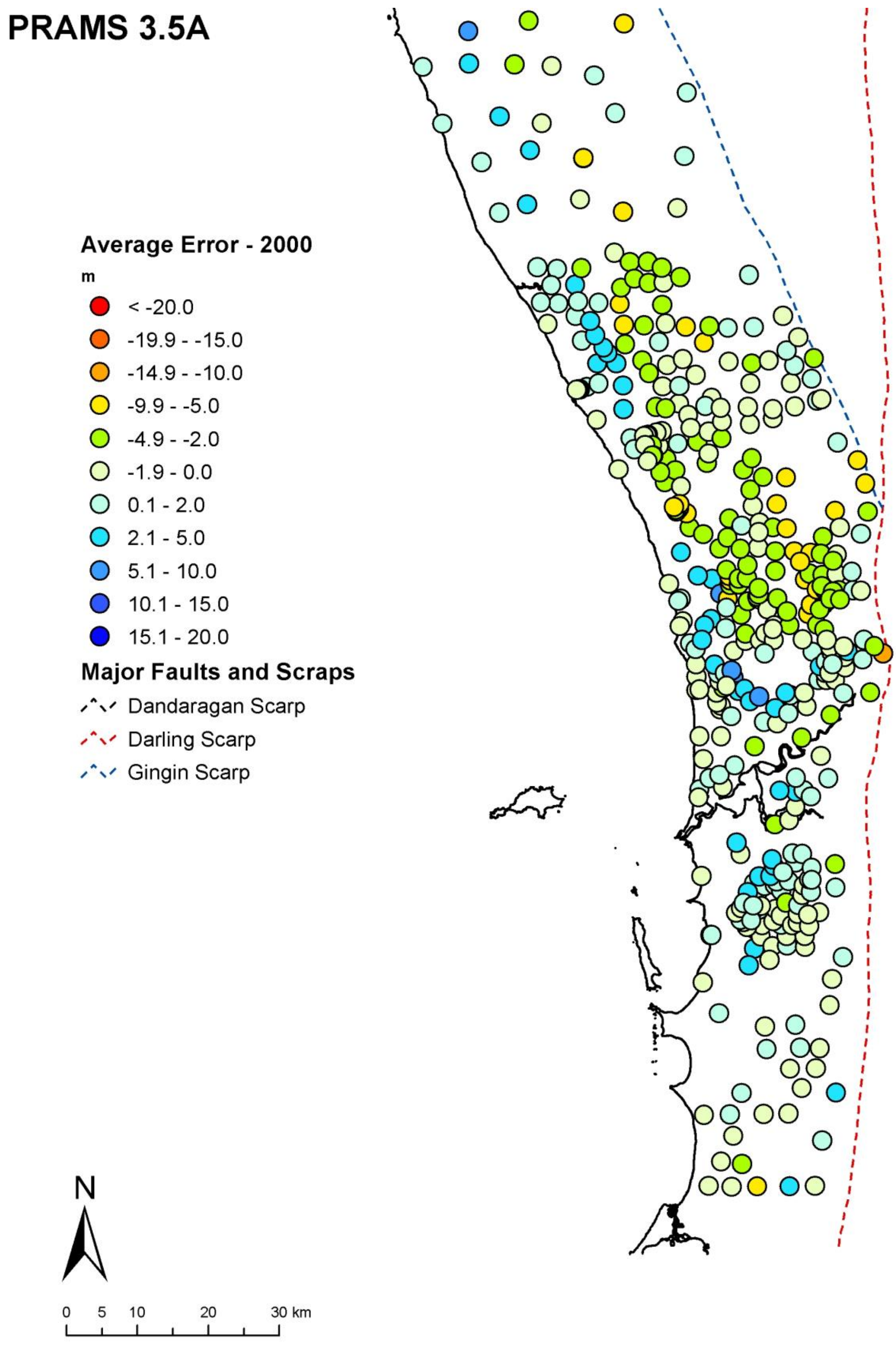

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Figure 29: Verification – Superficial Spatial Error 2000

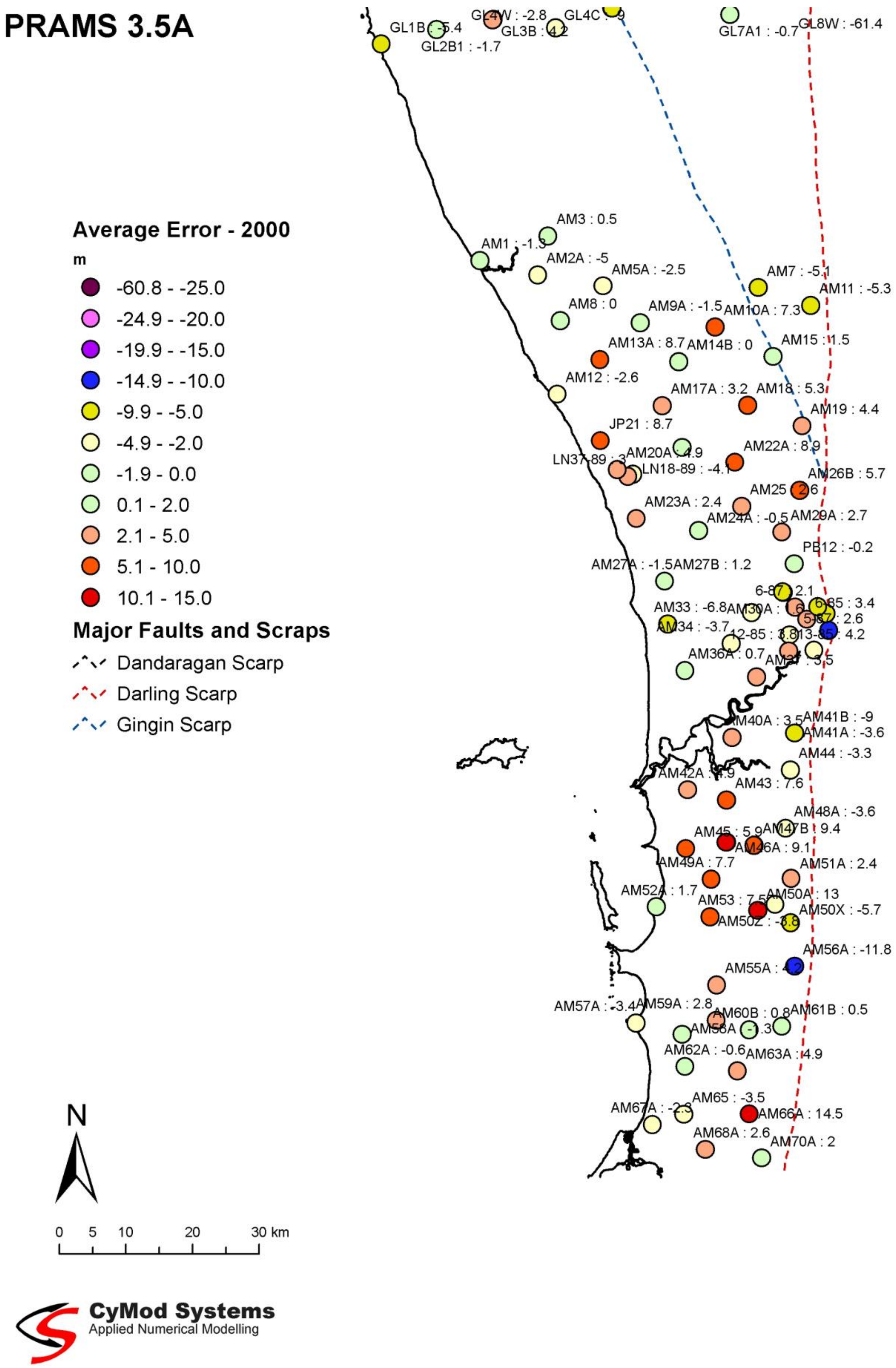

Figure 30: Verification – Leederville Spatial Error 2000

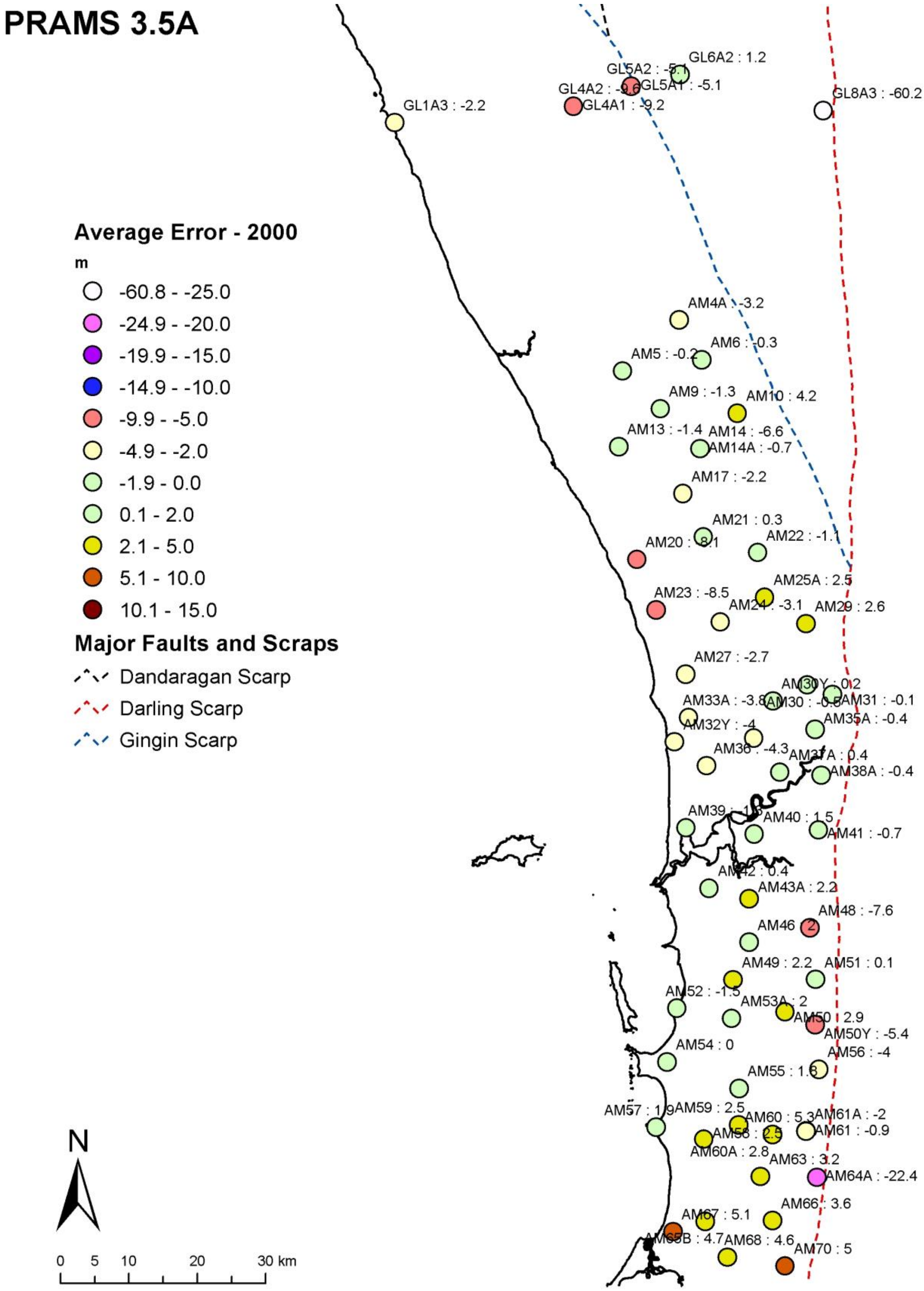

Figure 31: Verification – Yarragadee Spatial Error 2000

4.7 PRAMS 3.5B Calibration

Table 4-2 summarises the calibration error in the PRAMS 3.5B (unfaulted) model. The error in the model is consistently higher than in PRAMS 3.5A, but is not different enough to suggest one model is better than the other. However, the calibration in the Yarragadee is quantitatively poorer in PRAMS 3.5 B than in PRAMS 3.5 A, primarily due to the lack of block faulting. The differences reflect to a great extent the amount of effort spent on each model rather than a conceptual deficiency.

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	1.9	2.7	2.1	16.5	-8.3
Mirrabooka	3.6	6.1	4.6	30.4	-39
Leederville	3.7	5.1	3.9	14.2	-22.1
Yarragadee	6.3	9.5	8.6	28	-42.

Table 4-3: PRAMS 3.5B Summary of Transient Calibration Error

4.7.1 Superficial Aquifer

Figure 32 shows a comparison of predicted and measured water levels for the calibration bores completed in the superficial aquifer. From Figure 32, the model predicted water levels in general show a random distribution around the unity slope line, with little or no systematic deviation. However, the width of the distribution suggests that some significant differences between measured and predicted water levels do exist.

The relative absolute error in the calibration, over this period in the superficial 2.1%, suggesting a reasonable calibration has been achieved. The error is similar to PRAMS 3.5A, as the parameter distributions in the superficial aquifer are very similar.

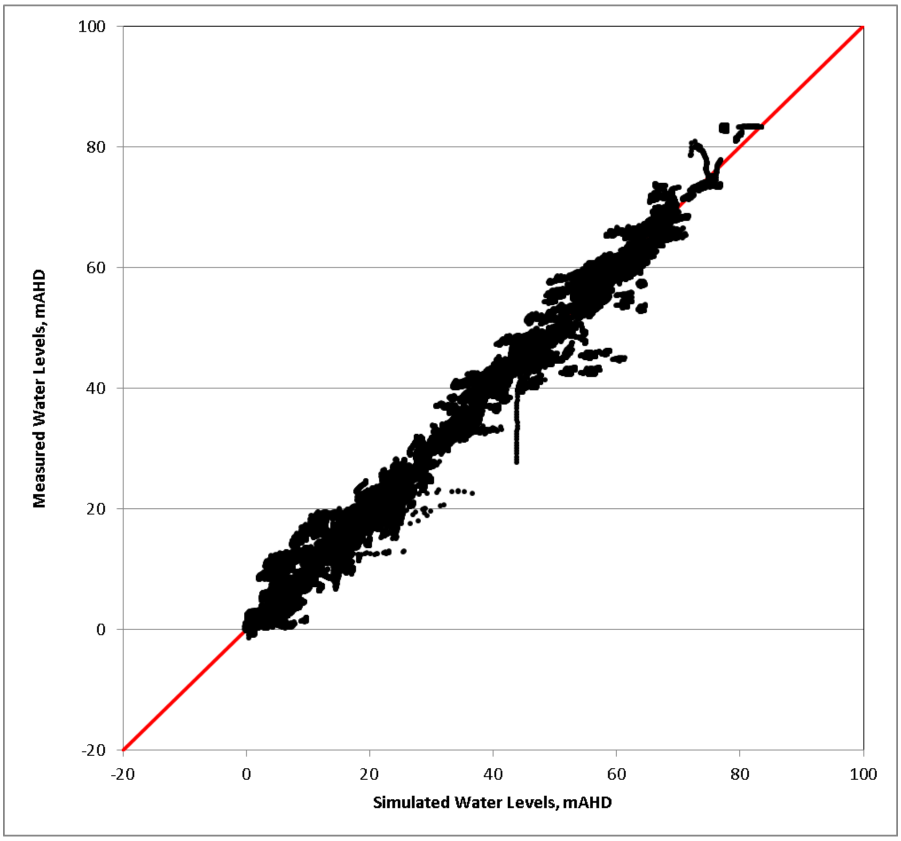

Figure 32: Calibration Error – Superficial Aquifer PRAMS 3.5B

4.7.2 Leederville Aquifer

Figure 33 shows a comparison of predicted and measured water levels for the calibration bores completed in the Leederville aquifer. From Figure 33, the model predicted water levels are not that well correlated to measured data. However, the relative absolute error in the Leederville aquifer calibration, over this period, is 3.9%, suggesting a reasonable calibration has been achieved. Note that the systemic error is less when compared to PRAMS 3.5A. The modelled piezometric levels in the Leederville aquifer are randomly distributed.

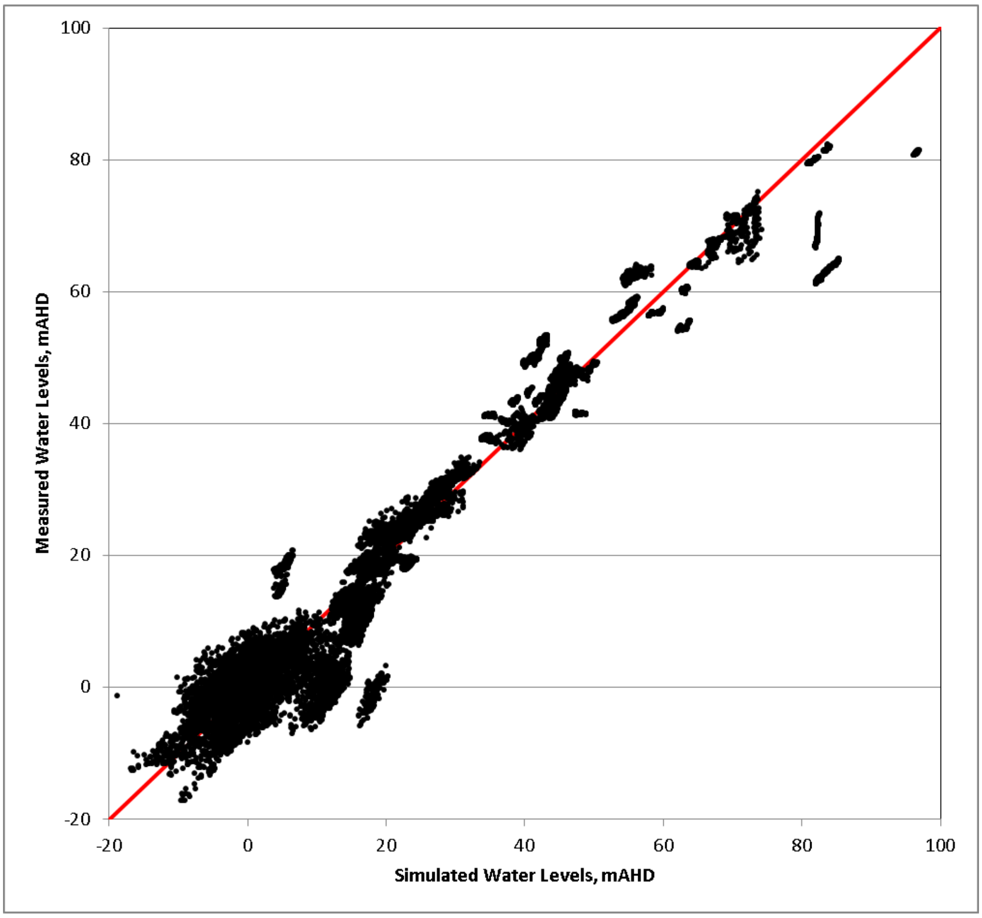

Figure 33: Calibration Error – Leederville Aquifer PRAMS 3.5B

4.7.3 Yarragadee Aquifer

Figure 24 shows a comparison of predicted and measured water levels for the calibration bores completed in the Yarragadee aquifer. From Figure 34, the model predicted water levels are reasonably correlated to measured data above 0 mAHD. The piezometric levels in the Yarragadee are not randomly distributed, but tend to be low for most bores, where the piezometric surface is between -10 and 20 mAHD. The width of the distribution is large, suggesting that abstraction and the effects of faulting may not be modelled accurately.

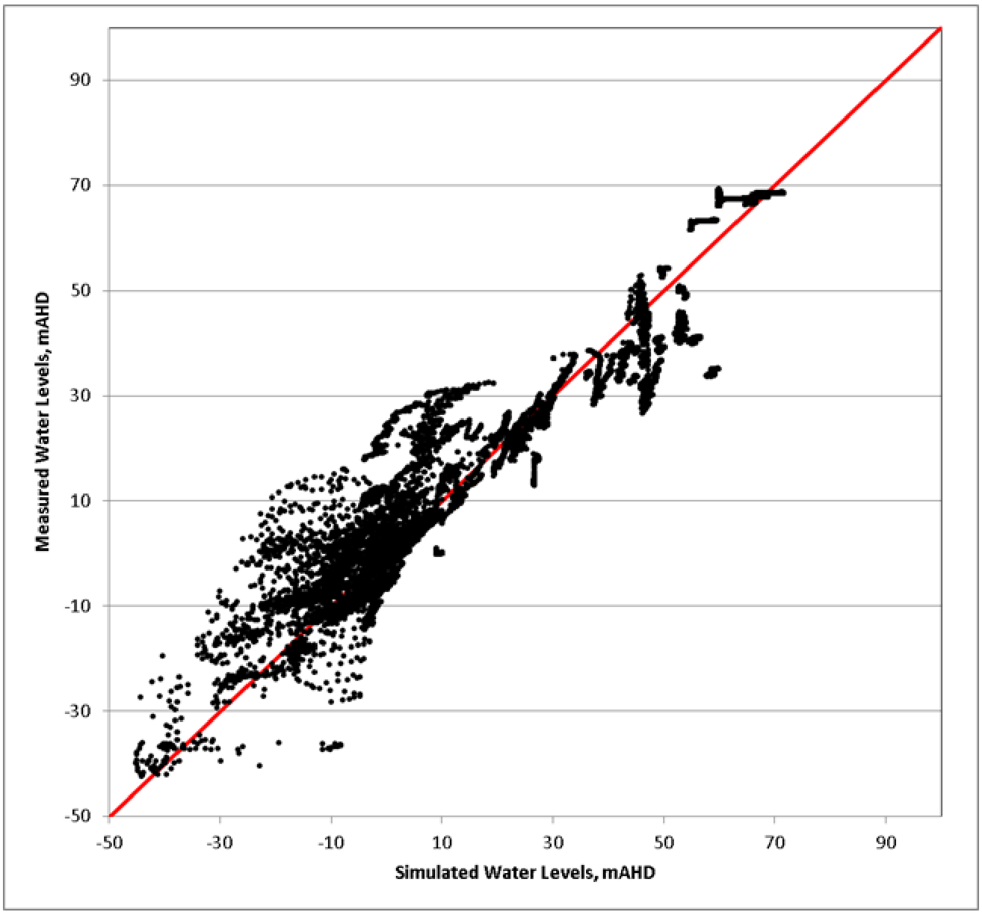

Figure 34: Calibration Error – Yarragadee Aquifer PRAMS 3.5B

5 MODEL LIMITATIONS

The calibration of a groundwater model does not ensure that it is an accurate representation of the system. The appropriateness and correctness of the conceptual hydrogeological model is typically more important than achieving a small error between simulated and observed heads and flows. Consequently, the application of the model should be constrained by the limitations inherent in the underlying conceptual model.

With respect to PRAMS 3.5A, the modelling of the conceptual model of the superficial aquifer has been significantly improved as a result of better estimates of private allocation, use of WAVES for all landuses and improved fidelity of model layering to geology. PRAMS 3.5A is a regional groundwater model having a spatial resolution of 500 metres and vertical resolution of 10 metres. The temporal resolution is 1 month. Based on these structural limitations and the quality of the calibration the model is considered suitable for:

- Regional and subregional resource estimation;
- Evaluation of landuse and climate changes on net recharge using the VFM; and
- The relative assessment of regional and subregional impacts due to changes in abstraction, and recharge for the artesian and superficial aquifers.

The model's structural limitations suggest that the model is not the preferred platform for assessing wetlands, lakes or other features in the superficial aquifer that are similar in scale to the horizontal and vertical resolution of the model. However, PRAMS 3.5A can act as a basis for developing higher resolution sub regional and local models that may be more appropriate for these types of evaluations.

6 SENSITIVITY ANALYSIS

The objective of sensitivity analysis is to quantifying the sensitivity of calibration parameters to observation data. By varying aquifer parameters and assessing the effect on simulated heads as compared to measured heads, a measure of the relative importance or uncertainty in model inputs can be made. A sensitivity analysis is undertaken by systematically changing calibrated aquifer parameters and determining the effect these changes have on observed data (i.e. bores where the model has been calibrated to measured heads). The change in the simulated heads due to these variations is an estimate of the sensitivity of the calibrated model to that parameter.

MODFLOW 2000 was used to generate dimensionless scaled sensitivities, which estimate the impact of calibration parameters on observation heads (measured heads in the aquifer, at monitor bores) that were used in calibrating aquifer parameters. These scaled sensitivities are dimensionless quantities that can be used to compare the importance of different parameters in calibrating the model to an observation. The sensitivity of parameters was based on composite scaled sensitivities as determined by the calibration bores used in calibrating the model. The composite sensitivities are an average of the sensitivity responses at all the monitor bores used in calibrating the aquifer in the model.

The model sensitivities were obtained using the following procedure:

- The net recharge as calculated by the coupled PRAMS 3.5 model was extracted from the cell-by-cell water balance for the period from 2000 to 2012;
- This net recharge was then input into a MODFLOW 2000 version of the calibrated model by assigning the net recharge, as a flux, for each stress period in the sensitivity model, as a specified recharge;
-
- A set of sensitivity parameters was defined for aquifer hydraulic conductivity, aquitard vertical hydraulic conductivity and specific storage for the superficial and Artesian aquifers, by layer;
- The model was run 4 times, using the calibration bores for each aquifer, so as to determine the sensitivity of each of the observations in each aquifer to the changes in the sensitivity parameters; and
- The composite sensitivities were extracted and analysed for each aquifer, to determine the relative sensitivity of measure heads in each aquifer to variations in the defined parameters.

Note that the composite sensitivities (i.e. the sum of the response at all the calibration bores) are based on varying all aquifer parameters in each layer. In this case, the composite sensitivities provide information on aquifer sensitivity, but not on specific zonations within a layer or individual monitor bore sensitivity. Table 6-1 summarises the sensitivity parameters used in the sensitivity analysis.

Note that the sensitivities (i.e. the sum of the response at all the calibration bores) are based on varying all aquifers parameters in each layer. Hence in this case the composite sensitivities provide information on aquifer sensitivity, but not on specific zonations within a layer or individual monitor bore sensitivity. Table 5-1 summarizes the sensitivity parameters used in the sensitivity analysis.

Parameter	Layers
Horizontal hydraulic conductivity, k_h	1-3, 6-8,12-13
Vertical hydraulic conductivity, k_v	5, 6-8,9,12-13
Specific Yield, S_y	
Specific Storage coefficient, S_s	5-8 and 12-13
Horizontal Flow Barrier conductance(m^2/day), H_c	6-8, 12-13

Table 6-1: Layer Sensitivity Parameters

The results of the sensitivity analysis are presented in Tables 6.2 through 6-4. These tables summarize the scaled sensitivities of k_h, k_v, S_s, S_y and H_c, in the superficial, Leederville and Yarragadee aquifers.

The present sensitivity analysis does not account for spatial variation in the aquifer parameters. Sensitivities can be calculated on a zonation basis, to identify which zones are the most sensitive with respect to changes at calibration bores. This analysis has not been done, but was recommended as part of a comprehensive sensitivity analysis of the PRAMS 3.0 model.

6.1 VFM Sensitivity Analysis

The sensitivity of the VFM was determined separately using an uncoupled VFM model. The results of that sensitivity analysis are described in Silberstein et al, 2003. In summary the sensitivity analysis found that in the long term, mean annual groundwater recharge is strongly correlated the mean annual rainfall, despite individual years showing significant discrepancies. Where the depth to water table is shallow, annual recharge is correlated well with annual rainfall. However, where the depth to water table is large, the correlation between the annual rainfall and annual recharge is very poor due to the delay in the recharge response. Analysis indicates that estimates of groundwater recharge are very sensitive to light extinction coefficient, leaf area index (LAI), the maximum rooting depth and the root distribution of the vegetation. Recharge is moderately sensitive to vegetation parameters of maximum carbon assimilation rate, slope of the conductance and rainfall interception and the soil holding water capacity and hydraulic conductivity. However, there are strong correlations between the root distribution and soil hydraulic characteristics that influence recharge quantity and timing (Silberstein, 2003).

6.2 Sensitivity Results

The results of the sensitivity analysis are summarized in Table 6-2, and are consistent with the conceptual model. The most important parameters for each aquifer are highlighted in green, with moderately important parameters highlighted in yellow.

The sensitivity analysis indicates that horizontal and vertical hydraulic conductivity is important for calibrating heads in layers 1, 2, 5-8 and 11-12. The results indicate that horizontal conductivity is the most important compared to vertical hydraulic conductivity. This is consistent given the amount of pumping, recharge and leakage that occurs in this aquifer. The superficial aquifer is the only aquifer that has a significant sensitivity to specific yield, which is the most sensitive parameter for the superficial aquifer.

In the Leederville, heads are more strongly influenced by the properties of the Wanneroo formation, and the vertical hydraulic conductivity of the Kardinya Shale and Osborne formations. This indicates that vertical processes are relatively important in the Leederville aquifer, and suggests that additional quantification and spatial mapping of vertical leakage in layers 5 through 8 of the model is required to improve the calibration. It also suggests that given the lack of direct measurement of vertical leakage or vertical aquifer properties in the Leederville and overlying aquitards, the model is sensitive to uncertainty in the estimates of vertical hydraulic conductivity in areas that are semi-confined.

Heads in the Yarragadee are more strongly influenced by horizontal hydraulic conductivity and specific storage. Also important is the vertical flow in the Leederville, which is related to the vertical movement of water in areas where the Yarragadee aquifer is unconfined. These small areas are more important than the vertical hydraulic conductivity of the overlying aquitards. The influence of the confining formations on Yarragadee heads is less significant than for the Leederville aquifer.

The Yarragadee is the only aquifer that has a significant sensitivity to specific storage. This reflects the magnitude of the vertical leakage relative the large storage associated with the Yarragadee aquifer.

The Yarragadee is more sensitive to conductance of the faults than the Leederville; reflecting the greater number of faults and the reduced influence of vertical leakage, compared to the Leederville.

Table 6-3 shows the 30 most important bores, in terms of the influence their measured heads have on calibrated aquifer parameters. Consequently, uncertainty in these measurements, for example due to measurement error or bore construction details will introduce more uncertainty into the model than other bores showing less sensitivity.

Superficial		Leederville		Yarragadee	
Parameter	Scaled Sensitivity	Parameter	Scaled Sensitivity	Parameter	Scaled Sensitivity
Sy_1	0.803	kh_7	3.265	kh_13	2.853
kh_3	0.499	kv_7	2.543	kh_12	2.303
kh_2	0.479	kv_5	1.514	kv_12	2.262
kh_4	0.419	kv_6	1.091	Ss_12	2.177
kh_1	0.360	kh_6	0.702	Ss_13	1.981
kv_4	0.181	kh_8	0.462	kv_7	1.485
kh_7	0.157	Ss_7	0.394	HFB_12-13	1.124
kv_5	0.127	HFB_6-8	0.349	kh_10	0.779
kv_7	0.094	kh_3	0.249	kv_11	0.601
kv_6	0.051	kv_8	0.247	kh_7	0.586
kv_12	0.038	kh_1	0.234	kv_5	0.474
kv_2	0.036	Ss_8	0.225	kv_8	0.455
kh_6	0.034	kh_2	0.217	kv_6	0.333
Sy_2	0.029	Ss_12	0.179	kv_10	0.311
kv_3	0.029	kh_13	0.163	kh_1	0.275
kv_8	0.019	Ss_13	0.162	kh_3	0.207
kh_13	0.019	Ss_6	0.143	kh_8	0.178
kh_12	0.018	HFB_12-13	0.142	kh_2	0.175
kh_8	0.017	kh_4	0.138	kv_9	0.124
kh_10	0.009	kv_4	0.129	kh_6	0.110
kv_10	0.009	kv_11	0.109	HFB_6-8	0.073
Sy_4	0.007	kh_12	0.095	kh_11	0.064
kh_5	0.006	kh_10	0.092	kh_4	0.050
kv_11	0.004	kv_12	0.090	Ss_7	0.045
kh_11	0.002	kv_10	0.057	kv_4	0.037
kv_9	0.001	Ss_5	0.024	kh_5	0.030
kh_9	0.001	kh_5	0.023	kh_9	0.027
		kv_9	0.021	Ss_8	0.027
		kv_3	0.020	kv_3	0.014
		kh_9	0.010	Ss_6	0.011
		kh_11	0.009	Ss_5	0.003
		kv_2	0.007	kv_2	0.003
		Ss_4	0.002	Ss_4	0.002

Parameter_layer (eg kv_4 is sensitivity of heads to changes in kv in layer four

Table 6-2: Scaled Composite Sensitivities by Layer

Superficial		Leederville		Yarragadee	
Monitor Bore	Scaled Sensitivity	Monitor Bore	Scaled Sensitivity	Monitor Bore	Scaled Sensitivity
GB21	0.264	AM34	0.655	AM36	1.01283
GB23	0.253	AM30Z	0.648	AM32Y	0.926364
GB20	0.247	AM24A	0.638	AM27	0.897635
13B	0.185	AM11	0.579	AM24	0.88617
13A	0.184	AM30B	0.577	AM34A	0.844648
GG6	0.178	AM36A	0.572	NG9B	0.799729
GNM1	0.177	AM35	0.538	AM30Y	0.781448
L10C	0.177	AM30A	0.513	NG3A	0.770213
L30C	0.175	AM37	0.496	NG3B	0.770085
L110C	0.175	AM27A	0.496	AM21	0.762329
NR12B	0.174	AM25	0.492	NG10A	0.72961
WM7	0.174	AM33	0.487	AM33A	0.72853
GB16	0.174	PB12	0.466	NG8A	0.713895
T650	0.174	AM27B	0.455	NG8B	0.713866
NR5D	0.173	AM22A	0.454	AM25A	0.708828
GC13	0.171	AM29A	0.453	AM30	0.707614
YY7	0.169	AM18	0.450	AM35A	0.702451
GNM31	0.169	AM23A	0.424	NG1A	0.694778
GB22	0.168	AM26B	0.414	AM26	0.694653
WM42	0.168	09-85	0.414	AM29	0.680414
PB2	0.163	GL8W	0.411	NG9A	0.675673
PM13	0.159	AM21A	0.411	AM31	0.667604
GC12	0.159	06-87	0.398	NG4B	0.665526
NR1B	0.158	GL1B	0.387	NG4A	0.66549
GG1	0.158	12-85	0.386	AM6	0.664262
GNM3	0.157	13-85	0.386	NG6A	0.662983
PM24	0.156	AM15	0.373	AM10	0.662826
GNM2	0.155	AM19	0.319	NG5A	0.624277
PB3	0.154	AM1	0.315	AM14A	0.618269
GNM16	0.153	AM14B	0.310	AM23	0.598092
L120C	0.150	AM17A	0.310	AM38A	0.597071

Table 6-3: Sensitivity of Layer Parameters to Measured Heads

7 WATER BALANCE

An average annual water balance for the PRAMS 3.5 model was calculated for the period from July 2010 to July 2013. The water balance was calculated using the cell-by-cell flow file as output by MODFLOW. The flow rates of source and flux components were integrated over the period to obtain cumulative volumes. This method of constructing the water balance from model cell-by-cell flow rate data is approximate, as it is based on the integration of rates rather than volumes. Comparison of these integrated flow components over the entire model run with MODFLOW cumulative totals, as report at the end of each stress period show that the error in an integrated water balance is generally less than 2%, if data is generated for each stress period.

Water balances are presented based on groundwater sub areas, as well as by land use zones. These water balances provide a basis on which to compare the PRAMS 3.5 model with independent water balance assessments.

7.1 Land use Area

The average annual water balance for the superficial aquifer was calculated for the land use distribution as determined for 2010. The water balance for the superficial aquifer, as based on land use, effectively sums up the net recharge for each model cell and aggregates it into totals based on the 14 different types of land use.

A water balance based on land use provides an indication as to how much recharge the VFM is calculating on average for each of the land use classifications. This calculated net recharge has been compared to estimates made with an uncoupled version of the VFM, and with experimental estimates to ensure that the VFM is calculating realistic estimates of recharge. Table 7-1 shows the estimated recharge by land use from 2008 to 2010. Net recharge for each land use is subdivided by area into the eight climatic zones used in the PRAMS 3.5 model. The weighted average of the total rainfall for each land use in each climatic zone is summed to determine the actual volume of water that fell on the land use area. The net recharge is the ratio of total model recharge to the total rainfall falling on a land use classification. From Table 7-1, net recharge varies from a maximum of 50% for commercial and industrial areas, to a negative recharge of 18% for lakes and wetlands. For areas of vegetation, high-density Banksia has the lowest net recharge of about 0%. No recharge for land use code 4 is calculated, as it was not used in the PRAMS 3.5 model.

Land use	Total Rainfall (GL)	VFM In (GL)	VFM Out (GL)	Net Recharge (GL)	Recharge
1 – High Density Banksia	347	38.5	38.6	-0.1	0%
2- Low Density Banksia	6546	948.3	113.8	834.5	13%
3- Pasture	15181	3328.2	475.5	2852.7	19%
5- Park	50	16.8	1.3	15.4	31%
6 – High Density Pines	19	0.6	0.2	0.5	3%
7- Medium Density Pines	144	9.1	0.2	8.9	6%
8- Low Density Pines	183	42.7	0.1	42.6	23%
9 – Urban	2370	1396.3	23.8	1372.5	58%
10 – Lakes	648	230.6	329.9	-99.3	-15%
11- Commercial	368	204.3	6.0	198.3	54%
17- Medium Density Pines	72	3.9	0.1	3.9	5%
18 – Low Density Pines	195	21.3	0.2	21.1	11%
22 – Medium Density Banksia	1388	126.5	38.5	88.0	6%
23 – Medium Density Banksia-shallow depth to water	1506	761.8	135.9	625.9	42%
Total	**29018**	**7129**	**1164**	**5965**	**18%**

Table 7-1: Land Use Water Balance 2008-2013

The estimates of net recharge for each land use are for relatively large areas that are subject to different climatic conditions, abstraction, depth to water and soil characteristics. As such, these estimates are averages and should only be used as indicative on a regional scale. Recharge by land use at a local or sub-regional scale must be calculated over an appropriate period, to obtain location specific recharge, see Xu et al 2003.

The land use water balance suggests that about 18% net recharge occurs over the entire model area. The net recharge of 18% is considered to be consistent with the conceptual hydrogeological model for the area.

7.2 Groundwater Sub Areas

The Swan Coastal Plain is, for the purposes of groundwater management, subdivided into 125 groundwater sub areas. Each of these sub areas has a groundwater license allocation for the aquifers that occur within the sub area's boundary. Since groundwater license limits are specified by groundwater sub area, the water balance for each of these areas can be used as a basis on which to assess the applicability of existing allocation limits. In addition, a comparison of the simulated water balance for each of the sub areas, which have been assessed using independent quantitative techniques, is an implicit measure of the uncertainty in the present licence allocation limits.

Figures 35 and 36 show the water balance zones, as based on groundwater subareas, used to construct the water balances for the superficial, Mirrabooka, Leederville and Yarragadee aquifers. The results of the water balance analysis are presented in Appendix I, as tables of source and sink components for each zone.

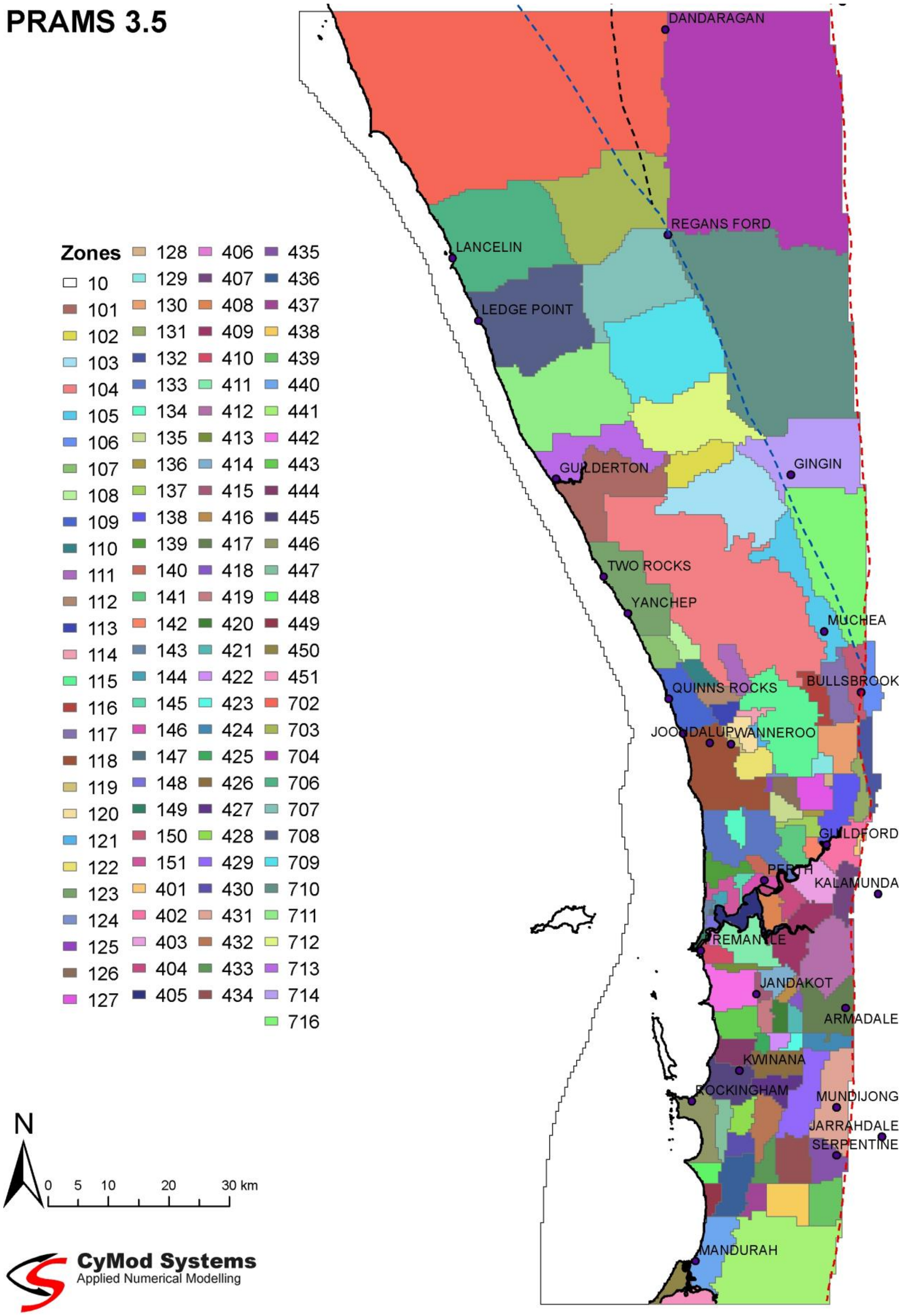

Figure 35: Water Balance Zones – superficial and Mirrabooka Aquifers

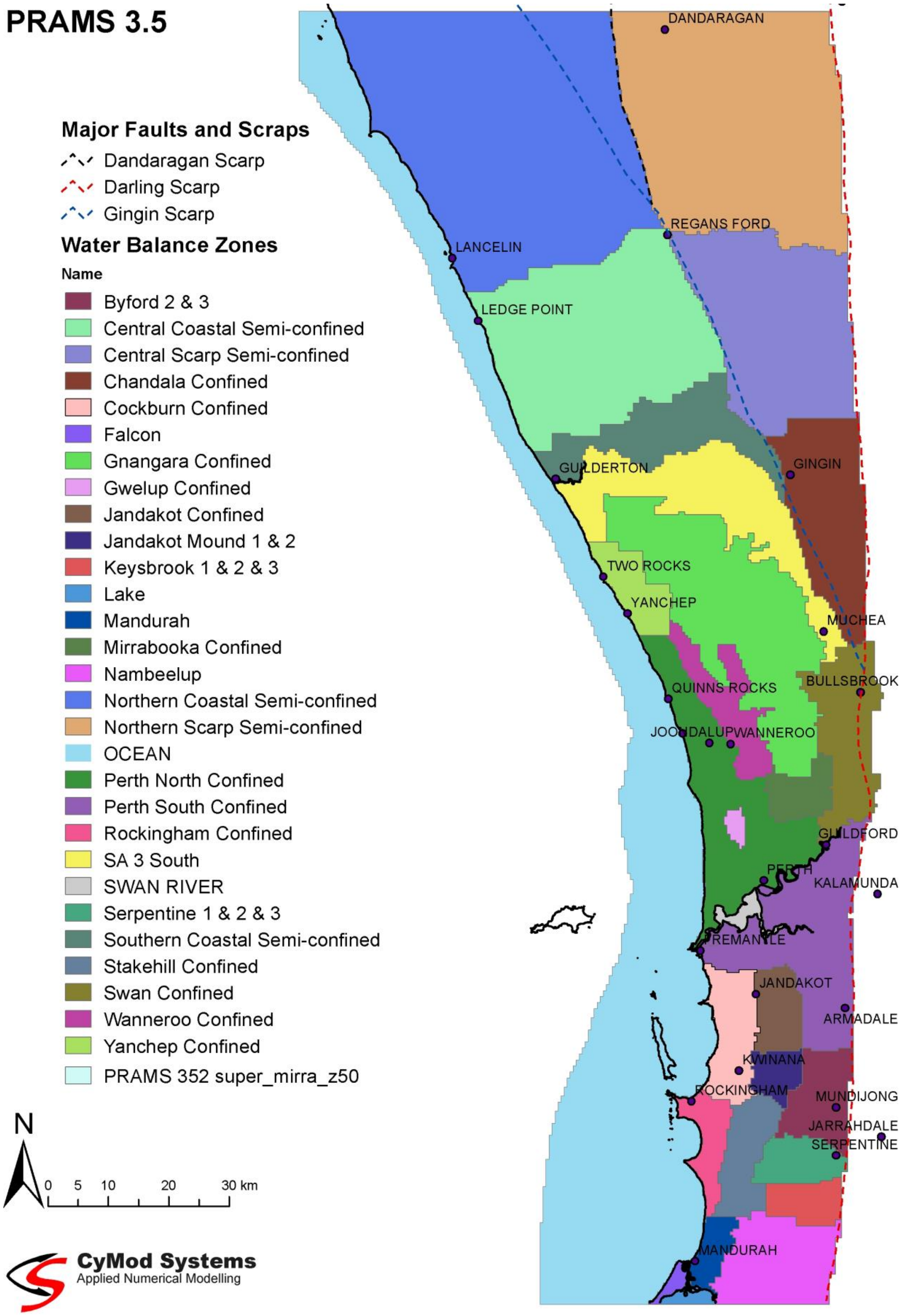

Figure 36: Water Balance Zones – Leederville and Yarragadee Aquifers

8 Conclusions and Recommendations

8.1 Conclusions

A coupled flow model of the Swan Coastal Plain was constructed and calibrated using available water level monitoring data. The construction of the model is consistent with, and based on the PRAMS 3.4 model, as developed by the DoW and includes the VFM as developed by CSIRO and the Water Corporation. The PRAMS 3.5 model is based on an updated geological interpretation of the Swan Coastal Plain, which includes block faulting (De Silva 2012). The model was constructed using available geological and hydrogeological information, and consists of a 13-layer model, covering approximately 10,000 square kilometres.

PRAMS 3.5 was calibrated and verified over the period 2000 to 2012 and 1980 to 2000, respectively. The present calibration of the model is adequate for relative assessment of changes in water levels in the central area of the model (i.e. Mandurah to Gingin Brook).

The model calibration error has been calculated for the 4 major aquifers in the model and is summarised below:

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	1.7	2.4	2.0	14.3	-13.9
Mirrabooka	2.1	2.1	1.4	17.4	-2.9
Leederville	4.4	5.7	3.1	16.7	-18.4
Yarragadee	4.0	5.3	3.6	20.4	-22.8

Most of the simulated heads at monitor bores in the superficial aquifer have a response consistent with measured data. The monitor bores maintain correct trends and the magnitude of the error is constant.

The largest errors are in the north of model, where there are limited measurements, complex geology and some uncertainty as to aquifer characteristics. Other areas of significant error are:

- At the interface of the Tamala Limestone and the Bassendean Sand, north of the Swan River; and
- Along the Darling Fault, south of the Swan River, where water levels tend to influenced by the Serpentine Fault;
- In the block faulted area in the confined aquifers.

In addition, the other major constraints on improving the calibration of the model are:

- The lack of seasonal pumping characteristics of large licensed users of groundwater;
- An insufficiently detailed conceptual hydrogeological model that does not address localised conditions, at the scale used in the model (i.e. 25 ha); and
- Generalised parameter distributions that lack the spatial resolution to account for changes in aquifer characteristics.

Verification of a model is best described as assessing whether the model has any predictive capability, by testing it against data that is independent from the calibration data. PRAMS 3.5A is verified using different temporal datasets. The temporal verification is from July 1990 to July 2000. This period is characterised by increasing public and private abstraction, significant landuse changes in terms of bush fires, urbanisation and variable rainfall. Consequently, the period provides significant variation in aquifer stresses from the calibration period.

A review of hydrographs shows that while there is some offset error in most bores, water level trends and responses to stress are consistent with measured data. Specifically, the increase in error is not large in the superficial and Mirrabooka aquifers, with distribution in error is similar to that during calibration. The largest increase in model error in the verification period is in the Leederville and Yarragadee aquifers. These errors are related to increased error at bores in areas of abstraction, suggesting some uncertainty in modelled abstraction, particularly in 2007 and 2008, where hydrographs show an increase in error, typically realised as an over prediction of drawdown.

Water levels in the superficial aquifer in most bores show consistent trends and qualitatively good correlation with changes in aquifer stresses. This suggests that the impacts of aquifer stresses are reasonably predicted in the model and represents a significant improvement over PRAMS 3.0 to 3.4, which tended to overestimate impacts due to changes in aquifer stresses. This improvement is attributed to better estimates of private abstraction after 2000, the use of WAVES for most landuses and the refinement of the climate zones.

Aquifer	Average Absolute Error (m)	Average RMS Error (m)	Average Scaled RMS %	Maximum Positive Error (m)	Maximum Negative Error (m)
Superficial	2.3	3.4	2.8	16.1	-28.7
Mirrabooka	1.7	1.8	3.7	6.8	-2.6
Leederville	4.6	5.6	3.5	23.8	-13.8
Yarragadee	3.3	4.6	4.7	9.3	-29.7

8.2 Recommendations

The calibration error in the PRAMS 3.5A model can be reduced by additional effort. This effort should address those areas showing significant calibration error (i.e. more than 3 metres). The additional calibration should be undertaken by the DoW and based on the organisational priorities.

Consequently, it is recommended that available spatial and flow data be acquired (if available) and included in future versions of PRAMS, as a way of extending the calibration to flow components.

Any updated model of PRAMS 3.5 should include the following changes:

- Improve the conceptualisation of the offshore boundary in the confined aquifers;
- Refinement of the model grid in areas on rapid changes in elevation in the confined aquifers.

Significant improvement in model calibration can be achieved if completed and validated water level and piezometric surfaces are established for all the aquifers, at selected times (i.e. every 5 years), over the entire domain of the model. This data will eliminate a significant amount of uncertainty with respect to initial conditions and provide spatial head distributions at regular intervals for the calibration of transient models.

The quality of the present calibration is primarily constrained by available resources and data quality, as well model grid spacing. To further improve the model, independent calibration of the model should be undertaken in sections consisting of the area:

a) North of Gingin Brook;
b) Between Gingin Brook and the Jandakot Mound; and
c) South of the Jandakot Mound to Mandurah.

These areas can be calibrated separately and the results used to update the PRAMS 3.5 model.

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APPENDIX A: MODEL LAYER SURFACES

APPENDIX B: MODEL LAYER THICKNESSES

APPENDIX C: VFM DATASETS

APPENDIX D:RAINFALL DATASETS

APPENDIX E: CALIBRATED AQUIFER PARAMETERS

APPENDIX F: CALIBRATION HYDROGRAPHS

APPENDIX G: VERIFICATION HYDROGRAPHS

APPENDIX H: PRAMS 3.5B CALIBRATION HYDROGRAPHS

APPENDIX I: AQUIFER WATER BALANCES.