The Development of the Gascoyne River Floodplain Aquifers Modelling System

GASFAMS V1.1
Volume 1

CyMod Systems Pty Ltd
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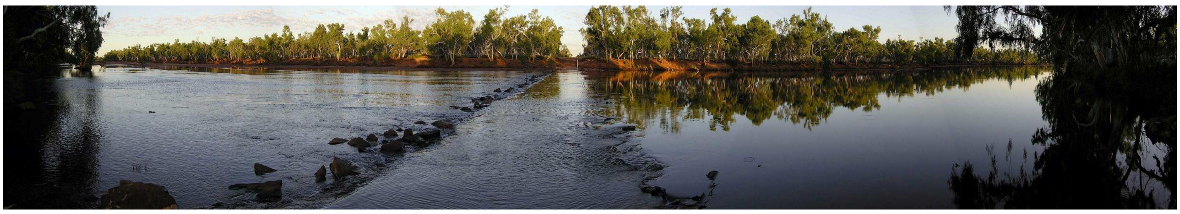

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EXECUTIVE SUMMARY

The Department of Water Western Australia (DoW) is reviewing the allocation plan for the management of surface and groundwater resources within the Lower Gascoyne region. The DoW will use numerical groundwater modelling to estimate the yield range and to help inform the allocation limit decisions. There is significant groundwater use for both public and private water supplies by the Water Corporation and the local horticulture industry in this area.

The current Lower Gascoyne River numerical flow model is based on the GRFAMOD model developed by Dodson (2002) with some modifications. The main modifications are:

- updating of the rainfall and flow data to December 2008;
- updating of the bore abstraction data to December 2008;
- the inclusion of layer elevations for all layers in the model and the conversion of confined layers to confined/unconfined;
- revision of parameters based on review of the quantitative geology;
- a new flow recharge model;
- the reduction of the importance of rainfall recharge as a mechanism for aquifer recharge;
- the use of the multi node well package to simulate abstraction; and
- addition of a solute transport model to simulate changes in water quality.

In general, GASFAMS V1.1 has been designed to simplify and generalise the GRFAMOD model so that it can be used for management of the water resources of the Gascoyne River aquifers.

The GASFAMS V1.1 modelling system consists of a Microsoft Access database containing abstraction, monitoring and environmental data, a MODFLOW 2000 groundwater model, a MT3DMS solute model and Visual MODFLOW as the model pre and post processor. The construction, validation and updating of the GASFAMS V1.1 database highlighted some dataset deficiencies that need to be corrected within the DoW datasets, in order for GASFAMS V1.1 to become a more reliable management tool.

The GASFAMS V1.1 model covers an area of 1150 km^2 (of which 28.7 km^2 represents the course of the Gascoyne River). The model grid consists of a block centred finite-difference mesh of 200 columns and 151 rows. From east to west the finite-difference grid is irregular, with cells ranging from 250 to 2000 metres. From north to south the cells range in size from 50 to 1050 metres. The vertical thickness of the floodplain aquifer is divided into 10 separate layers. Layers 1 and 2 represents the River Bed Sand (RBS) and bottom section of the RBS / Older Alluvium Aquifer (OAA) interface. Layers 3 through 10 represent the OAA to the top of the Toolunga formation which effectively forms the impermeable base of the model.

The modelling of river flows uses a simplified approach where the stage height at any point along the river was interpolated on to the active flow area, using a hydraulic grade line and the measured stage height at Nine Mile Bridge. Where the interpolated stage height is below the river bed elevation, no recharge occurs. The advantage of this approach is that it eliminates the need to explicitly account for river bed topography and local surface flow in the river, when adding stage height to river bed elevation. The disadvantage is that flow stage heights are assumed to be piecewise linear and are a function of only one reference level, which will introduce some error into the spatial distribution of applied river stage height.

To increase the fidelity of the model with how private bores are operated, the Multi-Node Well package for MODFLOW was used to simulation abstraction. The Multi-Node Well (MNW) package allows MODFLOW to simulate abstraction from wells completed in multiple model layers, and prevent the drying of pumping cells in the model.

The GASFAMS V1.1 is run as a transient model consisting of a saturated flow model and a solute transport model. The saturated flow component of GASFAMS was calibrated from May 1991 to December 1999. Stress periods were defined as either calendar months, or the start and end of significant flow in the Gascoyne River. Model output was monthly. The average absolute error is a measure of the fit of the model, and is 5.1% for the calibrated flow model. This percentage error is consistent with the accepted modelling guidelines which generally recommend a percentage error less than 5%. The average absolute error for the solute model is a measure of the fit of the model, and is 9%. This percentage error is larger than the accepted modelling guideline which generally recommends a percentage error less than 5% and suggests the solute model is not well calibrated. As most of this solute error is due to initial conditions, additional water quality data can be used to improve the calibration, via better estimates of the water quality distribution in the aquifer.

The GASFAMS V1.1 model was verified over the period from 2000 to 2008. The average absolute error for the validation period is 4.0% for the calibrated flow model. This percentage error is consistent with the accepted modelling guidelines which generally recommend a percentage error less than 5.0%. The average absolute error for the solute model, during the validation period is 9%. This percentage error is more than the accepted modelling guideline, which generally recommends a percentage error of less than 5%, and suggests the solute model is not adequately calibrated, and there is still significant error in the model.

With respect to the Lower Gascoyne River aquifer, the modelling of the conceptual model of the RBS and OAA aquifers has been improved by the addition of further drilling data and the subsequent review of the quantitative geology. However, the vertical discretisation of the aquifer is a general representation of the actual geology of this aquifer, which prevents small scale structures from being accurately modelled. The model’s structure makes it more suitable for estimating groundwater resources at the sub-regional level.

The present limitation on using the GRASFAMS model for modelling abstraction in Subarea A is the distribution of salinity in the area. The production of groundwater in this area tends to be dependent on water quality, rather than hydraulic parameters. Consequently, for GASFAMS to be useful for water trading analysis and licence variations, additional water quality data and the vertical distribution of salinity in Subarea A needs to be defined through field measurements.

In terms of recharge, the model is consistent with the conceptual hydrogeology, but uses a simplified approach to estimating stage height along the Gascoyne River. This simplification is a source of error with respect water levels in the model, and should be improved using a surface water flow model.

The table below summarises the applicability of the model to the stated objectives.

Objective	Achieved	Comments
Simulate groundwater flow within and between all hydrogeological units in the Gascoyne River floodplain groundwater system.	Yes	
Establish water budgets for each aquifer.	Yes	
Under a range of scenarios, including pumping and climate variations, predict the scale of changes in recharge, groundwater potentiometric heads/water levels and groundwater salinity within the hydrogeologic units.	Yes No	Flow model can predict changes in water levels due to changes in aquifer stresses Solute model is not able to predict salinity of individual bores
Evaluate likely changes in groundwater discharge to ocean environments.	Yes	
Predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions.	Yes	
Provide results that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs).	Yes	
Estimate the likely range and uncertainty of water level changes as a result of pumping and climatic stresses.	Yes	

EXECUTIVE SUMMARY (VOLUME 2)

The Department of Water, Western Australia (DoW) is developing strategies for the management of groundwater resources in the Carnarvon Groundwater Area (GWA) and the western portion of the Gascoyne GWA lying within the Gascoyne River floodplain to the west of Rocky Pool. There is significant groundwater use by both public and private water supplies by the Water Corporation and the local horticulture industry in these areas. The DoW is undertaking a review of the groundwater allocation limits within the study area and will use numerical groundwater modelling to establish a quantitative basis for defined allocation limits.

The objective of the GASFAMS V1.1 groundwater flow and solute model is to provide a quantitative tool that can be used to assess alternative resource management strategies for the Lower Gascoyne River aquifer. The objectives of this project are to further characterize the groundwater resources in Subarea A and Subareas B-L, to serve as input into a management plan. Additional objectives are:

- Simulate the impacts of increased abstraction from Subarea A and Subareas B-L on water levels and water quality under normal and dry conditions.
- Estimate water resources using water quality criteria constraints.
- Estimate the maximum aquifer yields under normal and dry conditions against water quality criteria, for a range of scenarios, including pumping and climate variations.
- Estimate the likely range and uncertainty of water level changes as a result of pumping and climatic stresses.

Sixteen management scenarios were developed for assessment using GASFAMS V1.1; the original six modelled using GASFAMS V1.0 and 10 additional scenarios for Subarea A. These management scenarios are listed below.

Given that forward modelling is focused on Subarea A, the GASFAMS V1.0 model, developed in 2009 and whose emphasis was scenario modelling in Subareas B-L, was modified by refining the finite difference grid in Subarea A from 50x250m to 50x83m. This refinement allows the more accurate simulation of solute transport and private abstraction with additional MODFLOW packages (MT3DMS & MNW). The grid refinement required the updating of:

- Topography;
- Riverbed, and river stage height;
- Initial heads and solute concentrations;
- EVT reference surface and extinction depth; and
- Bore locations.

Aquifer properties, geometry and boundary conditions did not need to be updated. Once GASFAMS V1.0 was updated to GASFAMS V1.1, the latter was used to simulate forward scenarios.

Scenario No.	Scenario Name	Description	Length of simulation	Climate data to be used	Water use
1	Base case – moderate frequency recharge climate	Flow event approximately every 10 months, though the events vary in magnitude. Average dry spell is 8 months. Longest dry spell 16 months. Maximum stage height at 9 mile Bridge 6.9m.	Minimum 8.6 years	Moderate frequency recharge – 1990 to 1999 climate data	Subarea A – 5.8 GL/year Subareas B-L – 12.2 GL/year Total – 18 GL/year
2	Low frequency recharge	Low frequency recharge flow sequence has two drought periods of about 30 months, which is likely to represent a conservative (i.e. low) recharge estimate. Maximum stage height 7.7m at 9 mile Bridge.	Minimum 8.6 years	Low frequency recharge – 2000 to 2007 climate data	Subarea A – 0 GL/year Subareas B-L – 18 GL/year Total – 18GL/year
3	Maximise water use during moderate frequency recharge climate	Use maximised until 20% of current bores run dry or water quality exceeded the criteria in moderate frequency recharge climate conditions	Minimum 8.6 years	Moderate frequency recharge – 1990 to 1999 climate data	Subarea A – 5.8 GL/year Subareas B-L – >12.2 GL/year Total – >18GL/year
4	Maximise water use during low frequency recharge	Use maximised until 20% of current bores run dry or water quality exceeded the criteria in drought condition	Minimum 8.6 years	Low frequency recharge – 2000 to 2007 climate data	Subarea A – 0-5.8 GL/year Subareas B-L – >18 GL/year Total – >18GL/year
5	4 GL Brickhouse borefield – moderate frequency recharge climate	Simulates the abstraction of 4 GL/annum from a modelled new borefield at Brickhouse containing 27 production bores (with 407 m^3/day abstraction for each bore) during moderate frequency recharge climate conditions.	Minimum 8.6 years	Moderate frequency recharge – 1990 to 1999 climate data	Subarea A – 5.8 GL/year Subareas B-L – >12.2 +4 GL/year Total – >22 GL/year
6	4 GL Brickhouse borefield – low frequency recharge	Simulates the abstraction of 4 GL/annum from a modelled new borefield at Brickhouse containing 27 production bores (with 407 m^3/day abstraction for each bore) during low frequency recharge conditions.	Minimum 8.6 years	Low frequency recharge – 2000 to 2007 climate data	Subarea A – 0-5.8 GL/year Subareas B-L – >18 + 4 GL/year Total – >22 GL/year
7	Grower estimated usage from historical crop area - moderate frequency recharge	Growers have stated that water usage was higher in previous years due to high production of bananas in 1980's. Usage for Subarea A based on theoretical usage and expected Subareas B-L usage (350ha @ 20,000kL/ha)		Moderate frequency recharge – 1990 to 1999 climate data	Subarea A – 8.6 GL/year Subareas B-L – >12.2 +4 GL/year Total – >24.8GL/year
8	Grower estimated usage from historical crop area - low frequency recharge	Growers have stated that water usage was higher in previous years due to high production of bananas in 1980's. Usage for Subarea A based on theoretical usage and expected Subareas B-L usage (350ha @ 20,000kL/ha)		Low frequency recharge – 2000 to 2007 climate data	Subarea A – 8.6 GL/year Subareas B-L – >18 GL/year Total – >26.6GL/year

9	Current licensed allocation for Subarea A - moderate frequency recharge	Subarea A is currently over allocated, simulate aquifer if all allocations were activated		Moderate frequency recharge – 1990 to 1999 climate data	Subarea A – 11 GL/year Subareas B-L – >12.2 +4 GL/year Total – >27.2 GL/year
10	Current licensed allocation for Subarea A - low frequency recharge	Subarea A is currently over allocated, simulate aquifer if all allocations were activated		Low frequency recharge – 2000 to 2007 climate data	Subarea A – 11 GL/year Subareas B-L – >18 GL/year Total – >29GL/year
11	Modified low frequency recharge	Modified low frequency recharge flow sequence has two drought periods of about 30 months but climate scenario includes large recharge prior to and after this period. If recharge before and after drought was not as good, the implications for water availability need to be investigated.	Minimum 8.6 years	Low frequency recharge climate data preceded and followed by lower recharge events	Subarea A – 0 GL/year Subareas B-L – 18 GL/year Total – 18GL/year
12	10,000kL limit in Subarea A	Simulate >10,000kL per month being abstracted (Based on bores with high historical use from 2007-2010 abstracting 15 000KL/month (based on historical use figures) from Oct – Jan.		Moderate frequency recharge – 1990 to 1999 climate data	
13	10,000kL limit in Subarea A	Simulate >10,000kL per month being abstracted (Based on bores with high historical use from 2007-2010 abstracting 15 000KL/month (based on historical use figures) from Oct – Jan (again based on historically observed high use months).		Low frequency recharge – 2000 to 2007 climate data	
14	Current licensed allocation for Subarea A	Simulate dry recharge conditions using the 5th percentile climate sequence. Abstraction in Subarea A only occurs when river is not flowing.	20 years	Dry stochastic climate sequence, 5th recharge potential percentile	Subarea A – 11 GL/year Subareas B-L – >22 +4 GL/year Total – >37 GL/year
15	Current licensed allocation for Subarea A	Simulate average recharge conditions using the 50th percentile climate sequence. Abstraction in Subarea A only occurs when river is not flowing.	20 years	Average stochastic climate sequence, 50th recharge potential percentile	Subarea A – 11 GL/year Subareas B-L – >22 +4 GL/year Total – >37 GL/year
16	Current licensed allocation for Subarea A	Simulate wet recharge conditions using the 95th percentile climate sequence. Abstraction in Subarea A only occurs when river is not flowing.	20 years	Wet stochastic climate sequence, 95th recharge potential percentile	Subarea A – 11 GL/year Subareas B-L – >22 +4 GL/year Total – >37 GL/year

Forward Simulation Results

Results for Scenarios 1 through 6 indicate that:

- Results are consistent with previously run scenarios using GASFAMS 1.0, but in most cases the amount of fresh water available in Subarea A is less than the allocations;
- The optimized cases for 3 and 4 do not significantly change the available water sources in Subarea A, as draw-point distribution is the limiting factor in extracting water from Subarea A;
- The results for Subareas B-L show that results for low frequency recharge conditions produce significantly more fresh water than the moderate frequency recharge case. These differences are due to both the recharge sequence used, and as well as actual production bores in use. Significant optimization of the borefields in Subareas B-L occurred after 2000, which is reflected in the results for the low frequency recharge period.

Note that yearly and by bore results were not able to be obtained for the scenarios due to an error in how MT3DMS package, used in GASFAMS 1.1, extracts the simulated water quality for multi-node wells. The program output results to incorrect locations, therefore average values were obtained by correcting the spatial error in the database. Based on the quantitative results:

- The total volume of abstracted water from Subarea A is constrained both by the number of bores (i.e. available infrastructure), but also by the water quality produced from those bores, with the estimated maximum fresh water abstraction of 4.1 GL/annum on average.
- The available resources in Subareas B-L are sufficient to meet the maximum allocation of 26 GL/annum, without significant water quality issues.
- The location and operating strategy in Subareas B-L has a significant effect on the total fresh water available, as reflect in the different fresh water resources under moderate frequency recharge and low frequency recharge conditions.
- The average TDS of abstracted brackish water in Subarea A provides an opportunity for co-mingling production from selected bores to obtain additional resources meeting the 1000 TDS criterion.
- Abstraction from the Brickhouse borefield is not materially impacted over the 10 year abstraction period by changes in water quality.

Results for Scenarios 7 and 8 indicate:

- the average abstraction of fresh water from Subarea A is 6.4 GL/annum, and 2.2 GL/annum of brackish water;
- Total abstraction from Subarea A is 8.6 GL/annum indicating that with duplicate bores, it is likely the area would be able to produce 8.6 GL/annum.
- If all bores are produced, a total of 8.6 GL/annum would be abstracted at an average water quality of 1020 mg/L.
- Over the course of the 10 years in the low frequency recharge simulation, the average abstraction of fresh water from Subarea A is 5.8 GL/annum, and 2.6 GL/annum of brackish water.
- Total abstraction from Subarea A is 8.4 GL/annum indicating that with duplicate bores, it is likely the area would be able to produce 8.6 GL/annum.
- Ii all bores are produced, a total of 8.4 GL/annum would be abstracted at an average water quality of 1200 mg/L.
- Based on the results of these scenarios, it may be possible to increase the monthly allocation for those bores that have good water quality to a total of 6.4 GL/annum. However, additional sampling and water level monitoring should be undertaken to confirm the modelling results.
- Given the average water quality there may be opportunities for increasing total

abstraction above 6.4 GL/annum if blending of water could be undertaken at the basin or sub basin scale.

Scenario	Subarea A						Basin B – L					
	Fresh (< 1000 mg/L)			**Saline (> 1000 mg/L)**			**Fresh (< 1000 mg/L)**			**Saline (> 1000 mg/L)**		
	Abstraction (GL/a)	% of Expected	Average TDS (mg/L)	Abstraction (GL/a)	% of Expected	Average TDS (mg/L)	Abstraction (GL/a)	% of Expected	Average TDS (mg/L)	Abstraction (GL/a)	% of Expected	Average TDS Concentration (mg/L)
1	4.3	74	483	1.6	28	2500	9.0	73	455	2.2	18	1085
2	0.0	0	0	0.0	0	0	18.0	100	473	0.0	0	0
3	4.3	74	490	1.6	28	2571	11.9	73	435	3.5	22	1141
4	4.1	71	447	1.7	29	2881	21.8	99	465	0.0	0	0
5	4.3	74	483	1.6	28	2585	9.3	36	428	6.0	23	1650
6	4.1	71	442	1.7	29	2887	25.5	98	500	0.3	1	1004
7	6.4	74	464	2.2	26	2644	9.0	73	428	2.2	18	1630
8	5.8	67	420	2.6	30	2926	17.9	99	480	0.0	0	0
9	8.1	74	433	2.9	26	2667	11.5	94	411	3.7	30	1145
10	7.4	67	420	3.3	30	2976	17.9	99	320	0.0	0	0
11	4.1	71	482	1.8	31	2500	7.1	58	435	2.5	20	1080
12	4.9	69	480	2.3	33	2500	8.4	69	435	2.9	24	1075
13	4.7	66	433	2.5	35	2948	17.8	99	473	0.0	0	0
14	3.6	33	614	1.6	14	2535	20.5	79	495	5.8	22	2133
15	8.0	73	431	2.8	26	2723	20.5	79	488	5.5	21	2134
16	7.8	71	461	3.0	28	2694	20.9	80	471	5.2	20	2179

Results for Scenarios 9 and 10 indicate:

- That over the course of the 8.6 year moderate frequency recharge simulation, the average abstraction of fresh water from Subarea A is 8.1 GL/annum, and 2.9 GL/annum of brackish water.
- Total abstraction is 11.0 GL/annum indicating that with duplicate bores, it is possible the area could produce 11 GL/annum.
- If all bores are produced, a total of 11 GL/annum would be abstracted at an average water quality of 1020 mg/L.
- Over the course of the 10 year low frequency recharge simulation the average abstraction of fresh water is 7.4 GL/annum and 3.3 GL/annum of brackish water. The total abstraction from the Subarea A is 10.7 GL/annum, indicating that even with duplicate bores, Subarea A will have difficulty producing 11 GL/annum.
- If all bores are produced, at total of 10.7 GL/annum would be abstracted at an average water quality of 1210 mg/L. This exceeds the TDS criteria by 210 mg/L and suggests that during low frequency recharge it will be more difficult to increase total abstraction above 7.0 GL/annum using the blending of water.
- It may be possible to increase the monthly allocation for those bores that have good water quality can be increased to 7.0 GL/annum. However, additional sampling and water level monitoring should be undertaken to confirm the modelling results.

Results for Scenario 11 indicate:

- That over the course of the 10 year modified recharge simulation; the average abstraction of fresh water from Subarea A is 4.1 GL/annum, and 1.81 GL/annum of brackish water. Total abstraction is 5.8 GL/annum.
- These results suggest that Subarea A has limited sensitivity to the recharge sequence used in the simulations, as the results are similar to scenarios 1 and 3.
- For Subareas B-L, the average abstraction of fresh water from Subareas B-L is 7.1 GL/annum and 2.5 GL/annum of brackish water. Total abstraction is 9.6 GL/annum.
- These results show a significant reduction in fresh water abstraction compared to the scenario 1, 2 and 3.

This suggests that Subareas B-L has some sensitivity to the recharge sequence used in the simulations. Based on the results of these scenarios, it suggests that Subareas B-L is sensitive to the occurrence of large floods, which is consistent with the conceptual model of recharge in this area.

Results for Scenarios 12 and 13 indicate:

- That over the course of the 8.6 year moderate frequency recharge simulation, the average abstraction from Subarea A is 4.9 GL/annum of fresh water, and 2.3 GL/annum of brackish water.
- Compared to the results of Scenario 1, the results do not show any significant difference in the total volume water abstracted meeting water quality criteria.
- That the average abstraction from Subarea A is 4.7 GL/annum of fresh water and 2.5 GL/annum of brackish water.
- Compared to the results of Scenario 3, the results do not show any significant difference in the total volume water abstracted meeting water quality criteria.
- These results suggest that increased monthly abstraction from large users, even under low frequency recharge conditions, should not result in a significant increase in TDS in abstracted water.

Results for Scenarios 14, 15 and 16 indicate:

- Under a 5th percentile 20-year dry sequence, the average abstraction from Subarea A is 3.6 GL/annum of fresh water, and 1.6 GL/annum of brackish water.
- Under long term average climate conditions, the average abstraction from Subarea A is 8.0 GL/annum of fresh water, and 2.8 GL/annum of brackish water.
- Under the 95th percentile 20-year wet sequence, the average abstraction from Subarea A is 7.8 GL/annum of fresh water, and 3.0 GL/annum of brackish water.
- Under a 5th percentile 20-year dry sequence, the average abstraction from Subareas B-L is 20.5 GL/annum of fresh water, and 5.8 GL/annum of brackish water.
- Under long term average climate conditions, the average abstraction from Subareas B-L is 20.5 GL/annum of fresh water, and 5.5 GL/annum of brackish water.
- Under the 95th percentile 20-year wet sequence, the average abstraction from Subareas B-L is 20.9 GL/annum of fresh water, and 5.2 GL/annum of brackish water.
- Compared to the results of Scenarios 9, the results of Scenarios 15 and 16 do not show any significant difference in the total volume water abstracted meeting water quality criteria.
- Under prolonged low frequency recharge conditions, there is a significant reduction in aquifer deliverability and abstracted water quality.

Aquifer Yield Estimates

Based on the results of the sixteen forward simulations, aquifer yield ranges were constructed by assessing the 5th percentile annual abstraction and mean annual abstraction, for both Subarea A and Subareas B-L, and using these values to construct normally distributed yield ranges.

The 5th percentile annual abstraction is defined as the abstraction that can be realised in 19 out of every 20 years, i.e. there is a 95% chance of meeting this abstraction in any given year. The mean annual abstraction (50th percentile) is similarly defined as the abstraction that can be realised in 1 out of every 2 years.

For Subarea A, the freshwater abstraction for Scenarios 11 and 15 represent the 5th and 50th percentiles, respectively, of the Subarea A yield range. Due to the uncertainty with regards to yield in Subareas B-L, and the insensitivity of yield in Subareas B-L to differing climates, as shown by Scenarios 14, 15 and 16, the 5th and 50th percentiles were defined as the freshwater abstraction realised by Scenario 5 and Scenario 15, respectively.

The aquifer yield estimates for Subarea A and Subareas B-L suggest that:

- there is a 95% probability that 4.1 GL of fresh water can be pumped from Subarea A on an annual basis;
- there is a 50% probability that 8.0 GL of fresh water can be pumped from Subarea A on an annual basis;
- Though the estimated yield range indicates that there is a 5% probability that 11.9 GL of fresh water may be pumped out of Subarea A in a given year, this may be limited by aquifer storage and recharge rates and there may be some difficulty experienced in realising this amount of abstraction, even under the most favourable conditions.
- there is a 95% probability that 10.7 GL of fresh water can be pumped from Subareas B-L on an annual basis;
- there is a 50% probability that 20.5 GL of fresh water can be pumped from Subareas B-L on an annual basis;
- Though the estimated yield range indicates that there is a 5% probability that 30.3 GL of fresh water may be pumped out of Subareas B-L in a given year, this may be limited by aquifer storage and recharge rates and there may be some difficulty experienced in realising this amount of abstraction, even under the most favourable conditions.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
RBS	River Bed Sand
OAA	Older Alluvium Aquifer
NMB	Nine Mile Bridge
DoW	Department of Water
ARM	Above River Mouth
PWS	Public Water Supply
aaMAX	Average Annual Maximum Water Level
aaMIN	Average Annual Minimum Water Level

1 INTRODUCTION

The Department of Water (DoW) is undertaking a review of allocation limits and water management rules in the Lower Gascoyne. There is significant groundwater use for both public and private water supplies by the Water Corporation and the local horticulture industry in this area. The DoW will use numerical groundwater modelling to estimate the yield range and to help inform the allocation limit decisions.

In 2002, the DoW developed the first version of Gascoyne River Floodplain Aquifer Model, GRFAMOD (Dodson, 2002) to better understand the recharge to groundwater in the alluvial aquifers from river flows in the Gascoyne River, to assist in management of the groundwater resources of the Lower Gascoyne River. This model is a three-dimensional numerical model that is physically based, as much as possible, on the surface water-groundwater flow system of the Gascoyne River floodplain aquifers.

The DoW recognised that an updated model, incorporating solute transport, was necessary to improve the management of the aquifer resources of the Lower Gascoyne River. This report describes the construction, calibration and forward simulation using the Gascoyne River Floodplain Aquifers Modelling System (GASFAMS V1.1), an updated groundwater flow and solute transport model of the Lower Gascoyne River. Conclusions and recommendations are made based on the outcome of model simulations with respect to the management of water resources in the Lower Gascoyne River.

2 MODELLING OBJECTIVES

The objective of the GASFAMS V1.1 groundwater flow and solute model is to provide a quantitative tool that can be used to assess alternative resource management strategies for the Lower Gascoyne River aquifer. The model is required to simulate the water level and water quality response of the aquifer system to changes in climate and abstraction. The numerical model is required to replicate the conceptual hydrogeological model, and to then provide a means of assessing the likely impacts of varying river flows and various management alternatives for public and private abstraction on water levels and water quality, into the future.

The objectives of this project are to develop a model that will enable the Department of Water to:

- Simulate groundwater flow within and between all hydrogeological units in the Gascoyne River floodplain groundwater system.
- Establish water budgets for each aquifer.
- Under a range of scenarios, including pumping and climate variations, predict the scale of changes in recharge, groundwater potentiometric heads/water levels and groundwater salinity within the hydrogeologic units.
- Evaluate likely changes in groundwater discharge to ocean environments.
- Predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions.
- Provide results that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs).

- Estimate the likely range and uncertainty of water level changes as a result of pumping and climatic stresses.

The model will be required to interface simply and effectively with the ArcGIS Geographical Information System (GIS) and the modelling data management system operated by the DoW. The model must be suitable for use by modelling professionals or hydrogeologists and serve as a tool for water resources management.

The basic approach in meeting these objectives was:

a) collecting the essential data required for the modelling purposes, particularly for the period after 1999;
b) reviewing the conceptual hydrogeology and numerical model (GRFAMOD) of Dodson (2000 & 2002);
c) defining a revised model architecture and constructing a new model;
d) calibrating and verifying the numerical model to December 2007;
e) undertaking sensitivity analysis; and
f) simulating predictive scenarios.

The modelling work is constructed to comply with the Murray Darling Basin Commission guidelines for a complex groundwater model (MDBC, 2001).

2.1 Previous Modelling

Groundwater modelling of the Lower Gascoyne River aquifer has been undertaken since 1975 to simulate and manage the aquifer system. The earliest model was known as GASIM, which was later developed into the GASMOD program. Over time a number of modifications were made, however the basic modelling concepts for all versions of GASMOD were the same. The division of the river into eleven natural storage basins formed the basis of the conceptual model. These basins (Basins A to L, excluding Basin I) were represented in the model by a depth versus storage/area relationship, which was modified during calibration (Dodson, 2002).

As part of research undertaken by Dodson (2002) a MODFLOW96 flow model was developed for the Lower Gascoyne River Floodplain, call GRFAMOD. Subsequently, this model has formed the basis for the current modelling of the aquifer system. GRFAMOD is a nine layer model using a quasi three-dimensional approach. The vertical hydraulic gradient in the aquifer after river flow was recognised as significant, being several orders of magnitude greater than the horizontal hydraulic gradient. However, any confining beds are not explicitly discretised into individual layers but are approximated using a leakage term between the riverbed sand and the older alluvium, and between arbitrary layers of the older alluvium itself. Because of its large size, GRFAMOD has been run over short intervals of time within the calibration period. The different lengths of model runs have been selected on the basis of whether or not there were any flows in the river.

The GRFAMOD model area is 652 km^2, of which 28.7 km^2 represents the course of the Gascoyne River. The model grid covering this area consists of a block centred finite-difference mesh of 550 columns and 230 rows. The row and column spacing is uniform throughout the model, each cell being 100m square. The vertical thickness of the floodplain aquifer is arbitrarily divided into eight separate layers approximately 5m thick or greater, plus a ninth layer representing the uppermost riverbed sand. The layers are used to represent the spatial distribution of horizontal and vertical hydraulic conductivity, and changes in head with depth. The model was calibrated against a single flood event, and then replicated to model flow and non-flow periods. Consequently, GRFAMOD consisted of a series of uncalibrated models that simulated river flows and the intervening non-flow period. The construction of input data sets, in particular abstraction and river boundary conditions, was complicated and time consuming.

There are numerous simplifying assumptions made in GRFAMOD that limit the accuracy of the model output. The major assumptions occur in the interpolation of spatial hydrogeological parameters and temporal representation of monthly groundwater pumping and mean river stage heights from two stream gauging stations at Nine Mile Bridge and Fishy Pool (to the east of the model area). The model requires the re-wetting of dry cells which impacted model convergence and increased the error in the volumetric budget water balance.

After a review of the GRFAMOD model, it was decided to construct a new model using the data contained in GRFAMOD and information obtained from investigative studies undertaken since 2001, including:

- A Department of Agriculture drilling program in the Brickhouse Station area (Global Groundwater, 2005); and
- Monitoring and abstraction data from 2001 as supplied by the DoW.

The new model was in part designed to eliminate the complicated methodology for constructing the river and abstraction boundary conditions, in addition to adding a solute transport capability for simulating water quality in the aquifer system.

3 ENVIRONMENTAL SETTING

3.1 Location

The town of Carnarvon, situated approximately 900 kilometres north of Perth, is the regional centre for the Lower Gascoyne district in Western Australia. It lies at latitude 24°53′02″S and longitude 113°39′40″E at the mouth of the Gascoyne River on the Indian Ocean. The study area includes the Carnarvon Groundwater Area (GWA) and the western portion of the Gascoyne GWA lying within the Gascoyne River floodplain to the west of the Rocky Pool, a distance of approximately 56km inland (Figure 1).

3.2 Climate

3.2.1 Temperature

The study area has an arid climate with erratic and unreliable rainfall, hot summers and mild winters. At Carnarvon Airport, the highest mean annual maximum temperature is recorded in February (33°C) and the lowest mean annual minimum temperature is recorded in July (11°C). In the inland catchment at Gascoyne Junction, January is the hottest month (41°C) and July is the coolest (9°C). Complete details are given in Appendix A.

3.2.2 Rainfall

Rainfall data was obtained from the Bureau of Meteorology (BoM) stations shown in Table 1, and is provided in Appendix A.

BoM Reference	BoM Context Name	BoM Name
506001	GASCOYNE RIVER	GASCOYNE JUNCTION
506003	GASCOYNE RIVER	FISHY POOL
506014	GASCOYNE RIVER	JIMBA
006022	GASCOYNE JUNCTION	GASCOYNE JUNCTION
506016	GASCOYNE RIVER	YINNETHARA CROSSING
006011	CARNARVON AIRPORT	CARNARVON AIRPORT

Table 1: Rainfall Stations

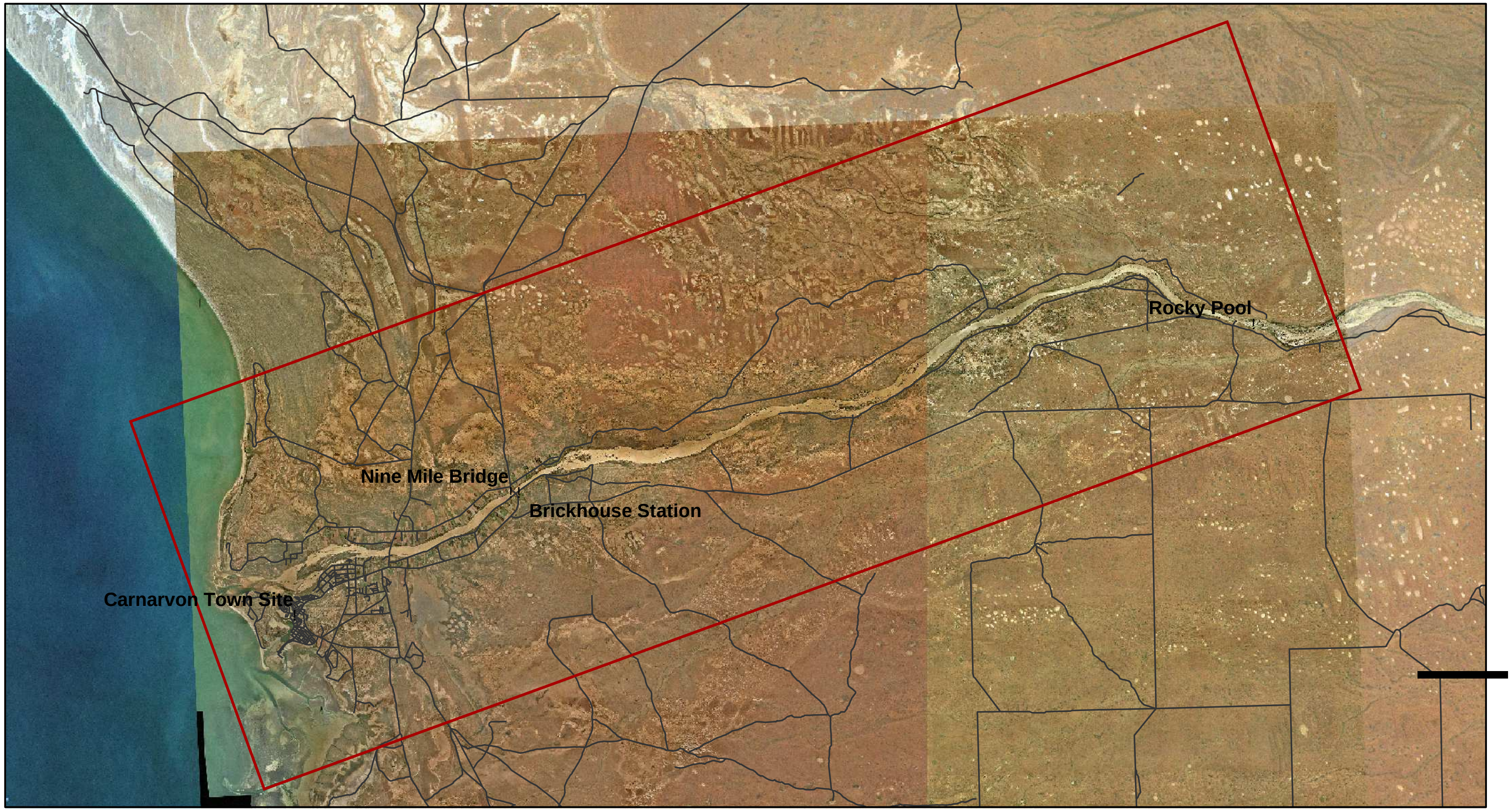
The Brickhouse and Carnavon Airport meteorological stations were the closest stations to the model area that had the most appropriate and useful data for use in the conceptualisation of the model. The total annual precipitation for the Brickhouse and Carnarvon Airport stations are given in Appendix A. Precipitation at Carnarvon Airport is summarised by month in Table 2.

Month	Average Rainfall (mm/month)	Average Rainfall (mm/day)
January	11.8	0.38
February	19.4	0.69
March	15.0	0.48
April	13.2	0.44
May	37.4	1.21
June	47.9	1.60
July	47.0	1.52
August	18.5	0.60
September	5.9	0.20
October	5.6	0.18
November	4.1	0.14
December	1.9	0.06
Total	**228.6**	

Table 2: Precipitation (Carnarvon Airport), 1945 - 2007

CyMod Systems
Applied Numerical Modelling

Gascoyne River Floodplain Aquifers Modelling System



DISCLAIMER NOTES
Users of this information should review or consult the primary data and information sources to ascertain the usability of the information

ACKNOWLEDGEMENT
DATA SOURCES
- Geoscience Australia
- SKM
- Department of Water

SCALE 1:275000

0 2.5 5 10
Kilometres

GDA 94
MGA ZONE 50

Legend

Study Area

Roads

Figure 1: Study Area

3.2.3 Evapotranspiration

Based on available data, the mean annual evapotranspiration for Carnarvon Airport was 2,620 mm. Potential evapotranspiration at Carnarvon Airport is summarised by month in Table 3.

Month	Average Potential Evapotranspiration (mm/month)	Average Potential Evapotranspiration (mm/day)
January	311.5	*10.05*
February	273.8	*9.78*
March	273.3	*8.82*
April	197.7	*6.59*
May	153.2	*4.94*
June	113.0	*3.77*
July	116.2	*3.75*
August	150.1	*4.84*
September	196.8	*6.56*
October	253.2	*8.17*
November	274.6	*9.15*
December	307.2	*9.91*
Total	**2620.4**	

Table 3: Potential Evapotranspiration (Carnarvon Airport), 1945 – 2007

3.3 Land Use

Although land use in the catchment is predominantly pastoral and mining, within the Lower Gascoyne River (Subarea A) the main agricultural activity is commercial horticultural. The Lower Gascoyne River also includes the town site. Above Nine Mile Bridge (NMB), the major land use is pastoral, with native vegetation predominating. The actual distribution of land use was not able to be quantified as no datasets were supplied describing the nature or distribution of commercial agricultural or other economic activities.

3.4 Public Water Supply

The water supply for Carnarvon is provided from groundwater and is supplemented by surface water when the river is flowing. The water supply is divided into:

- public water supply (PWS) and scheme water supply operated by the Water Corporation, and
- private bores.

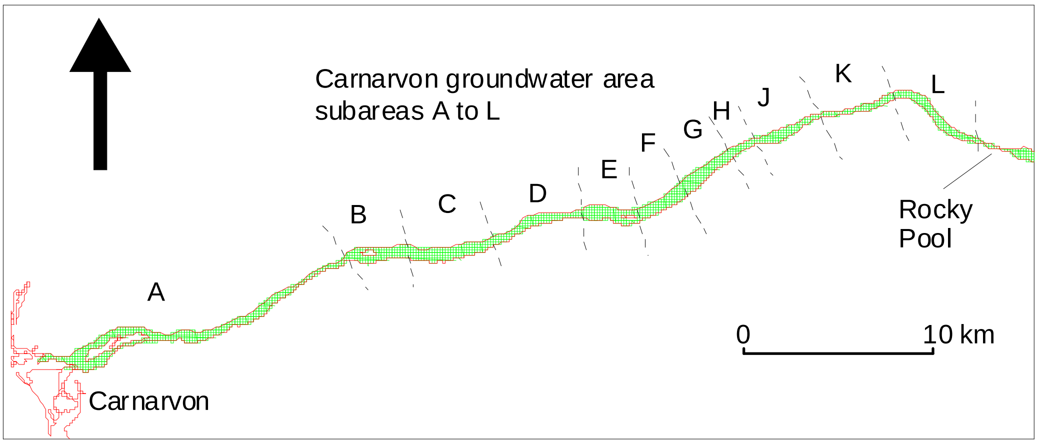
The Water Corporation borefield (the Scheme) supplies water for town use and for the horticulture industry, while private abstraction is used mainly for the horticulture industry. The private borefield area is known as Subarea A and the public water supply area (Water Corporation borefield) is known as Subareas B-L. They are referred to as ‘Subarea A’ and ‘Subareas B-L’ respectively hereafter in this report. The public water supply and scheme borefield extends from east of Nine Mile Bridge up to Rocky Pool, 56km Above River Mouth (ARM). Private borefields exist between Nine Mile Bridge and Water Supply Island to the west, with a small extension east of the bridge along McGlades Road on the north side of the river (Dodson, 2002), as shown in Figure 2.

The Water Corporation is licensed to abstract up to 6.8 GL/annum for the Scheme, while the private users are licensed to abstract 5.8 GL/ annum. Table 4 summarises the abstraction from each basin from 1991 to 2007. Note that pumping from Subarea A is unrestricted during declared periods of river flow.

Year	Subarea A Total (GL)	Basins B – L Total (GL)
1991*	3.1	3.6
1992	4.2	6.0
1993	3.3	6.9
1994	4.4	5.6
1995	4.6	4.6
1996	4.3	3.4
1997	5.5	3.5
1998	5.6	4.3
1999	8.9	3.2
2000	5.8	3.6
2001	6.2	3.7
2002	4.3	6.1
2003	4.0	7.2
2004	5.6	5.1
2005	4.5	4.9
2006	5.8	6.8
2007†	2.4	3.4

* Data for 1991 from April only
† Data for 2007 to July only

Table 4: Annual Water Corporation Abstraction 1991 – 2007



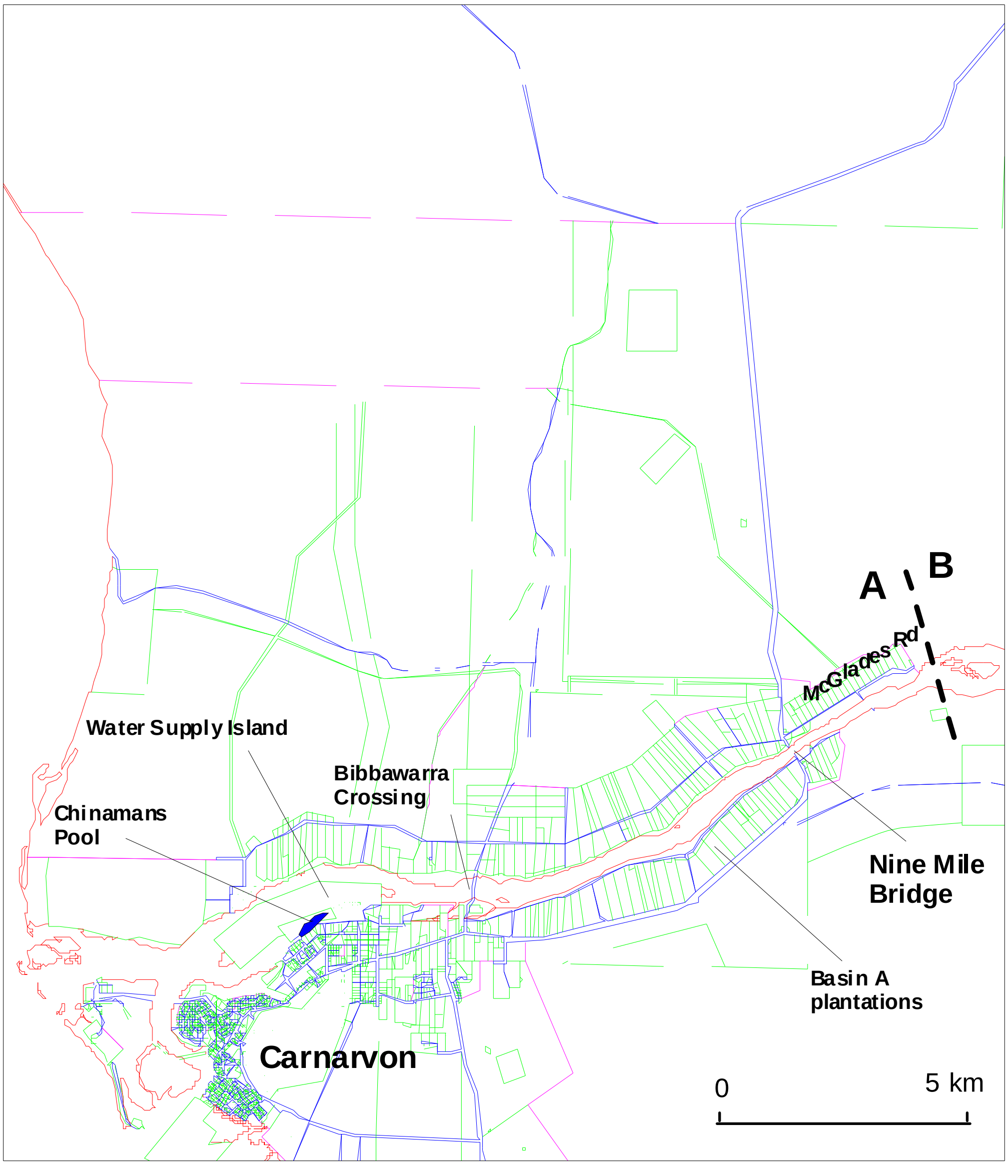


Figure 2: Groundwater Management Subareas

4 GEOLOGY

4.1 Geomorphology

The Gascoyne River extends about 700 km inland from the Indian Ocean coast. The river rises below Wilgoona Hill in the Robinson Ranges west of the Gibson Desert and flows into Shark Bay and the Indian Ocean at Carnarvon. The catchment physiography can be divided into two distinct areas; an inland, etched, granitic plain, and the Carnarvon Basin, which comprises the Kennedy Range plateau and a flat coastal plain (Dodson, 2001).

The general topography of the river basin in the model area is flat lowland coastal plain. Rocky Pool to the east has an elevation below 45 mAHD, from which there is a gentle slope toward the coast in the west. The levee banks of the river are higher than the surrounding lowland in many places. There are a number of vegetated sand dunes and between them interspersed clay pans which become inundated during heavy rainfall. The river bed morphology is greatly altered during flowing.

The east Carnarvon Basin is of greater relief than the coastal plain and the drainage is better defined than the arid interior with small tributaries draining the Kennedy Range. From the western margin of the Kennedy Range the coastal plain has little relief, and gently slopes from approximately 60 mAHD down to the Indian Ocean over a distance of about 140 km (Dodson, 2001).

Boodalia Channel, a geologically recent, abandoned river channel that breaks away from the present day course of the river, exists on the south bank of the Gascoyne River immediately downstream of Rocky Pool. This channel may have also entered the Indian Ocean south of the current river mouth.

4.2 Soils

The model area has generally unconsolidated sandy soils. The Gascoyne river channel comprises a wide, sandy bed with abundant sand bars and terrace formations. Much of the low-lying coastal plain in the study area consists of bare clay pans, gravel and shingle patches or sand dunes.

4.3 Regional Geology

The stratigraphy of the entire Carnarvon Subarea And the Gascoyne sub-basin is presented in the 1:250,000 Kennedy Ranges map sheet (GSWA, 1985) and has also been previously described by Hocking, Moors and Van de Graaff (1985) and Allen (1971). The stratigraphic sequence is represented in Table 5.

Age	Formation	Maximum Thickness Intersected (m)	Lithology
Quaternary	Riverbed sand	12	Sand, gravel, cobble, minor silt, clayey sand, clay, silt, sand and gravel, partly indurated.
	Older alluvium	30 - 60	
Tertiary	Cardabia Calcarenite	5 - 60	Calcarenite, chalky calcisiltite
Late Cretaceous	Toolunga Calcilutite	100 - 290	Calcilutite, calcisiltite

Table 5: Regional Stratigraphy of the Study Area

4.4 Geological Units within the Study Area

The Lower Gascoyne River flows along a well-confined braided channel through Quaternary alluvial terraces, built upon a gently-dipping substrate of early Tertiary and Mesozoic sedimentary rocks. The pre-Quaternary sequence outcrops only rarely in the model area, but it's stratigraphy is documented from exposures in the Kennedy Ranges (Hocking et al., 1985) and exploratory wells in the area (Allen, 1972). It consists of Cretaceous shallow marine limestone and shales, with radiolarite and glauconitic horizons, unconformably overlain by early Tertiary shallow marine sandstones and limestones.

The principal pre-Quaternary units appearing in outcrop and boreholes in the model area are the late Cretaceous Toolunga Formation and the Tertiary Cardabia Formation. A fault-bounded, north to north-east trending anticline in Cretaceous deposits appears approximately 55km from the coast at Rocky Pool (Allen, 1972), and these are the most westerly outcrops of the pre-Quaternary substrate in the model area (GSWA, 1985, Kennedy Range 1:250 000 Geological Map Sheet). The Toolunga Formation here is a calcilutite with minor sandstone interbeds. Some remnants of the Cardabia Formation appear at Rocky Pool, but its main occurrence is at depths of 50 metres or more below the floodplains as calcareous sandstones and siltstones (Allen, 1972; Skidmore, 1997). West of Rocky Pool, the geological sequence dips at less than 5 degrees to the west, and is found at 50-70 metres depth below the flood plain.

Built up over the Tertiary-Mesozoic substrate is the Quaternary alluvial system deposited by the current Gascoyne River and its previous incarnations. These are poorly-sorted sediments, ranging from clay to gravel size, alternating and sometimes graded into one another. The sand and gravel fraction of the alluvium has been estimated at 20-30% at best and often less in places (Martin, 1990; Skidmore, 1997) and sandy lithologies are often laterally discontinuous, as expected in a fluvial deposition setting.

The principal aquifer for the region is the aggraded sand deposits within and below the Gascoyne River channel, known informally as the River Bed Sand (RBS). The thickness of these deposits varies from a few metres to eighteen metres in places (Allen, 1972). The alluvial terraces provide a secondary aquifer with substantially greater storage, but less efficient recharge, known as the Older Alluvium Aquifer (OAA).

4.4.1 Alluvial System Morphology

West of Rocky Pool, the river emerges from the foothills of the Kennedy Ranges and the river deposits open up into an alluvial plain. Three main alluvial systems are defined on the GSWA 1:250,000 series maps: one relating to the current river channel and its associated delta environment at the town of Carnarvon, and two other older plain/delta systems relating to the abandoned Boodalia and Brown channels to the south. The Boodalia channel diverges from the current river course 3km upstream from Rocky Pool and continues to the coast in a course semi-parallel to and south of the Gascoyne River, while the Brown Channel occurs even further south by 10km or more.

Three key features of the Gascoyne River environment affect the nature of the alluvial deposits:

- The morphology of these recent alluvial systems indicates that the river channel tends to remain within it's current channel long enough to deposit substantial fine-grained overbank deposits, before avulsing to a new channel location. A relatively stable terrace morphology promotes development of ponding areas, such as those seen at the McNeill basin, Coburn Marsh and the many inter-dunal ponds on the modern plain (GSWA, 1985).
- The sediment load of the river varies widely in particle size, from clay to gravel fractions, also resulting in alluvium of a mixed character – clay and silt is deposited overbank in areas of ponding, while most of the sand fraction is deposited as aggrading channel bedloads and on the overbank during flow stages only.
- Sporadic river flow events occur due to the very low average rainfall in the region, which allow for added stability of the alluvial terrace surfaces, including development of small-scale dunes and evaporative crusts. As before, sheet flood deposits and isolated ponding would be expected to dominate the overbank area.

The sedimentary facies associated with these features is an alluvial wedge containing isolated sand sheets and channel-derived sand bodies within a matrix of sandy silt and clay. A broader braided plain with a larger fraction of coarse sediments would favour lateral aggradation of sand and gravel deposits over a wider area, with more ephemeral channel avulsion, and less isolation of sandy units within the alluvial wedge.

If it can be assumed that ancient river channels followed a similar depositional pattern to the most recent ones, it may be expected that graded sand deposits from 10-20m thick (the current thickness of the River Bed Sand) may be present in places at depth within the alluvium, however their lateral continuity is likely to be limited.

4.4.2 Subsurface Geological Units

Previous authors (Allen, 1972; and Dodson, 2001, 2002) considered that the lithologies within the alluvium cannot be correlated over any significant distance and expressed doubts as to whether the Older Alluvium Aquifer could be a productive aquifer for this reason. If the sand bodies within the alluvium are truly isolated from each other (i.e. occurring as discrete former channels separated by finer alluvium) and separated from the current channel sand, then this may be true. However, if high-permeability deposits can be related to each other over a scale of hundreds of metres, then they may be incorporated into a model representation whose spatial resolution is 100m, as is the case for the current GASFAMS model.

The study of Martin (1990) involved a program of drilling transects perpendicular to the river and out into the alluvium, including a geophysical survey to aid subsurface correlation. Geological cross-sections from this study show sand sheets correlated over distances of more than 1-2km, and sometimes up to 5km, within a matrix of sandy clay dominated deposits. Detailed lithological logs from this study were revisited in the current review, which concurs that correlation of sandy units is possible on a scale of at least 1-2km, for sand thicknesses of at least 5 metres.

The methodology for the development of a geological model for the current study is described in Section 4.5 below. Since the study area of Martin (1990) covers at least one third of the river length between Rocky Pool and the coast to the west, it is considered that this approach is valid for and can be applied to the remainder of the model area. The current study has attempted to identify all of the more substantial sand bodies within the alluvium that can be correlated over at least 500m and are thicker than 5m, using the WIN bore database, maintained by the Department of Water (DoW) for the Carnarvon district. The new geological model represents real areas of higher transmissivity within the alluvium, at variable depths and with their bounds defined as much as the data allow. It also reflects the theoretical sedimentary facies expected for the Gascoyne alluvial system, as described above.

4.5 Subsurface Mapping Methodology

The current methodology adopted for the geological conceptualisation of the model area, involved the systematic checking of all lithological logs contained within the Department of Water's Water Information (WIN) database (Figure 3), with individual lithologies being assigned a geology summary code, normally based on the principal lithology mentioned in the log interval. The codes used are summarised in Table 6.

Geology Code	Description	Comments
cl	clay, mudstone, limestone or shale	
zst	siltstone	many units logged as cl may be zst, distinction not clear-cut
scl	sandy clay	poorly sorted and fine grained If sand equal to or less than 30%, coded as cl only
zsst	sandstone with clay or silt	proportions of clay/silt were more than 30%, but less than 50%
sst	sandstone	including all fine to coarse sand
gsst	gravel	including pebbles over 10mm size
Special codes independent of grain size		
RIVER BED SAND	River bed sand	
cr	coffee rock	
lcl	lateritised clay and sand	
cfm	Cardabia Formation	
tfm	Toolunga Formation	green/gray bentonitic shale or clay near 65m depth or white calcilutite beneath identified unconformity

Table 6: Geology Codes used in Lithological Logs

Using these codes, clusters of sandy lithologies (i.e. zsst, sst, gsst) were grouped together as a sand unit (Figure 4 and Figure 5), when they contained no intervening intervals of fine-grained lithologies, or one or two fine-grained intervals of less than 2 metres in thickness. Logs containing multiple thin (1-5m) interbeds of coarse and fine lithologies, often grading into each other, were not considered appropriate for large-scale correlation and were not incorporated into sand bodies.

Clusters of silty units (i.e. zst, scl) and clay units (cl, lcl) were also identified. However, further analysis demonstrated that these units could not be correlated as isolated layers or well-defined bodies. In places, fine-grained interbeds between sandy sheets could be correlated over hundreds of metres, but the observed variable nature of logging techniques employed within the database made it impossible to distinguish “sandy clay”, “clay” and “silt” from each other, and thinner units often became untraceable from bore to bore as the fine-grained fraction became dominant. Therefore, the approach adopted was to view the silt and clay fraction of the alluvium as a matrix of fine-grained sediment that contains and surrounds the more well-defined sandy units.

Special units, such as “coffee rock”, and “laterite” were also not correlated over more than a few hundred metres laterally. These labels describe inherently localised lithotypes, and may not be expected to form an identifiable unit over the scale of kilometres. “RBS” and “Cardabia Formation” were not always identified in the logs. These units were probably logged in generic terms in most cases – surface sand for the RBS and basal sand for the CFM; in the latter case it may not be possible to identify its actual occurrence over the model area for this reason. However, there are no published hydrogeological parameters available for the Cardabia Formation, and therefore it has been assumed that it can be treated as a sandy unit within the alluvial wedge.

4.5.1 Sand Body Correlations

An attempt was made to correlate sandy units from a total of 315 bore logs; all those with a lithological sequence of at least 50 metres depth. These were mostly restricted to the immediate vicinity of the Gascoyne River, although the three perpendicular transects of Martin (1990) - transects B, C & D - and two other transects - A1 and A2 - enabled the extension of the sand bodies into three dimensions in certain places (Figure 4 and Figure 5). The sand units have been termed as per the transect number, their position in the transect - top (T), middle (M) or base (B) - and the sand unit number, e.g. CB1, AT2, etc. in Figure 4 and Figure 5.

Some notable gaps in the coverage occur between the A and B transects, and around the town of Carnarvon. It is assumed that sandy units also appear there and further out from the river, although this assumption cannot be documented further. There are fewer large sand bodies documented near the delta area at Carnarvon, even in areas with relatively good bore data coverage. This might be expected due to a general decrease in coarse-grained material deposited lower down the river tract at lower river-flow velocities. The typical extent of sand bodies down-river from transect B is approximately 1.5km, and thicknesses ranged from 5-10 metres. Any undocumented sand body in the area would probably likewise not exceed these dimensions, unless it was an ancient river channel.

In contrast, up-river from transect C, the sandy fraction of the alluvium substantially increases. Some sand bodies extend for 5km in transects D, and thicknesses can reach 27m. Sand bodies in this location also merge in places, in which case they were arbitrarily separated at a convenient depth, so that they could be spatially defined within the model. This is attributed to the fact that this area may have been a historically common site for river channels to emerge from the hinterland onto the plains, and that as previous channels avulsed a relatively greater proportion of channel sands accumulated here. Bores from southern transects C and D, and to the south of the abandoned Boodalia Channel also contain significant proportions of sand, and it is assumed that a similar occurrence of sand bodies may occur beneath it. Evidence in support of this assumption is provided in Martin (1990) which noted that there were significantly higher transmissivities between transects C and D south of the river and flows within the alluvium here were parallel to the river, unlike the regular groundwater flow direction perpendicular to the river channel. The 1000 mg/l TDS contour also broadens out into this area, indicating further infiltration of fresh recharge water from river flows into this aquifer area, indicative of an enhanced transmissivity. The data for the sand body correlations is presented in Appendix E.

4.5.2 Geological Model for the River Bed Sand

Since the RBS is the principal aquifer for the region, particularly during river flow recharge periods, the geometry of this informal unit was modelled separately. Where the logs noted that the surface deposits were in the RBS, or when the bore was obviously located in the river bed, the surface sand units down to approximately 18m were not included in the sand body correlations for the alluvium. Therefore, some surface-level sand bodies will be in direct contact with the RBS.

Since many of the river bore logs do not distinguish clearly where the RBS begins and ends, the detailed study of Allen (1972) was adopted to model the thickness variations of the RBS. This study shows transects across the river bed, clearly picking the base of the RBS unit each time. Figure 6 shows the inferred thickness of the RBS as calculated from data from Allen (1972), Dodson (2002) and available bore logs. Figure 7 shows the river bed sand elevation and thickness long-section along the river centre line from A to A’, as indicated in Figure 6.

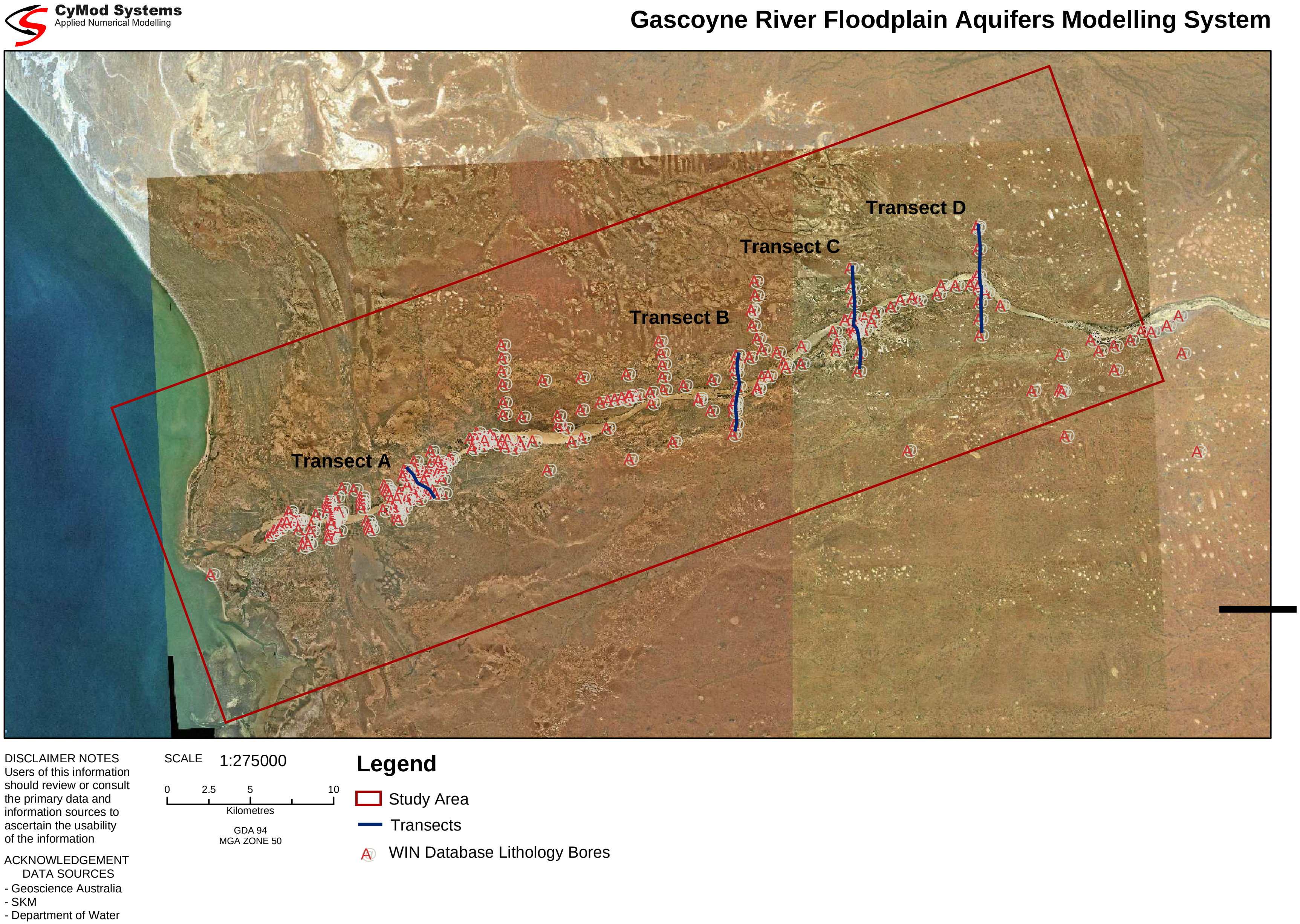


Figure 3: WIN Database Bores with Lithology

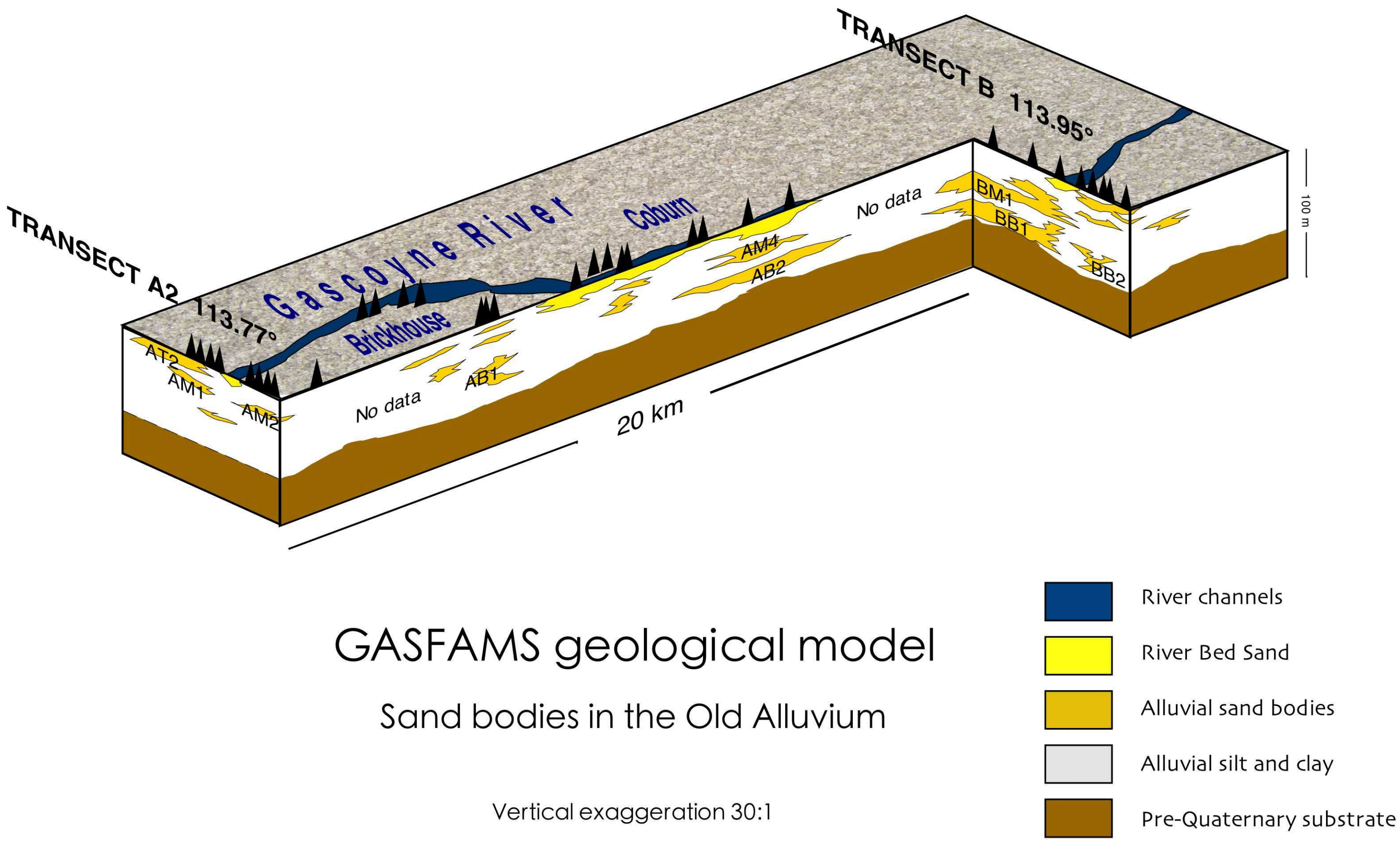


Figure 4: GASFAMS V1.1 Geological Model – Subareas B-L

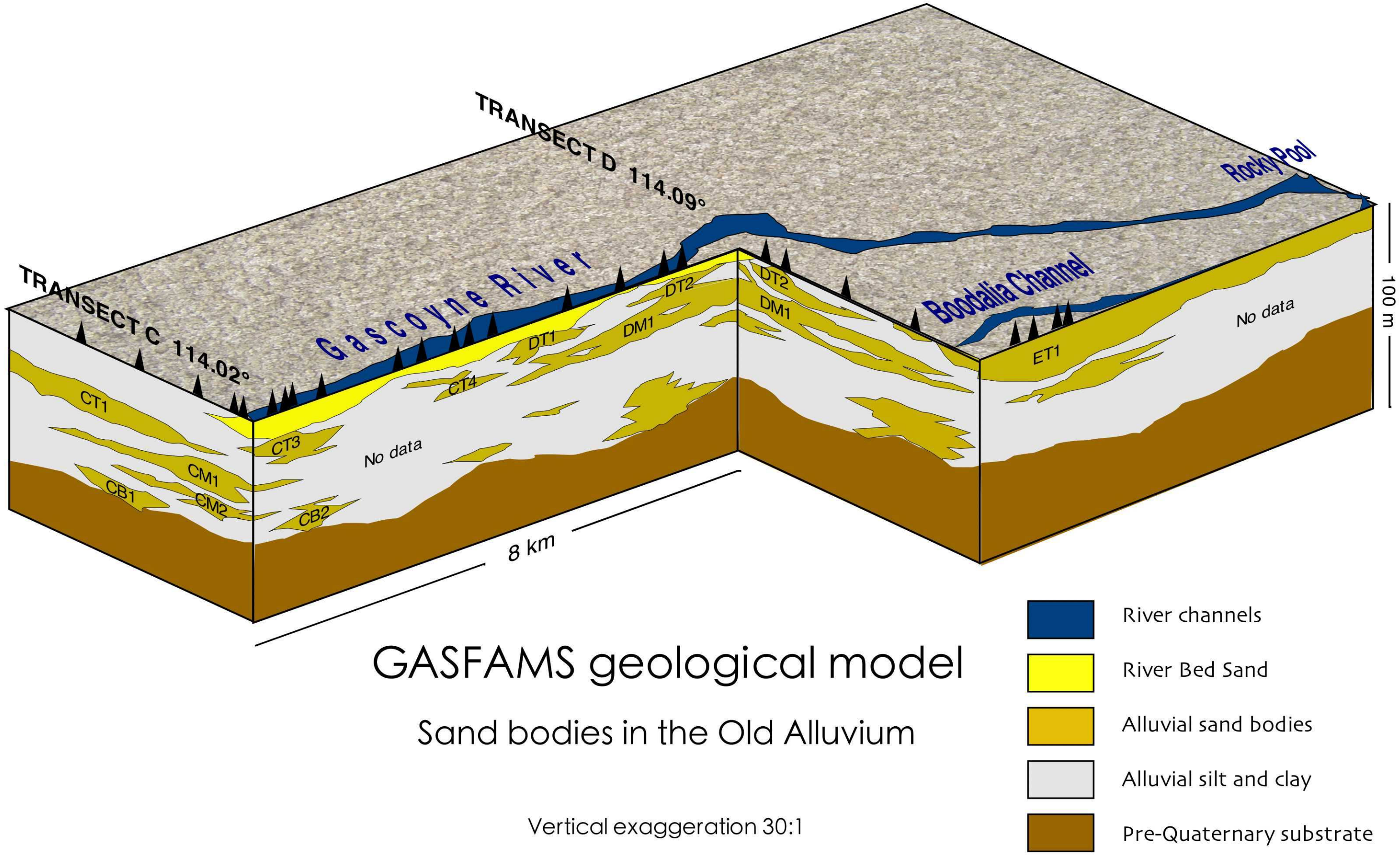


Figure 5: GASFAMS V1.1 Geological Model – Subarea A

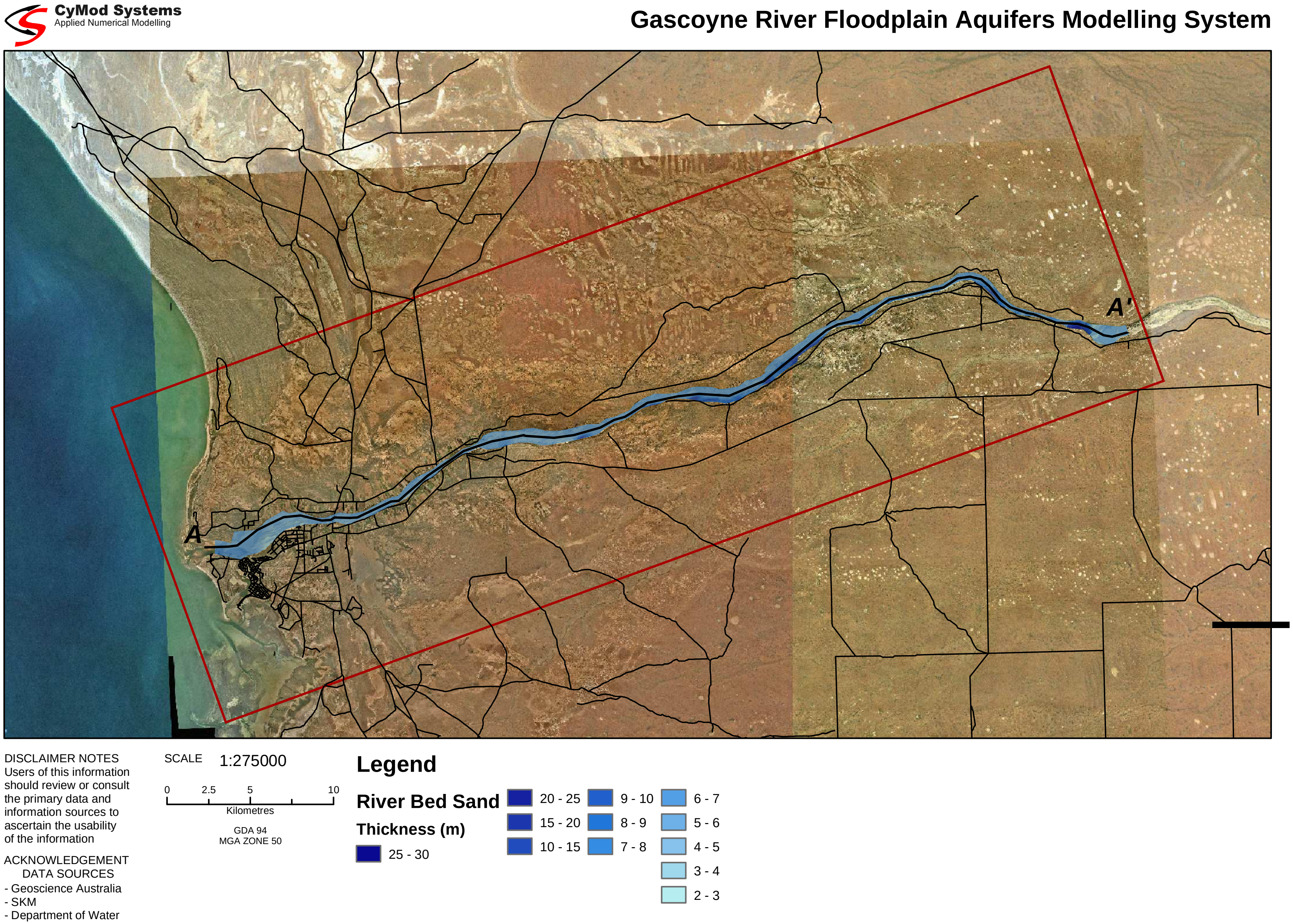


Figure 6: River Bed Sand Thickness

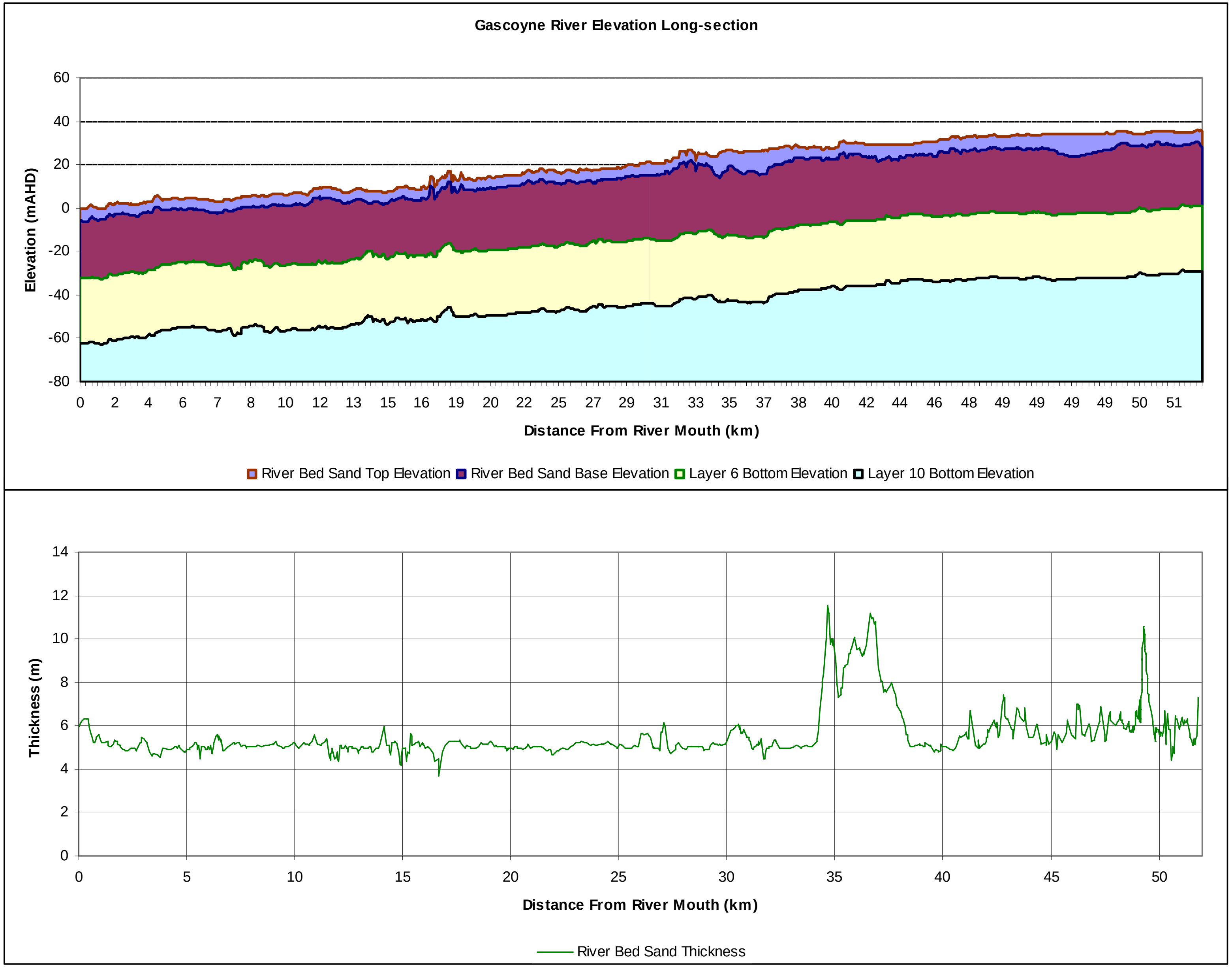


Figure 7: River Bed Sand Top and Bottom Elevations and Thickness

5 HYDROGEOLOGY

5.1 Aquifer Systems

Figures 8 and 9 schematically show the conceptual hydrogeology of the Gascoyne River floodplain with respect to groundwater flow processes. Figures 10 and 11 schematically show the conceptual hydrogeology of the Gascoyne River floodplain with respect to solute transport processes.

Several authors (Allen, 1972; Skidmore, 1977; Martin, 1990a, 1990b; Dodson, 2001, 2002) have described the hydrogeology of the area previously. Within the floodplain of the Gascoyne River, the groundwater system is hosted within a regional, unconfined to semi-confined aquifer system. The generally sandy aquifer is semi-confined by finer grained sediments in places. Based on available bore data the thickness of the aquifer ranges between 68m in the east to 50m in the west, at the coast.

Recharge to the sediments occurs mainly through direct infiltration resulting from episodic surface water flow within the river course. The surface water quality information obtained for the river gauge stations (Table 8) recorded Total Dissolved Solids (TDS) values between 62 and 1,053 mg/L. It is considered that the this fresh surface water (i.e. river flow) is contained largely within the river bed/channel, but also infiltrates the surrounding sediments laterally away from the river, to form a fresh water lens within the aquifer system overlying more saline or hypersaline groundwater in the deeper horizons of the aquifer. Lateral inflow of saline groundwater to the local aquifer from the surrounding regional groundwater system occurs at distance away from the immediate vicinity of the direct recharge influence of the river, and may cause increasing salinities, especially in response to pumping. In addition, saline inflow can occur at the marine water interface at the coast to the west; saline water intrusion has been reported by Skidmore (1977).

The western boundary of the aquifer system is the saltwater interface at the Indian Ocean and in the east; the flow system is bordered by the Toolunga Calcilutite on the western side of the northeast trending fault at Rocky Pool. It should be noted that there is no surface expression of the fault to the southwest of Rocky Pool, as the calcilutite is buried beneath the floodplain sediments (Allen, 1971). It is therefore assumed that the groundwater flow system is likely to be continuous with the alluvium east of Rocky Pool and south of the Gascoyne River (Dodson, 2001), and therefore lateral inflow to the local aquifer is likely to occur in this area.

The groundwater system is grouped into two distinct aquifer units which are in hydraulic connection with each other; the riverbed sand aquifer (RBS) and the underlying older alluvium aquifer (OAA), which together comprise the Gascoyne River Floodplain aquifer system.

5.1.1 Riverbed Sand Aquifer (RBS)

The RBS, consisting of the bed load of the current course of the Gascoyne River, is a single layered unconfined aquifer that contains fresh groundwater of recent age, recharged frequently by the episodic flowing of the Gascoyne River. Besides surface water filling from the intermittent river flows, fresh groundwater stored in the aquifer unit also leaks downwards to recharge the older alluvium aquifer (Allen, 1972; Martin, 1990). The RBS is an unconfined aquifer with a maximum saturated thickness of about 12m and an average saturated thickness of about 5m, based on the current data review (Figure 7).

Hydraulic gradients are low within the aquifer, resulting in low groundwater velocities and flow through the aquifer. After extended dry periods, when the sand becomes unsaturated locally due to falling groundwater levels, there is probably no groundwater throughflow (Dodson; 2002). Variations between average annual maximum and average annual minimum water levels confirm the observations by earlier workers that changes between river flow events and direct recharge from the river forms the major source of recharge to the RBS and irregular rainfall is a source only to a lesser extent.

5.1.2 Older Alluvium Aquifer (OAA)

The geological sequencing undertaken during the current study indicates that the OAA is a multi layered aquifer unit, which is semi-confined to confined in places. Borehole logs indicate a maximum thickness of 68m with a decrease in thickness westward. Skidmore (1997a) reported that the older alluvium comprises predominantly clay, silty clay, gravel and sandy clay, clayey sand, silty sand and minor sand, gravel and laterite. The various sediment sequences were categorised during the current study into six major classes for easier conceptualisation of the OAA aquifer unit.

Vertical and lateral leakage occurring from the overlying RBS aquifer unit is thought to be the principal recharge mechanism to the OAA unit, which exhibits a delayed response in observed groundwater levels to flowing or changes in the river level. Surface water flow within the river system and its immediate vicinity results in a groundwater mound developing with the RBS aquifer units that lies beneath the Gascoyne River and consequently within the underlying OAA unit due to vertical leakage as recharge (Martin, 1990; Dodson, 2002). The laterally restricted extent of this recharge mound may be an indication that the rate of vertical infiltration during a river flow event is greater than the rate of horizontal groundwater through-flow away from the mound (Dodson, 2002).

Textural variations within the aquifer in the vicinity of the river course are deemed to restrict the lateral movement of groundwater and hence lead to mounding during higher flow periods. During dry periods, with little or no surface water flow within the river course, hydraulic gradients on the groundwater surface reduce as the water table recedes and the mound flattens as the rate of vertical infiltration reduces and movement of water to the north and south of the river becomes relatively more significant.

Multiport wells drilled perpendicular to the Gascoyne River in three transects (Martin, 1990b) measured potentiometric heads at different depths within the aquifer profile (reproduced in Dodson, 2002). Isopotentials were presented to show conditions, following a no-flow period of four months soon after commencement of a major flow and after three months of flow. The isopotential patterns indicated the hydraulic connection between the RBS and OAA aquifer units prior to a river flow event (December 1988) and variability in the rise in groundwater heads in the OAA after the start of river flow (May 1989). This variability was considered to indicate the heterogeneous and anisotropic nature of the older alluvium due to the presence of low permeability finer grained sediments (Martin, 1990). After three months of flow, in July 1989 the potentiometric levels in the OAA rose further than a kilometre distance from the river course in response to the river flow, with the rise decreasing in magnitude with distance from the river (Martin, 1990b). Close to the river the groundwater level response was recorded to be up to 4m in some multiports. It can be concluded that aquifer response to river flow events is rapid and water stored in the system is substantially recharged via vertical leakage during river flow, and that lateral dispersal through the aquifer is slower from the river.

Groundwater outflow from the OAA occurs mainly by pumping/abstraction, through-flow in the system, outflow westward to the Indian Ocean and possible leakage to the underlying basement.

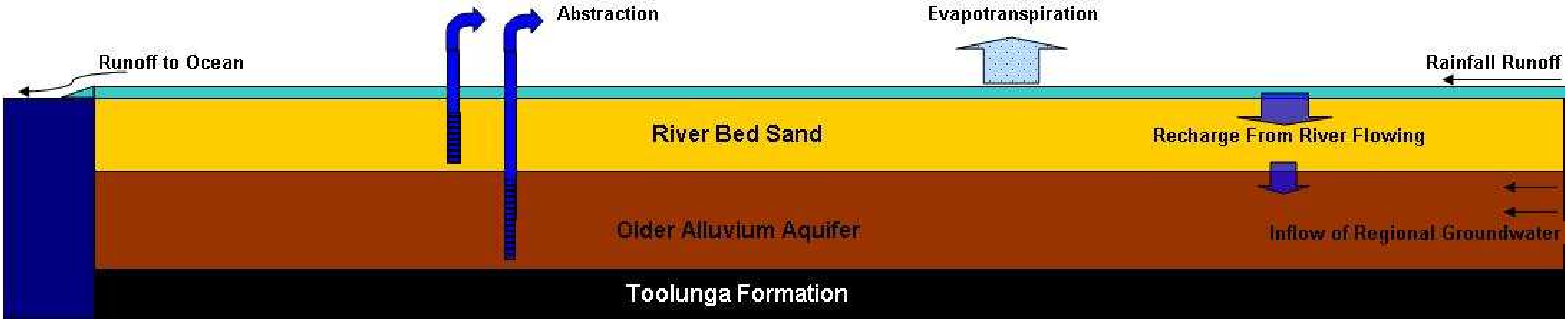


Figure 8: Flow Conceptual Hydrogeology

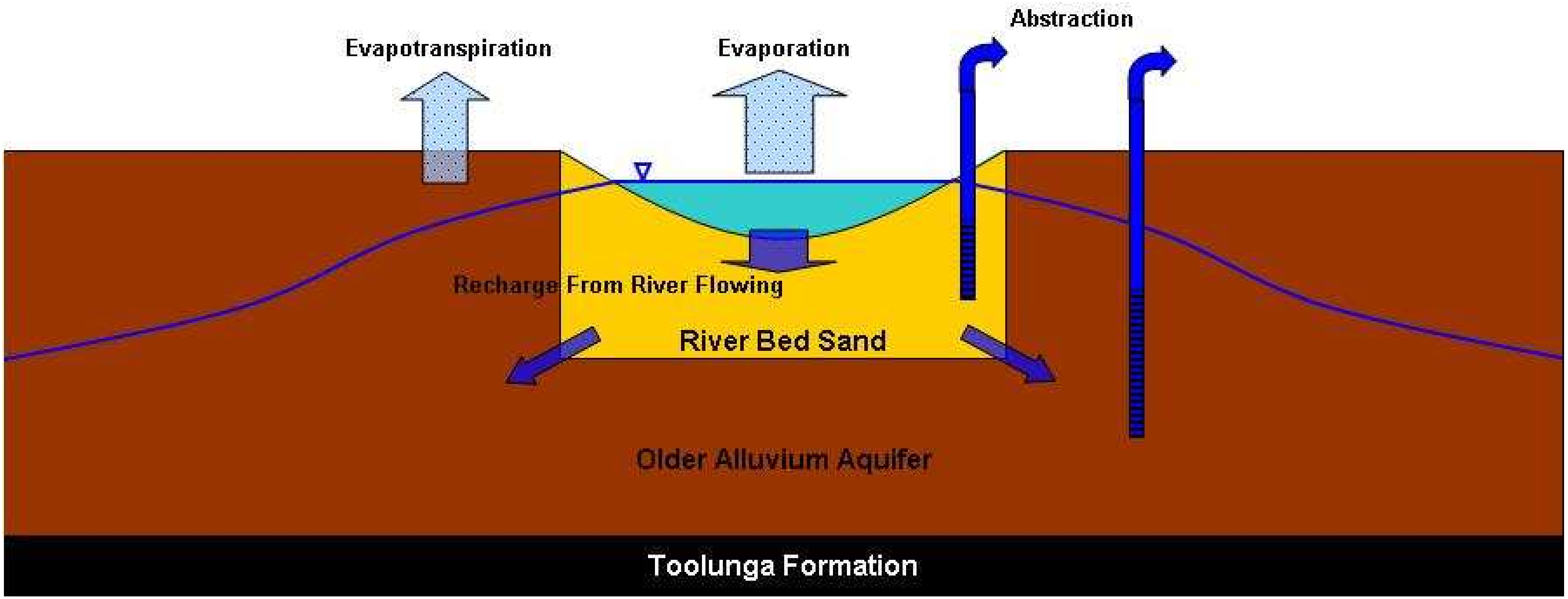


Figure 9: Flow Conceptual Hydrogeology

Figure 10: Solute Transport Conceptual Hydrogeology – Long Section

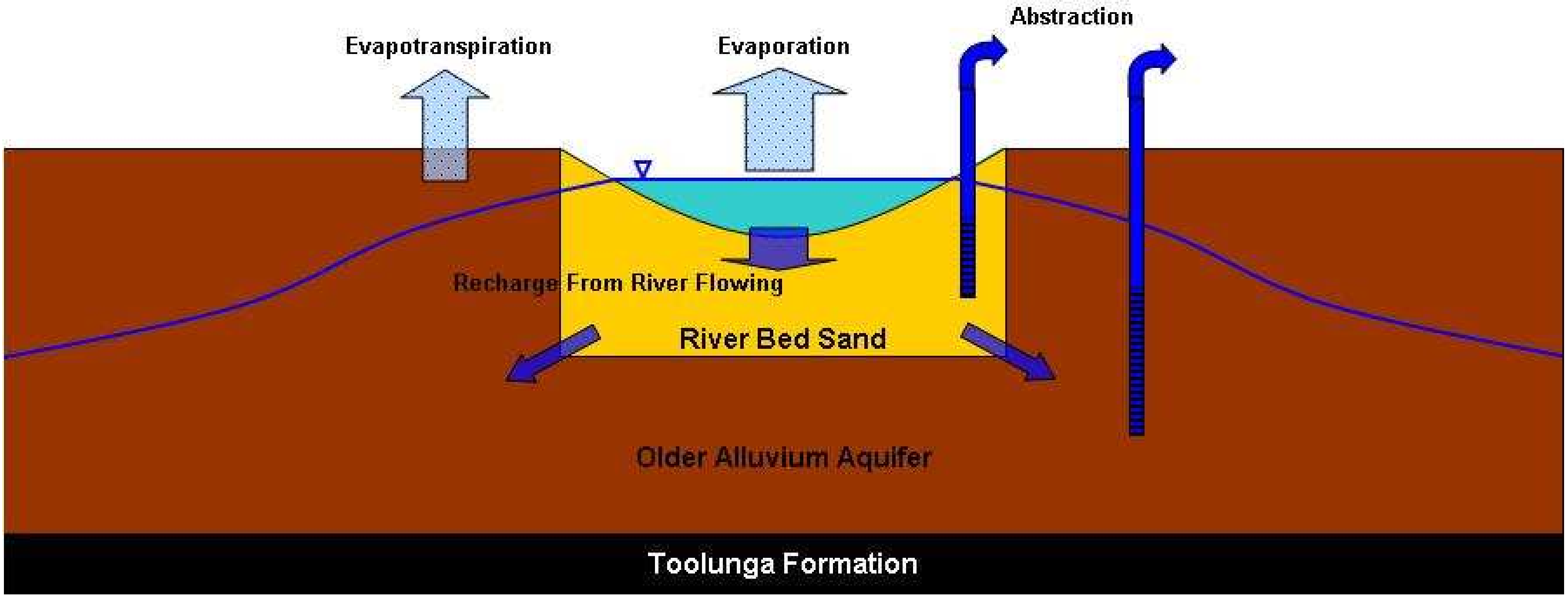


Figure 11: Solute Transport Conceptual Hydrogeology – Cross Section

5.2 Aquifer Boundaries

Evidence for pre-existing deposits from the ancient river system underlie the two recent surface systems, represented by the RBS and OAA aquifer units, to a depth of at least 60m in many parts of the river plain, as observed within the bore record. The alluvial deposits extend to depths of between 10 and 20 mBGL (metres Below Ground Level) up to 8 km from the river to the north and south.

Dodson (2002) assumes that the Toolonga Formation is impermeable for his model, although the sole pumping-test information for this unit indicates a permeability of 4 m/day, within the wide range of values for the alluvium. However, Allen (1972) notes that groundwater and isohaline contours at Rocky Pool indicate that the outcropping Cretaceous unit acts as a flow barrier relative to the alluvium, and bores at Rocky Pool indicate that there are no significant aquifers at depth until the Birdrong Formation at approximately 182.8 mBGL, which is confined and saline. In addition, the geological units directly underlying the Toolonga Formation, namely the Muderong Shale and Windalia Radiolarite, almost certainly exhibit low permeability. The current study therefore adopts the Toolonga Formation as an effective impermeable base to the model, consistent with Dodson (2002).

There is no hydrogeological information on the Cardabia Formation, an early Tertiary unit of sandstones and siltstones that overlies the Toolunga Formation in bores, which does not occur at outcrop within the region. It is sometimes described as well-cemented sandstone in logs, but otherwise there is no reason to exclude it from the alluvial wedge for the purposes of the modelling.

Since groundwater monitoring data is laterally sparse at distance from the river, the method of net groundwater volume calculation was adopted to assess the flow envelope and extent of the aquifer boundary to the north and south, away from the river. Groundwater levels for the high rainfall periods (varying between February and July) during the 1985 to 2002 period were extracted from the hydrographs for the OAA. Similarly, water levels were assessed for typical average dry months (November to January) for this period. Average annual maximum (aaMAX) and average annual minimum (aaMIN) groundwater heads were derived from this data and compared to define the zone of influence of the Gascoyne River on groundwater levels. The zone of influence boundary is defined as where the difference between aaMAX and aaMIN groundwater heads is zero, as shown in Figure 12. An approximate distance of 3.6km away from the river was derived as the radius of influence, and represents the minimum extent of the modelled area. This approach and the distance estimated is assumed to be a reasonable estimation, since Martin (1990) concluded that beyond 1500m there was no discernible response to river flow within the older alluvium three months after the flow event.

Dodson (2002) observed that monitoring of multi-port bores at a lateral distance from the river over a six-year period indicated fluctuations in watertable levels between 0.43 and 2.21m in the south of the river, and between 1.24 and 1.47m in the north of the river. The model boundaries in the GRFAMOD model (Dodson, 2000) were set at 4km distance north and south of and parallel with the river course and principal area of groundwater abstraction. It was argued (Dodson, 2002) that the depths to the water table below the ground surface (approximately 16m in the south of the river, and 21m in the north of the river) were beyond the influence of evapotranspiration from vegetation present within the study area. Therefore the observed watertable fluctuations at 1,500m lateral distance were in response to river flow or groundwater abstraction, and hence an effective boundary must occur beyond this distance. Since the monitoring data for the selected bores have not been continuous between 2002 and 2005 this exercise was not repeated or extended during the current study and the distance derived from the radius of influence calculations is assumed to be in line with previous approaches.

To the north of the river, in the absence of any obvious hydraulic boundaries, the northern boundary of the model is situated beyond the calculated extent of influence of 3.6km from the river. Evidence for a region of higher permeability south of the river for 10km downstream of Rocky Pool from the sand body correlations led to the inclusion of the abandoned Boodalia Channel and the region between the channel and the Gascoyne River into the model. The Boodalia channel, while not modelled explicitly, is assumed to approximate to a groundwater flow line, and hence equivalent to a no-flow boundary perpendicular to this line, which forms the southern extent of the model. This is considered to be a more defensible and conservative assumption than the head-dependent boundary adopted in GRAFMOD.

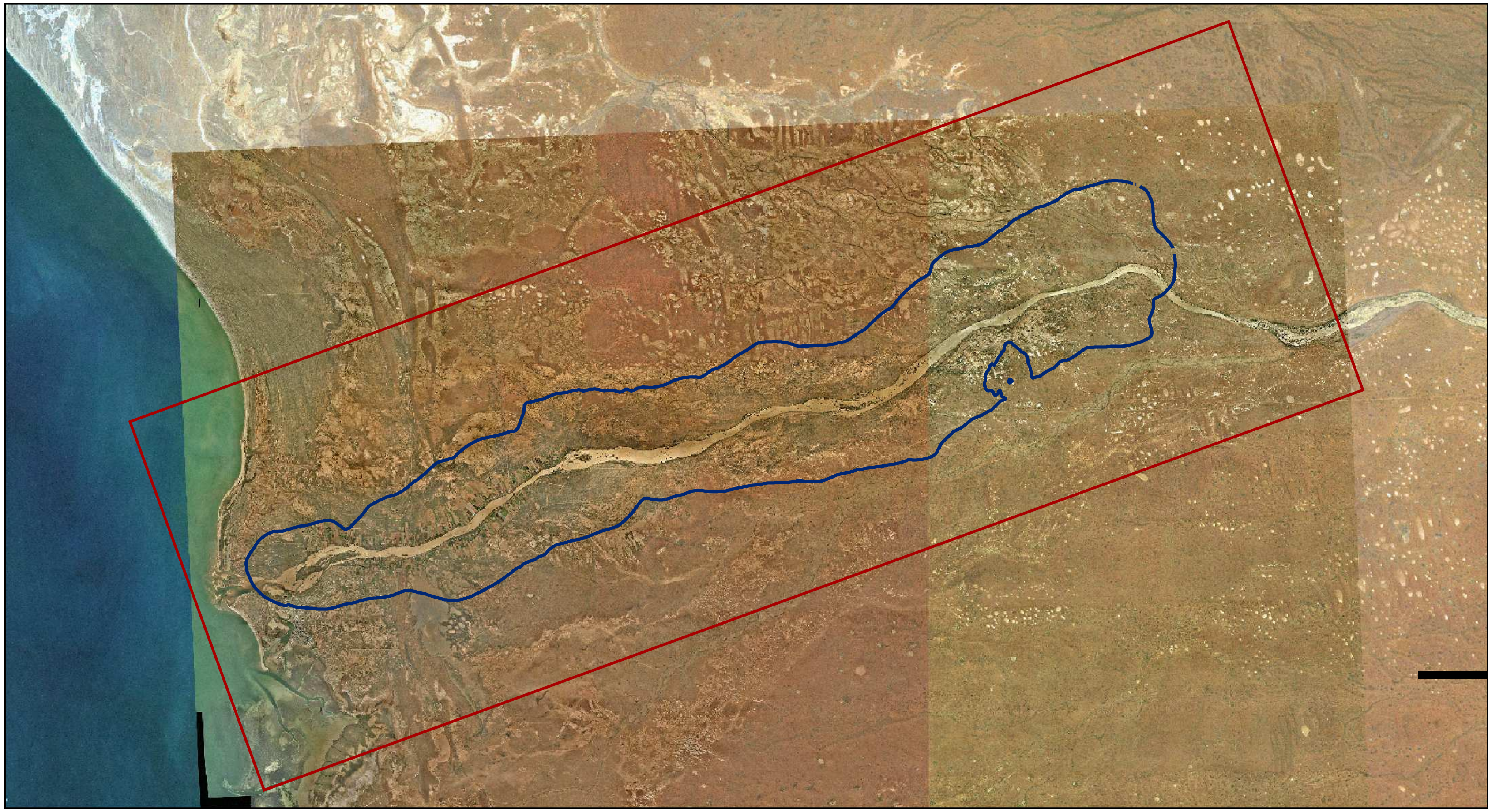
To the west, the saltwater interface at the Indian Ocean / river mouth is a natural western boundary for the model area. In the east, the no flow boundary formed by the outcropping Toolunga calcilutite on the western side of the NE trending fault at Rocky pool is assumed to be the eastern boundary.

5.2.1 Surface Water-Groundwater Interaction

The higher conductivity and storativity of the RBS aquifer unit allows it to be readily saturated during river-flow episodes and hence vertical leakage will occur into the underlying OAA aquifer unit as surface flow continues to provide a source of recharge to the overlying RBS during ‘wet’ months. Ponding within the finer sediments may happen with water slowly receding after the wet season. Since the lateral hydraulic conductivity is greater than the vertical hydraulic conductivity, excess water stored within the RBS that is not lost vertically by downward leakage may flow laterally and discharge back into to the river flow as baseflow after the highest flow period.

CyMod Systems
Applied Numerical Modelling

Gascoyne River Floodplain Aquifers Modelling System



DISCLAIMER NOTES
Users of this information should review or consult the primary data and information sources to ascertain the usability of the information

ACKNOWLEDGEMENT
DATA SOURCES
- Geoscience Australia
- SKM
- Department of Water

SCALE 1:275000

0 2.5 5 10
Kilometres

GDA 94
MGA ZONE 50

Legend

Study Area

Zone of River Influence

Figure 12: Zone of Influence of Gascoyne River

5.3 Aquifer Tests and Aquifer Parameters

The results of twelve pumping-tests conducted along the Gascoyne River between 1968 and 1971 were reported by Allen (1972). Vogwill (1972) conducted a pumping-test analysis on two bores screened in the RBS aquifer unit. Allen (1972) concluded that, based on the methods of Boulton (1963) and Chow (in Kruseman and de Ridder, 1976) that the OAA was a leaky confined aquifer.

Transmissivities of between 4.6 and 248 m^2/day were reported for the OAA aquifer unit based on two constant-rate pumping tests conducted within the older alluvium using the Boulton (1963) analysis method in Martin (1988b). The two bores selected by Martin contained mostly clay (bore 7/74) and the second is sand (bore 1/87), reflecting the approximate compositional range of the OAA. Aquifer parameters have been also derived from Hvorslev slug test analysis (various authors) to arrive at an average hydraulic conductivity value of 3.7 m/day and an average transmissivity of 185 m^2/day for the OAA (Martin, 1988a).

Eight production bores were test-pumped for twenty-four hour duration during the 1993/94 borefield investigation (Skidmore, 1997a). The results indicated an average hydraulic conductivity (K_h) value of 3.8 m/day and a transmissivity value of 205 m^2/day for the OAA, estimated using the Theis (1935) recovery method for confined aquifers. However, since observation bore data were not available for analysis, these results were reported to be unreliable by Skidmore (1997a). It is commented that many of the historic pumping-tests were conducted on bores that were fitted for production, at sites where the thickest intervals of sand with the least clay had been intersected, and hence the test results are biased towards sandy sections of the older alluvium and thus are likely to represent the upper limits of hydraulic conductivity.

The average vertical hydraulic conductivity (K_v) for the OAA entire profile reported previously was between 0.01 and 0.03 m/day respectively, estimated by measuring the concentration of tritium in groundwater and by an empirical groundwater balance technique (Martin, 1990). It is commented that the vertical leakage will depend on the variability of vertical conductivity of individual clay and sand lenses within the older alluvium. Dodson (2002) reported that when many clay beds exist in a single layer the real vertical leakage becomes infinitely small and not all clay lenses could be represented adequately in the previous GRFAMOD model.

The DoW WIN database also contains estimates of drawdown for eleven bore yield tests conducted during pumping. Transmissivity values were estimated using discharge volumes and the maximum recorded drawdown using Logan's approximation method (Kruseman and De Ridder, 1983), which uses the equation:

$$k_D(T) = \frac{1.22 \times Q}{S_{mw}}$$

where:

$k_D(T)$ = transmissivity (m^2/day)
Q = discharge (m^3/day)
s_{mw} = maximum drawdown (m)

The ranges of aquifer parameters for both the RBS and OAA aquifer units, based on all the above methods are given in Table 7.

	Thickness (m)	Kh (m/day)*	Kv (m/day)	Transmissivity (m^2/day)*	Specific yield	Storage Coefficient
RBS	4 -12	20-812 (164)		78-3,980 (850)	0.29-0.32	
OAA (based on pumping-tests only)	3 - 57	0.8-121 (18)	0.03	5-830 (166)	~0.15	0.0005 to 0.006 (0.0025)
OAA (based on pump tests and slug tests)		0.8-121 (11)		5-830 (175)		0.0001
OAA based on pump tests, slug tests and Logan's estimate				5-830 (167)		

Averages in brackets

Table 7: Summary of Aquifer Parameter Ranges

5.4 Groundwater Bores and Water Levels

Groundwater level data obtained from the DoW WIN data base were assessed for data integrity and continuity. It is commented that the DoW database has not been updated to a significant degree since 2002 and no data was obtained post-2005. Subsequent requests for data resulted in water level and flow data for 257 bores between 1912 and 2008.

Groundwater quality data is available for 218 bores, of which 227 bores had one or more readings recorded since 1990. Forty of these have only one set of readings since January 1990; and hence were not included in the analysis. Only 37 of the remaining 187 bores have data since 2000. It was therefore concluded that data from the remaining 150 bores were suitable for use as calibration bores in the numerical model.

A review of a combination of the DoW datasets produced by Skidmore (1977), Martin (1990) and Dodson (2002) was carried out. More recent data from 1990 onwards was assessed, including hydrographic data. All bore data, available logs and depths were assessed to assign each bore to the relevant aquifer unit (RBS/OAA). Deeper piezometers, observation bores and production bores were categorised as OAA bores. Bores listed as observation bores with no known screen depths but shallow drilled depths were ascribed as RBS bores; bores listed as shallow production piezometers (GR) were also included as RBS bores. A final list of OAA and RBS bores used for the model conceptualisation and water balance analysis (based on screened interval, lithology, depths, etc.) is included in Appendix E.

The highest groundwater levels for bores in each year and an average of the maximum annual groundwater levels were obtained from the hydrographs. An attempt was made to analyse the difference between the wettest and the driest periods' average maximum groundwater levels based on rainfall data. Groundwater levels for March 1990, September 1991, June 1992, October 1993, September 1996, November to December 1997 and September 1999 were selected for water table analysis. However in the final water balance analysis (refer to Section 9) the maximum water levels between the years 1985 and 2002 were selected for analysis.

5.5 Groundwater Storage

River flow, vertical infiltration, groundwater throughflow and evapotranspiration are the major factors that influence groundwater storage in the RBS aquifer. The specific yield of the RBS was previously estimated to be between 0.29 and 0.32 (Vogwill, 1972) and 0.30 based on pump tests (Allen, 1972). A conservative specific yield of 0.25 was used by Allen, (1972) to arrive at 20 x 10^6 m^3/annum groundwater held in storage. Using a specific yield of 0.30, storage was calculated to be 28 x 10^6 m^3/annum (Dodson, 2002).

Groundwater storage in the OAA aquifer unit was previously estimated based on the extent of drilling programmes north and south of the river and also the fresh nature of the aquifer based on TDS values less than 500 mg/L. Previous estimates have ranged between 100 x 10^6 m^3/annum (Allen, 1972) up to 340 x 10^6 m^3/annum (Martin, 1990b), using an effective porosity of 0.1. Dodson (2002) argued that both estimates were conservative, since knowledge of the extent of freshwater present within the Water Corporation groundwater Scheme borefield was unknown at the time of Allen (e.g. 1972), and since Martin (1990a) had excluded consideration of any freshwater contained within the OAA in Subarea A. During the current work storage estimates were carried out as detailed in Section 9.

5.6 River Levels and Flow

Available daily river flow data for six river gauge stations were obtained from the WIN database and are shown in Table 8.

WIN Site Id	Site Type	Feature Type	AWRC Reference	AWRC Context Name	AWRC Name
16491	Surface	Stream gauging	704139	Gascoyne River	Nine Mile Bridge
16493	Surface	Stream gauging	704193	Gascoyne River	Fishy Pool
16494	Surface	Stream gauging	704194	Gascoyne River	Jimba
15104174	Surface	Stream gauging	704195	Gascoyne River	Yinnetharra Crossing
23012585	Surface	Stream gauging	7041391	Gascoyne River	9 Mile Br / Left Bank
23012586	Surface	Stream gauging	7041392	Gascoyne River	9 Mile Br / Right Bank

Table 8: River Gauge Stations

The main gauging stations within the coastal plain are Nine Mile Bridge and Fishy Pool (inland). The station at Nine Mile Bridge is the most relevant; being located approximately 15km upstream of the river mouth and with a long data record, since 1957. Annual flow volumes from 1990 to 2006 for the Nine Mile Bridge gauging station are shown in Table 9.

Year	Total Flow at Nine Mile Bridge (GL/annum)
1990	872
1991	117
1992	722
1993	3
1994	435
1995	1811
1996	492
1997	1
1998	570
1999	1702
2000	3134
2001	442
2002	0
2003	0
2004	341
2005	50
2006	249

Table 9: Nine Mile Bridge Annual Flow

Mean annual flow at Nine Mile Bridge is 940 GL/annum and the maximum flow event flowed 3134 GL in 2000. Between 1985 and 2006, comprising over 7,916 days of recorded data, 5,730 days (or 72%) were no-flow days at this station. Overbank flows leave the river upstream of this site during large flows, as the active delta extends up to Rocky Pool (SKM, 2002). There is a significant loss of surface water volume during river flow across the width of the coastal plain indicated a reduction in stream discharge from Fishy Pool to Nine Mile Bridge (Dodson, 2002). Transmission loss between Fishy Pool and Nine Mile Bridge gauging stations is calculated to have a mean of 12%. Therefore, groundwater recharge from river flow was estimated by an alternative method in the water balance equation (refer to Section 9).

6 FLOW MODEL CONSTRUCTION

The GASFAMS V1.1 numerical flow model uses the data contained in the GRFAMOD groundwater model developed by Dodson (2002), and other data to construct a flow and solute transport model of the Lower Gascoyne River. Based on a review of the GRFAMOD model, the new model was constructed of the study area, having the following changes:

- Non-uniform rectangular cell grid;
- 10 vertical layers;
- updating of the rainfall and flow data to 2008;
- updating of the bore abstraction data to 2008;
- the inclusion of layer elevations for all layers in the model and the conversion of confined layers to confined/unconfined;
- revision of parameters based on review of the quantitative geology as per Section 3;
- a new river flow recharge model;
- the deprecation of rainfall recharge as a mechanism for aquifer recharge;
- the use of the multi node well package (MNW) to simulate abstraction; and
- the addition of a solute transport model to simulate changes in water quality.

The design and construction of the numerical groundwater model are described below, in terms of the MODFLOW datasets used, the approximations made with respect to the saturated flow and solute transport numerical models. In general, GASFAMS V1.1 has been designed to simplify and generalise groundwater flow in the lower Gascoyne River, so that it can be used for management of the water resources of the Gascoyne River aquifers.

6.1 Modelling System

The GASFAMS V1.1 model was constructed using a groundwater modelling system consisting of the numerical groundwater models, a database containing calibration, geological and abstraction data, and pre- and post-processors. The major components are described below.

6.1.1 Saturated Flow Model

After a review of available saturated/unsaturated flow models and in consideration of the DoW’s preference to use Visual MODFLOW as the pre-processor, two programs were evaluated during the construction phase of the numerical model: MODFLOW-2000 and MODFLOW Surfact for modelling saturated flow. Table 10 shows the advantages and disadvantages of each with respect to the construction and running of the model, relative to using Visual MODFLOW the preprocessor, as it applies GASFAMS V1.1.

Variable	MODFLOW-2000	MODFLOW Surfact	Comments
Computation time	Good, < 30 minutes	Average, > 1 hour	Use of pseudo soil function increases computation time for MODFLOW Surfact
Stability	Average, requires the use of the wet/dry function	Poor, failed to converge in many cases	No options to solve convergence issues in either package
Simulation of Wells	Uses the Multi Node Well module which is not efficiently supported by Visual MODFLOW	Good - Uses the fracture well package which is equivalent to the multi node well package	Requires pseudo soil functions for MODFLOW Surfact
Solute transport	MT3D – supported by Visual MODFLOW and widely used	ACT – not supported by Visual MODFLOW	
River Module	Visual MODFLOW supports MODFLOW River package.	Visual MODFLOW supports MODFLOW River package.	
Support of EVT	Visual MODFLOW does not support the layer property which is required due to dry nodes in layer 1	Implicitly works well with pseudo soil functions.	Long execution times using pseudo soil functions for MODFLOW Surfact

Table 10: Modelling System Comparison

Most of the initial work on the model was directed at developing a MODFLOW-Surfact model that could simulate saturated/unsaturated flow in the RBS and OAA, and then be used to simulate solute transport using the same platform. The use of MODFLOW Surfact excluded using MIKE11 to simulate one-dimensional surface water flow in a surface/groundwater coupled model. Consequently, the development of a MIKE11 river flow model for the calibration and validation periods was not undertaken, and was replaced by the River package. However, the development of the MODFLOW Surfact model became problematic due to increasing computational times and instability associated with the use of pseudo soil functionality in the model to account for unsaturated flow. Subsequent to model development, it was determined that Visual MODFLOW 4.3 does not support the solute transport aspects of MODFLOW-Surfact V3, and that new versions of Visual MODFLOW were unlikely to support these solute transport capabilities, making the continued development of this model not viable in the context of the DoW. Effectively, only the MODFLOW-Surfact V3 flow model can be generated using Visual MODFLOW, the transport component would need to be generated using another pre-processor.

The MODFLOW-Surfact model was converted to a standard MODFLOW-2000 model, using the wet/dry option to account for desaturation/rewetting of the RBS during droughts and due to pumping, followed by river flow. The implications of this approach versus a pseudo soil function approach are described in detail below. Unfortunately, Visual MODFLOW 4.3 (VM) does not efficiently support some aspects of MODFLOW-2000 required to simulate the Gascoyne River aquifer system. This has necessitated the use of Groundwater Vistas to generate the multi node well file and PMWin to construct flow sequences as used in the River module of MODFLOW-2000. The MNW file can be generated by Visual MODFLOW 4.3 but it is not amenable for use with more than about 20 production bores. Consequently, Groundwater Vistas was used to generate historical abstraction data (consisting of more than 400 production bores over an 18 year period). The use of Visual MODFLOW for future production bores is viable given that they will be entered a few at a time into the model.

The use of MODFLOW-2000 provides an opportunity to use MT3DMS as the solute transport model. MT3DMS is a well-supported, widely used solute transport model that is available in Visual MODFLOW 4.3. As is the case for MODFLOW-2000, some of the required functionality to take advantage of all the capabilities of MT3DMS is missing from Visual MODFLOW, such as the mass loading boundary condition, and unrealistic limitations that no more than 400 solute calibration observations can be used at any one time by Visual MODFLOW. The solute model calibration required the use of custom dynamic link library (dll) as supplied by Waterloo Hydrogeologic to allow the input of more than 5000 solute concentration observations.

6.1.2 Datasets and Model Database

The GASFAMS modelling system consists of a Microsoft Access database containing abstraction, monitoring and environmental data, a MODFLOW-2000 groundwater model, MT3DMS solute transport model, using Visual MODFLOW as the pre- and post-processors. The construction, validation and updating of the GASFAMS database for use by Visual MODFLOW required considerable time and resources. The difficulty in constructing a viable database, coupled with the constraints imposed by Visual MODFLOW highlighted the deficiencies in some of the datasets and required the use of approximations to implement the model via MODFLOW-2000. These dataset deficiencies need to be corrected within the DoW datasets if GASFAMS is to become a viable management tool for the DoW. The major dataset deficiencies highlighted in developing the model database are described below.

The monitor bore construction data is incomplete in terms of elevation, screen locations and naming convention. Visual MODFLOW requires that all bores, whether production or monitoring, have screen intervals that fall within the model top and bottom surfaces. This constraint is reasonable but difficult to meet when dealing with a large number of bores, located over a large area, and interpolated topography. The DoW should obtain the required data for all bores for input into GASFAMS and other models and ensure it is available in machine readable digital format. The minimum data required for each bore is:

1. Location in UTM coordinates, both in UTM -49 and UTM -50 projection ;
2. Top of casing elevation in mAHD;
3. Cased depth of the hole; and
4. The completion interval, defined as the top and bottom of each screen interval.

Some of the source data used in GRFAMOD model was not able to be located and was extracted from the model as is. This included private and public abstraction from 1991 to 2000 as well as some of the salinity data. The source data files for GRFAMOD should be located or replicated and placed in a corporate database so as to provide a basis on which to develop models efficiently and without replication of effort.

Data was supplied from many sources, and in many formats which had small but important inconsistencies such as variation in names, coordinates in different projections, no unique identifying number or cross reference that could be use to cross reference bores from different datasets. Under these circumstances it was difficult to ensure fidelity in the construction of the data base and that all useful data was exploited in the construction of the model.

The following needs to be undertaken by the DoW prior to undertaking any additional numerical modelling of the Lower Gascoyne River:

- All bore construction data be reviewed and validated and entered into a corporate database;
- All bores to have a unique identifier that is consistent across all databases and all datasets;
- Multiple water level or water quality readings need to be stored with a unique identifier related to the bore unique identifier;
- A reference table constructed that relates all previous bore designations to the unique bore identifier;
- The proper name of all bores be established and non conforming labels to be expunged from all datasets;
- Water level, abstraction data, and water quality data as collected in Subarea A to be checked and then entered into a corporate data base - the use of local spreadsheets should be discouraged;
- Data should be disseminated only as indexed tables, using referential integrity rules;
- Collected data should be input into the database within six months, and only after quality assurance.
- Monthly abstraction data from public and private bores should be stored in a database, as monthly volumes.
- Monthly water quality data from public and private bores should be stored in a database, as electrical conductivity and equivalent TDS.

The GASFAMS database has been updated with water level and water quality data to December 2008, using data supplied by the DoW. The private abstraction data was updated to November 2007. The Water Corporation abstraction data was updated to November 2007.

6.1.3 System of Units

The GASFAMS model falls into two UTM zones. Since a groundwater model must be in a single Cartesian coordinate projection system, all spatial data must be projected in UTM Zone -50 or UTM Zone -49, GDA94 for it to be used in the model. GRFAMOD uses UTM Zone -49, AMG84. The use of UTM -49 reflects that most abstraction and monitoring bores are in Subarea A, which falls within the UTM -49 zone, However, the bores east of Nine Mile Bridge are in UTM -50, and this projection was used for Version 1 of the GASFAMS model. The use of UTM Zone -50 requires that all data in UTM Zone -49 be reprojected and dual sets of coordinates be maintained in the database. All projection used the GDA94 spheroid as required by the DoW.

The system of units used in the GASFAMS model is shown in Table 11, by model component. All other units are derived from these, and must be consistent in each model.

Model	Length	Time	Mass
MODFLOW	metres (m)	Day (d)	-
MT3DMS	metres (m)	Day (d)	grams (g)

Table 11: Systems of Units

6.2 Spatial Discretisation

6.2.1 Horizontal Discretisation

The GASFAMS model is designed to predict time-varying recharge to the superficial aquifer, under a variety of land use and climatic conditions on the Gascoyne River Coastal Plain, allowing for the ephemeral nature of the Gascoyne River. Consequently, the horizontal discretisation must account for the spatial distribution of landuse and the existing river channel. The landuse in Subarea A is typically at a 10-20 hectare resolution, while the river channel has a characteristic width of 500 to 1000 m.

The current Lower Gascoyne River model covers an area of 1150 km^2 (of which 28.7 km^2 represents the course of the Gascoyne River). The model grid consists of a block centred finite-difference mesh of 344 columns and 151 rows, after refinement of the GASFAMS V1.0 model grid in Subarea A from cell sizes of 50x250m to cell sizes of 50x83m. From east to west the finite-difference grid is irregular, with cells ranging from 83 to 2000 metres in width. From north to south the cells range in size from 50 to 1050 metres long, with highest resolution along the river bed. The use of variable size elements provides sufficient resolution for allowing the accurate consideration of the river, the calculation of small flows, large stage height differences between flows and will allow the grid to be used in the solute transport model. Figure 1 shows the Lower Gascoyne River model domain, while Figure 13 shows the model finite difference grid, illustrating the concentration of cells in the river flood plain.

6.2.2 Vertical Discretisation

Figures 8 and 9 show the conceptual hydrogeological model used in the development of the numerical model. The vertical thickness of the floodplain aquifer is divided into 10 separate layers. The top layer represents the uppermost riverbed sands (RBS) and accounts for topography. Layer 2 represents the bottom section of the RBS and in some places the OAA. As indicated in the conceptual geology, the differentiation of the RBS from the underlying OAA along the existing flow channel is not necessarily well defined. Layers 3 through 10 represent the OAA to the top of the Toolunga formation which effectively forms the impermeable base of the model. The lower eight layers of the model represent the older alluvium and intervening clay layers, and are a uniform 5 metres thick except for layers 9 and 10 which are 10 m, and of variable thickness, respectively. Given the available bore information, the exact mapping of sand and clay distributions proved difficult due to discontinuities and variations in lithological log descriptions.

The uniform thickness layers are used to provide adequate vertical resolution to simulate vertical gradients observed in the OAA, as well as to improve solute transport model performance, which tends to be better when constructed with a uniform vertical grid (Chen, 2005). These layers are also used to represent the spatial distribution of water quality, horizontal and vertical hydraulic conductivity, and changes in head with depth. The choice of a 5m layer thickness was based on predicted maximum observed changes in water levels over the area. The model layers for the multiple layer representation of the OAA were manually constructed by proportional triangulation between data points.

As the potentiometric head decreases with distance from the river, the area of active cells in each layer changes. Layer 2 directly underlies the riverbed sand and has fewer active cells than Layer 3 as the potentiometric head falls below the bottom of Layer 2 with distance from the river. Owing to the thinning of the older alluvium around Rocky Pool, the number of active cells in this region also changes with each layer. Layer geometry is shown in Appendix B.

Formation	Model Layer	Thickness	Comments
River Bed Sand	1, 2	Variable, from 3 to 12 m	Includes sub-cropping sand sequences in the OAA
Older Alluvial Aquifer	3-10	Layers 3-8: 5m Layer 9: 10 m Layer 10: up to 20 m	Models the sand, silty sand non-differentiated alluvial at depth.

Table 12: Summary of Model Layering

6.2.3 Temporal Discretisation

Temporal discretisation subdivides the model simulation period into stress periods and time steps in a manner analogous to spatial discretisation. Two types of temporal discretisation are used by MODFLOW: stress periods and time steps. Stress periods define a period over which stresses (i.e. abstraction, river flow, evaporation and other boundary conditions) remain unchanged or are constant. Time periods subdivide stress periods into smaller units so that an accurate numerical solution can be obtained, and reflect the characteristics of the model.

In the case of stress periods, a non uniform sequence was used, as defined by the occurrence of river flows. In the absence of river flows, a maximum length was set as calendar month. Time steps must be sufficiently short to allow accurate solution of the model. In the case of a flow model, the time step length is related to the characteristic time constant of the model, and can be approximated by:

$$T_c = \frac{S \cdot a^2}{4T}$$

where:

T_c = model characteristic time constant (days)
S = storativity
a = characteristic length (m, usually the minimum dimension of an element), and
T = representative transmissivity (m^2/day)

Using S = 0.005, a = 200 m, and an average T = 250 m^2/day, an initial minimum time step of 0.20 days is calculated. In general, adequate convergence is achieved with initial time steps on the order of 1 day. The time stepping in a solute model is generally calculated by the program, to meet stability criteria and is typically shorter than flow time steps.

As shown in Table 13, 23 flows occurred from April 1991 to December 2008. An analysis of the flow flows, peak stage heights and flow durations were used to generate the temporal discretisation for two 10-year simulations periods. The 1990 to 2000 simulation models moderate frequency recharge flowing conditions and contains 125 stress periods, while the 2000 to 2010 simulation models low frequency recharge flowing conditions and contains 141 stress periods. The use of non-uniform stress periods allows improved resolution of river flow events, while being numerically efficient in terms of overall number of model time steps required to complete the simulation.

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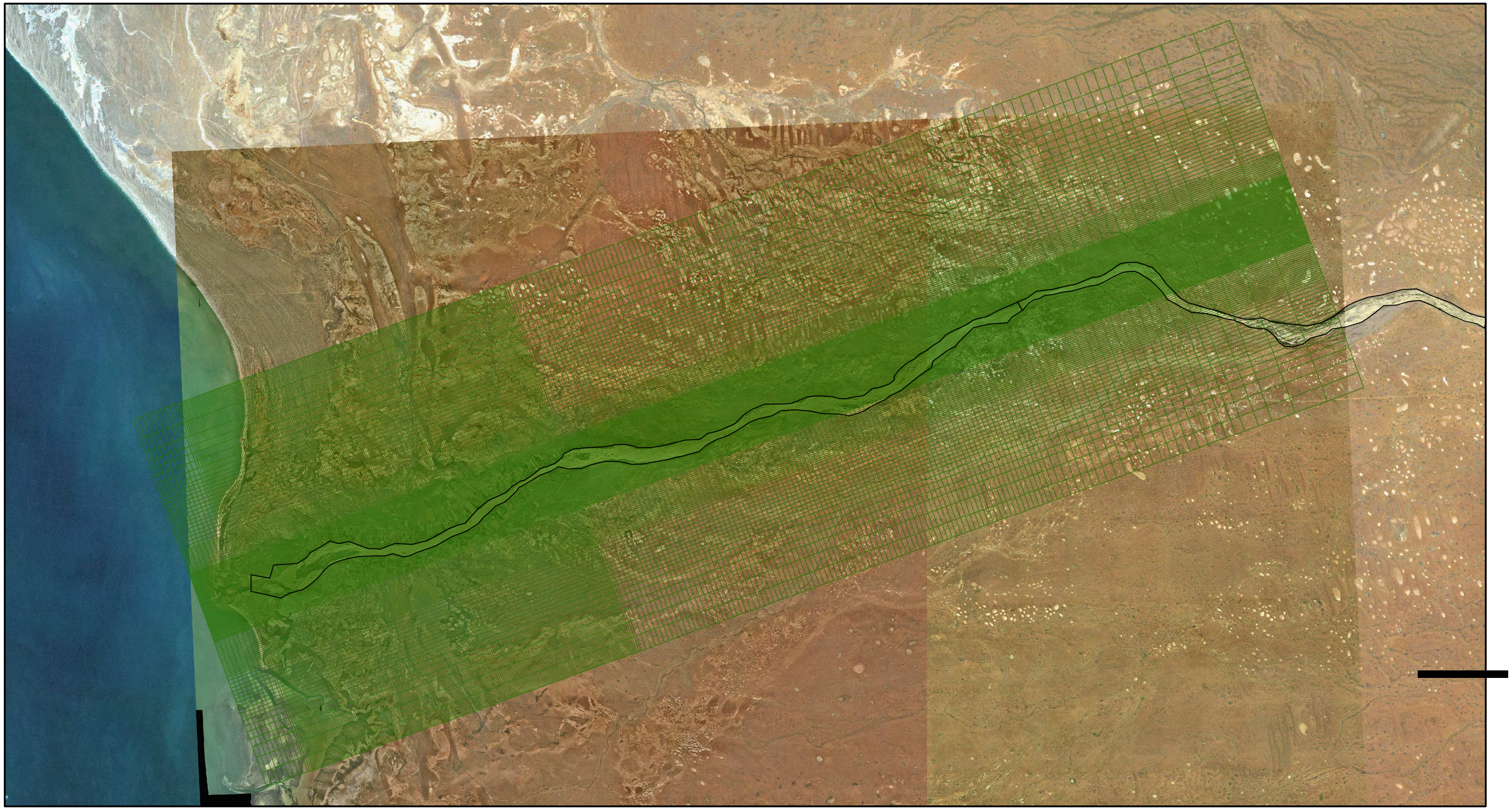

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SCALE 1:275000

0 2.5 5 10
Kilometres

GDA 94
MGA ZONE 50

Legend

Gascoyne River
Model Grid

Figure 13: Model Finite Difference Grid

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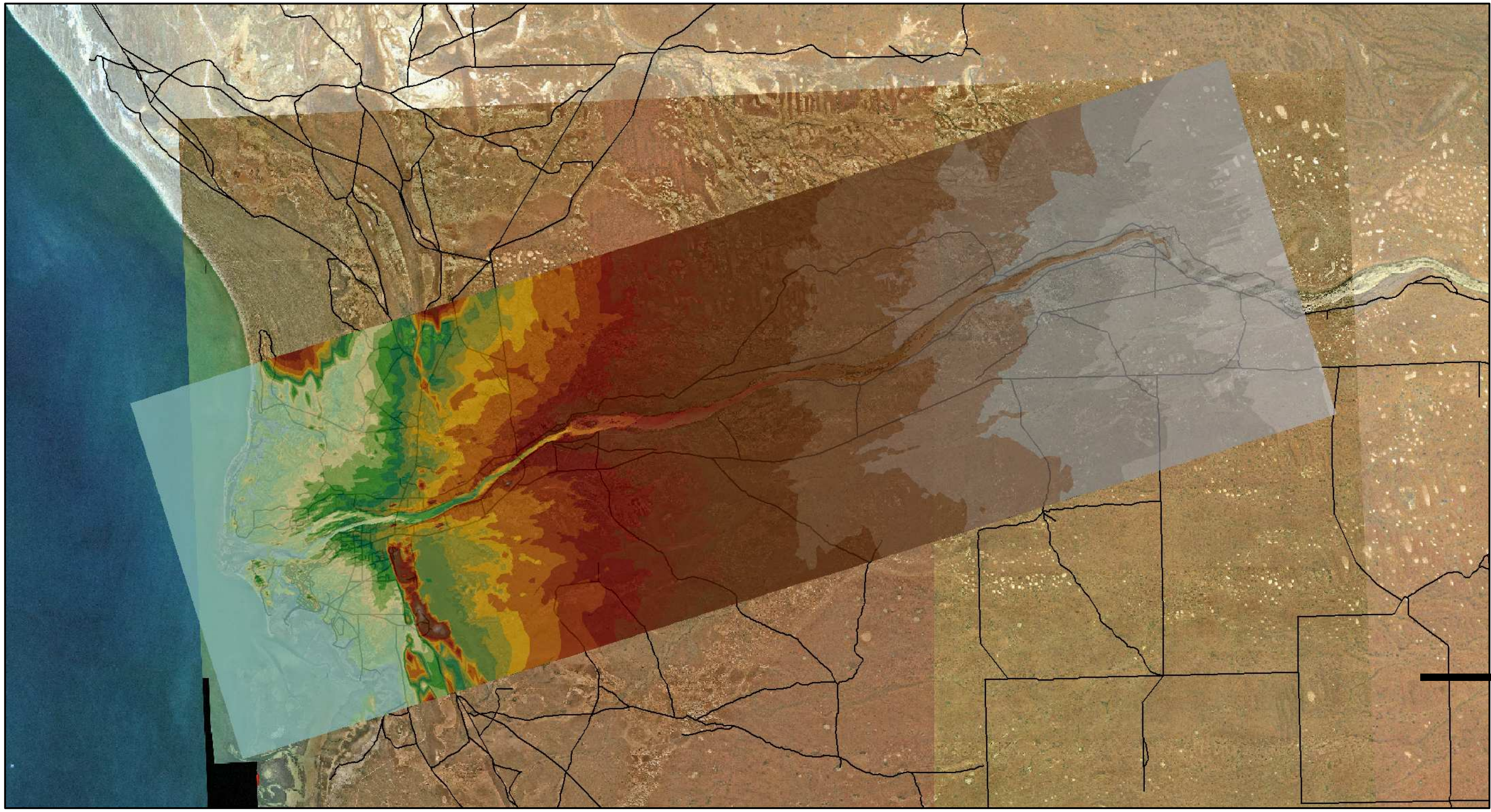

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SCALE 1:275000

0 2.5 5 10
Kilometres

GDA 94
MGA ZONE 50

Legend

Topography

Elevation (mAHD)

- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16 - 18
- 18 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 40
- 40 - 45
- 45 - 50
- 50 - 55

Figure 14: Topography

Flow Start Date	Peak Stage Height (m)	Flow Duration (days)	Simulation
July 1991	0.46	25	Moderate Frequency Recharge Flow Conditions
April 1992	2.95	31	
February 1993	0.53	4	
March 1994	3.64	6	
February 1995	6.90	11	
November 1995	0.06	14	
December 1995	0.97	18	
February 1996	0.07	10	
April 1996	1.77	20	
February 1997	3.66	18	
June 1998	4.14	19	
December 1998	0.88	1	
January 1999	6.40	9	
March 2000	7.70	11	Low Frequency Recharge Flow Conditions
February 2001	3.83	14	
January 2004	2.02	23	
February 2004	2.27	7	
July 2004	1.61	7	
May 2005	1.27	24	
January 2006	5.21	29	
April 2007	1.95	23	
July 2007	0.63	13	
February 2008	2.98	5	

Table 13: Flow Peak Stage Heights and Durations

6.2.4 Ground Surface

The upper surface of the model represents ground surface (topography) and is used as a reference surface for all head dependent boundary conditions. The topography was constructed as digital terrain model (DTM) using the TIN (triangulated irregular network) feature of ArcGIS, and is shown in Figure 14. The DTM was constructed from three datasets using the following procedure:

- A high definition DTM of the Gascoyne River was supplied by the DoW, as constructed by SKM for a flood study (SKM, 2002);
- Available bore elevations, as taken from the WIN database were then added to this SKM DTM to ensure local elevations in the vicinity of monitor locations were accurate;
- 9 second data (250 m spacing) as supplied by Geoscience Australia was used to model the ground elevation in areas not covered by the above two datasets; and
- Topographic constraints were then added such as the ocean to constrain the interpolation.

The accuracy of the SKM dataset is considered to be better than 0.5 m, and elevations at bores should be within 0.10 m. The 9 second data is less accurate, given the wide spacing and is typically stated as 5m on moderate topography. The accuracy of the upper surface of the model directly affects the model accuracy as it is used for specifying reference elevations in head dependent boundary conditions such as the river module and for evapotranspiration. The accuracy of the interpolated upper model surface is not the same as the digital elevation data. The interpolated model surface is based on Kriging interpolation of the DTM onto the centroids of the model grid nodes. This interpolation results in elevations that are not necessarily representative of the predominant ground elevation within an element. Consequently, any variables that depend on this topographic elevation may introduce errors into the model at the same order of magnitude as the error in interpolated elevation.

6.3 Flow Model Parameters

6.3.1 Aquifer Parameters

CyMod Systems has reviewed the available data for the formations making up the aquifer model for the Lower Gascoyne River and estimated ranges for selected aquifer parameters based on work done by Dodson (2001) and Hydro Solutions (2008).

The older alluvium has been represented as a multiple layer aquifer with confining clay beds represented by low vertical conductance between layers. Thus layers 3 to 10 in the OAA are confined to semi-confined beneath an upper layer. Layer 2 is confined to semi-confined by the clay layers within the older alluvium. The uppermost layer in the model represents the riverbed sand in the existing river channel, and OAA elsewhere.

Table 7 summarises the range of hydraulic conductivity and specific yield for selected formations. Typically, a ratio of 10:1 and 100:1 between horizontal and vertical hydraulic conductivity has been used to define the range of vertical hydraulic conductivity, based on the results of pumping-test analysis, natural gamma logs and the groundwater balance (Dodson, 2002, HydroSolutions, 2009). These ranges represent best estimates of the upper and lower bounds for aquifer properties that may be assigned during calibration and have been assigned based on formation geological boundaries. The spatial distribution of the aquifer parameters may be subsequently modified as part of the calibration of the model. Hydraulic conductivity values are consistent with the aquifer pumping-test results which ranged from 1 to 300 m/day for the older alluvium, and 50 to 2000 m/day for the riverbed sand (Dodson, 2002).

6.3.1.1 Land Coverage

The Gascoyne region is primarily utilised for pastoral and mining activities. Horticultural plantations line the Gascoyne River from approximately 5km above the river mouth to just east of the Northwest Coastal Highway (Dodson, 2002).

The historically restricted availability of water has led to the plantations installing water efficient irrigation practices, such as trickle irrigation, plastic lay flat to reduce evaporative losses and large areas of shade cloth. There are no comprehensive studies or estimates of groundwater returns from irrigation to the watertable within the Lower Gascoyne River irrigation area. However, owing to the depth of the watertable (generally > 10 m) and the sandy clay nature of the soils, irrigation returns to the watertable are assumed small.

Given that there is limited recirculation of irrigation and in the absence of applicable landuse datasets, the model does not account for spatially variable recharge due to landuse variation.

6.4 Initial Conditions

Two sets of initial conditions were constructed, one for the calibration period and one for the validation period. The initial conditions consist of interpolated water levels and total dissolved solids (TDS) concentrations for May 1991 and January 2000. The May 1991 initial condition was based on the availability of abstraction data after 1991. The validation period was chosen to start in January 2000, immediately preceding a large flow event. The initial conditions used in the calibration and validation simulations are presented in Appendix C.

Table 14 summarises the data sets used for constructing the initial water levels and concentrations for the calibration and validation models.

Date	Measured Data	Other Constraints	Comments
May 1991, water levels	230 measurements, taken from May 1991 to June 1991	Ocean is set at 0.865 mAHD (Dodson, 2002). Includes water levels as measured at 27 Brickhouse bores in 2005.	Brickhouse bore data was used to improve inferred water levels north of the Gascoyne River. Heads are the same in all layers of the model
May 1991, TDS	660 measured concentrations taken over the period from May 1991 to Dec 2005	Ocean is set at 35000 mg/L TDS was modelled to increase with depth in Subarea A.	The first available reading from a bore, measured after 1991 was taken as an estimate of water quality in the area Brickhouse bore data was used to improve inferred TDS concentrations north of the Gascoyne River.
January 2000, water levels	80 measurements, taken over the period from January 2000 to May 2000 1991	Ocean is set at 0.865 mAHD (Dodson, 2002). Includes water levels as measured at 27 Brickhouse bores in 2005	Brickhouse bore data was used to improve inferred water levels north of the Gascoyne River. Heads are the same in all layers of the model
January 2000, TDS	439 measured concentrations taken over the period from January 2000 to Dec 2005	Ocean is set at 35000 mg/L TDS was modelled to increase with depth in Subarea A. Distribution was constrained manually by manually drawn contours	The first available reading from a bore, measured after January 2000 was taken as an estimate of water quality in the area Brickhouse bore data was used to improve inferred TDS concentrations north of the Gascoyne River.

Table 14: Initial Water Levels Data Set Summary

The impact of the initial heads on subsequent water levels is limited as flow events act to minimise the amount of influence that preceding heads have on subsequent water levels post flow. Hence, though the use of a variety of temporal and spatial data may introduce some error into the model, the error is not propagated in time.

The impact of initial conditions on solute concentrations is more significant than in the case of water levels. The initial solute distribution will persist over a long period and will influence subsequent simulated concentrations. For areas that have low recharge, through flow or pumping, salinity changes are likely to be small over the model period. Hence, measured data taken at different times in these areas are reasonable estimates of prevailing conditions at the start of the model, such as in the Brickhouse area. Alternatively, measured concentrations in the RBS and OOA in the proximity of the river may introduce error in the model, given the changes in water quality due to river flows and abstraction.

Based on data supplied by the DoW, the salinity in some areas of Subarea A as defined by TDS increases with depth. To account for this affect, a salinity gradient was applied to the solute initial condition with salinity increasing linearly with depth, beginning in layer 4. This correction is inherently empirical in nature, being based on limited data, but does reflect the present conceptual model of salinity in the area. In this case, salinity increases by 1000 mg/L per layer, as estimated from data at bores L6D and L6S, for data taken in 2009.

6.5 Boundary Conditions

The conceptual hydrogeology of the Lower Gascoyne River proposes that most groundwater resources originate from river recharge during flowing. The river flow recharge infiltrates the RBS and also vertically and horizontally migrates to the OAA through areas where there is good hydraulic connection. Stored groundwater is lost through evapotranspiration, removed by abstraction or flows to the ocean. Little, if any, groundwater flows either north or south from the river, and a basement high to the east limits inflows from upstream. Consequently, based on this conceptual model, there are potentially 22 boundary conditions that may be defined: 20 conditions associated with the east and west boundaries of each layer, one condition for the top of the model and one condition for the bottom of the model.

The western boundary has been modelled as a constant head coincident with the shoreline of the Indian Ocean, with a mean sea level of 0.865 mAHD (Dodson, 2001). This constant head boundary is active only in layers 1 through 3. Placing the constant head boundary only in layers 1-3 at the coastline recognises the existence of a stationary salt water interface which is approximated by a specified flow boundary condition where the flux is zero (no-flow boundary).

The eastern boundary at Rocky Pool consists of no flow conditions where the basement outcrops or is near the surface. However, the model assumes some head dependent flow where throughflow from the OAA alluvium to the east is may occur, and consequently, a general head boundary condition is assigned to the OAA.

Due to the lack of monitoring data, the northern and southern boundaries for the study area are difficult to define. Based on limited monitoring data over a six year period, it was determined that the response to river flow was greatest near the river but diminished with distance (Dodson, 2002). Beyond 1500m there was no discernible response to river flow within the OAA three months after the flow event (Martin, 1990b). Consequently, the model boundaries were set more than 1500 m away from the river, and defined as no flow boundaries, except in layer 10. In layer 10, a constant head boundary is defined along a section the north boundary to maintain a flow gradient away from the river. The basic principal used in defining the north and south boundaries is to prevent the main stresses (river flow and abstraction) from interacting with the model boundaries.

The current model adopts the Toolonga Formation as an effective impermeable base to the model, consistent with Dodson (2002) and HydroSolutions (2009).

6.5.1 Surface Water-Groundwater Interaction

The higher conductivity and storativity of the RBS aquifer unit allows it to be readily saturated during river-flow episodes and hence vertical leakage will occur into the underlying OAA aquifer unit as surface flow continues to provide a source of recharge to the overlying RBS during river flows. Ponding within the finer sediments of the RBS may happen with water slowly receding after river flows. Since the lateral hydraulic conductivity of the OAA is greater than the vertical hydraulic conductivity, excess water stored within the RBS that is not lost vertically by downward leakage or evapotranspiration may flow laterally in the OAA, or move downstream and discharge back into to the river flow as baseflow after the highest flow period, dependent on river topography.

The flowing of the Gascoyne River is the largest contributor to recharge of the aquifer in the modelled area, and is modelled using the RIVER package of MODFLOW (McDonald and Harbaugh, 1988). The RIVER package works by simulating recharge into or discharge out of the RBS aquifer due to the influence of surface water features. MODFLOW's RIVER package requires three parameters to be defined, namely river bed hydraulic conductance, hydraulic head in the river and the elevation of the river bed. Any model cell with a river conductance greater than zero is treated as a river cell by MODFLOW.

As indicated above, using an interpolated ground surface as the basis for estimating the river bed level may introduce errors into the calculation of head at elements having the River boundary condition. For elements with water levels above the river bed level and river stage height, the river boundary conditions will act to discharge water at a rate proportional to the head differences and bed conductance. For elements with water levels below the river bed level and river stage height, the river boundary conditions will act to recharge water at a rate proportional to the head differences and bed conductance. Consequently, any error in the river bed level or the flowing stage height will be directly reflected in the calculated flux into the aquifer. This error will be directly proportional to the error between the actual flowing level or riverbed elevation and the model parameters.

6.5.2 Flow Events

Daily river flow and stage level data as provided by the DoW were used to identify and quantify Gascoyne River flow events between 1991 and 2008. Two characteristics of a flow event dictate how it is modelled using the river package, namely stage height and spatial extent. The river stage height is defined as the difference between the river level during a flow event and the baseline river level. In the case of the Gascoyne River, the base line river elevation is the river bottom during no flow conditions. The river stage height defines the head in the river available for recharge as used by the RIVER package.

During a flow event, rainfall runoff from the floodplain flows into the Gascoyne River, initiating river flow and recharge to the RBS and OAA. Recharge is related to the flowing volumes and flow stage heights, in that if there is no flow in the river, or no water levels above the riverbed level, no recharge will occur. River flow rates and stage heights during flow events were recorded at two monitoring stations, namely Nine Mile Bridge (NMB) and Fishy Pool. Hydraulic gradelines for the river in flow from the ocean to Nine Mile Bridge and from Nine Mile Bridge to Rocky Pool were calculated from topography and were used to estimate river flows and stage heights from Rocky Pool to the ocean, for input into the model as estimates of river stage height along the Gascoyne River. Appendix D tabulates each flow event's stage height (metres above baseline), and maximum and average daily flow volumes, and shows the estimated maximum spatial extent of the river during each flow event, based on the inferred hydraulic grade line and the measured stage height at NMB.

For each flow event, an interpolated flow surface was constructed and intersected with topography to define the spatial extent of the flow. It was found that flows with stage heights less than 2 metres were contained to the Gascoyne River channel, while flows with stage heights greater than 2 metres were found to extend beyond the river channel, inundating the surrounding land to some extent. These two typical flow envelopes were used to assign the spatial extent of river conductance values to model cells for small and large flows, thereby defining the extent of influence of each flow event. The small and large flow envelopes are shown in Figures 15 and 16, respectively.

The stage height at any point along the river was interpolated on to the active flow area, using the hydraulic grade line and the measured stage height at Nine Mine Bridge. Where the interpolated stage height is below the river bed elevation, no recharge occurs. The advantage of this approach is that it eliminates the need to explicitly account for river bed topography and local flow in the river, when adding stage height to river bed elevation. The disadvantage is that flow stage heights are assumed to be piecewise linear and are a function of only one reference level, which will introduce some error into the spatial distribution of applied river stage height.

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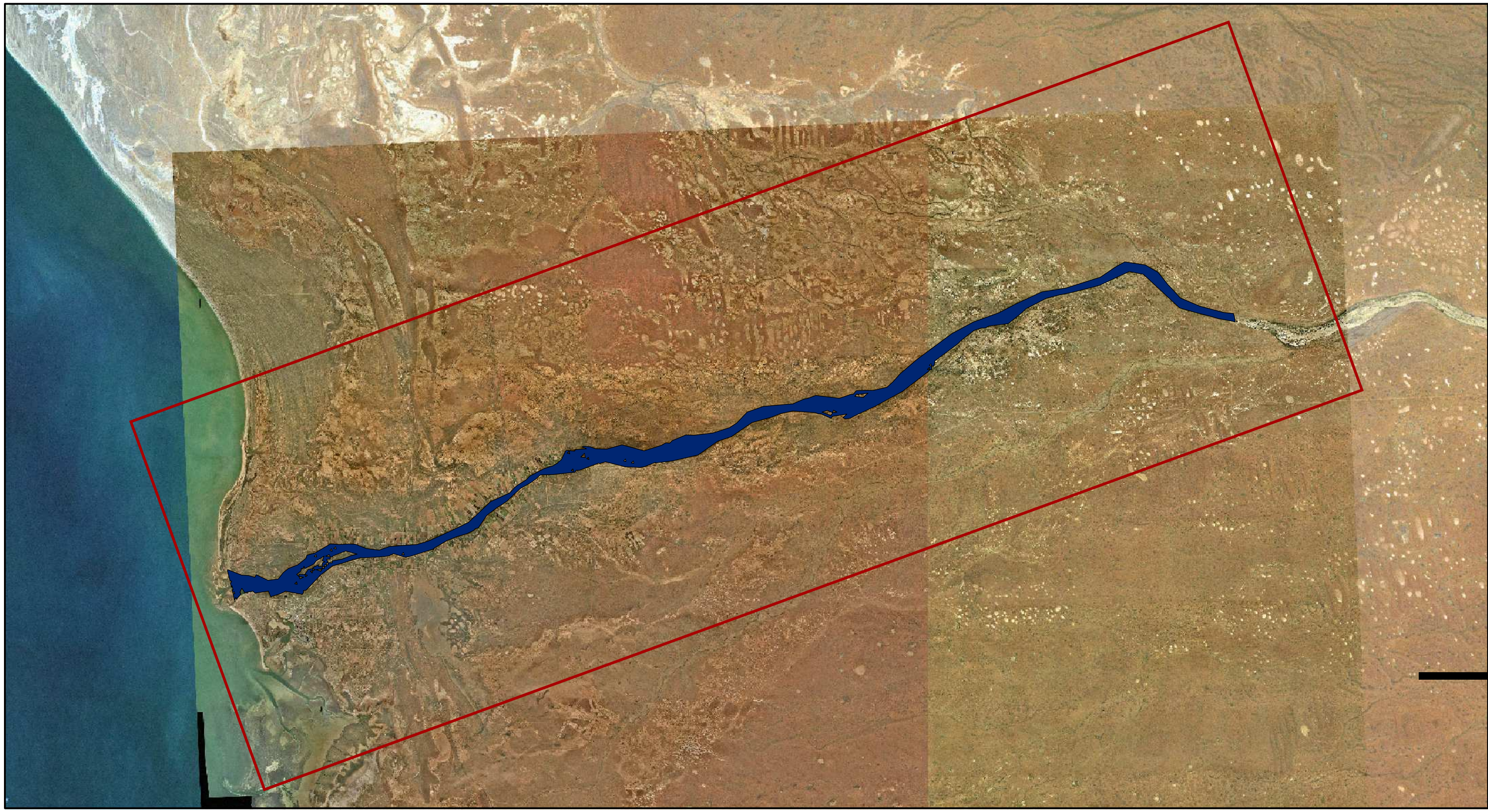

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0 2.5 5 10
Kilometres

GDA 94
MGA ZONE 50

Legend

Small Flow Extent
Study Area

Figure 15: Flow Extent, Stage Height Less than 2 metres

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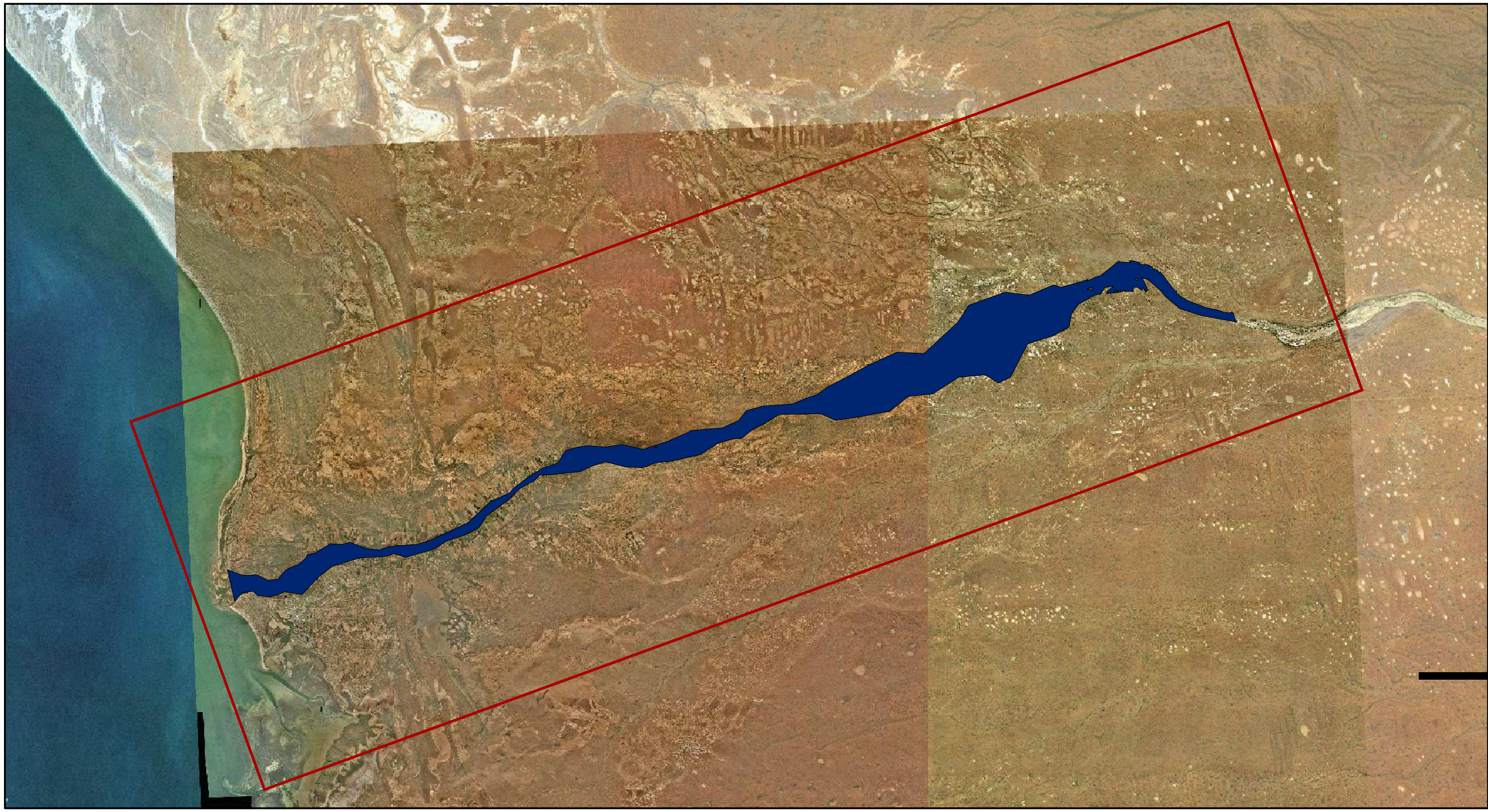

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SCALE 1:275000

0 2.5 5 10
Kilometres

GDA 94
MGA ZONE 50

Legend

Large Flow Extent

Study Area

Figure 16: Flow Extent, Stage Height Greater than 2 metres

6.6 Rainfall Recharge

6.6.1 Climatic Data

The region has an arid climate with hot summers and mild winters; however there is a distinct difference the inland and coastal regions in the catchment. January is typically the hottest month in the inland catchment with a mean daily maximum temperature of 41°C (Dodson, 2002). February is typically the hottest month for the coastal area with a mean daily maximum temperature of 33°C (Dodson, 2002). The coolest month for the inland catchment and coastal catchment is July, the mean daily maximum temperature for Gascoyne Junction (176km ARM) is 23°C, and for Carnarvon it is 22°C.

Although three weather stations exist within the model domain, GASFAMS uses a single rainfall station (Carnarvon Airport, station number 6011). This station is used as the basis for estimating recharge and evapotranspiration over the entire model domain. Spatial variations in rainfall were implicitly accounted for in the calibrated rainfall recharge coefficients used.

The evaporation data utilised in the model was recorded at Carnarvon Airport, using a Class A pan. Evaporation is typically highest in January, whilst the minimum occurs in June and July. The mean annual potential evaporation rate for Carnarvon Airport is 2613mm.

6.6.2 Direct Rainfall

The primary source of recharge to the Lower Gascoyne River aquifer system is from river flow events as described above. A review of the literature shows that rainfall events of less than 38 mm/month do not cause any recharge to groundwater, as evidenced by a change in water levels (Allen, 1972). In the event of rainfall in the absence of a flow event, it is deemed that there is no net recharge to the aquifer if the rainfall totals less than 38 mm/month (Dodson, 2002).

Rainfall was plotted against flow stage heights to identify periods of rainfall in the absence of flowing. Of these rainfall periods, months with rainfall greater than 38 mm were identified and used to calculate recharge. A comparison of flow events versus rainfall at Carnarvon Airport, Figure 17 shows that from 1991 to 2008 there are only 4 events of rainfall greater than 38 mm/month without river flow, suggesting that most recharge is not related to local rainfall. Dodson (2002) estimated that recharge outside of the RBS was between 1% and 5%. In the context of flow recharge to the aquifer systems, the net rainfall recharge is a comparatively minor source of water into the riverbed sand and OAA layers of the model. Consequently, rainfall recharge has been set to zero in the GASFAMS model.

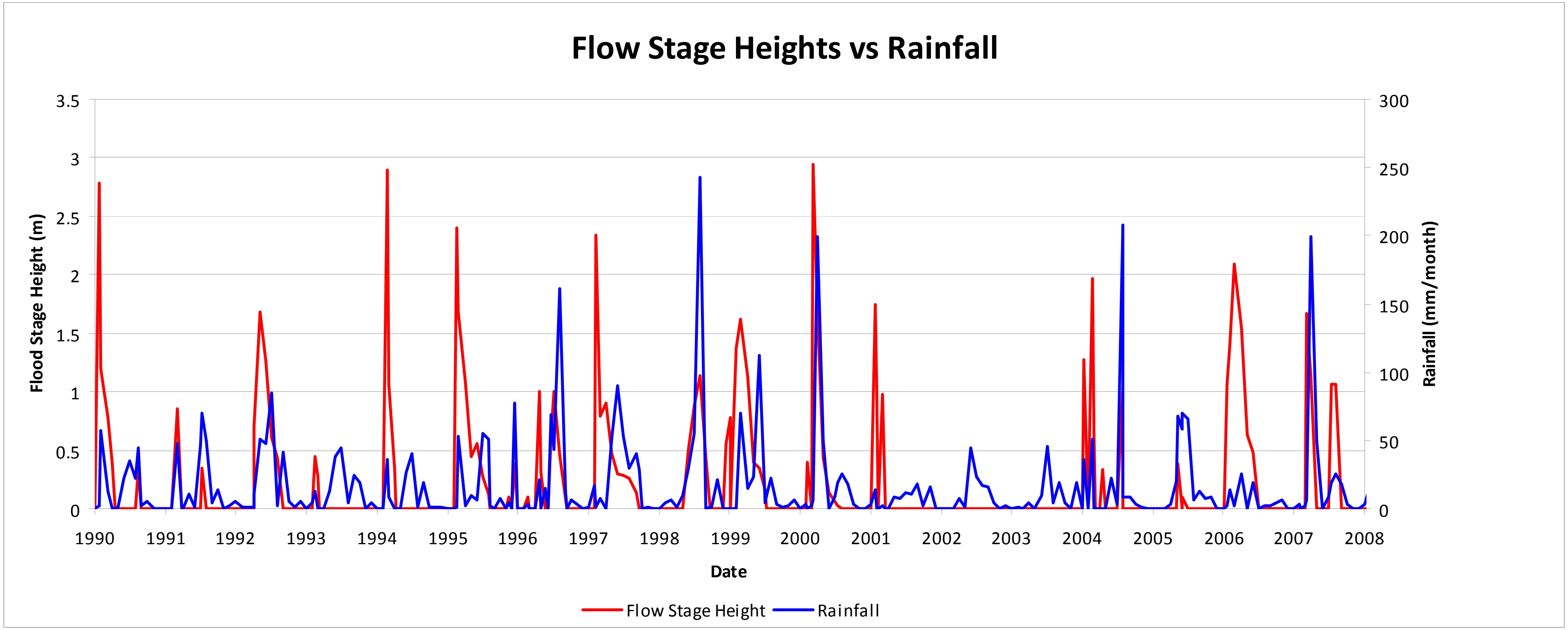

Figure 17: Flow Heights versus Carnarvon Airport Monthly Rainfall

6.6.3 Evapotranspiration

The extinction depth for transpiration used in the Lower Gascoyne River model is 4m (Dodson, 2002) and is based on the rooting depth of local vegetation. The volume of evaporation over the bare riverbed sand is significant given the area. It is estimated that evaporation will only occur if the watertable is within 0.60m of the surface (Allen, 1972). However, it was also observed that vegetation on the banks of the river are sourcing water from the RBS, thereby increasing the effective extinction depth in the RBS. The extinction depth for evaporation cells in the RBS has been estimated and modelled at 2.0 m below the surface. In the OAA the extinction depth is estimated as being on average 4 m, based on the occurrence of vegetation and soil type and rooting depth. These parameters were subject to calibration.

6.7 Abstraction

Abstraction from the GASFAMS model area occurs from both the RBS and OAA aquifers. There are two major types of abstraction from these aquifers:

1. Water Corporation abstraction (public licensed abstraction for public water supply and irrigation) from Subareas B-L; and
2. Licensed abstraction by private users, primarily for irrigation purposes, from Subarea A.

All groundwater abstraction is licensed by the DoW, the government regulatory body for water in Western Australia. The government of Western Australia has regulated groundwater abstraction in the area since 1959. The philosophy behind the regulation is to give a reliable water supply for the irrigation area during critical drought periods, while ensuring the availability and quality of public water supply.

Each of these abstractions was quantified both spatially and temporally, on a monthly basis over the model calibration and verification period using available pumping data. Measured abstraction is available for both private and public bores, and was obtained from the DoW and Water Corporation. This data was placed in the modelling data base and used to generate model abstraction.

6.7.1 Licensed Private Bores

The DoW licences abstraction from the RBS and OAA aquifers within the Lower Gascoyne River floodplain. An assessment number and a license are assigned to each plantation. Following assessment each plantation is issued with a unit allocation with a maximum draw of 72 000 kL/annum. In some cases however, DoW may allocate more or less than one unit allocation. Unrestricted pumping of groundwater and surface flow is permitted during periods of river flow. Allocations are re-assessed from time to time during extended no flow periods. However the actual withdrawal can exceed this figure owing to periods of unrestricted pumping. Abstraction is also controlled by water quality, with a maximum TDS 0f 1000 m/L in Subarea A, and 800 mg/L in Subareas B-L.

Measured abstraction for 494 bores in Subarea A was provided by the DoW from 1999 to June 2007, as monthly volumes by licence. These monthly volumes were assigned to draw points associated with the licences via the WIN database. Private abstraction prior to 1999 was extracted from the GRFMOD model well database, converted to UTM Zone -50, and placed in the GASFAMS model database.

The well abstraction data was input into the model by:

- extracting monthly volumes for each draw point 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.

Figure 18 shows the locations of private licensed bores in the GASFAMS model domain. Note that bores outside of Subarea A, and with no production history are not included in the model.

6.7.2 Water Corporation Abstraction

The water supply for the township of Carnarvon is sourced from a public borefield which extends from NMB, 16 km ARM, to Rocky Pool, approximately 54 km ARM, as shown in Figure 19. For management purposes the floodplain aquifer abstraction is sub-divided into Basins, and the public scheme (referred to as Scheme water) is classified as Subareas B-L. The public water supply (PWS) demand is approximately 1.5GL per annum and is sourced from Subareas B-L. The allocation for PWS is 1.8 GL, with a 1% growth rate projected until 2010 for public water supply demand (Water Corporation, 1999a).

Some supplementation of irrigation water supply by the public scheme also occurs. Irrigation demand is primarily met from Subarea A private wells first. However, under drought conditions, rising groundwater salinity and reduced well yields result in a need to supplement irrigation demand from the Scheme water supply. The principle mechanism driving demand for irrigation water from the scheme is the time between river flows.

Water Corporation typically measures and reports abstraction as monthly volumes, for each of their 114 operating bores. The Water Corporation provided raw data of abstraction volumes for their bore fields from 1999 to 2008. This data was collated and processed for input into the model 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

Note that all abstraction data from 1991 to 2000 was extracted from GRFAMOD, as monthly volumes and flow rates and stored in the well database associated with the GASFAMS model. After 2000, measured abstraction was extracted from spreadsheets supplied by the Water Corporation. Table 15 summarises the annual abstraction from the two basins. Effectively, the total for Subarea A is private abstraction, while the total for Subareas B-L is public abstraction.

Year	Total (GL/annum)	Subarea A Total (GL/annum)	Basins B – L Total (GL/annum)
1991*	6.73	3.09	3.64
1992	10.24	4.22	6.01
1993	10.19	3.32	6.86
1994	9.94	4.37	5.57
1995	9.21	4.65	4.56
1996	7.70	4.29	3.41
1997	8.95	5.49	3.46
1998	9.98	5.65	4.33
1999	12.11	8.92	3.19
2000	9.41	5.81	3.61
2001	9.90	6.19	3.71
2002	10.38	4.31	6.06
2003	11.26	4.03	7.23
2004	10.67	5.56	5.11
2005	9.37	4.50	4.87
2006	12.58	5.82	6.76
2007†	5.76	2.38	3.38

* Data for 1991 from April only
† Data for 2007 to July only

Total number of private bores (Subarea A): 494
Total number of WC bores (Subareas B-L): 114

Table 15: Annual Gascoyne River Aquifer Abstraction 1991 – 2007

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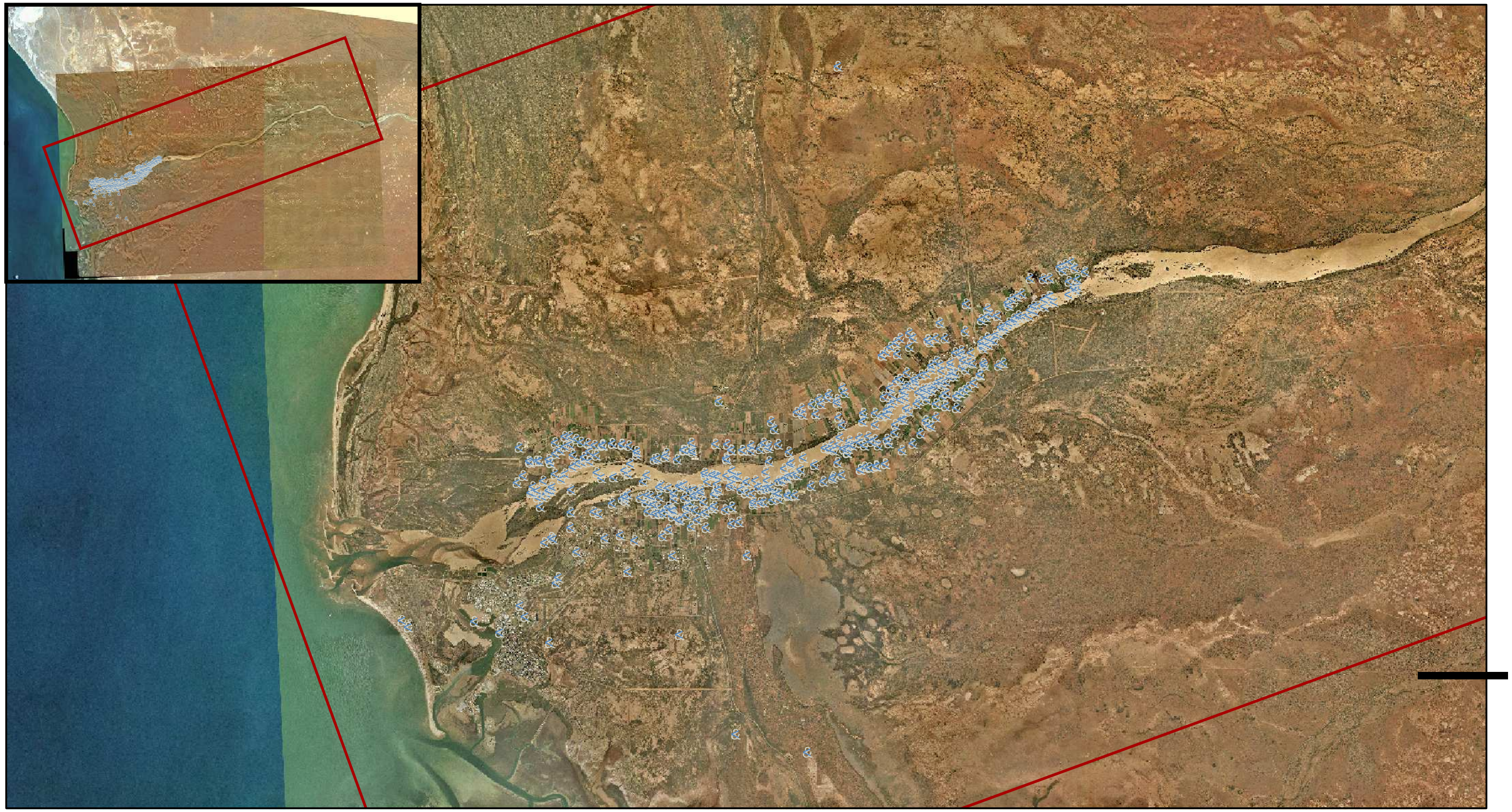

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SCALE 1:125000

0 1 2 4
Kilometres

GDA 94
MGA ZONE 50

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Legend

Study Area

Private Abstraction Draw Points

Figure 18 : Private Abstraction Draw Points – Subarea A

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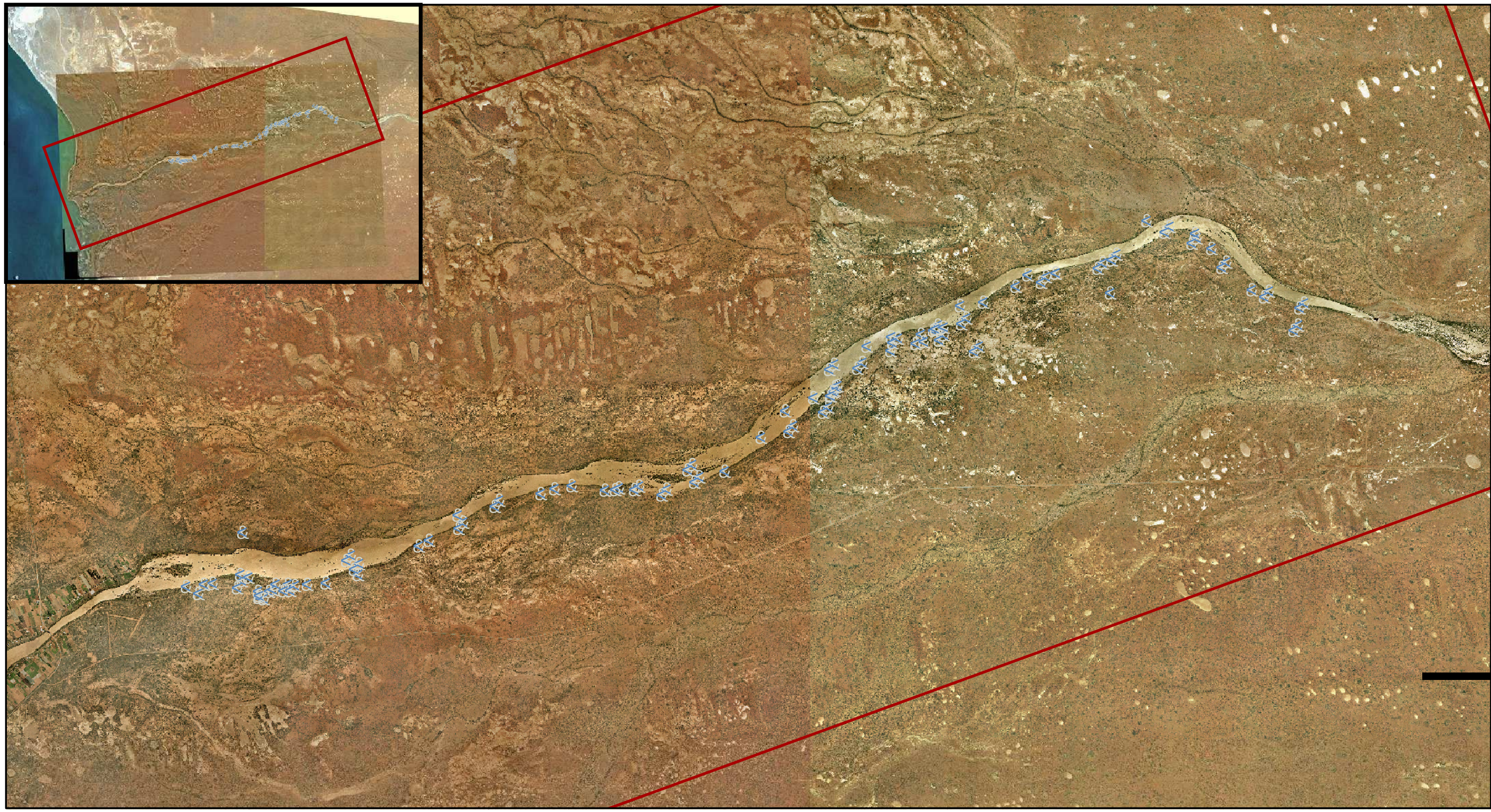

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SCALE 1:150000

0 1 2 4
Kilometres

GDA 94
MGA ZONE 50

Legend

Study Area

Public Abstraction Draw Points

Figure 19: Public Abstraction Draw Points – Subareas B-L

6.7.3 Multi-Node Well Package

Due to the nature of the aquifer system the abstraction of water from the RBS and OAA is difficult to simulate efficiently with the standard well package of MODFLOW-2000. Some of the complexity of the GRFAMOD model stems directly from trying to simulate the abstraction of water from a heterogeneous aquifer, through multiple bores completed in different layers using this package. The two main issues with modelling abstraction using the WELL package, from the RBS and OAA aquifers are:

- The standard MODFLOW well package only allows abstraction from a single layer; and
- Once a well goes dry it is lost permanently from the model.

The first issue is problematic in that in many cases bores associated with private allocations are completed at different depths, and pumped in succession, as each in turn loses deliverability and goes dry. In addition, most bores are completed in the RBS, which has high transmissivity so that most of the flow is initially from this aquifer. To model this situation in MODFLOW, using the WELL package requires multiple bores completed in different layers, and apriori knowledge of when one bore goes dry and another should start pumping. Dodson over came this problem by intervening in the model run and initializing or resetting abstraction from wells based on experience with the model, and layer transmissivity (Dodson, 2002).

With respect to the second issue, the operational mode of MODFLOW is inconsistent with how bores are managed on the Lower Gascoyne River. Bores in the Lower Gascoyne River are reactivated when the aquifers are recharged by river flow. Hence if a bore does dry in the standard well package it will remain off, even though the aquifer may be subsequently recharged and groundwater is available. To simulate this situation requires manual intervention and the running of multiple concatenated models to simulate multiple river flow sequences, the procedure used in GRFAMOD.

The solution to the above problems is to better simulate how abstraction bores work, rather than manipulate the model. Subsequent to the development of the GRFAMOD model, the Multi-Node Well (MNW) package was introduced (USGS, 2002). The GASFAMS numerical model utilises the MNW package of MODFLOW-2000 to simulate abstraction from wells completed over multiple model layers. The completion of wells over multiple layers introduces two new characteristics of abstraction not previously modelled:

- Total bore abstraction is made up of different abstraction volumes from each model layer, with each layer’s contribution proportional to its transmissivity; and
- The possibility of flow between layers via the bore, simulating a high vertical conductivity wellbore.

Measured abstraction as recorded in the GASFAMS database was used to construct a MNW file. However, additional parameters are required to allow the MNW to simulate bore effects and to manage the bore in the event of lost deliverability. In this case, wells that are reduced to an abstraction of less than 1 m^3/day are turned off and reactivated when they can abstract more than 2 m^3/day. The hysteresis in the stop and restart flow rates prevents model instability.

Completion details for all wells were input into the model, with the MNW package subsequently calculating the abstracted volumes from each model layer for each well, and the flow between model layers. In the absence of completion details abstraction was assumed to be from the top 4 model layers. One disadvantage of the MNW package is that well abstraction is not necessarily maintained at historical levels, but is rather under the control of the MNW. Consequently, actual model abstraction is a measure of the fidelity of the model. If the MNW package replicates measured abstraction, it implies that the model hydrogeological conditions are consistent with aquifer characteristics in the vicinity of production bores.

7 SOLUTE TRANSPORT MODEL CONSTRUCTION

The GASFAMS solute transport model was constructed to simulate the movement of TDS in the RBS and OAA aquifers. The solute transport model was constructed using Visual MODFLOW 4.3, and simulated using MT3DMS (Modular Transport in Three Dimensions, Multiple Species) transport modelling package (Zheng et al., 1999).

The simulation of solute transport uses the flow model solution as calculated by MODFLOW-2000 for determining advective transport (transport due to the movement of water). Consequentially, the same finite difference grid as defined by the horizontal and vertical discretisation in the flow model is also used by the solute transport program. MT3DMS also solves for the other components of solute transport (i.e. dispersion and diffusion) using the finite difference approach.

Described below are the parameters used in the construction and implementation of the GASFAMS solute transport model.

7.1 Solutes

The only solute modelled using the solute transport model is TDS or its equivalent EC (Electrical Conductivity). Measured EC as reported by the DoW was converted to TDS using empirical relationships based on laboratory data.

7.2 Aquifer Parameters

The solute transport model requires four additional aquifer parameters: porosity, and longitudinal, transverse and vertical dispersivity. Parameter values for the RBS and OAA are presented in Table 16.

Parameter	Calibration Value	Comments
Longitudinal Dispersivity	25 m	Typical value use at the aquifer scale
Transverse Dispersivity	2.5 m	Assumed value
Vertical Dispersivity	1.25 m	Assumed value
Porosity	0.35	Based on soil type
Seawater	35,000 mg/L	Density is constant

Table 16: Solute Transport Model Parameters

7.3 Initial Conditions

Water quality data from 253 bores in the Lower Gascoyne River region were collected and used to create an interpolated distribution of TDS, representing the historic aquifer concentrations of TDS in the Gascoyne River region in May 1991 and January 2000. These interpolated surfaces were used as an initial concentration condition for the solute transport model and also for scenario evaluation. The interpolated concentration surfaces are given in Appendix C.

7.4 Boundary Conditions

The assigning of solute boundary conditions is analogous to flow model boundary conditions except that concentration or mass flow is specified rather than head or groundwater flow. All of the flow boundaries conditions of the solute model are set as specified concentration boundaries. These boundaries set the concentration of any ground water flow into the model at the estimated regional concentration and at the concentration of seawater. Concentrations of solute leaving a model boundary are determined during the simulation.

7.5 Rainfall and Evapotranspiration

7.5.1 Rainfall

The primary source of recharge to the Lower Gascoyne River aquifer system is from river flow events as described in Section 6. As the net rainfall recharge is a comparatively minor source of water into the RBS and OAA it has been ignored. However, the addition of salt from rainfall cannot be ignored, as the solute remains in the soil after evaporation or evapotranspiration. Consequently, TDS from rainfall is modelled as a distributed mass loading set at 0.001 g/m^2/day, as determined from annual rainfall. Rainfall is deemed to have a TDS concentration of 10 mg/L.

7.5.2 Evapotranspiration

No TDS is removed from the aquifer system by evapotranspiration.

7.6 River Flow Events

The addition of solute to the aquifer system via flow events is modelled with a TDS concentration of 55 mg/L (Dodson, 2002).

7.7 Abstraction

TDS removed from the model due to abstraction is removed in the abstracted water at the concentration as calculated in the model cell from which water is pumped.

8 MODEL CALIBRATION AND VALIDATION

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. In the case of the Lower Gascoyne River there is insufficient data and no identifiable period that can be considered in steady state. Consequently, the model was not calibrated in steady state, but under transient conditions.

The transient calibration of the model, without an initial steady-state condition is problematic in that model artefacts may exist due to non-representative conditions at the beginning of the model. To minimise this problem, and begin the simulation under relatively benign conditions, the start date of the model was set as May 1991. The start date occurs after a large flow event, which effectively recharges the aquifer and results in water levels being at or near maximum levels. The disadvantage of this start date is that recent river flow causes vertical gradients in the aquifer system. However, as indicated under initial conditions, the inferred initial heads assigned to the aquifer were uniform for all layers, reflecting the limited number of bores in deeper layers.

The model was iteratively calibrated by adjusting selected parameters in MODFLOW. Typically the following process was used:

- review the error in predicted water levels in the superficial aquifer and adjust horizontal and vertical hydraulic conductivity as required;
- review the error in the aquifers and adjust horizontal and vertical hydraulic conductivity, and storage to reduce to error; and
- rerun 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.

8.1 Transient Calibration

Once a viable set of initial conditions are established, the transient model was calibrated for the period from May 1991 to 1999. Stress periods were defined as calendar months, or the duration of significant flow in the Gascoyne River, as shown in Table 13. Model output was monthly. The flow model was simulated using MODFLOW-2000 version 1.18, with the Block-Centred Flow (BCF6) package, and the PCG2 solver. Head and residual convergence criteria were 0.001 m and 1 m^3/day respectively.

The solute transport model was simulated using MT3DMS 5.2, utilizing advection and dispersion, using the Basic Transport (BTN), Advection package (ADV) and the dispersion package (DSP). The BTN package for MT3DMS is the same as for MT3D, and is similar to the BAS package for MODFLOW. The ADV package provides information for solving the advection term of the transport equation; in particular, the transport of solutes by means of ground-water flow. In GASFAMS, advection is solved using the third-order Total Variation Diminishing (TVD) method. This method minimises the numerical problems in the transport of particles. Additionally, this method provides the best solution for a model that contains cells of different sizes such as that used in the GASFAMS model grid (Dausman et al, 2004).

The Sink and Source Mixing (SSM) package provides information for solving the source and sink components of the transport equation. The GASFAMS model utilises the implicit finite-difference method by using the Generalised Conjugate Gradient Solver (GCG) package to solve the equations of the SSM package. The GCG package is activated to solve the SSM portion of the transport equation implicitly.

A review of calibration runs showed that the maximum water balance error is typically less than 0.25% in any one stress period and less than 0.6% for the entire model run. The mass balance error is typically less than 0.003% for any stress period and less than 0.03% for the entire model run.

8.2 Calibrated Model Parameters

The following parameters were adjusted as part of the model calibration: horizontal hydraulic conductivity, k_h, vertical anisotropy, a_v, storage, S, specific yield, S_y, river stage and to a lesser extent conductance. No adjustment of any boundary conditions was made during calibration.

The spatial distribution of the calibrated aquifer parameters is given in Appendix F. The ranges of the calibrated aquifer parameters are consistent with those suggested in the conceptual hydrogeological model (Table 7).

8.3 Monitor Bores

8.3.1 Calibration Bores – Water Levels

Based on the review of the available data sets, 164 bores were selected that were considered suitable for calibration. These bores were selected based on the quality and quantity of water level data, available screen data, the depth at which the bores are completed, and an assessment of whether the bores adequately reflect local and regional water levels.

The calibration bore data was extracted from the modelling database. The database has a total of 1447 monitor bores (with water level readings), and approximately 27,000 water level readings. Data begins in 1970 and finishes in November 2007. Initial model head distributions and transient calibration hydrographs are all based on this data. Figure 20 shows the location of the water level calibration bores.

The location of the bores in the model, with respect to layer is based on the top and bottom elevation of the screens, relative to model layers. In the absence of recorded screen elevations, a bore is assumed to be completed with 3 metres of screen from the bottom or total depth of the well.

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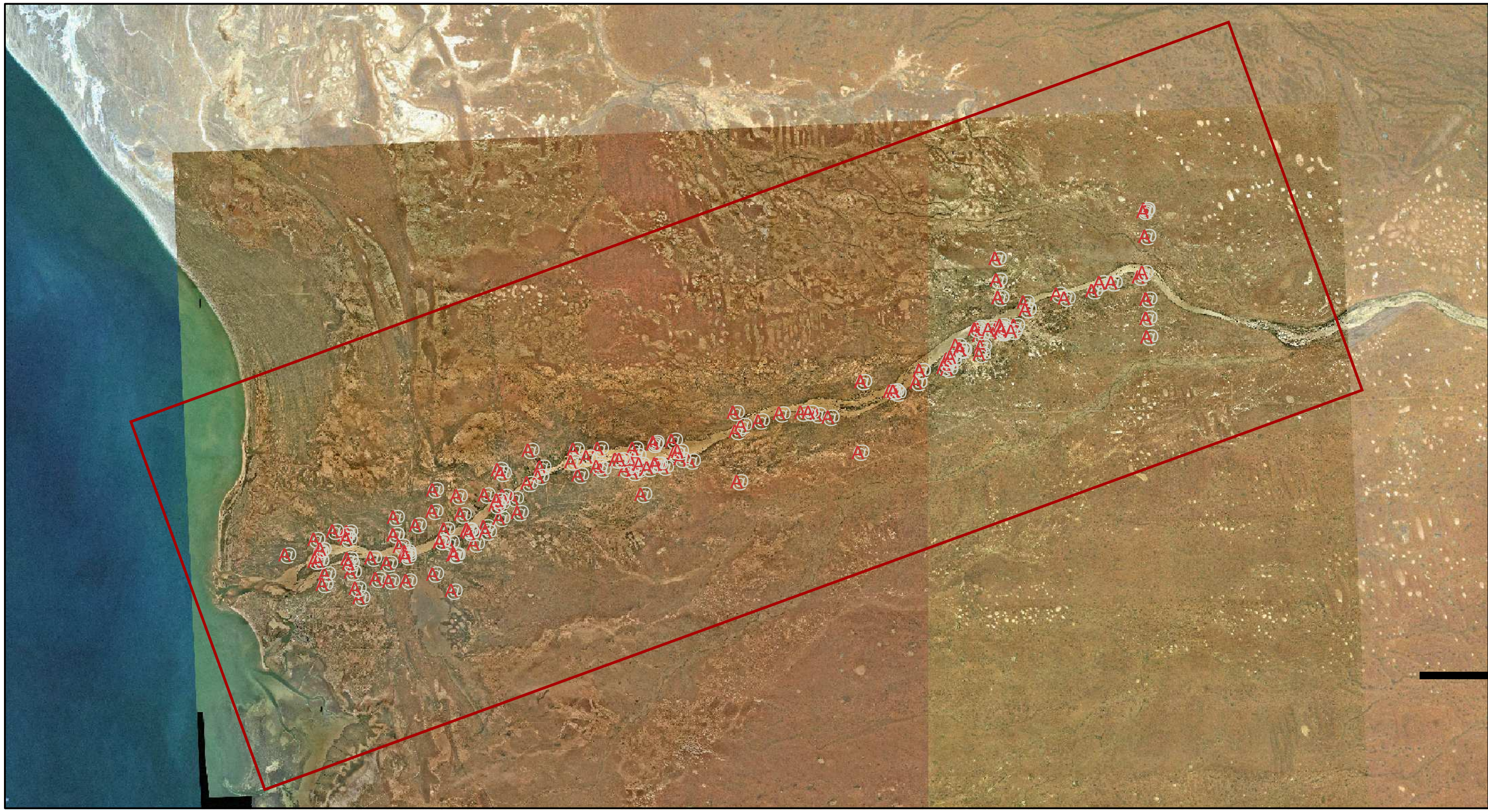

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SCALE 1:275000

0 2 4 8
Kilometres

GDA 94
MGA ZONE 50

Legend

Study Area

Flow Model Calibration Bores

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Figure 20: GASFAMS Flow Model Calibration Bores

8.3.2 Calibration Bores – Water Quality

Based on the review of the available data sets 207 bores were selected for calibration. The calibration bore data was extracted from the modelling database. The database has a total of 1447 monitor bores (with TDS level readings), and approximately 18,000 TDS readings. Data begins in 1946 and finishes in November 2008. Initial model TDS distributions and transient calibration hydrographs are all based on this data. Figure 21 shows the location of the calibration bores.

The location of the bores in the model, with respect to layer is based on the top and bottom elevation of the screens, relative to model layers. In the absence of recorded screen elevations, a bore is assumed to be completed with 3 metres of screen from the bottom or total depth of the well.

8.3.3 Solute Model Calibration

The calibration of a solute model is analogous to the calibration of a flow model. Measured concentrations of TDS are required, having sufficient spatial and temporal variation, to allow the minimization of error between simulated and measured data. In the GASFAMS model there is a lack of spatially variable water quality data at relevant bores over the GASFAMS model domain, with most water quality readings taken from bores in Subarea A at widely spaced time intervals. The water quality data as reported by private users was also used to develop calibration data set. The data is of unknown quality and has been found not to correlate with changes in head or spatial proximity to the saline interface, and may bores have no identifiable trend (Dodson, 2001). Under these circumstances it is difficult to construct a viable conceptual model for the mechanism of TDS changes in the aquifer systems. This effectively constrains the model calibration to simulating generic effects that are consistent with the assumed distribution of TDS, such as upconing, the increase in salinity due evaporation and the lateral migration of higher TDS water from the OAA.

In addition to the lack of data, there are two complicating factors in the case of solute modelling:

- The GASFAMS model is not a variable density model and is unable to accurately account for the movement of brackish water due to density difference. Given some of the measured concentrations in bores in Subarea A, concentrations are high enough for density differences to be important; and
- There is no effective conceptual model of the source or fate of TDS; hence there are no relevant calibration parameters to manipulate to obtain the measured concentration distributions.

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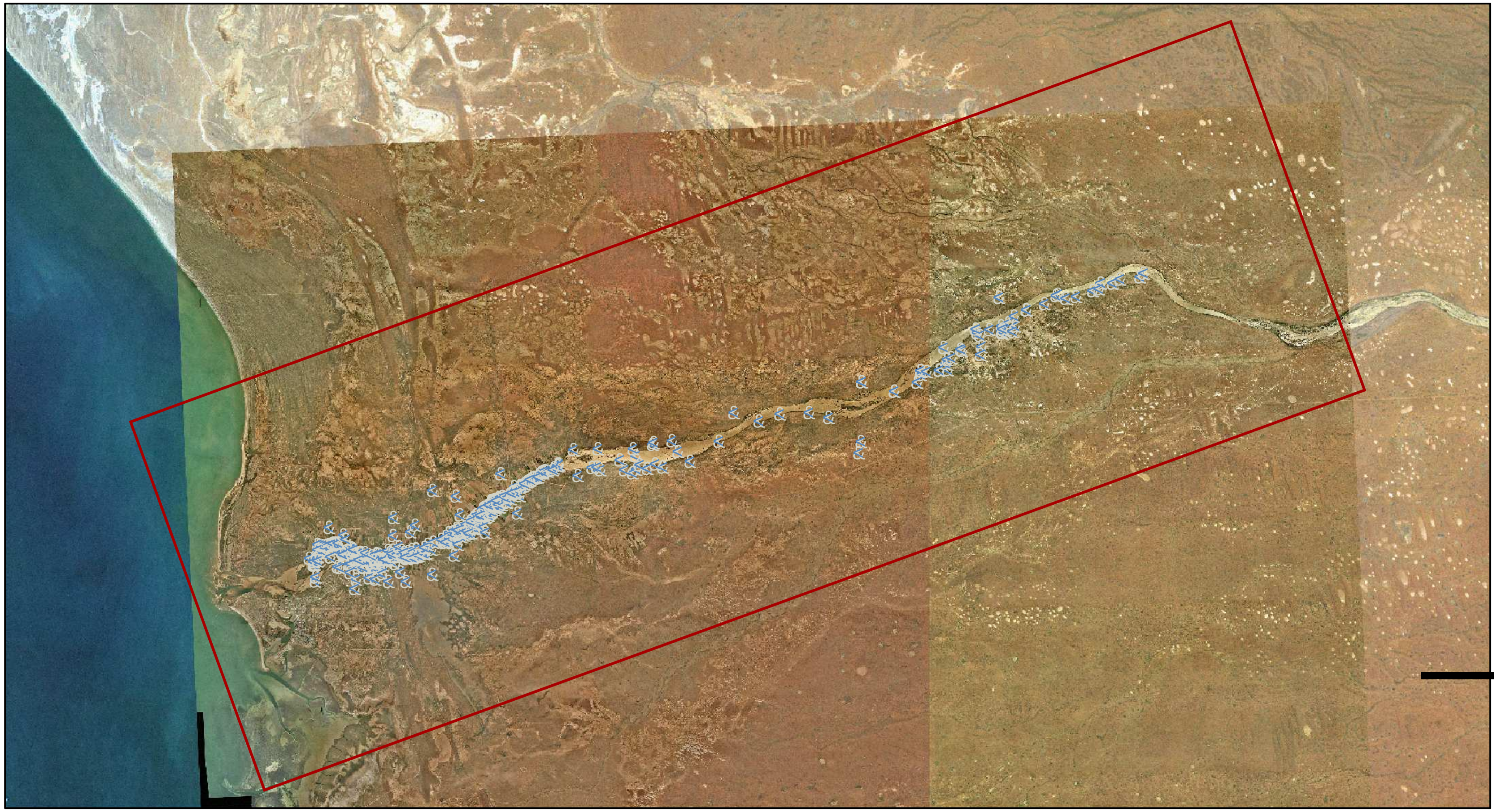
Gascoyne River Floodplain Aquifers Modelling System



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SCALE 1:275000

0 2 4 8
Kilometres

GDA 94
MGA ZONE 50

Legend

Study Area

Solute Model Calibration Bores

ACKNOWLEDGEMENT
DATA SOURCES
- Geoscience Australia
- SKM
- Department of Water WA

Figure 21: Solute Model Calibration Bores

8.4 Calibration and Verification – Discussion

Calibration of a model compares model predictions and measured data over a selected period, to allow the adjustment of aquifer parameters to minimise error. However, complete elimination of model error is not possible. The residual error between measured and predicted heads or concentration is indicative of deficiencies either in the calibration process or the conceptual model. The deficiencies in the calibration process typically relate to inappropriate calibration bores, errors in data, and numerical limitations inherent in the model implementation. Deficiencies in the conceptual model typically manifest themselves as systematic errors over large areas, localised areas of high error, and errors that are intractable or insensitive to parameter variations.

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. The verification of a numerical model is difficult and suffers from the same limitations as demonstrating that a groundwater model is a 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. The Lower Gascoyne River model was verified using the period from 2000 to 2008.

Table 17 summarises the calibration error in the model. The average absolute error is a measure of the fit of the model, and represents a percentage error of 5.1%. This percentage error is consistent with but above the accepted modelling guidelines which recommends a percentage error less than 5% (Aquaterra, 2000). The RMS error is larger than the absolute average error as this estimator weights larger error more than small. The fact the RMS error is larger than the average absolute error indicates that some of the error is due to large error in a few bores. The range of the error shows that there are significant errors in some bores. The large negative and positive maximum error is associated with pumping bores in Subareas B-L. Appendix I shows the spatial distribution of calibration error for both heads and solute.

Average Absolute Error (m)	Average RMS Error (m)	Maximum Positive Error (m)	Maximum Negative Error (m)
1.66	2.24	16.12	-8.27

Table 17: Summary of Transient Water Level Calibration Error

Figure 28 shows a comparison of predicted and measured water levels for the calibration bores completed in the Lower Gascoyne River aquifer. Appendix G shows the calibration hydrographs for the same set of monitor bores, a selection of which are presented in Figures 22, 23, 24 and 25. From Figure 28, the model predicted water levels in general show the error to be non-systematic in that the points are randomly scattered around the unity slope line. However, the scatter is relatively large, with a number of outliers having significant error. A review of the hydrographs show that source of error tends to be due to:

- Interpolation of initial water levels, which results in the simulated heads at the start of the model being different than those actually measured;
- Overshooting of the peak water levels due to river flow, which reflects the generalization of the flowing stage height using a 2 segment piecewise linear hydraulic grade line;

- Over or under response of bores away from the Gascoyne River to flowing.

The interpolation error of initial conditions reflects the clustered nature of the data, where some areas have a high density of the data, while other areas have low density. The elongated shape of the model makes it more difficult to interpolate data on to known locations, and maintain fidelity with the measured data. Due to the nature of the system, this error is short lived and generally extinguished by subsequent river flows in areas close to or in the river. The error tends to be more pronounced and of longer duration for bores completed in the OAA, due the lower transmissivity of this aquifer.

The overshooting (and undershooting) of the water levels due to river stage heights is a consequence of using an approximation of flow level for the Gascoyne River. The area of inundation is fixed, and stage height at any point is related to the stage height at Nine Mile Bridge by a linear trend surface. As each flow is unique, stage heights downstream and upstream of NMB may not be well represented by the fixed spatial extent and the linear relationship to NMB stage height, thereby introducing error in the river boundary condition. Since the river boundary condition is a head dependent flux, any error in head will be reflected in aquifer water levels. These errors can be reduced by improving the algorithm for estimating river stage height along the river channel. The existing MIKE11 model could be adapted to predict the flowing water level at several locations between Rocky Pool and the ocean, to improve the estimated stage height in the river. This would significantly improve the simulated river stage height and eliminate some of the error injected into the model due to the simulation of river flow. The use of MODFLOW-2000 allows the integration of MIKE11 into the model, as a replacement for the river package. Mike 11 was not used in the GASFAMS model as the existing model only simulated a single flow event in 2001. Consequently, the MIKE11 model would need to be extended to include all flow events from 1990 to 2008, requiring the development of additional datasets, and calibration. Experience with MIKE11 tends to suggest that use of this package in a fully dynamic simulation would significantly increase the computation requirements of the GASFAMS model.

The over and under response of a bore to a particular flow event indicates some loss of fidelity in the river stage height or flow envelope. It may also reflect changes in the river bed and how river water flows. These changes are difficult to capture model, and are only amendable to localise calibration of flow extent and stage height, which is essentially an exercise in curve fitting. However, for bores that show a lack of response to all flow events, a refinement of aquifer properties in the immediate vicinity of the monitor bore is indicated.

A review of the verification simulation shows that the error in this model is similar to the error in the calibration model, suggesting that the calibrated model has some predictive capability. Figure 30 shows the comparison of predicted and measured water levels for the monitoring bores used in the verification. Given that the verification period presents an entirely different hydrological regime than the calibration period, the results of the verification further support the conclusion that the model has some predictive capability. The average absolute error is a measure of the fit of the model, and is 4.0% for the verification flow model. This percentage error is consistent with the accepted modelling guidelines which generally recommend a percentage error less than 5.0%.

The error in the verification model is similar in nature to that found in the calibration model, and tends to be for the same bores. This suggests that some remedial calibration of these outstanding bores may be effective in reducing model error. In the absence of an improved river stage height model, it is unlikely the present flow modelling approach can be significantly improved upon.

Figure 29 shows a comparison of predicted and measured TDS concentrations for the solute model calibration bores completed in the Lower Gascoyne River aquifer. Appendix H shows the calibration solute concentration graphs for the same set of monitor bores, a selection of which are presented in Figures 26 and 27. From Figure 29, the model predicted concentrations in general show the error to be non-systematic in that the points are randomly scattered around the unity slope line. However, the scatter is larger, with a number of outliers having significant error. There are also some patterns in the data that indicate the model response is not the same as measured data, and that solute concentrations are unchanging in the model. A review of the solute calibration curves shows that the source of error tends to be:

- Interpolation of initial TDS concentrations that results in the simulated concentrations at the start of the model being different than actually measured;
- A lack of response in the model, with TDS typically not varying as much as measured data.

The apparent lack of response of bores in Subarea A is the major source of error in the model. Typically, measured concentrations levels change more rapidly than model concentrations. Whether these measured changes reflect changes in the aquifer (i.e. the average TDS in a cell) or bore conditions is not known. It is unlikely given the rate of change in measured data, that the present model will be able to match these changes, give the cell size, and the vertical distribution of TDS and hydraulic conductivity. Consequently, it is recommended that the finite difference grid be refined in the Subarea A area to improve the response of the solute model to changes in TDS.

Average Absolute Error (mg/L)	Average RMS Error (mg/L)	Maximum Error (mg/L)	Minimum Error (mg/L)
230	335	2525	1

Table 18: Summary of Transient Concentration Calibration Error

Table 18 summarises the calibration error in the solute transport model. The average absolute error is a measure of the fit of the model, and represents an error of 9%. This error is larger than the accepted modelling guideline which generally recommends a percentage error less than 5%. The RMS error is larger than the absolute average error as this estimator weights larger error more than small. The fact the RMS error is larger than the average absolute error indicates that some of the error is due to large error at a few bores. The maximum and minimum range of the error shows that there is some significant error in a few bores due to uncertainty with respect to small scale structures, e.g. clayey lenses, which may exist in the river bed, resulting in significant error between measured and simulated salinity.

The verification is evaluated by qualitatively viewing selected hydrographs to compare simulated and measured response, and by summarizing the error between simulated and measured water levels at selected bores, to determine model error statistics for the period. A summary of the water level and concentration error in the model during the verification period is shown in Tables 19 and 20, respectively. Figure 30 shows a plot of measured versus simulated heads, and Figure 31 measured versus simulated concentrations for the verification period.

Average Absolute Error (m)	Average RMS Error (m)	Maximum Positive Error (m)	Maximum Negative Error (m)
0.29	0.85	7.46	-4.76

Table 19: Summary of Water Level Transient Verification Error

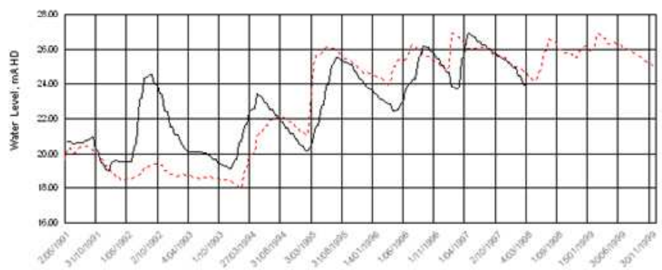
Average Absolute Error (mg/L)	Average RMS Error (mg/L)	Maximum Error (mg/L)	Minimum Error (mg/L)
316	825	9411	0

Table 20: Summary of Concentration Transient Verification Error

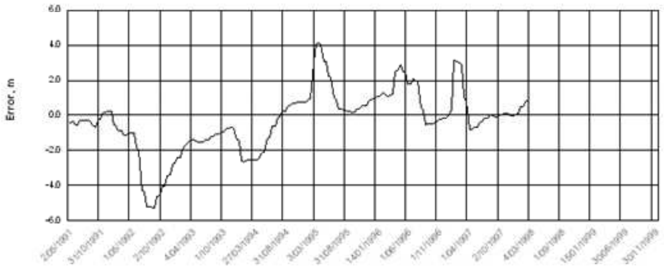
Bore: P13-74 **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



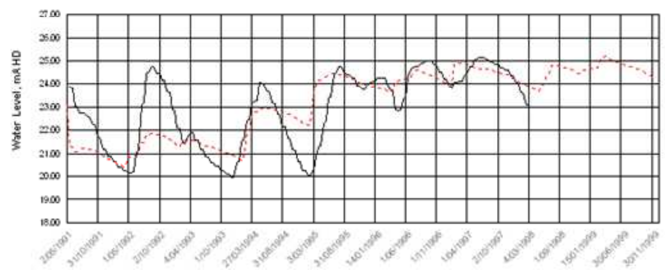
Statistics

Average Error	1.35	m
Standard Deviation:	1.82	m
RMS error:	1.84	m
Maximum:	5.25	m
Minimum:	0.00	m

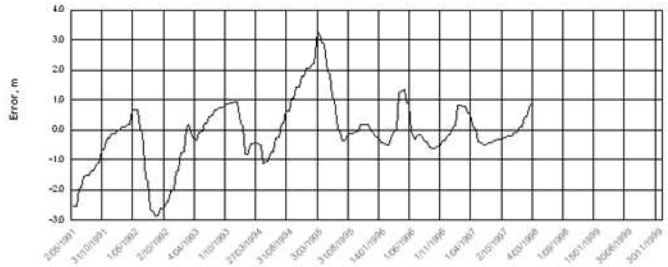
Bore: P11-77 **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



Statistics

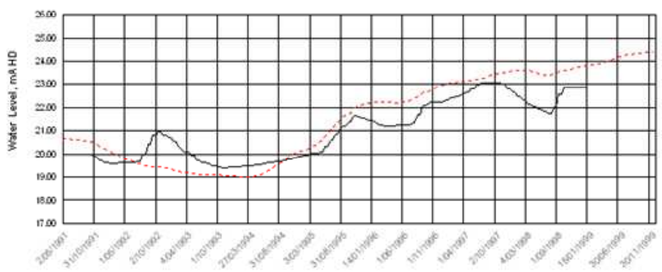
Average Error	0.79	m
Standard Deviation:	1.12	m
RMS error:	1.12	m
Maximum:	3.27	m
Minimum:	0.01	m

Figure 22: Hydrographs: Upstream Calibration

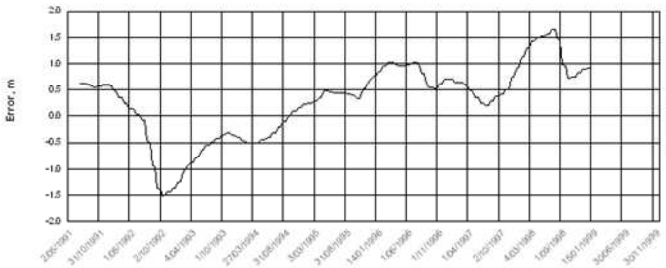
Bore: -L58- **GASFAMS V1**

Simulated Measured

Calibration Hydrograph



Calibration Error



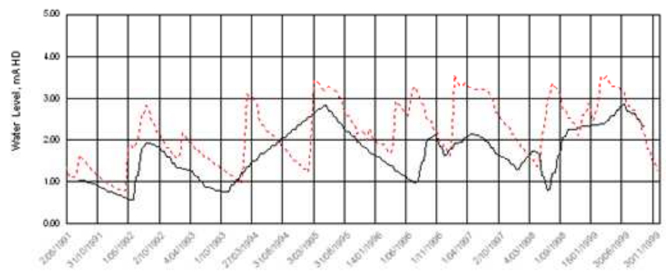
Statistics

Average Error	0.66	m
Standard Deviation:	0.71	m
RMS error:	0.76	m
Maximum:	1.66	m
Minimum:	0.01	m

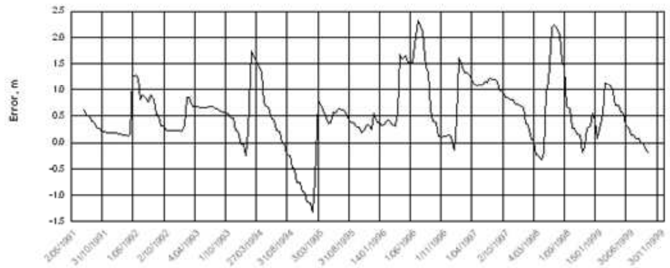
Bore: -L47- **GASFAMS V1**

Simulated Measured

Calibration Hydrograph



Calibration Error



Statistics

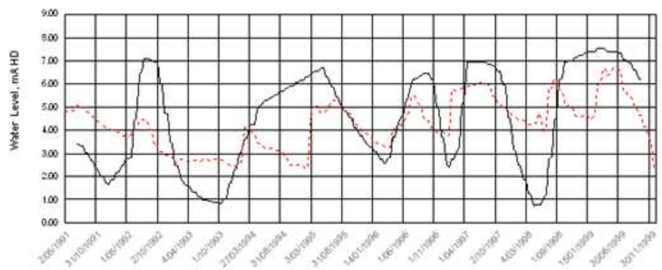
Average Error	0.68	m
Standard Deviation:	0.63	m
RMS error:	0.86	m
Maximum:	2.32	m
Minimum:	0.00	m

Figure 23: Hydrographs: Upper Middle-stream Calibration

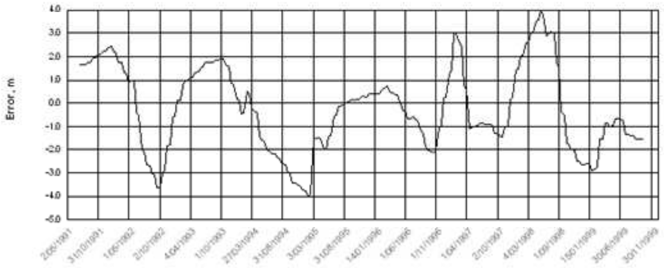
Bore: -L38- **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



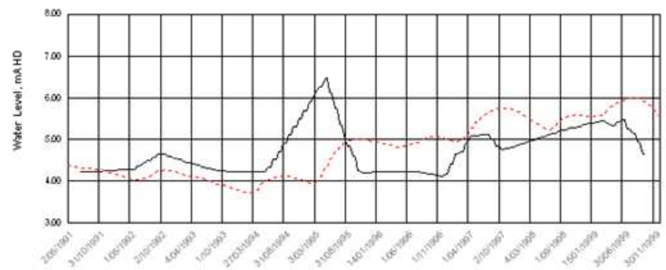
Statistics

Average Error	1.49 m
Standard Deviation:	1.77 m
RMS error:	1.79 m
Maximum:	4.01 m
Minimum:	0.02 m

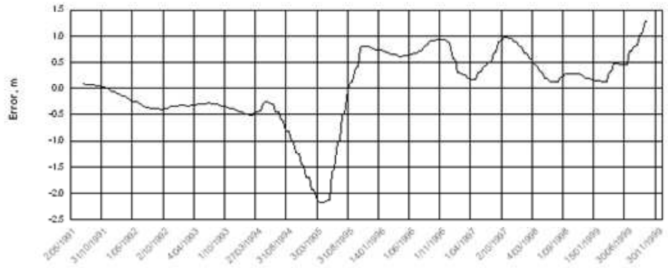
Bore: -L24- **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



Statistics

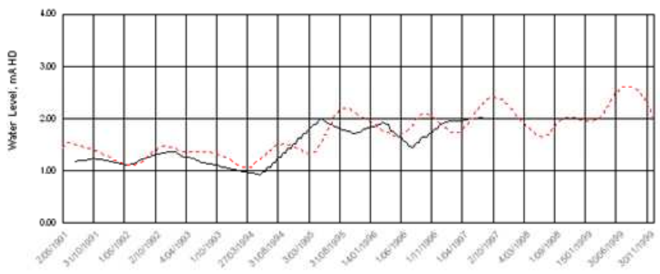
Average Error	0.57 m
Standard Deviation:	0.73 m
RMS error:	0.73 m
Maximum:	2.18 m
Minimum:	0.00 m

Figure 24: Hydrographs: Lower Middle-stream Calibration

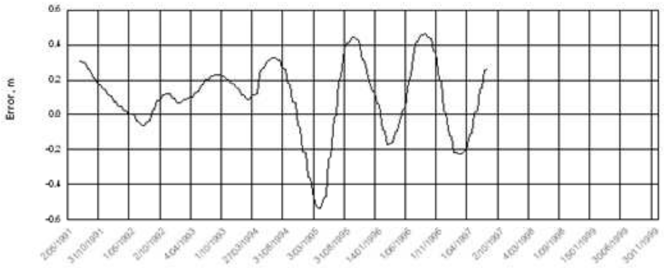
Bore: -L10- **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



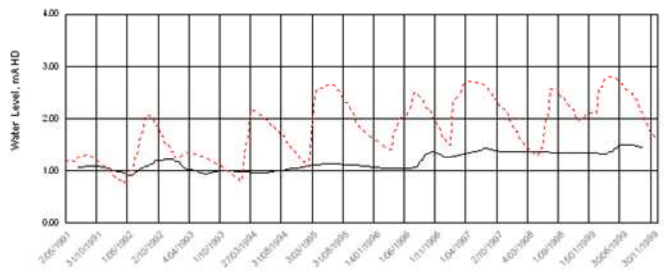
Statistics

Average Error	0.19 m
Standard Deviation:	0.22 m
RMS error:	0.24 m
Maximum:	0.54 m
Minimum:	0.00 m

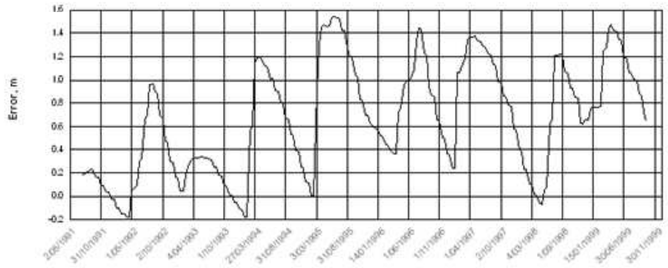
Bore: -L6- **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



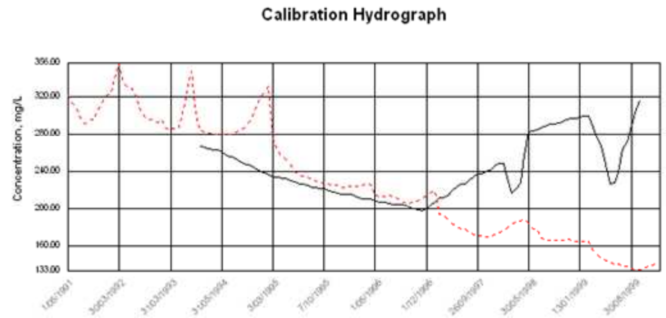
Statistics

Average Error	0.69 m
Standard Deviation:	0.48 m
RMS error:	0.83 m
Maximum:	1.53 m
Minimum:	0.00 m

Figure 25: Hydrographs: Downstream Calibration

Bore: 12-F **GASFAMS V1**

Simulated — Measured

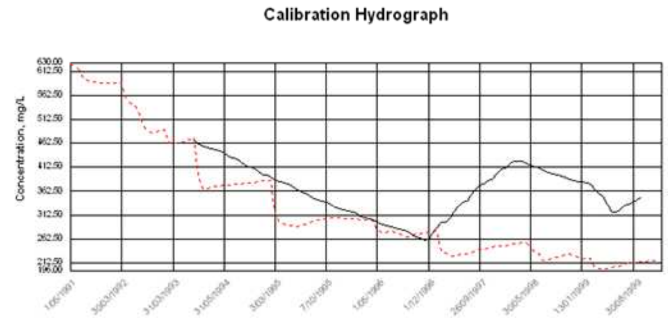


Statistics

Average Error	52.32 mg/L
Standard Deviation:	63.74 mg/L
RMS error:	71.04 mg/L
Maximum:	181.29 mg/L
Minimum:	3.24 mg/L

Bore: 27-O **GASFAMS V1**

Simulated — Measured



Statistics

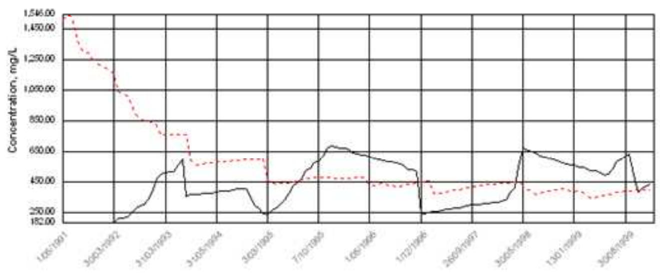
Average Error	82.72 mg/L
Standard Deviation:	62.89 mg/L
RMS error:	102.95 mg/L
Maximum:	188.30 mg/L
Minimum:	1.06 mg/L

Figure 26: Solute Graphs: Subarea A Calibration

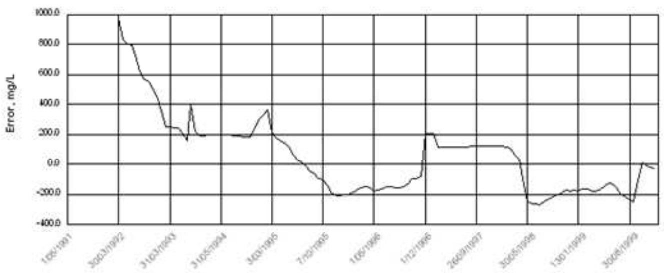
Bore: 36-H **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



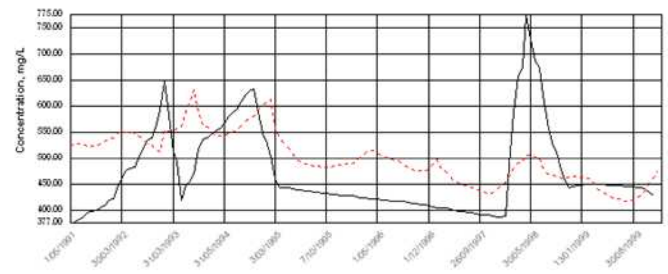
Statistics

Average Error	203.98 mg/L
Standard Deviation:	253.26 mg/L
RMS error:	259.77 mg/L
Maximum:	975.83 mg/L
Minimum:	12.13 mg/L

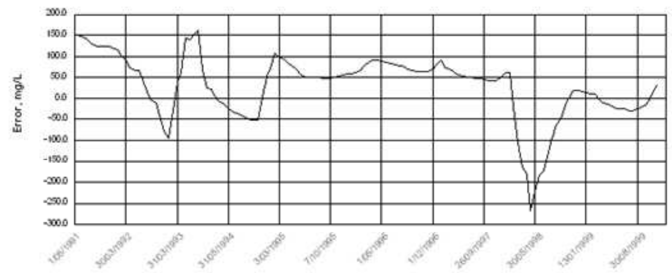
Bore: NO. 1 **GASFAMS V1**

Simulated — Measured

Calibration Hydrograph



Calibration Error



Statistics

Average Error	66.78 mg/L
Standard Deviation:	75.39 mg/L
RMS error:	81.44 mg/L
Maximum:	267.65 mg/L
Minimum:	0.11 mg/L

Figure 27: Solute Graphs: Subarea A Calibration

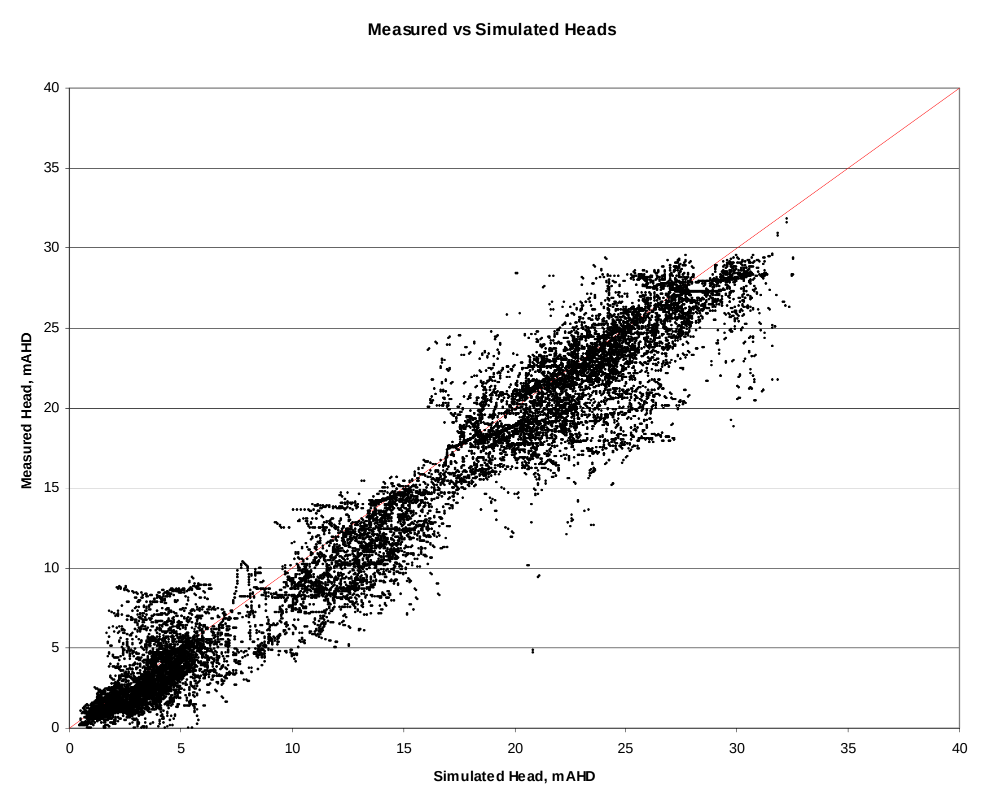


Figure 28: Calibration: Measured vs. Simulated Heads

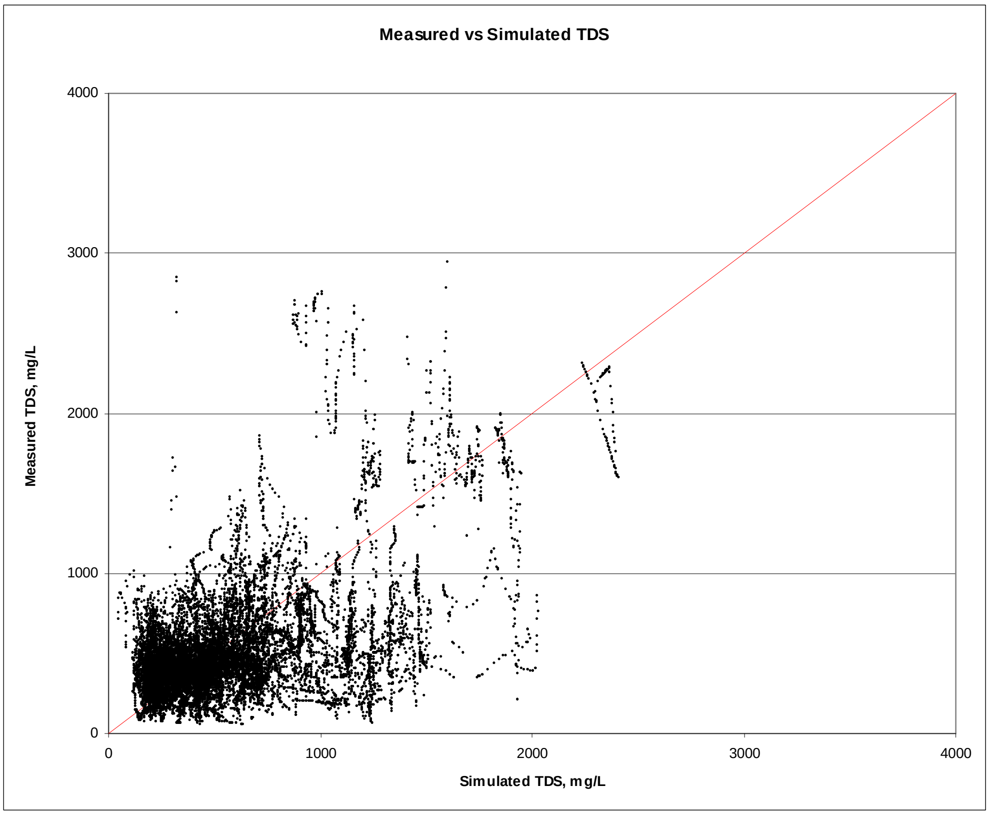


Figure 29: Calibration Measured vs. Simulated Concentrations

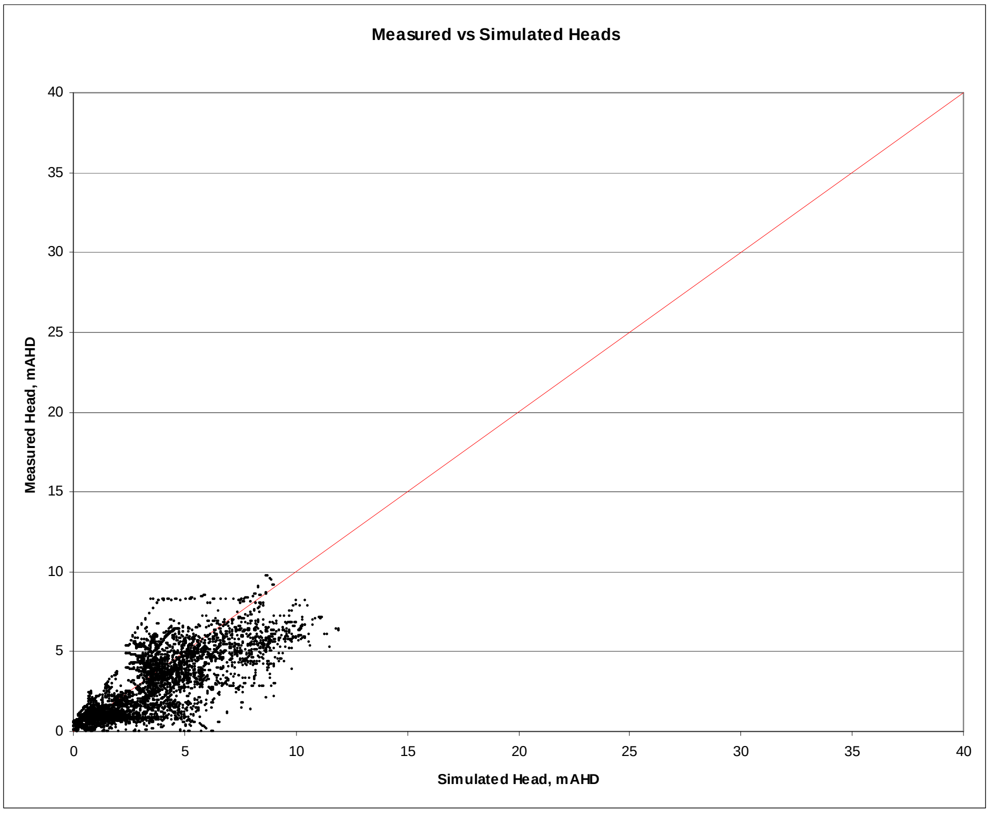


Figure 30: Verification Measured vs. Simulated Heads

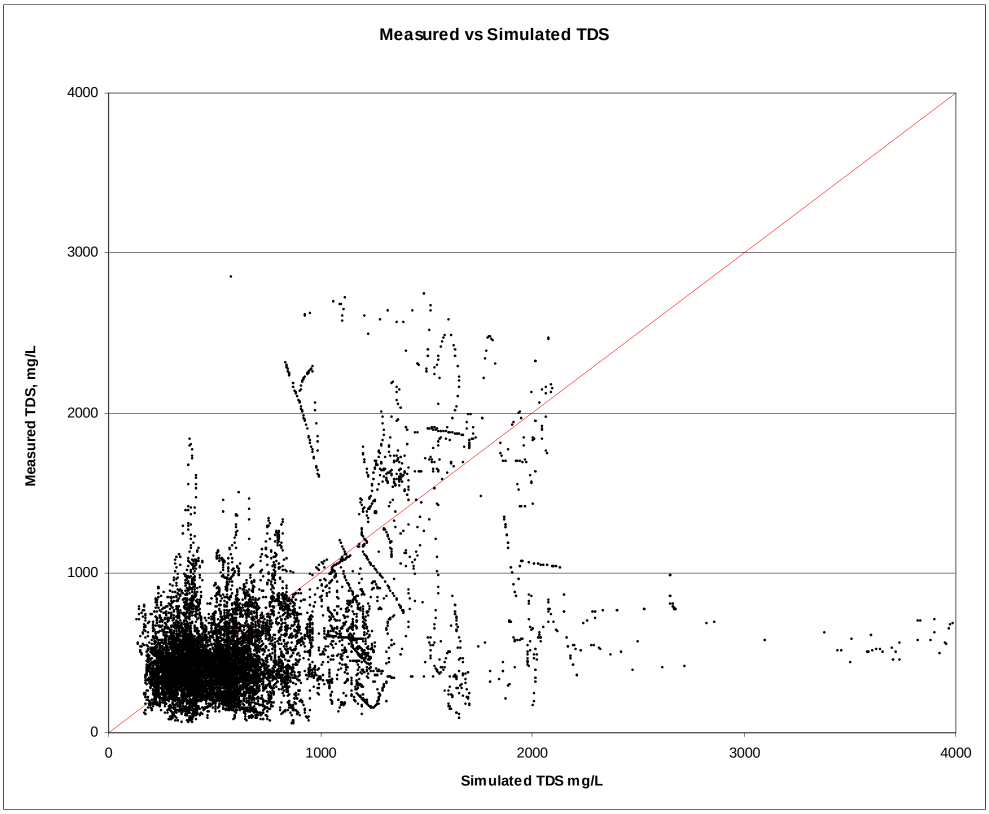


Figure 31: Verification Measured vs. Simulated Concentrations

8.5 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 Lower Gascoyne River aquifer, the numerical implementation of the conceptual model of the superficial aquifer has been improved by the addition of further drilling data and the subsequent review of the quantitative geology. However, the vertical discretisation of the RBS and OAA aquifers is only an approximate representation of the actual geology of these aquifers. The model's structural scale makes the model unsuitable for estimating groundwater resources and storage at a local scale (i.e. a single bore). Table 21 summarises the applicability of the model to the stated objectives.

Objective	Achieved	Comments
Simulate groundwater flow within and between all hydrogeological units in the Gascoyne River floodplain groundwater system.	Yes	
Establish water budgets for each aquifer.	Yes	
Under a range of scenarios, including pumping and climate variations, predict the scale of changes in recharge, groundwater potentiometric heads/water levels and groundwater salinity within the hydrogeologic units.	Yes No	Flow model can predict changes in water levels due to changes in aquifer stresses Solute model is not suitable to predict salinity of individual bores
Evaluate likely changes in groundwater discharge to ocean environments.	Yes	
Predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions.	Yes	
Provide results that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs).	Yes	
Estimate the likely range and uncertainty of water level changes as a result of pumping and climatic stresses.	Yes	

Table 21: Model Applicability to Stated Objectives

9 WATER BALANCE

A water balance of the RBS and OAA aquifers as developed in the current study is presented below. The values of input parameters adopted are based on the discussion presented in the preceding sections. Following careful analysis of the available data, the period between 1985 and 2002 was selected for hydrograph and groundwater balance analysis, on the basis of reasonably good and continuous groundwater information.

9.1 Water Balance Components

9.1.1 Hydraulic Properties

For the purpose of the water balance calculations the following hydraulic parameters are considered to be representative of the system:

- RBS aquifer unit:
  - Horizontal hydraulic conductivity (K_h): 20 – 800 m/day
  - Vertical Hydraulic conductivity (K_v): 0.1 x K_h m/day
  - Thickness (b): 4 - 12 m
  - Transmissivity (T): 200 – 4000 m^2/day
  - .Specific yield (unconfined storage): 0.2 (dimensionless)
- OAA aquifer unit:
  - Horizontal hydraulic conductivity (K_h): 1 x 10^{-1} – 1 x 10^{2} m/day
  - Vertical Hydraulic conductivity (K_v): 0.03 m/day
  - Thickness (b): 50 m
  - Transmissivity (T): 175 m^2/day
  - Storativity: 1 x 10^{-3} – 1 x 10^{-4} (dimensionless)

A weighted specific yield of 0.075 and a vertical hydraulic conductivity (K_v) of 0.03 m/d have been assumed for the water balance calculations.

9.1.2 Storage

The volume of groundwater held in storage is the product of the estimated saturated volume of aquifer and the effective storativity. Water table contours were assessed for the selected period to estimate average annual maximum/minimum groundwater heads (aaMAX and aaMIN) in the OAA and RBS aquifers separately. Flow tube analysis for the same periods was conducted and water table maps were used to estimate recharge from river flow and to define an envelope of groundwater taken into storage from river recharge, based on the difference between aaMAX and aaMIN volume, where aaMAX is the average annual maximum water level and aaMIN is the average annual minimum water level. The difference between these to potentiometric surfaces is an estimate of the annual average change in aquifer storage. The average effective area of the recharge envelope was estimated to be approximately 322,000,000 m^2. The “apparent volume” and envelope area define a mean change in head available for leakage from the RBS into the underlying OAA. The product of the “apparent volume” multiplied by effective porosity gives an annual average change in storage within the system.

Previous estimates of storage have ranged between 100 x 10^6 m^3 (Allen, 1972) up to 340 x 10^6 m^3 (Martin, 1990b), using an effective porosity of 0.1. The current estimate based on the difference between the aaMAX and aaMIN, assuming a weighted specific capacity of 0.075

is between these previous estimates, at 195 x 10^6 m^3. The difference is likely to be ascribable to varying assumptions, including interpolation error, the exclusion of water with salinity greater than 500mg/L TDS west of Rocky Pool and any freshwater in the older alluvium within Subarea A by Martin (Martin, 1990b).

9.1.3 Abstraction

The allocated maximum abstraction for the alluvium aquifer, comprising both the RBS and OAA aquifer units was based on the measured abstraction rate for the model area, recognizing that pumping in excess of the allocation limits occurs when the river is flowing.

9.1.4 Evapotranspiration

A simplified evapotranspiration model was used to estimate the evapotranspiration rate based on watertable drawdown within the estimated recharge envelope, based on the aaMAX and aaMIN volumes.

The total area of water table change and effective areas between each 1m change in water table was estimated from a flow net. An evaporation extinction depth model was developed for varying percentages of evaporation using pan evaporation at Carnarvon airport to estimate monthly evapotranspiration losses. The monthly evapotranspiration losses were integrated over the period, and corrected using a pan correction factor of 0.70.

9.1.5 River Recharge

The river recharge is the primary source of water which is consistent with the conceptual hydrogeological model. This source term is effectively the dependent variable, which is being estimated using the water balance technique.

9.1.6 Rainfall Recharge

The total rainfall recharge was for the period was assumed to be zero, which is consistent with the conceptual hydrogeological model.

9.2 Conceptual Water Balance

A simplified water balance for the conceptual area comprising all of the components that enter or leave the 3-dimensional boundaries defined for the conceptual model area was derived using the equation for change in total storage where:

$\Delta V = (R_{riv} + I) - (O + A + E)$

Where:

- Input components are:
  - R_{riv} = River recharge
  - I = Groundwater Inflow
- Output components are:
  - O = Groundwater outflow
  - A = Abstraction
  - E = Evapotranspiration
- ΔV = change in storage volume.

Table 22 summarizes the water balance analysis based on the above parameters, and shows a comparison to that obtained for the calibration period.

Inputs	Component	Average Conceptual (GL/annum)	Modelled 1991-2000 (GL/annum)	Comparison (GL/annum)
R	River recharge	18.8	27.6	11.8 x10^{6} (Martin, 1990)
I	GW Inflow	0	0.08	
Total		18.8	27.7	
Outputs				
O	GW outflow	5.1	1	4,800,000 (Martin, 1990)
A	Abstraction	12.6	9.3	1,800,000 (Martin 1990)
E	Evapotranspiration	23.6	16.7	5,200,000 (Martin, 1990)
Total		41.3	25	
Change in storage				
	aaMAX-aaMIN 'volume'	392	-	340 x 10^{6} m^{3} (Martin, 1990)
ΔV	Water Balance ΔStorage	-29	2.5	

Table 22: Water Balance Comparison

Tables 23-25 summarised the average annual water balance for the calibration and verification models, and described in Section 11.3. The zonations used are shown in Figures 36 and 37.

Zone	Storage (GL)	Recharge (GL)	Wells (GL)	Evaporation (GL)	Inflows (GL)
1	0.12	9.55	-3.04	-4.66	0.00
2	1.79	1.19	-0.87	-5.03	0.61
3	-0.85	14.1	-0.53	-6.33	0.01
4	-1.89	1.49	-0.59	-0.85	0.06
5	0.05	0.00	-1.24	0.00	0.51
6	-1.26	0.00	-3.36	0.00	-0.01
Total	-2.05	26.4	-9.61	-16.9	1.19

Table 23: Calibration Water Balance Summary

Zone	Storage (GL)	Recharge (GL)	Wells (GL)	Evaporation (GL)	Inflows (GL)
1	-0.61	13.39	-1.13	-7.94	0.00
2	1.34	2.11	-1.82	-6.19	0.64
3	-1.96	17.9	-1.22	-12.86	0.01
4	-4.69	9.31	-2.20	-2.15	0.05
5	-0.10	0.00	-0.97	0.00	0.53
6	-1.61	0.00	-0.98	0.00	0.30
Total	-7.62	42.7	-8.31	-29.1	1.54

Table 24: Verification Water Balance Summary

Zone	Storage (GL)	Recharge (GL)	Wells (GL)	Evaporation (GL)	Inflows (GL)
1	4.19	0.52	-1.05	-2.81	0.00
2	3.06	0.09	-1.75	-2.99	0.64
3	5.51	4.3	-1.65	-6.19	0.01
4	2.97	0.42	-2.74	-0.85	0.06
5	0.51	0.00	-1.47	0.00	0.54
6	-0.78	0.00	-1.27	0.00	0.24
Total	15.5	5.3	-9.94	-12.8	1.50

Table 25: Verification Water Balance Summary – Low Frequency Recharge Period

10 SENSITIVITY ANALYSIS

The objective of sensitivity analysis is to quantify the sensitivity of model calibration parameters to observation data. By systematically 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.

GASFAMS V1.1 uses MODFLOW-2000 to solve the flow equations for the saturated aquifer. MODFLOW-2000 has the capability to calculate sensitivities from the observation data used to calibrate the model. These capabilities were 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 are used to compare the importance of different parameters in calibrating the model to an observation. The composite sensitivities are an average of the sensitivity responses at all of the monitoring bores used in calibrating the model.

The model sensitivities were obtained using the following procedure:

- A set of sensitivity parameters were defined for aquifer hydraulic conductivity, vertical hydraulic conductivity, specific yield, river conductance, and well abstraction for the RBS and the OAA.
- The model was run to generate the composite sensitivities for 6 parameters, using the set of calibration bores.
- 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 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 26 summarises the sensitivity parameters used in the sensitivity analysis.

Parameter	Layers
Horizontal hydraulic conductivity, k_h	1,2, 1,2, 3-10
Vertical hydraulic conductivity, k_v	1-2, 3-10
Storage coefficient, Sy	1, 2
River Bed Conductivity, C_k	-

Table 26: Layer Sensitivity Parameters

10.1 Sensitivity Results

The results of the flow sensitivity analysis are summarized in Table 27, and are consistent with the conceptual model. The most important parameters are highlighted in green, yellow and orange.

The sensitivity analysis indicates that horizontal and vertical hydraulic conductivity in the RBS and in RBS/OAA are the most important for calibrating heads in model, followed by specific yield in the RBS. Note that river conductance and abstraction are also important. The OAA parameters in Subareas B-L are not that important for calibrating heads reflecting the low transmissivity of the aquifer and the source of recharge.

The sensitivity of the calibrated heads to the hydraulic conductivity of the OAA in Subarea A reflects the number and location of the monitoring bores used for calibration and effect of lateral flow in this area.

Formation	Parameter	Layer	Composite Sensitivity
OAA	K_h	1-2	0.19
Alluvial Sand, Subarea A	K_h	1-2	0.22
RBS	K_h	1-2	0.25
Alluvial Sand	K_h	3-6	0.20
Alluvial Sand	K_h	3-6	0.19
Brickhouse Alluvial Sand	K_h	7-10	0.19
Subarea A Alluvial Sand	K_h	7-10	0.19
Subareas B-L Alluvial Sand	K_h	7-10	0.21
OAA, RBS	k_v	1	0.30
OAA, RBS	k_v	2	0.30
RBS	**River Conductance**	1-2	0.94
OAA	S_y	1-8	0.26
RBS, Alluvial Sand	S_y	1-8	0.29

Table 27: Scaled Composite Sensitivities

With respect to the solute model, the only parameters that are relevant to calibration are the initial concentration distribution, and dispersivity. The uncertainty in the initial distribution dominates the effect of dispersivity.

11 CONCLUSIONS AND RECOMMENDATIONS

A numerical model of the Lower Gascoyne River was constructed and calibrated using available geological, water level and water quality data.

The construction of the model is based on, and is consistent with, the previous conceptual hydrogeological model and MODFLOW numerical groundwater model (GRFAMOD), as developed by Dodson (2002). The model is based on the conceptual hydrogeology of the Lower Gascoyne River as described by Dodson (2002), and updated to reflect more recent drilling results in the Brickhouse area. The modifications to the model include:

- updating of the rainfall and flow data to 2008;
- updating of the bore abstraction data to 2008;
- the inclusion of layer elevations for all layers in the model and the conversion of confined layers to confined/unconfined;
- revision of parameters based on review of the quantitative geology as per Section 3;
- a new flow recharge model;
- the deprecation of rainfall recharge as a mechanism for aquifer recharge;
- the use of the multi node well package to simulate abstraction; and
- the addition of a solute transport model to simulate changes in water quality.

GASFAMS V1.1 has been designed to simplify and generalise GRFAMOD so that it can be used for management of the water resources of the Gascoyne River aquifers.

The GASFAMS V1.1 model is implemented using MODFLOW-2000, and MT3DMS with Visual MODFLOW as the pre-processor.

The GASFAMS V1.1 model was calibrated over the period from May 1991 to December 1999. The model was verified using the period from January 2000 to December 2007.

The flow model calibration error has been calculated and is summarised below:

Average Absolute Error (m)	Average RMS Error (m)	Maximum Positive Error (m)	Maximum Negative Error (m)
1.66	2.24	16.12	-8.27

The flow model verification error has been calculated and is summarised below.

Average Absolute Error (m)	Average RMS Error (m)	Maximum Positive Error (m)	Maximum Negative Error (m)
1.29	1.77	7.46	-4.76

Based on the error analysis, the GASFAMS flow model is adequately calibrated and performs well in the verification period, suggesting the model may have some predictive capability.

The solute transport model is not as well calibrated as the flow model. The average absolute error is a measure of the fit of the model, and represents a percentage error of 9%. This percentage error is larger than the accepted modelling guideline which generally recommends a percentage error less than 5%. The RMS error is larger than the absolute average error as this estimator weights larger error more than small. The fact the RMS error is larger than the average absolute error indicates that some of the error is due to large error in a few bores. The maximum and minimum range of the error shows that there is some significant error in some bores.

The table below summarises the applicability of the model to the stated objectives.

Objective	Achieved	Comments
Simulate groundwater flow within and between all hydrogeological units in the Gascoyne River floodplain groundwater system.	Yes	
Establish water budgets for each aquifer.	Yes	
Under a range of scenarios, including pumping and climate variations, predict the scale of changes in recharge, groundwater potentiometric heads/water levels and groundwater salinity within the hydrogeologic units.	Yes No	Flow model can predict changes in water levels due to changes in aquifer stresses Solute model is not suitable to predict salinity of individual bores or well enough calibrated to predict changes in hydrogeological units for short term management.
Evaluate likely changes in groundwater discharge to ocean environments.	Yes	
Predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions.	Yes	
Provide results that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs).	Yes	
Estimate the likely range and uncertainty of water level changes as a result of pumping and climatic stresses.	Yes	

11.1 Recommendations

The following needs to be undertaken by the DoW prior to undertaking any additional numerical modelling of the Lower Gascoyne River:

- All bore construction data to be reviewed, validated and entered into a corporate database;
- All bores are to have a unique identifier that is consistent across all databases and all datasets;
- Multiple water level or water quality readings are to be stored with a unique identifier related to the bore unique identifier;
- A reference table relating all previous bore designations to the unique well identifier;
- The proper name of all bores be established and non-conforming labels to be expunged from all databases;
- Water level, abstraction data, and water quality data as collected in Subarea A is to be checked and then entered into a corporate data base - the use of local spreadsheets should be discouraged;
- Data should be disseminated only as indexed tables (tables that are subject to referential integrity with respect to the unique well identifier);
- All data should be input into the database within six months of collections and after quality assurance;
- Monthly abstraction data from public and private bores should be stored in a database, as monthly volumes.

It is also important that any bores drilled by private and public entities be included in the DoW databases, to ensure that relevant data is available. An efficient mechanism for capturing this type of data, with quality assurance procedures, needs to be developed as a matter of urgency within the DoW to ensure all available data is readily accessible for review, analysis, and use in groundwater modelling projects.

With respect to monitoring, it is recommended that:

- A set of bores be selected as primary monitoring bores, and water level data be collected at least monthly, and water quality data and vertical salinity profiling undertaken at least quarterly at these bores;
- Water level monitoring in the selected bores should be undertaken using down-hole data recorders, with a maximum recording interval of 6 hours.
- Measured water level and water quality data should also be collected immediately after large flow events;
- In the case of the proposed Brickhouse borefield, a set of purpose built monitor bores should be installed as part of borefield construction and license conditions. These bores need to be monitored as above, with down-hole data recorders and quarterly water quality and salinity profiling;
- Conductivity surveys of selected bores be undertaken on a quarterly basis to establish the vertical extent and distribution of TDS is the aquifer;

To improve the performance of the GASFAMS V1.1 model, given its sensitivity to river stage height, it is recommended that the existing MIKE11 model of the Gascoyne River be used to construct a flow stage time series for all flows since 1990. This flow series will provided an estimated stage height at various points along the Lower Gascoyne River. The stage height time series can then be used as input into the model, as a specified head in the MODFLOW River package at a number of locations along the river channel, or directly as a boundary condition.

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