Lower De Grey Groundwater Model

- Final Report
- June 2010
Lower De Grey Groundwater Model

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Executive Summary

A numerical groundwater model of the alluvial aquifers of the Lower De Grey River in the Pilbara was created using the FEFLOW finite element modelling code. The model incorporates the physical processes (such as pumping, rainfall, flooding, river recharge and evapotranspiration) that control and influence the storage and movement of groundwater in the alluvial sediments surrounding the river.

The model was calibrated by modelling historical conditions and comparing the modelled groundwater levels with observed data. The normalised RMS Error was one parameter used to indicate the quality of the model calibration. However, a sensitivity analysis indicated that a wide range of model input parameter values that cause different model outcomes but result in an acceptable RMS Error. As a result the RMS Error statistic was not used in isolation as a model calibration criterion. In addition to the RMS Error, calibration relied on visual inspection of the recorded and modelled hydrographs at observation bore locations, and on professional judgement of appropriate ranges of parameters, informed by pumping test data, Bureau of Meteorology data, vegetation survey data, and experience with modelling rainfall infiltration and evapotranspiration in other places.

A series of predictive scenarios were run using the calibrated model to predict possible future groundwater conditions 50 years in the future (given certain assumptions regarding climate and river flow). It was found that an increase in pumping at the currently operating Namagoorie borefield from 7 GL/year to 8 GL/year could result in an increased drawdown of approximately 1 m near the borefield, with no discernable effect on groundwater fed pools in the De Grey River.

Likewise, it was found that commencement of pumping from the Bulgarene borefield at a rate of 2 GL/year could also result in an increased drawdown of approximately 1 m near the borefield. However, in this scenario the cone of depression reached the De Grey and Ridley rivers, causing decreased water levels in both Bulgarene and Muccangurra pools. This decrease in pool water level could have a significant effect on the size and permanency of those pools, especially during drier times of the year.

In neither increased pumping case did the increased cone of depression reach the assumed seawater interface, suggesting that there is no apparent risk of further salt water intrusion.

Extraction from the newly discovered Pardoo Creek aquifer was also modelled, though the results served only to highlight that more data are required before a useful model for this region can be developed.
1 Introduction

1.1 Background to this project
The Department of Water in Western Australia is responsible for the management of the groundwater resources of the Pilbara Region and is currently developing a regional water resource management plan aimed at creating an equitable means of allocating water to key stakeholders including the environment. The overall objective of the work is to encourage responsible development of the water resources of the Pilbara that will encourage economic development while at the same time preserving the unique ecological communities and cultural features for which the region is renowned. To this end it is important for the Department to be able to predict likely impacts of groundwater extraction and other forms of development. The development of a calibrated groundwater model will provide an important predictive tool that the Department can use in future to help ensure groundwater development of the area is undertaken in a sustainable manner.

1.2 Modelling Study Objectives
The modelling work forms an integral part of the Department of Water’s management plan for the Pilbara. The project is aimed at quantifying the potential groundwater resources of the study area and in particular in assessing the long term sustainable yield of the aquifer under various assumptions of future groundwater extraction regimes and climate.

The Lower De Grey River groundwater model covers the alluvial aquifers in the De Grey Catchment, from upstream of the Namagoorie Borefield to the ocean. This will allow the impact of both bore field development and seawater intrusion to be assessed. The model extent is shown in Figure 1-1, and the aquifer extent is discussed in Section 2.7.
Figure 1-1 - Model Extent
2 Hydrogeological Conceptualisation

2.1 Available Data
At the commencement of the modelling project, the Department of Water supplied SKM with the following data relevant to building and calibrating a groundwater model for the De Grey River:

- Bore hydrographs for 24 bores, with data collection generally about 1 time per month starting in the 1970s and continuing to 2009
- Sporadic / once off water level readings for a further 279 bores in the vicinity of the model area. Many of these are outside the model domain and recorded prior to the model start date.
- Bore logs for 83 bores
- Pool hydrographs for 5 pools, with data collection generally about 1 time per month starting in 2000-2001 and continuing to 2009
- Namagoorie Borefield extraction volumes, with a data gap from 1989-1995
- ArcMap shapefiles showing bore locations, roads, geology and aquifer contours generated by Davidson (1974)
- ArcMap shapefile showing locations of permanent, semi-permanent and ephemeral pools surveyed along the De Grey river
- Aerial photography
- Geophysical data, of which the EM data was beneficial for delineating the alluvial aquifer
- DTM and LiDAR elevation data
- Several reports and articles discussing previous investigations (see reference list)

Climate data were not supplied and SKM sourced this data from the Bureau of Meteorology.
2.2 Regional Setting
The model lies within the Pilbara region of Western Australia. The major industry in the Pilbara is mining, with the majority of Australia’s iron ore found in the region. The climate is tropical-arid, with cyclones bringing heavy rains during the summer months and very little rainfall during winter months. Grasses and low shrubs dominate the plains (Figure 2-1), with large trees dependent on groundwater found along ephemeral and semi-permanent river channels (Figure 2-2). Rivers in the Pilbara tend to flow only after summer storm events for a period of several weeks, and then remain as a series of groundwater dependent pools throughout the rest of the year.

- Figure 2-1 – Pilbara grasses
2.3 Regional Stratigraphy
The primary water bearing formations in the De Grey area are the Cainozoic (Quaternary and Tertiary) alluvium deposits following the modern and historic paths of the De Grey River. These sediments consist of sand and clay lenses with occasional gravel beds, with thickness ranging from several meters up to 75 m. Though the modern De Grey has migrated several kilometres to the south west of the original palaeochannel, there is good connection between the palaeochannel and the modern alluvial sediments. Throughout much of the model region the distinction between Quaternary and Tertiary sediments is arbitrary as the two sets of alluvium act as one aquifer with alternating sand, clay and gravel lenses. Though there is much variation in stratigraphy from borehole to borehole due to the meandering of the river over time, there is typically a gravel unit at the base of the palaeochannel. This gravel unit is the target of both the Namagoorie and Bulgarene borefields. In many (but not all) locations this gravel unit is separated from recent sand deposits by clayey sand, as shown in Figure 2-3 (WorleyParsons Services, 2005). Unfortunately, not all bores in the region have been logged with sufficient detail to determine the various components of the alluvium layers, instead labelling all shallow sediments as undifferentiated alluvium (including cross sections by Davidson, see Figure 2-4).

The water table in the Cainozoic alluvium tends to be close to the ground surface (5-10 m below ground level). At some locations a thin (1 m) kankar layer has developed due to the rising and falling water table. This calcareous alluvium is best counted as part of the main alluvium aquifer than as a separate lithographic layer.

Beneath the Cainozoic alluvial sediments lies Mesozoic grey sandy shale and sandstone, and weathered clay. In some locations there is up to 80 m of Mesozoic clay separating the Cainozoic
alluvial material from deeper Archaean bedrock. This unit is an aquitard and does not transport water. Bedrock in the De Grey area is folded Archaean greenstone and granite. Some weathered and fractured zones may produce localised aquifers but generally the rock does not bear water.

The major stratigraphic layers are summarised in Table 2-1. For this project the base of the groundwater model will be set to the base of the Mesozoic (Broome) shale and sandstones.

Figure 2-3 – Interpreted geological cross section of the Namagoorie Borefield area (WorleyParsons Services, 2005)
Figure 2-4 – Interpreted geological cross section of the Namagoorie Borefield area. Contours show interpreted base of alluvium. (Davidson, 1974)
Table 2-1 - Summary of Hydrostratigraphy (Haig, 2009)

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Lithology</th>
<th>Description</th>
<th>Aquifer Properties</th>
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<tr>
<td>Cainozoic (Quaternary)</td>
<td>Alluvium (sand, gravel, clay lenses)</td>
<td>Modern alluvium along the river channels</td>
<td>Aquifer with good connection to deeper Tertiary palaeochannel</td>
</tr>
<tr>
<td>Cainozoic (Tertiary)</td>
<td>Alluvium (sand, gravel, clay lenses, pisolite and calcrete)</td>
<td>Palaeochannel alluvium in the original course of the De Grey river. This channel lies adjacent to the modern De Grey to the north east.</td>
<td>Productive aquifer, both unconfined and confined depending on location</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Grey sandy shale and sandstone</td>
<td>Possibly part of Early Cretaceous Broome Sandstone</td>
<td>Low permeability</td>
</tr>
<tr>
<td>Archaean</td>
<td>Granite and greenstone.</td>
<td>Basement</td>
<td>Weathered water bearing horizon in some locations, else non-water bearing</td>
</tr>
</tbody>
</table>

2.4 Namagoorie Borefield
The Namagoorie Borefield was commissioned in 1979 to supply water to Port Hedland. It consists of 11 production bores and 18 monitoring bores and is licensed for 7 GL/year extraction. Extraction has ranged between 3.5 and 7.1 GL/year, with an average extraction of 5.3 GL/year. The bores are to the east of the De Grey River, as shown in Figure 2-8.

2.5 Groundwater Dependent Ecosystems and Pools
The shallow alluvial aquifer supports both permanent and semi-permanent groundwater dependent pools along the river bed during dry parts of the year, and supplies water to phreatophytic vegetation such as Eucalyptus Camaldulensis (River Red Gum), Eucalyptus Victrix (Coolibah) and Melaleuca Argenta (Cadjeput). Figure 2-11 shows the locations of surveyed pools, while Figure 2-5 shows aerial photography of the pools close to the highway bridge.

Pool and bore hydrographs show a strong connection between the pools and the aquifer. During flood events, the aquifer is recharged through the pools as through the rest of the river bed; during dry periods the pools are maintained by groundwater flows.

Due to the sandy river bed, pool geometry and position has been noted to change over time. However, an estimate of current pool locations and geometry (based on LiDAR, survey and aerial photography) will be sufficient for groundwater modelling purposes as future pools are expected to behave similarly to current pools even if in slightly different spatial arrangements.
As the water table is close to ground surface, phreatophytic vegetation is found across much of the aquifer. These larger trees on the river banks and plains provide habitat and vegetation corridors that support a diverse ecosystem. The banks and river pools of the De Grey and other Pilbara rivers directly support the Pilbara’s only freshwater wetland ecosystem. Of all the Pilbara rivers, the De Grey has the most reliable pools and the greatest diversity of flora and fauna, including more than 50 species of macroinvertebrates, 20 species of fish, 9 frog species, 145 bird species, 38 mammal species and 98 reptile species. Some 38 of these bird, mammal and reptile species are of conservation significance. The pools are also of significance to the traditional owners of the land, the Ngarla, Warrarn and Njamal peoples, who use the pools for various purposes including fishing, swimming, hunting, and ceremonial activities. Maintaining the river pools and healthy ecosystems is an important consideration in current and future water resource management in the Lower De Grey River catchment. It is assumed that the groundwater dependent ecosystems within and adjacent to the De Grey River channel will be adversely affected by future groundwater developments that cause a permanent decline in groundwater levels at these locations.

*Figure 2-5 – De Grey River pools and riparian vegetation near road crossing*
2.6 Sea Water Intrusion

The tide at Broome varies between ±4.9 m AHD, with larger tides occurring every two weeks in phase with lunar cycles as shown in Figure 2-6. LiDAR data shows that the river bed at Homestead pool (approx. 18 km from the coast) is +6 m AHD, only 1 m above high tide levels. From this it can be inferred that seawater may travel a significant distance inland along the river channel during high tide when there is no fresh water outflow. Seawater will also enter the model area by permeating coastal mudflats and the aquifer material itself. Figure 2-9 shows the -10 m AHD EM survey, in which it can be seen that highly conductive seawater intrudes approximately 15 km inland, and Figure 2-7 shows seawater interface contours at 10 m depth intervals. This seawater interface occurs at the approximate maximum extent of high tide flowing up the river.

![Figure 2-6 – Hourly Tide Data for Broome](image-url)
Figure 2-7 – Seawater Interface Contours
2.7 Aquifer Extent

The De Grey aquifer has been studied on a number of occasions in the past as it is seen as a productive and relatively reliable resource, and because it currently supplies water to Port Hedland via the Namagoorie Borefield. However, no study to date has mapped out the full extent of the aquifer and there is a conspicuous lack of reliable bore data between the coast and the De Grey homestead.

Davidson (1974) describes a drilling program involving 49 bores at the location of the present day Namagoorie Borefield, from which he developed the contours shown in Figure 2-8. These contours describe the upper end of the aquifer but do not show the downstream extent. In an attempt to describe the downstream extent, Fugro was engaged by the Department in 2009 to use geophysical methods of defining the aquifer. Their Electro Magnetic (EM) survey clearly shows the Tertiary alluvium aquifer (Figure 2-9), but interference close to the coast from seawater prevented them from giving aquifer geometry any closer than 15 km to the shoreline. Figure 2-10 shows the base of alluvium that Fugro was able to extract from their data in the region unaffected by seawater.

Electromagnetic survey results clearly delineate a sharp interface between fresh and saline water some distance inland (refer for example to Figure 2-9). Results at various levels (0, -10 and -20 m AHD) suggest that the interface is almost vertical (Figure 2-7). Due to lack of aquifer geometry information in the area affected by salt water, the model was only extended to the salt water interface with the model boundary at this location defined as a head dependent boundary condition with the head determined during calibration. Any increase in flux into the model domain through the boundary will indicate the movement of the salt water further inland from its current location.

In addition to the deep sand and gravel aquifer shown in the EM survey, there exists a shallower Quaternary alluvium which maintains the permanent pools and riparian vegetation. Figure 2-11 shows a map of the modern alluvium and the estimated pre-European Eucalyptus riparian vegetation zones, which may indicate the extent of the Quaternary aquifer. In regions where there is no other data, it has been assumed that these modern alluvium deposits are 5 m thick following the current river alignment.

Figure 2-12 and Figure 2-13 show maps of alluvium depth based on the combined data from Davidson (1974), Fugro (2009) and vegetation mapping, and Figure 2-14 shows the data converted to m AHD. Where Fugro and Davidson aquifer geometries overlap, an average aquifer depth has been calculated without preference to either dataset.

Figure 2-13 also shows the possible Pardoo Creek aquifer, based on the Fugro EM data. The materials that form this aquifer have been assumed to be the same as for the De Grey aquifer, however, this should be confirmed by field investigations if it is seen as a potential resource.
Figure 2-8 – Base of alluvium (Davidson, 1974)
Figure 2-9 – EM survey, -10 m AHD
Figure 2-10 – Base of alluvium (Fugro, 2010)
Figure 2-11 – Modern Alluvium
Figure 2-12 – Combined alluvium map
Figure 2-13 - Combined alluvium depth
Figure 2-14 – Base of alluvium
2.8 Groundwater Flow Direction
Based on measured groundwater elevations, the interpreted groundwater flow direction is from southeast to northwest, approximately parallel with the De Grey River, as shown in Figure 3-25.

2.9 Hydraulic Conductivity
Haig (2009) describes a series of pumping tests in which it was found that the Tertiary gravel aquifer had transmissivity ranging from 58 – 1400 m²/day, with an average of 560 m²/day. Assuming an average bore depth of 50 m, this would be equivalent to an average hydraulic conductivity of approximately 10 m/day, ranging between 1 to 25 m/day.

Worley Parsons (2003) developed a groundwater model for the De Grey area, with calibrated horizontal hydraulic conductivities of 2 m/d for the Quaternary alluvium, 10-30 m/day for the Tertiary alluvium, and 2 m/d for a confining clay layer between the two alluvial layers. They set vertical hydraulic conductivity equal to horizontal hydraulic conductivity for the alluvial aquifer layers, but ranging between 0.0005 – 0.1 m/day in the clay layer.

2.10 Rainfall Recharge
The Pilbara region is arid-tropical with hot dry conditions through most of the year. Average maximum daily temperatures remain above 35°C October-April, with daily maximum temperatures dropping to 27°C during June-July (Figure 2-16). Average annual rainfall at Port Hedland is 311 mm, falling during summer months. Rainfall is extremely variable as it is dependent on cyclones and storms (Figure 2-16), with an average of 0.8 cyclones per year impacting the model area (Figure 2-15) Davidson (1974) determined that approximately 3% of rainfall infiltrates and recharges the aquifer.
Figure 2-15 – Average annual number of tropical cyclones

Based on a 2 x 2 degree resolution gridded analysis using 36 years of data (1969/70 to 2005/06 tropical cyclone seasons).
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Figure 2-16 – Port Hedland Temperature and Rainfall
2.11 River Recharge
The De Grey River is the largest and most reliable of the Pilbara rivers, with only 1 year during the 30 year record having no flow. On average, the De Grey flows 2 to 3 times each summer, each time for about 2 to 4 weeks following a cyclone or storm. Due to the sandy river bed (Figure 2-17), the alluvium aquifer adjacent to and beneath the river is quickly recharged during river flow events. Davidson (1974) estimated that 91% of aquifer recharge (15 GL/year) was from the river (Table 2-2).

- Figure 2-17 – De Grey sandy river bed
2.12 Evapotranspiration
Evapotranspiration is the combined processes of evaporation and transpiration that act to remove water from the aquifer. Although evapotranspiration processes are active in both the saturated and unsaturated zones, it is the saturated zone component that is important in terms of numerical model development.

Evapotranspiration is only active when the water table is close to the surface. In non-vegetated regions evapotranspiration is effectively limited to those areas where the water table is within about 0.5m of the surface. The presence of vegetation and the associated uptake of water through the plants roots results in evapotranspiration being active to a greater depth (perhaps 10 m below the surface near native trees). Water will also evaporate directly from the aquifer through the various pools along the river.

Daily pan evaporation at Port Hedland ranges between 11.5 mm and 6.4 mm (Figure 2-18). Davidson (1974) reports that transpiration could be taken as 50% of pan evaporation, while the Bureau of Meteorology reports that average regional actual annual evaporation is in approximately 350 mm/year (Figure 2-19). As average annual rainfall is only 311 mm/year (Section 2.10), it may be inferred that approximately 100% of rainfall evaporates.

Figure 2-18 – Port Hedland Evaporation
Figure 2-19 – Average annual areal actual evapotranspiration
2.13 Water Balance

The water levels in the De Grey River aquifer do not remain constant over time. Some years the aquifer is recharged to a greater extent, and there are extended dry periods during which the aquifer is depleted. Based on chloride concentrations, climate data and vegetation extent, Davidson (1974) estimated the following water balance showing that evapotranspiration accounts for over 85% of water lost from the aquifer. These data are useful for obtaining a background to the aquifer, but as this water balance was developed prior to the commissioning of the Namagoorie Borefield (extraction of 7 GL/year), the calibrated groundwater model water balance will not perfectly match Table 2-2.

<table>
<thead>
<tr>
<th>Inflow Location</th>
<th>Volume</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
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<td>91.8</td>
</tr>
<tr>
<td>Rainfall</td>
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<td>8.2</td>
</tr>
<tr>
<td>Overall</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outflow Location</th>
<th>Volume</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpiration</td>
<td>13.75</td>
<td>82.8</td>
</tr>
<tr>
<td>Pool Evaporation</td>
<td>0.65</td>
<td>3.9</td>
</tr>
<tr>
<td>Outflow</td>
<td>2.2</td>
<td>13.3</td>
</tr>
<tr>
<td>Overall</td>
<td>16.6</td>
<td>(approx. 17 GL/yr)</td>
</tr>
</tbody>
</table>

2.14 Bore Hydrographs and Schematic Diagram

Figure 2-20 shows the aquifer extent and hydrographs from selected groundwater observation bores over the period Oct 1995 to July 2009. It can be seen that the groundwater level in bores U1 and U3 in the deeper part of the aquifer respond strongly to stream flow, while bore E1 the shallower upstream part of the aquifer has a weaker response. These hydrographs indicate that the primary location of river recharge is near bore U1. Bore I1 has a greater response to river flow than E1, indicating that there must also be recharge from the river near the Shaw River intersection.

The drawdown between recharge events is partly due to evapotranspiration, and partly due to extraction from the Namagoorie Borefield. These processes are shown schematically in Figure 2-21 and Figure 2-22.
Figure 2-20 – Selected Bore Hydrographs (Blue hydrographs show De Grey river flow, red shows groundwater levels)
Figure 2-21 – Schematic Diagram for Recharge during Wet Season

Figure 2-22 – Schematic Diagram for Discharge during Dry Season
3 Model Design

3.1 Modelling Software
There are two commonly used groundwater simulation packages that are suitable for application in this project. The finite difference MODFLOW package has been the industry standard numerical simulation code for many years. It was developed by the US Geological Survey and has been widely used throughout all groundwater modelling projects. In recent years the FEFLOW finite element simulation package has become a widely used tool for simulating groundwater flow and solute transport. Each of these codes have specific advantages and disadvantages that should be considered in choosing the modelling platform to be used for the current project.

The choice of modelling software package to use for a particular project depends on a number of factors related to the aquifer that is being modelled and the current and possible future uses of the model. In particular reference to the Lower De Grey Model the following issues were considered:

1. Modflow has difficulty in dealing with cells that dry and re-wet as the water table is predicted to fall below and then rise above the base of any cell. This is likely to be of concern in the current model due to the fact that the aquifer is recharged on sporadic occasions as the river flows during and shortly after cyclone events. As a result it is expected that water levels in the aquifer will rise and fall dramatically during the course of model runs. FEFLOW does not have the same problems with drying and re-wetting cells and as such has an advantage over Modflow in this regard.

2. Modflow utilises a regular rectangular grid of elements while the finite element formulation of FEFLOW allows the use of cells of rectangular or triangular shape. This feature provides additional flexibility in modelling complex geometries of the geology and/or aquifer boundary conditions. In this case the geometry of the model domain is relatively simple and as such there is no real advantage in using FEFLOW.

3. Groundwater flow models developed in FEFLOW can be easily extended to incorporate density dependent solute transport simulation. This feature is required if the model is to be used (in the future) to explicitly model the migration of salt water through the aquifer. Although recent versions of Modflow have similar capability (using the SEAWAT package), our experience with this feature suggests that it is not a reliable package and appears to be inferior to that available in FEFLOW.

Given the foregoing discussion the FEFLOW package was used for the development of the Lower De Grey model.
3.2 Model Complexity

Model complexity is defined as the degree to which a model application resembles the physical hydrogeological system (MDBC, 2000) and the following three classifications are suggested:

- A “Basic Model” is of low complexity that can be used for preliminary quantitative assessments and model results may need to be checked by further field measurement.
- An “Impact Assessment Model” is of medium complexity and requires more data and resources than a Basic Model and can be used to predict groundwater response to future stress applications with a reasonable degree of confidence.
- An “Aquifer Simulation Model” is a high complexity model requiring substantial investment of time, funds and data. These models are expected to provide accurate and detailed estimations of groundwater responses to a range of changes in hydrogeological conditions.

In determining the complexity of each model to be developed, it is necessary to assess the amount and quality of hydrogeological data available to base each model on, the use to which each model will be applied, and the time and financial resources available for the project.

There is a reasonable coverage of hydrogeological data for the area. However, there is no data for the region close to the coast where the aquifer is affected by saline intrusion. Pumping rates are known, but there is uncertainty in the number of river pools and their permanency, especially as the morphology of the river bed can change over time. Due to the use of estimates and the objectives of the model, it was proposed that the model be classified as medium complexity, i.e. an “Impact Assessment Model”, however this classification could change in future as more data become available and as the model is refined and improved.

3.3 Modelling Approach

The model was created using data from a variety of sources. First the model grid was created using digital elevation data to generate the ground surface. Bore stratigraphy data and geophysical data were used with gridding and interpolation tools to generate the base of alluvium surface. Rainfall, evaporation, pumping and river stage data have been obtained from the Bureau of Meteorology and the Department of Water.

The model was calibrated using observation bores over the historical period of 1983 to 2009 as continuous stream flow and observation bore data exists for that period (Figure 3-1). Pumping records are missing between December 1989 and July 1995, but rates were assumed based on Port Hedland consumption data covering that period (see Section 3.8). The model parameters were calibrated primarily by a process of trial and error using professional judgement, with the automatic parameter estimation software PEST used to determine whether to focus on parameter adjustment or model structural improvements. The model parameters included:

- hydraulic conductivities;
- percentage of rainfall infiltrating;
- depth and magnitude of evapotranspiration;
- boundary conditions on sea water interface side of the model; and
- magnitude of recharge due to flood events.

As calibration will not use data from 1975-1980, these years may be used after calibration for verification purposes.

3.4 Grid Design

Prior to generating the finite element grid the model region was split into several sub-regions (super elements) to better allow non-homogeneous discretisation (Figure 3-2). The sub-regions created bounded or defined the following features:

- The De Grey alluvial aquifer
- De Grey river channel
- Pardoo creek (possible palaeochannel)
- Rest of model area

Locations of extraction bores and pools were added as locations of interest that would require grid refinement.

Pardoo creek was added as a separate region as there is a possibility that a palaeochannel follows the creek, based on the Fugro EM data shown in Figure 2-9. Although this region will be modelled, it is not expected to interact significantly with the main De Grey alluvial aquifer due to a basement outcrop occurring where the two aquifers meet.
The finite element mesh was automatically generated by FEFLOW using the Triangle method to generate a triangular mesh refined near points of interest such as production bores, rivers and pools. The mesh is shown in Figure 3-3. Node spacing in each region is approximately:

- Non-palaeochannel areas: 2 km
- Pardoo Creek palaeochannel: 600 m
- De Grey palaeochannel: 500 m
- De Grey river: 200 m
- De Grey river pools: 50-150 m
- Production wells: 50 m
Figure 3-3 – Lower De Grey groundwater model mesh

The model has four slices (3 layers), representing:

1) Ground surface (Figure 3-4)
2) Base of Quaternary alluvium (Figure 3-5)
3) Base of Tertiary alluvium (Figure 3-8)
4) Base of Mesozoic shale and sandstone (Broome formation) (basement) (Figure 3-9)
The ground surface slice was imported from a combination of DTM and Lidar data. The Lidar data covers a strip along the De Grey River, while the DTM covers the entire model area. It was found that the two elevation data sets were not consistent, and the Lidar data was on average 1.5 metres below the DTM data. The Lidar is considered much more accurate than the DTM as the Lidar was flown using aircraft and is ground truthed whereas the DTM was captured from the space shuttle and can be unreliable. Combining the two data sets in the model led to a sharp change in elevation at the Lidar boundary in the order of 1.5 m, as shown in Figure 3-6.

Surface elevation plays an important role in the model in the calculation of evapotranspiration (ET) and flooding extent. The closer the water table is to the surface the greater the ET, and the lower the ground level the more prone to flooding. The majority of ET occurs from the river bed and trees along the bank, where accurate Lidar data is available, but flooding occurs over a much greater
area. To increase accuracy, the DTM data was translated downwards by 1.5 m to match the Lidar data. Figure 3-7 shows that this correction lessens the border effect, though doesn’t do away with it entirely in all locations.

The base of quaternary alluvium layer was set at 25 m below ground surface level in the deep palaeochannel areas. In locations where the basement is close to the surface, the base of quaternary was set just below ground surface. Elevations for this slice are shown in Figure 3-5.

Figure 3-5 – Base of quaternary alluvium elevation
- Figure 3-6 – Uncorrected surface elevation near river showing Lidar boundary effect

- Figure 3-7 – Corrected surface elevation near river showing reduced Lidar boundary effect

Border effect reduced
The base of tertiary alluvium (Figure 3-8) was generated based on the Davidson bore set and Fugro EM data as described in Section 2.7.

The basement slice was generated from Fugro interpreted basement data. This data did not cover the entire model, so basement was extrapolated in the south-eastern part of the model (Figure 3-9). As the broome formation is not the focus of the model, and extrapolation generally occurs in regions where there is no palaeochannel, it is not expected that the extrapolation will affect model results.

Due to the influence of seawater on Fugro’s EM data, the basement elevation close to the coast may be unreliable and may be modelled as deeper than in reality. Again, as the broome formation is not the focus of the model, it is not expected that this will affect model results.

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The mesh has a total of 26,212 nodes and 38,955 elements covering an area of 4,500 km$^2$. Only 1.8% of triangles violate the Delaunay criterion, a small percentage indicating that the mesh is regular and should not impede solution generation.

### 3.5 Time Steps

The model was run using FEFLOW’s automatic timestep mode. In this mode, FEFLOW calculates the best timestep length based on how fast heads are changing. To allow the model to solve as quickly as possible using this mode, boundary conditions were changed as infrequently as possible. To this end, model data was generally entered in monthly timesteps. As FEFLOW automatically interpolates between data points, monthly averages were given for the first and last day of each month to generate step functions. The exception was river stage data, which was entered using a daily timestep whenever the stage changed by more than 10 cm. In between stage changes no data was entered, allowing FEFLOW to dynamically increase the model timestep.

**Figure 3-9 – Basement elevation**
3.6 **Head Boundary Conditions**

Two head boundary conditions were applied to slice 1 to represent the Ocean and the De Grey River.

The ocean was simulated using a +0.2 m AHD constant head boundary along the coast. The boundary was set at +0.2 m AHD rather than 0 m AHD (the long term average sea level) because seawater has a greater density than fresh water and thus a higher equivalent freshwater piezometric head is required to balance the sea water pressures.

The De Grey, Shaw and Ridley rivers were also simulated using head boundaries. Nodes within the river banks were given time varying head conditions based on the river stage measured at the Coolenar river gauge. As the river bed elevation rises gradually from 0 m AHD near the coast to +50 m AHD at the upstream end of the model, the Coolenar gauge site readings were translated up and down to match river bed levels and interpolated along the length of the river. The Shaw and Ridley rivers were only modelled in the palaeochannel region due to lack of gauge data away from the De Grey River and because the palaeochannel is the main area of interest.

Pardoo Creek was not modelled as there were no gauge data available and no observation data in Pardoo Creek against which to calibrate.

Figure 3-10 shows the locations of the head boundaries in Slice 1.
3.7 Flux Boundary Conditions

The region impacted by saline intrusion (see Section 2.6) was inactivated and not modelled as there was no data that could be used to generate palaeochannel surfaces. This inactivation was achieved by applying a zero flux boundary condition. Figure 3-11 shows which cells were inactivated in slices 2-4. All cells were left active in layer 1 to allow modelling of fresh river water flowing over the saline wedge.
3.8 Production Wells
The Namagoorie borefield pumps water from the tertiary alluvial sediments, so bores were added to slice 2 as shown in Figure 3-12. The grid was refined near the wells, as shown in Figure 3-13.
Figure 3-12 – Slice 2 Production Wells
Figure 3-13 – Grid refinement near production wells
Pumping data have historically been recorded for each bore individually, with the number of kilolitres extracted from each pump read at intervals ranging between several days to several weeks. To allow the model to run smoothly, extraction data were summed using a monthly time scale and equivalent constant pumping rates were calculated for each month. However, even with this monthly smoothing, possibly due to the exact timing of readings, some months ended up with zero extractions from a particular bore, while the next month ended up with double the average extraction. To counter these anomalies a second data smoothing round was completed in which large extractions were spread evenly to the preceding month if no extractions were recorded in that month. An example of this second round of smoothing is given in Figure 3-14.

<table>
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<th>Model Day</th>
<th>Bore 10/76</th>
<th>Date</th>
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<td>-1175</td>
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<td>181</td>
<td>-1175</td>
</tr>
</tbody>
</table>

- Figure 3-14 – Example of extraction data smoothing to preceding months when no extraction was recorded in the preceding month. Bore data in kL/day.

It can be seen in Figure 3-15 that pumping records are missing during the years 1989-1995. During these years and the 5 preceding years, total consumption in Port Hedland remained relatively constant. To fill the data gap, it was assumed that the pumping split between Yule and De Grey also remained the same as during the 5 years preceding the missing data. Based on this assumption, an average annual pumping cycle was produced for each production bore based on the data from 1985 to 1989. These average annual pumping cycles were then applied to each of the bores during the period of missing data.
3.9 Rainfall and Evapotranspiration

Rainfall and evapotranspiration (ET) are both added to the model using FEFLOW’s “In(+)/out(-)flow on top” equation editor. Equation 3-1 shows how this is achieved. In FEFLOW, equations are read from right to left on horizontal lines, with IF statements written on the right hand side, and the results if true written on the left. From Equation 3-1 it can be seen that the flux on top is calculated as recharge minus ET (in units of m/day). Equation 3-1 is equivalent to the pseudo-code shown in Equation 3-2, which may be more readable by those unfamiliar with FEFLOW.
Equation 3-1 – Rainfall and evaporation

\[ R = \begin{cases} 
  \text{POWER.2L} \cdot 0.03 & \text{if } REFST.\text{RechZone} = 1 \\
  0 & \text{otherwise}
\end{cases} \]

\[ ET = \begin{cases} 
  \text{POWER.2D} \cdot 1 & \text{if } \langle \text{Head} \rangle > \text{REFST.\text{GroundSurface}} \\
  \text{POWER.2D} \cdot \text{REFST.ETexp} \cdot \langle \text{REFST.\text{GroundSurface} - Head} \rangle & \text{if } \langle \text{Head} \rangle \langle \text{REFST.\text{GroundSurface} - REFST.\text{ETexp}} \rangle \\
  0 & \text{otherwise}
\end{cases} \]

\[ Q_p = \frac{R \cdot ET}{1000} \]

Equation 3-2 – Rainfall and evaporation pseudo-code

IF (Recharge Zone = 1)
THEN (Recharge = 3% * Rainfall)
ELSE IF (Recharge Zone = 0)
THEN (Recharge = 0)
END IF

IF (Evapotranspiration Zone = 1)
THEN
  IF (Head > Ground Surface)
  THEN (Evapotranspiration = Pan Evaporation)
  ELSE IF (Extinction Depth < Head < Ground Surface)
  THEN (Evapotranspiration = Pan Evaporation * e^{-ETexp*(Ground Surface - Head)})
  ELSE IF (Head < Extinction Depth)
  THEN (Evapotranspiration = 0)
  END IF
ELSE IF (Evapotranspiration Zone = 0)
THEN (Evapotranspiration = 0)
END IF

Flux on top = (Recharge – Evapotranspiration) / 1000

* Note that the infiltration value of 3% was updated during calibration
In Equation 3-1, recharge is specified as 3% of rainfall (rainfall is given in power function 21), though this value for percentage of rainfall infiltrating was varied during calibration. In the final calibrated model, a reference distribution was used to define two different areas of infiltration.

Most of the model was defined with Recharge Zone = 1, however, areas of outcropping basement were defined as Recharge Zone = 0 to prevent rain falling there to infiltrate to the aquifer.

Figure 3-16 – Recharge Zone distribution, with zero recharge over outcropping bedrock

ET is specified as pan evaporation (power function 20) if head is at or above ground surface (reference distribution ‘Groundsurface’), or an exponential decay in pan evaporation when the groundwater level falls from ground surface to a specified extinction depth.

The effect of the parameter “ETexp” in the evapotranspiration function (refer to Equation 3-2) is illustrated in Figure 3-17. It can be seen that with a smaller value for “ETexp”, evapotranspiration
rate is increased for all groundwater levels between the ground surface and the extinction depth. In addition to varying the extinction depth across the model dependent on vegetation type, “ETexp” was varied across the model to account for vegetation density.

Extinction depth was varied over the model with shallow extinction depth defined on areas of bare ground such as the river bed, moderate extinction depth in grass lands and shrub lands, and deeper extinction depth in treed areas. A vegetation map provided by the Department was used to determine locations of Eucalyptus trees and shrub lands, and satellite imagery was used to determine the location of bare ground.

- Figure 3-17 – Exponential evapotranspiration decline
3.10 Flooding

Within the model area, the De Grey river bed is typically 3 to 5 m below the surrounding land surface. Figure 3-18 shows that at the Coolenar gauge site, flood peaks can be expected to break the banks approximately once every 2 years (50% chance of exceeding 4 m flood height).

![Figure 3-18 – Yearly flood peak exceedence probability at Coolenar gauge site (36 years of data)](image)

To model flooding appropriately, it was necessary to determine both the timing and the extent of over bank flow.

Just as river stage heights were translated from the Coolenar gauge based on relative river bed heights, so were flood stage heights calculated. To determine whether any particular piece of land might become inundated, it was necessary to first determine how high the ground surface is relative to the river nearby. The slope of the river bed was determined, and from this a gradually sloping surface was created representing the change in river bed along the length of the model. This gradient is shown in Figure 3-19. This river bed slope was used as the basis for all flood height calculations.

The river bed slope surface was then subtracted from the ground surface elevation, to give a data set showing the approximate height of the ground above the river bed, shown in Figure 3-21. This plot can be interpreted as roughly the flood height required to cause inundation of any particular piece of land.
Each time step, the river height was added to the river bed gradient, and any ground point that was below the resulting level was considered inundated. The weaknesses of this form of flood modelling are that there is the possibility for low areas unconnected with the river to be modelled as inundated when the intervening land is dry, and flooded land is assumed to dry up as soon as the river subsides. The advantages are that the extent of flooding will naturally vary depending on the stage height and more extensive flooding will occur during wetter periods.

Flooding was included in the model using the “In(+)/out(-)flow on top” equation editor for slice 1. Flood water fluxes were added to the rainfall and evapotranspiration fluxes described in Section 3.9, in the form shown in Equation 3-3.

**Equation 3-3 – Flood flux**

\[
\text{Flood} = \begin{cases} 
\frac{k \cdot \Delta T}{\Delta T_0} + \text{Flood} & \text{if } \left\{ \text{POWER.100 + REFSTR.BedSlope} \right\} \geq \text{Head} \text{ then } 0.01 \text{ else } 0 \text{ end } \text{ and } \left\{ \text{POWER.100} > \left\{ \text{REFSTR.GroundSurface} - \text{REFSTR.BedSlope} \right\} \right\} \text{ if } \text{REFSTR.FloodArea} = 1 \\
0 & \text{otherwise}
\end{cases}
\]

\[
Q_p = \frac{k \cdot \Delta T}{\Delta T_0} + \text{Flood}
\]

In FEFLOW, equations are read from right to left, with the first part of the calculation checking reference distribution ‘FloodArea’ to determine whether to apply the flooding rules. Flooding is allowed to occur close to the river in the palaeochannel area, but is disabled across the river bed, where flux is dependent on the river head boundary, and in areas outside the palaeochannel as these areas are expected to have little capacity to absorb flood water. Figure 3-20 shows the FloodArea reference distribution.

The second part of the equation checks whether the flood height (river stage height minus river bed level, represented by Power function 100) is greater than ground level (ground elevation minus river bed level).

The third part of the equation checks whether the flood height is above the groundwater head. This check is necessary to prevent artesian conditions being created by the addition of too much flood water. The maximum ground water head that a flood can create in the model thus becomes equal to the flood height.

If all the necessary checks are passed, then a set amount of water is added to the model node. In Equation 3-3, that amount is 0.01 m/day, though this value was updated during calibration. This equation is also presented in Equation 3-4 as pseudo code.
### Equation 3-4 – Flood flux pseudo code

IF (Flood Area = 1) THEN
  IF (River Stage > (Ground Surface – Bed Level)) THEN
    IF ((River Stage + Bed Level) > Groundwater Head) THEN
      Flood Flux = 0.01 m/day
    END IF
  END IF
END IF

* Note that the flux value of 0.01 m/day was updated during calibration

Figure 3-22 shows the area inundated by a 5 m flood using this method, while Figure 3-23 shows the area inundated by a 7 m high flood (flood height measured as river stage above bed level).

---

**Figure 3-19 – Approximate gradient of river bed**
Figure 3-20 – Floodable area shown in red
Figure 3-21 – Approximate height of ground surface above river bed
Figure 3-22 – 5 m flood inundation area (40% annual probability of occurrence)
Figure 3-23 – 7 m flood inundation area (20% annual probability of occurrence)
3.11 Groundwater Dependent Ecosystems and Pools
Calculating the effect of pumping on groundwater dependent ecosystems and pools is one of the major purposes of the model. To enable water levels at the pools to be accurately modelled, the model was slightly refined at pools and extra nodes were added approximately along the centre line of pools, resulting in more accurate evaporation flux calculation.

Evaporation and flow from pools were modelled using the head boundary condition described in Section 3.6. The head boundary condition allowed flux both to and from river nodes during river flow events, while during dry period the boundary condition only allowed water to leave the model, effectively turning the river into a drain. Budget and hydrograph analysis can be used to confirm that water continues to be lost from pools and that the water level has not dropped below the river bed.

3.12 Hydraulic Conductivity
Prior to calibration, a literature review revealed the following guideline hydraulic conductivities for the formations included in the model:

- Quaternary alluvium: $K_h = 5$ m/day
- Tertiary alluvium: $K_h = 1-25$ m/day
- Broome: $K_h = 0.01-? m/day$

Vertical hydraulic conductivities are expected to be low due to the presence of clay layers and lenses, and will be set to 10% of horizontal hydraulic conductivity at the beginning of calibration.

These hydraulic conductivity estimates were modified and improved during calibration.

3.13 Storage
FEFLOW requires two parameters that describe the volume of water that is stored in the soil strata. These are Specific Yield (Storativity (drain/fillable)) and Specific Storage (Storage compressibility). Specific yield describes the volume of water that can be extracted from unit volume of soil in an unconfined aquifer when draining by gravity. It will be less than the porosity of the soil as the soil will remain wet after being drained. Soil porosity is often in the range 0.25 – 0.3 (that is, 25% to 30% of the soil is voids that may be filled with either water or air). The specific yield is often in the range 0.1 to 0.2, with the difference between the specific yield and the total porosity being the fraction of water still clinging to soil particles after the water table has receded.

Specific storage is similar to specific yield in that it is a measure of the volume of water that can be extracted from an aquifer. However, it applies to confined aquifers and represents the volume of water that will be released from a unit volume of soil if the head drops 1 m. Generally it is appropriate to use the value $5 \times 10^{-6}$ as this represents the elasticity of water. This indicates that as
pressure is relieved, water in a confined aquifer will expand slightly, giving the impression that water has been “produced” by the aquifer.

### 3.14 Wet and Dry Periods (Cumulative Difference from Mean)

Cumulative difference from the mean plots for both rainfall and stream flow (Figure 3-24) show that the calibration period covers a series of wet and dry periods, as detailed in Table 3-1. As the model has been calibrated over both wet and dry periods, it is expected that it will give adequate predictions of both wet and dry future climate scenarios.

#### Table 3-1 – Summary of wet and dry years

<table>
<thead>
<tr>
<th>Period</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983 - 1988</td>
<td>DRY</td>
</tr>
<tr>
<td>1988-1990</td>
<td>WET</td>
</tr>
<tr>
<td>1990-1993</td>
<td>DRY</td>
</tr>
<tr>
<td>1993-1999</td>
<td>AVERAGE</td>
</tr>
<tr>
<td>1999-2001</td>
<td>WET</td>
</tr>
<tr>
<td>2001-2004</td>
<td>AVERAGE</td>
</tr>
<tr>
<td>2004-2006</td>
<td>DRY</td>
</tr>
<tr>
<td>2006-2007</td>
<td>WET</td>
</tr>
<tr>
<td>2007-2009</td>
<td>DRY</td>
</tr>
</tbody>
</table>

### 3.15 Initial Heads

Initial heads were interpolated from observation bores as shown in Figure 3-25. Water levels were taken from many bores scattered across the model area that were drilled and measured in 1970-1972 in addition to the calibration bores. The bores that were drilled and measured only in the ’70s were not used for calibration as the model calibration start date was 1/1/1983, thus the number of bores used for calibration is smaller than the number used to generate the initial water level distribution.
- Figure 3-24 – Cumulative difference from the mean plots
Figure 3-25 – Initial Water Level Distribution
4 Calibration

4.1 Calibration Method
The model was calibrated by running transient simulations using historic data covering the period 1/1/1983 to 31/12/2008. Two methods of calibration were used to obtain the final calibrated model parameters:

- Trial and error transient calibration by which model parameters were adjusted manually using professional judgement and understanding of the system at hand
- Automatic parameter estimation using the PEST package

The trial and error approach was the main method used for calibration as it allowed focussed searching for a good parameter set and so was faster at finding good solutions. In comparison, the automated PEST module needed to run the model approximately 100 times before giving recommendations as to which parameters should be used. Further, the trial and error approach allowed the adjustment of river stage heights, flooding extent, evaporation, rainfall, and zones of different hydraulic conductivities, while PEST was capable only of modifying hydraulic conductivities and specific yield in zones that were already defined. However, PEST was still useful in determining whether calibration efforts should be focussed on updating hydraulic conductivities, or whether other parameters needed to be investigated.

Both PEST and the trial and error method of calibration used comparisons between observed groundwater heads and calculated groundwater heads to determine the goodness of fit of each set of parameters. A total of 25 observation bores and 5 observed pools were used for this purpose, at locations shown in Figure 4-1. All observation bores were placed in slice 2, representing the deeper gravel sediments, while observation pool data was assigned to slice 1. With such a large number of observation bores in the model it was not possible to perfectly match the hydrographs of them all, especially since the model had only two aquifer layers (plus the Broome layer) and so was limited in modelling vertical hydraulic gradients. However, the calibration results presented in Sections 4.2 and 4.3 show that a good calibration was obtained.
Figure 4-1 – Observation Bores
4.2 Quantitative Calibration Results

The primary method for quantitatively assessing the goodness of fit of calculated data is through calculation of the Normalised Root Mean Square Error (RMS) (Equation 4-1).

\[
RMS = \sqrt{\frac{\sum_{i=1}^{n} (X_{\text{calc}} - X_{\text{obs}})^2}{n}}
\]

Normalised RMS = \[
\frac{RMS}{(X_{\text{obs}})_{\text{max}} - (X_{\text{obs}})_{\text{min}}}
\]

Where

- n is the number of observations
- \(X_{\text{obs}}\) is the measured head
- \(X_{\text{calc}}\) is the calculated head

- Equation 4-1 – Normalised root mean squared

The required calibration accuracy is generally set in accordance with the model complexity as defined by the MDBC Groundwater Flow Modelling Guidelines (MDBC, 2000). For a medium complexity “Impact Assessment Model” such as this a normalised RMS error of approximately 10% is considered appropriate.

This normalised RMS error for the calibrated Lower De Grey model using all observation points is 4.31%, indicating that the calculated data are a good fit to the observed data. It should be noted that pool observations are directly affected by the river input and so are not good representations of model calibration. However, if pool observations are ignored, the normalised RMS error is essentially unchanged at 4.30%. All other results presented here include the pool observations.

Figure 4-2 shows that the normalised RMS error varies with time. In general, the largest errors occur during river flow events, for it is difficult to match both the magnitude and timing of rapidly changing water levels. With only a few outliers, the normalised RMS lies between 2% and 6%, and is always less than 10%.
The volume of water lost from the model to evapotranspiration over the calibration period was \(2,200,000,000\) m\(^3\). With a surface area of \(4,500,000,000\) m\(^2\), this is a loss of \(19\) mm/year. This evapotranspiration loss is much smaller than the 350 mm/year discussed in Section 2.12, most likely due to the fact that the model only considers saturated sediments yet much evapotranspiration occurs from unsaturated sediments closer to the ground surface. Indeed, with only 3% of rainfall infiltrating to the aquifer in the model, the remaining 97% is assumed to evaporate or run overland to creeks and streams. If the entire remaining 97% of rainfall is assumed to evaporate, total evapotranspiration reaches \(320\) mm/year, just over the average annual rainfall. Note that with rainfall of only 311 mm/year it is extremely unlikely that the model can be made to predict 350 mm of evaporation to match Figure 2-19.

The calculated water levels are plotted against observed water levels in Figure 4-3, and a histogram of the residuals is plotted in Figure 4-4. The mean residual value is -0.21 m, meaning that the model is currently slightly under predicting heads. The shape of the residuals histogram is roughly the shape of a normal distribution, as expected.
Figure 4-3 – Scatter plot of observation bore water levels

Figure 4-4 – Residuals histogram for calibrated model
4.3 Qualitative Calibration Results
Observation bore hydrographs for the calibrated model are included in Appendix A. From these hydrographs it can be seen that bores close to the river show response to flow, and the shapes of the hydrographs are generally correct. Note that some hydrographs match observed data better than others, and while some hydrographs have obvious differences to observed data, when taken together the hydrographs show that the model is performing adequately for an Impact Assessment Model.

4.4 Head Boundary Conditions
The head boundary conditions were not changed during calibration but remained the same as described in Section 3.6.

4.5 Sea Water Interface
The sea water interface in slices 2-4 was not changed during calibration but was kept as described in Section 3.7.

4.6 Production Wells
Production wells were not changed during calibration but were kept as described in Section 3.8.

4.7 Rainfall and Evapotranspiration
Rainfall and evapotranspiration were modelled as described in Section 3.9, with a rainfall infiltration of 3% within the aquifer area, and 1% in the outer areas of the model. This allowed for the fact that rain is expected to infiltrate slower and be held for longer in the unsaturated zone in the non-aquifer areas. The distribution of infiltration rate is shown in Figure 4-6.

The exponential evaporation function described in Equation 3-1 was used with “\( \alpha \)” ranging between 0.5 and 0.9, as shown in Figure 4-7. “\( \alpha \)” was decreased in dense treed areas where evaporation is stronger, and increased where necessary in areas where calibration suggested evaporation was too strong. The effect of “\( \alpha \)” on ET rate is shown in Figure 4-5.
If head was above ground surface, 100% of pan evaporation was applied. When the water surface was below ground, the following extinction depths were applied.

- **Bare coastal mudflats**: Extinction depth = 0.5 m
- **Grass lands**: Extinction depth = 10 m
- **Shrub lands**: Extinction depth = 15 m
- **Eucalyptus trees near pools and river banks**: Extinction depth = 25 m

Figure 4-8 shows how these four categories of extinction depth were applied between the Namagoorie Borefield and the river.
Figure 4-6 – Rainfall infiltration distribution
Figure 4-7 – Distribution of exponential evaporation parameter “\( \alpha \)"
4.8 Flooding
Floods were modelled as described in Section 3.10, with a calibrated flood flux of 0.012 m/day. Although this flux is only applied during flood peaks, it implicitly includes the flux experienced afterwards when the flood peak has passed when pools remain on the ground surface for several days.

Figure 4-8 – Extinction depth near Namagoorie borefield based on vegetation map
4.9 Groundwater Dependent Ecosystems and Pools

Between floods the pools are represented by head dependent boundary conditions which only allow flow out of the model. As an indicative example to determine whether the model was accurately modelling pools, the permanent pool J96 was investigated in detail. In the final calibrated model, the J96 pool remains wet 97% of the time, as indicated by evaporation and river boundary fluxes. This is a good result as it confirms that the model sees the J96 pool as being a permanent feature.

Figure 4-9 shows the modelled flux out of the J96 pool, in which it can be seen that during dry periods between 2 and 50 m$^3$/day is evaporated from the pool. For a pool area of 54,000 m$^2$ this is a range of 0.04 to 0.92 mm/day. Bureau of Meteorology records show that pan evaporation should be about 6 mm/day, indicating that during these dry periods the modelled surface area of J96 may have shrunk somewhat.

During wet periods the model predicted that up to 10,000 m$^3$/day could discharge from groundwater to the river. Over the pool surface area of 54,000 m$^2$, this volume is equivalent to 185 mm/day, well above pan evaporation but understandable when considering a decline in river stage height.

- Figure 4-9 – Flux out of J96 Pool
4.10 Hydraulic Conductivity

Table 4-1 shows the calibrated hydraulic conductivities. These hydraulic conductivities are slightly larger those presented following the literature review in Section 3.12, but of the same order of magnitude.

- Table 4-1 - Summary of calibrated hydraulic conductivity

<table>
<thead>
<tr>
<th>Description</th>
<th>Hydraulic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy alluvium</td>
<td>$K_h = 10 \text{ m/day}$</td>
</tr>
<tr>
<td></td>
<td>$K_z = 1 \text{ m/day}$ across plains</td>
</tr>
<tr>
<td></td>
<td>$K_z = 10 \text{ m/day}$ in De Grey river bed</td>
</tr>
<tr>
<td>Gravelly alluvium</td>
<td>$K_h = 30 \text{ m/day}$</td>
</tr>
<tr>
<td></td>
<td>$K_z = 5 \text{ m/day}$</td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td>$K_h = 0.7 \text{ m/day}$</td>
</tr>
<tr>
<td></td>
<td>$K_z = 0.1 \text{ m/day}$</td>
</tr>
</tbody>
</table>

The alluvium hydraulic parameters were applied within the bounds of both the De Grey and Pardoo aquifers on slices 1 and 2, with the Broome Sandstone parameters applied elsewhere across the model domain and in slices 3 and 4. As water levels in some locations dropped beneath the bounds of slice 1, FEFLOW automatically adjusts the mesh and parameters to match those assigned at the particular elevation at the start of the simulation. This is particularly noticeable along Pardoo Creek where much of the assumed palaeochannel has been automatically reassigned with Broome Sandstone hydraulic parameters after the water levels there dropped below the assumed base of alluvium, though the effect is also noticeable at the edges of the De Grey aquifer where layer 1 is thin.

Figure 4-10 to Figure 4-13 show the arrangement of calibrated hydraulic conductivities. Note that FEFLOW uses units of $10^{-4}$ m/s rather than the standard m/day and so the values on the legends will differ from Table 4-1.
- Figure 4-10 - Slice 1 horizontal hydraulic conductivity

- Figure 4-11 – Slice 1 vertical hydraulic conductivity
- Figure 4-12 – Slice 2 horizontal hydraulic conductivity

- Figure 4-13 – Slice 2 vertical hydraulic conductivity
**4.11 Storage**
To achieve appropriate water level changes at a distance from the river, it was necessary to reduce the specific yield from the initial assumed level of 0.2 to a lower 0.1. The physical effect of this change was to reduce the void spaces in layer 1 so that water level changes could be effected using a smaller volume of water. Specific yield was assumed to be homogeneous across the model.

Specific storage was maintained at $5 \times 10^{-6}$ as this represents the elasticity of water.

**4.12 Sensitivity**
During calibration it was found that so long as hydraulic conductivities were kept within ±50% of the initial values, results remained similar. The model was found to be much more sensitive to flooding, evapotranspiration, river stage height, and ground surface elevation. A quantitative sensitivity analysis is presented in Section 5.

**4.13 Water Balance**
The water balance for the alluvial sediments is presented in Table 4-2. Similar to Davidson’s water balance (presented in Table 2-2) the model predicts that the major source of water for the aquifer is the river, and the major loss of water is through evapotranspiration. Note that the area for which Davidson derived the water balance is not the same as the model area. The FEFLOW model investigates a larger area, and so the total volumes of water are not expected to be identical.

| Table 4-2 – Water Balance for alluvial area (GL/year) |
|----------------|-------|-------|
|                | In    | Out   | Net  |
| River          | 42    | -27   | 15   |
| Flood          | 13    | -27   | 13   |
| Pump           | -5    | -5    | -5   |
| Rain           | 5     | 5     | 5    |
| Evap           | -27   | -27   | -27  |
| Storage        | 1     |       |      |

A water balance for the whole model is shown in Table 4-3. It can be seen that ocean inflows supply as much water to the model as the river. This is understandable as the ocean boundary is a similar length to the river, and is active all the time, unlike the river which only flows after floods.
Most of this ocean water seems to be evaporating close to the coast, explaining the large contribution of evaporation. Note that with little data relating to coastal parameters, the flow from the ocean may not be well calibrated.

**Table 4-3 – Water Balance for whole model (GL/year)**

<table>
<thead>
<tr>
<th></th>
<th>In</th>
<th>Out</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>River</td>
<td>42</td>
<td>-27</td>
<td>15</td>
</tr>
<tr>
<td>Flood</td>
<td>13</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>-5</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>Rain</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Evap</td>
<td>-85</td>
<td>-85</td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>46</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td></td>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen in Table 4-2 and Table 4-3 that pumped extractions are 5 GL/year. This is the average over the calibration period, during which time extractions increased from zero to the current licensed extraction limit of 7 GL/year. Other values presented here are likewise averages over the whole model period.

The storage term in both Table 4-2 and Table 4-3 represents rising and falling water levels in the aquifer. Storage in to the model (i.e. a positive storage value) represents a decline in average water levels, while storage out from the model (i.e. a negative storage value) represents an increase in average water levels.
5 Sensitivity Analysis

A sensitivity analysis was undertaken using the calibrated model. The following parameters were tested:

- Rainfall infiltration (%)
- Evaporation function exponential factor (α)
- Flood infiltration rate (m/day)
- Specific yield
- Hydraulic conductivity (both vertical and horizontal) (m/day)

Each of these parameters (with the exception of hydraulic conductivity) was multiplied by the following factors, and the RMS Error was recorded:

- 0.1
- 0.5
- 0.7
- 0.9
- 1.1
- 1.5
- 2
- 5
- 10

The sensitivity model run with hydraulic conductivity multiplied by 0.1 was not completed as the model had difficulty solving.

The purpose of using this range of factors was to determine parameter ranges that result in a calibrated model. The upper and lower factor limits of 0.1 and 10 represent the upper and lower limits of how far each parameter could reasonably be expected to vary from the chosen parameter values.

The parameter ranges used during the sensitivity analysis are presented in Table 5-1. Each of the parameter ranges is broader than the reasonable expected bounds for that parameter indicating that the analysis was not artificially constrained, as illustrated by Figure 5-1 showing the range of the ET “α” parameter.
- Figure 5-1 – Range of ET “α” applied during sensitivity analysis
Table 5-1 – Range of parameters altered during sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Area</th>
<th>Calibrated Value</th>
<th>Sensitivity Analysis Range</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall infiltration</td>
<td>Aquifer</td>
<td>3%</td>
<td>0.3% - 30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outer areas</td>
<td>1%</td>
<td>0.1% - 10%</td>
<td></td>
</tr>
<tr>
<td>ET alpha</td>
<td>Rocky Outcrops</td>
<td>0.9</td>
<td>0.09 - 9</td>
<td>See Figure 5-1 for effects of this parameter</td>
</tr>
<tr>
<td></td>
<td>General Area</td>
<td>0.7</td>
<td>0.07 - 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deep Rooted Trees</td>
<td>0.5</td>
<td>0.05 - 5</td>
<td></td>
</tr>
<tr>
<td>Flood Infiltration Rate</td>
<td></td>
<td>0.012 m/day</td>
<td>0.0012 - 0.12 m/day</td>
<td>Specific yield only makes physical sense for values less than approximately 0.3, so this range is greater than necessary.</td>
</tr>
<tr>
<td>Specific Yield</td>
<td></td>
<td>0.1</td>
<td>0.01 - 1</td>
<td></td>
</tr>
<tr>
<td>Hydraulic Conductivity</td>
<td>Sandy alluvium</td>
<td></td>
<td></td>
<td>Ranging between average values for:</td>
</tr>
<tr>
<td></td>
<td>- horizontal</td>
<td>10 m/day</td>
<td>5 - 100 m/day</td>
<td>Fine sand - fine gravel</td>
</tr>
<tr>
<td></td>
<td>- vertical in river bed</td>
<td>10 m/day</td>
<td>5 - 100 m/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- vertical elsewhere</td>
<td>1 m/day</td>
<td>0.5 - 10 m/day</td>
<td></td>
</tr>
<tr>
<td>Gravelly alluvium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- horizontal</td>
<td>30 m/day</td>
<td>15 - 300 m/day</td>
<td>Medium sand – gravel</td>
</tr>
<tr>
<td></td>
<td>- vertical</td>
<td>5 m/day</td>
<td>2.5 - 50 m/day</td>
<td></td>
</tr>
<tr>
<td>Broome sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- horizontal</td>
<td>0.7 m/day</td>
<td>0.35 - 7 m/day</td>
<td>Loam - fine sand</td>
</tr>
<tr>
<td></td>
<td>- vertical</td>
<td>0.1 m/day</td>
<td>0.05 - 1 m/day</td>
<td></td>
</tr>
</tbody>
</table>
The effect that varying the parameters had on the RMS Error is shown in Figure 5-2. The following observations may be made from Figure 5-2:

- As expected, the calibrated value for each parameter (i.e. the model run with multiplier of 1) results in the smallest RMS Error. An exception to this observation is the ET alpha parameter which gives a slightly better RMS Error when 10% larger than the calibrated model.
- Some parameters, such as Flood Infiltration Rate, Rainfall Infiltration Rate, and Specific Yield have a broad range through which changes to the parameter create little change in the RMS Error.
- Changes to the parameters through the ranges described in Table 5-1 generate only small changes in RMS Error. With the exception of ET “α”, none of the changes caused the RMS Error to become greater than 10%, which was the target RMS Error indicating a calibrated model. This means that for all parameter choices within sensible bounds, the model will seem to be calibrated.

**Figure 5-2 – Results of sensitivity analysis on RMS Error**
To illustrate the potential effect of parameter changes on model results, the evapotranspiration flux for each of the sensitivity analysis model runs has been presented in Figure 5-3 and Figure 5-4. Evapotranspiration has been reported as it represents the volume of water available to vegetation, and thus changes in evapotranspiration indicate a predicted impact on groundwater dependent ecosystems. From these figures it can be seen that:

- For the Rain Infiltration Rate, Flood Infiltration Rate and Hydraulic Conductivity, predicted evapotranspiration varies by less than 10% when parameter multiplication factors between 0.1 and 2 are used.
- For factors larger than 2, changes to Rain Infiltration Rate, Flood Infiltration Rate and Hydraulic Conductivity cause a significant change in evapotranspiration, even while the RMS Error indicates that the model is reasonably well calibrated.
- Changes in Specific Yield do not result in significant changes to evapotranspiration.
- As expected, changing evapotranspiration parameters has a significant effect on evapotranspiration.

These results indicate that while the model is relatively insensitive to small changes in rainfall, flood, specific yield and hydraulic conductivity parameters, changes large enough to cause a significant change in model outcomes could still result in a “calibrated model”. This means that caution needs to be employed when relying on the RMS Error of the model, and other means are required for determining whether a particular parameter set is most appropriate. This characteristic of the model was understood during the calibration period, and so, in addition to the RMS Error, calibration relied on:

- fitting the shapes of the various bore hydrographs;
- data from previously reported pump test investigations; and
- professional understanding of the physical processes such as rainfall infiltration and water table evapotranspiration, and hence an appreciation of acceptable parameter ranges to be used in calibration.
Figure 5-3 – Effect of parameter changes on ET

Figure 5-4 – Effect of parameter changes on ET (linear scale)
6 Prediction

6.1 Description of Scenarios

Six predictive scenarios were run over 50 year model periods. Descriptions of each of the scenarios are given in Table 6-1. The following parameters were changed from the calibrated model:

- Each of the scenarios used the final heads from the calibrated model as initial heads for the predictive run. In this way the models simulate future conditions starting from April 2010.
- River stage, evaporation and rainfall data series were generated for the 50 year run time by repeating the calibration data sets. This saved generating pseudo data and means we can be confident that the inputs are historically realistic.
- Pumps were assumed to operate at constant flow rates without variation for seasons.
- A small aerial flux was extracted from slice 1 to account for stock and domestic bores. This flux was excluded from coastal areas as shown in Figure 6-1. This area is 3,200,000,000 m². When 200,000 kL of stock and domestic use is spread over this area, we get an extraction of 0.000062354 m/yr (i.e. 0.06 mm/yr, or 3 mm over the 50 year run time).
- A head boundary was added to the seawater interface in slices 2-4 at the downstream end of the De Grey aquifer at the elevation of the final calibrated head (+2.5 m AHD, see Figure 6-2). The purpose of assigning this boundary was to determine the risk of salt water intrusion during increased pumping scenarios and to provide a quantitative estimate of the salt water flux crossing the location of the current interface.
- For the “dry” climate scenario 3, rainfall was reduced 10% but other inputs, including river inputs, were kept the same as in other scenarios. This assumption is questionable as the rainfall component of model recharge is relatively small and it is likely that a drier climate would also result in few river flooding events and lower river stage. However there are no available algorithms or models available to provide quantitative estimates of the impact of drier climate on flooding inundation and river stage.
- Scenarios 5 and 6 involved introducing additional bores. In Scenario 5, these bores were added to the existing locations of Bulgarene bores (Figure 6-3), with extractions split evenly between all bores. In Scenario 6 bores were added as shown in Figure 6-4, again with extractions split evenly between the bores. The grid was refined around each new bore as with the original Namagoorie bores. All bores were added to model slice 2.
Figure 6-1 – Stock and domestic bore active area
Figure 6-2 Modelled potentiometric surface showing 5 m and 0.5 m contours of final heads from the calibration model
Figure 6-3 – Location of Bulgarene bores

Figure 6-4 – Location of Pardoo Creek bores
6.2 Commentary on Scenario 6

Scenario 6 involved placing bores within the Pardoo Creek aquifer. As there is little information about the Pardoo Creek aquifer, results for this scenario should be treated with caution. Of particular relevance is the lack of stream flow data for Pardoo Creek, and the fact that the preliminary site visit to the De Grey River did not include a visit to Pardoo Creek. For these reasons Pardoo Creek itself was not included as a river boundary in the model, and so results reflect what would happen in that aquifer during periods of zero river recharge.

It was found during modelling that the Pardoo Creek aquifer dried out due to lack of river recharge. Because of this, the model took 10 times longer to run than other scenarios before it was terminated after 5400 days (approximately 15 years, close to 30% of the way through the model run). A plot showing the significant drawdown in the pumping bores is shown in Figure 6-5. The large fluctuations seen in some of the pumping well hydrographs in Figure 6-5 are caused by pumps being alternately turned on and off as the predicted water levels oscillate around the level of the slice from which water is extracted. As the predicted water level falls below the level of the pumping slice the extraction is turned off, the pumping rate is reduced and the water level recovers above the level of the slice and the pumping starts again.

- Figure 6-5 – Observation bore and pumping bore heads for Scenario 6
### Table 6-1 – Predictive Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climate</th>
<th>Abstraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current (based on historical climate)</td>
<td>No Abstraction</td>
</tr>
<tr>
<td>1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
6.3 Impact on Water Balance

The mass balance results for each of the scenarios are given in Table 6-2, with a net mass balance given in Table 6-3. From these tables, the impacts of increasing pumping or decreasing rainfall can be seen. It should be noted that because Scenario 6 ran over a shorter time period to the other scenarios, rainfall infiltration and flooding events were not identical to the other scenarios, leading to some differences in results.

Conceptually, the impact of pumping in the alluvial aquifer is a lowering of the water table and this can lead to:

- Additional leakage of water from the river and the pools with the possible drying of some pools that would otherwise be permanent features,
- Freed-up storage within the aquifer. Lower water tables mean that when the next flood comes through, there may be an increased volume of recharge due to the larger available storage.
- Change in the volume of throughflow towards the ocean and a potential for the salt water fresh water interface to migrate inland in response to depressed water levels in the fresh water aquifer.

Table 6-2 – Mass balance for the scenario model runs (GL/year)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>River In</td>
<td>47.1</td>
<td>49.2</td>
<td>49.2</td>
<td>49.4</td>
<td>50.2</td>
<td>46.6</td>
</tr>
<tr>
<td>Flood In</td>
<td>12.9</td>
<td>11.4</td>
<td>12.8</td>
<td>12.4</td>
<td>12.5</td>
<td>9.7</td>
</tr>
<tr>
<td>Ocean In</td>
<td>43.7</td>
<td>43.8</td>
<td>43.9</td>
<td>44.0</td>
<td>44.0</td>
<td>43.6</td>
</tr>
<tr>
<td>Sea Water Interface In</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Rain In</td>
<td>18.3</td>
<td>18.3</td>
<td>16.4</td>
<td>18.3</td>
<td>18.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Storage In</td>
<td>-0.1</td>
<td>-1.8</td>
<td>-2.2</td>
<td>-1.3</td>
<td>-1.3</td>
<td>-4.7</td>
</tr>
<tr>
<td>River Out</td>
<td>-38.4</td>
<td>-35.9</td>
<td>-35.7</td>
<td>-35.7</td>
<td>-35.4</td>
<td>-31.4</td>
</tr>
<tr>
<td>Ocean Out</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>Sea Water Interface Out</td>
<td>-1.3</td>
<td>-1.3</td>
<td>-1.3</td>
<td>-1.2</td>
<td>-1.3</td>
<td>-1.1</td>
</tr>
<tr>
<td>ET</td>
<td>-82.2</td>
<td>-79.9</td>
<td>-80.0</td>
<td>-80.0</td>
<td>-80.1</td>
<td>-78.0</td>
</tr>
<tr>
<td>Stock and domestic</td>
<td>0.0</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>Pumping Wells</td>
<td>0.0</td>
<td>-7.0</td>
<td>-7.0</td>
<td>-8.0</td>
<td>-9.0</td>
<td>-9.0</td>
</tr>
<tr>
<td>Storage Out</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

From Figure 6-6 it can be seen that a large portion of the water flowing into the model (approximately half) is seawater through the coastal head boundary. This water is then evaporated near the coast, raising the volume of ET considerably. The model is in fact indicating a region near...
the coast where groundwater and sea water are mixing at or near the ground surface and substantial volumes of water are discharged to the atmosphere through evaporation. This behaviour may be typical of extensive tidal mud flats with a diurnal cycle of seawater inundation and fresh water discharge. The “Sea Water Interface” component to the net mass balance of Table 6-3 refers to the fluxes across the salt water fresh water interface in all layers except Layer 1. It can be seen that the model predicts a net outflow of water across this boundary and as such the groundwater extractions included in the scenarios are not expected to lead to increased seawater intrusion.

Table 6-3 – Net mass balance for the scenario model runs (GL/year)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>River</td>
<td>8.7</td>
<td>13.3</td>
<td>13.4</td>
<td>13.7</td>
<td>14.8</td>
<td>15.2</td>
</tr>
<tr>
<td>Flood</td>
<td>12.9</td>
<td>11.4</td>
<td>12.8</td>
<td>12.4</td>
<td>12.5</td>
<td>9.7</td>
</tr>
<tr>
<td>Ocean</td>
<td>43.4</td>
<td>43.5</td>
<td>43.6</td>
<td>43.7</td>
<td>43.6</td>
<td>43.3</td>
</tr>
<tr>
<td>Sea Water Interface</td>
<td>-1.2</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-0.9</td>
</tr>
<tr>
<td>Rain</td>
<td>18.3</td>
<td>18.3</td>
<td>16.4</td>
<td>18.3</td>
<td>18.3</td>
<td>15.3</td>
</tr>
<tr>
<td>ET</td>
<td>-82.2</td>
<td>-79.9</td>
<td>-80.0</td>
<td>-80.0</td>
<td>-80.1</td>
<td>-78.0</td>
</tr>
<tr>
<td>Stock and Domestic</td>
<td>0.0</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>Pumping Wells</td>
<td>0.0</td>
<td>-7.0</td>
<td>-7.0</td>
<td>-8.0</td>
<td>-9.0</td>
<td>-9.0</td>
</tr>
<tr>
<td>Storage</td>
<td>-0.1</td>
<td>-1.8</td>
<td>-2.2</td>
<td>-1.3</td>
<td>-1.3</td>
<td>-4.7</td>
</tr>
</tbody>
</table>
Although Table 6-3 and Figure 6-6 show the river as a net source of water, it should be remembered that during dry periods much water is lost through the river bed in sustaining the groundwater dependent pools. This is discussed further in the next section.

Table 6-4 shows the differences in flows between Scenario 1 (no pumping) and Scenario 2. It can be seen here that:

- Scenario 1 has 7 GL/year less pumping. This results in 2.3 GL/year more water available to the ground water dependent ecosystems via ET, and 1.8 GL/year more water left in storage (ie reduced drawdown). The remainder of the 7 GL/year is accounted for by less recharge from the river.
- Scenario 3 has a 10% reduction in rainfall. This results in a loss of 1.8 GL/year of rainfall, which is balanced by a 1.6 GL/year gain in recharge from river and floods.
Scenario 4 has a 1 GL/year increase in pumping at the Namagoorie borefield. This is offset by an increase in recharge from the river and floods.

Scenario 5 has a 2 GL/year increase in pumping at the Bulgarene borefield. This is offset by an increase in recharge from the river and floods.

Scenario 6 has a 2 GL/year increase in pumping at Pardoo, offset by a decline in storage. Results for Scenario 6 are less clear than for the other scenarios as the model did not cover the same wet and dry periods as the other scenarios, which has affected rainfall, ET and river fluxes.

Table 6-4 – Net difference in mass balance between all scenarios and Scenario 2 (GL/year)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>River</td>
<td>-4.6</td>
<td>0.0</td>
<td>0.2</td>
<td>0.4</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Flood</td>
<td>1.5</td>
<td>0.0</td>
<td>1.4</td>
<td>0.9</td>
<td>1.0</td>
<td>-1.8</td>
</tr>
<tr>
<td>Ocean</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Sea Water Interface</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Rain</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.8</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.9</td>
</tr>
<tr>
<td>ET</td>
<td>-2.3</td>
<td>0.0</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Stock and Domestic</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Pumping Wells</td>
<td>7.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.0</td>
<td>-2.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>Storage</td>
<td>1.7</td>
<td>0.0</td>
<td>-0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

6.4 Impact on River and ET Fluxes

The major objective of the modelling is to determine whether the ground water dependent ecosystems would be adversely affected by further development of the De Grey aquifer. These impacts can be inferred in a number of ways; from specifically looking at water moving through individual pools to looking at water uptake by plants across the whole aquifer.

Figure 6-7 shows the cumulative loss of water from the aquifer via evapotranspiration from the fresh water aquifer region. As evapotranspiration generally reflects plant growth, a marked decrease in evapotranspiration would indicate less uptake and the vegetation would be either less healthy, less dense, or both. From Figure 6-7 it can be seen that the only significant difference in results is between Scenario 1 (the “no development” scenario) and all the others. A difference between Scenarios 2, 3, 4 and 5 cannot be discerned. Scenario 6 is not reported here as it focuses on effects near the Pardoo Creek, and within the De Grey aquifer it is identical to Scenario 2.
Figure 6-7 – Comparison of evapotranspiration from the De Grey aquifer

Figure 6-8 shows a comparison of flow specifically to the permanent pool at the highway crossing. It can be seen that there is no discernable difference on water movements between Scenarios 2-5, indicating that additional pumping from the Namagoorie borefield does not seem to have a significant adverse effect.

Figure 6-8 – Comparison of flow from the permanent pool at the highway crossing
6.5 Impacts on the Seawater Interface
At the seawater interface water leaves the model. In effect, this boundary condition is modelling the volume of water that may travel downstream towards the coast through the unexplored section of palaeochannel. Because the hydrogeological conditions in the section of palaeochannel between the modelled aquifer and the coast are not well known, values for the flux across this boundary may not be correct. However, the data presented here represents the current state of knowledge and is useful for comparing different scenarios.

From Figure 6-9 it can be seen that the flow through the boundary remains relatively constant for all scenarios. Of interest, there is no significant difference between Scenario 5 and the others, suggesting that the Bulgarene borefield may not have a large impact on seawater intrusion. However, as mentioned above, there is a considerable amount of uncertainty in this region of the model and these results should be treated with caution.

![Figure 6-9 – Flow through the seawater interface boundary](image)

6.6 Impact on Groundwater Heads
The final heads of each model run were compared to the final heads at the end of scenario 2, as that reflects the current level of extractions.
Figure 6-10 shows the final depth to groundwater at the end of Scenario 2. This data can be interpreted as the minimum rooting depth required for vegetation to access groundwater from the saturated zone. Figure 6-11 to Figure 6-15 show the differences in final water level between scenarios.

- For Scenario 1, Figure 6-11 shows that if there were no pumping, heads near the borefield could be 5 m higher than they are for continued pumping of the existing borefield at present rates.

- For Scenario 3, Figure 6-12 shows that if rainfall decreases by 10% then water levels near the river will remain steady, supposedly due to river recharge, but water levels away from the river may drop.

- For Scenario 4, Figure 6-13 shows that if pumping from the Namagoorie borefield were increased to 8 GL/year, the groundwater head at the borefield could drop by about 0.4 m.

- For Scenario 5, Figure 6-14 shows that if the Bulgarene borefield were developed to extract 2 GL/year then water levels there could drop by about 1 m. Due to the proximity to the river, the cone of depression would reach the river and could cause pools adjacent to the borefield to dry. The cone of depression does not appear to reach the assumed seawater interface.

- For Scenario 6, Figure 6-15 shows that if the Pardoo Creek aquifer is developed without being sure of frequency of recharge, there is the possibility that the pumps will run dry after 10-15 years. This assumes that appropriate sediments exist at Pardoo and that the groundwater is fresh. Note that other differences in water level such as higher levels close to the De Grey are likely due to the fact that the model ran for a different length of time than Scenario 2, and so the results are from a different time in the climatic cycle.

The hydrographs of each scenario have also been plotted for each observation bore to see the difference in water levels through time; these are included in Appendix B. The scenario hydrographs confirm that the final head data shown in Figure 6-11 through Figure 6-15 gives a representative view of the various scenarios. Observation bores within the various borefields show increased drawdown, whilst those further afield show very little difference in water levels between scenarios.
- Figure 6-10 – Scenario 2 final depth to groundwater
Figure 6-11 – Difference between Scenario 1 final heads and Scenario 2 final heads
Figure 6-12 – Difference between Scenario 3 final heads and Scenario 2 final heads
Figure 6-13 – Difference between Scenario 4 final heads and Scenario 2 final heads
Figure 6-14 – Difference between Scenario 5 final heads and Scenario 2 final heads, with interpreted seawater at -10 m AHD shown in red
Figure 6-15 – Difference between Scenario 6 final heads and Scenario 2 final heads (15 year Scenario 6 model run)
7 Discussion

A series of predictive model scenarios have been run and reported. The predictions consider a variety of groundwater extraction regimes as well as a climate change scenario and a no-extraction scenario. These were compared with a 7 GL/year extraction scenario that simulated a continuation of current conditions.

These model runs suggest that development of the Bulgarene borefield to extract 2 GL/year or increasing the licensed extraction volume of the Namagoorie borefield to 8 GL/year would have measurable effects, with water levels lowered in those areas where additional groundwater extraction is assumed. This increase in depth to water table is not expected to create a significant problem for vegetation that access groundwater from the saturated zone. However, in the case of the Bulgarene borefield (Scenario 5), the predicted cone of depression reaches the De Grey and Ridley rivers. A decrease in pool level at Bulgarene and Muccangurra pools of about 1 m as predicted by the model could have a significant effect on the size and permanency of those pools, especially during drier times of the year.

Figure 6-14 also shows that the resultant cone of depression from the Bulgarene borefield does not reach the assumed salt water fresh water interface and as such there is no perceived risk of salt water intrusion.

It was found by budget analysis that increased extraction was countered by a combination of increased recharge from the river and through flood plain inundation. Increased river leakage occurs in response to lower groundwater levels at the location of the river and pools. The increased flood inundation recharge relates to additional storage capacity due to depressed groundwater levels particularly in the region of the borefields. This model behaviour is driven by the flooding algorithm that checks at every time step and at every node to determine whether the flood height is above the existing groundwater level. Through this process flood waters are prevented from recharging the aquifer when the water table is at the ground surface.

A sensitivity analysis found that the RMS Error of calibration was relatively insensitive to changes in Rain Infiltration Rate, Flood Infiltration Rate and Hydraulic Conductivity. Substantial variations in these parameters (i.e. multiplying the parameter in question by 5 or greater) had a significant effect on the predicted evapotranspiration while the RMS Error of calibration remained below 10%. This observation suggests that caution needs to be employed when relying on the RMS Error as a calibration criterion. Other means are required for assessing the quality of the model calibration.
8 Recommendations for Further Work

The Lower De Grey River groundwater model has been defined as a medium complexity “Impact Assessment” model, as per the MDBC (2000) guidelines. The primary reason for this level of complexity is the constraints imposed on the model by data limitations. The data constraints have significant implications for model certainty and the level of confidence in results. The key data constraints and their impact on the model certainty are summarised in Table 8-1.

Once additional information has been obtained it would be appropriate for the modelling to be re-visited in order to incorporate the new information. This may require model re-configuration if the new data provide additional information on the location and geometry of the alluvial sediments. If suitable information on the saline parts of the aquifer can be obtained then the development of density dependent solute transport would be of particular value.
### Table 8-1 – Data constraints

<table>
<thead>
<tr>
<th>Data Constraint</th>
<th>River and pool levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>Only one permanent gauge exists, located at Coolenar pool near the centre of the model.</td>
</tr>
<tr>
<td><strong>Impact on Model</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Uncertainty</strong></td>
<td>Assumptions were made about how to extrapolate the Coolenar gauge data along the De Grey, and the gauge data were even applied to the Shaw and Ridley rivers in the absence of better data. Although the linear interpolation based on river bed levels should give a reasonable approximation of water levels, accuracy would be improved if additional measured data were available.</td>
</tr>
<tr>
<td><strong>Recommendation for data acquisition to improve model reliability</strong></td>
<td>Addition streamflow gauging stations (including one at homestead pool) would improve the accuracy of the calculated river levels in the model. Gauges on the Shaw and Ridley rivers within the aquifer are probably not required as the De Grey is the primary source of recharge.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Constraint</th>
<th>Extent of the De Grey aquifer downstream of Homestead pool</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>Aquifer geometry and hydrogeological conditions in the coastal fringe are not well known and there was no data that define the palaeochannel geometry in the downstream parts of the aquifer.</td>
</tr>
<tr>
<td><strong>Impact on Model</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Uncertainty</strong></td>
<td>Because the saltwater bearing part of the palaeochannel is not defined, it is not possible to give accurate answers to questions relating to seawater intrusion due to groundwater extraction.</td>
</tr>
<tr>
<td><strong>Recommendation for data acquisition to improve model reliability</strong></td>
<td>Ideally, this model would extend all the way to the coast and the actual interaction of the aquifer with the ocean would be modelled. To achieve this it will be necessary to conduct a drilling program in the areas currently contained within the no flow boundary condition. This drilling program should focus on following the De Grey river palaeochannel and mapping its depth and width from the Homestead to the coast. Due to the interference of salt water, geophysics have proven to be unhelpful</td>
</tr>
</tbody>
</table>
in defining the aquifer in this area.

<table>
<thead>
<tr>
<th>Table 8-1 – (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data Constraint</strong></td>
</tr>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Impact on Model Uncertainty</strong></td>
</tr>
<tr>
<td><strong>Recommendation for data acquisition to improve model reliability</strong></td>
</tr>
</tbody>
</table>

If the creek bed contains sandy or gravelly sediments and fresh water, then the next step would be to gauge the creek to determine the characteristics of flow such as frequency, volumes and stage elevations.

This data should also be used to determine whether overland flooding occurs at this location. An absolute minimum of two years stream flow data would be needed before generating a rainfall-runoff model of the catchment so that a longer time series of stream flow data could be generated.

Using this generated stream flow data, a groundwater model could be created to answer the specific question of what volume of extractions the aquifer may be able to sustain.
Table 8-1 – (cont.)

<table>
<thead>
<tr>
<th>Data Constraint</th>
<th>Flood extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>There were no formal datasets available that provided indications as to the extent of flooding. Flood extent was calculated using river stages and ground elevations</td>
</tr>
<tr>
<td>Impact on Model Uncertainty</td>
<td>The calculation used does not account for water flowing overland from higher elevation areas, or water lying in pools after flood events. As flood recharge provides a significant portion of water to the De Grey aquifer, increased reliability of flood estimates would increase the accuracy of the model.</td>
</tr>
<tr>
<td>Recommendation for data acquisition to improve model reliability</td>
<td>Aerial photography flown on days immediately following flooding events would provide suitable data from which the flood extent could be mapped.</td>
</tr>
</tbody>
</table>
Table 8-1 – (cont.)

<table>
<thead>
<tr>
<th>Data Constraint</th>
<th>Salt water interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>The saltwater interface has been assumed based on EM data</td>
</tr>
<tr>
<td>Impact on Model</td>
<td>While EM data is a good indicator of salt, it can also be confused by clays, and shallow effects may not be well represented.</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Water quality testing of bores near the Homestead for salt content could be used to confirm the location of the salt water interface. Sampling on a regular basis of several fresh bores close to the boundary would be useful to determine whether the boundary is moving over time and provide advance warning if aquifer extractions are leading to the landward migration of saline water. Salinity measurements in the river from the coast upstream would help to determine the tidal extent of the river which in turn will help to delineate the region where there is a potential for salt water to recharge the aquifer through the river bed.</td>
</tr>
</tbody>
</table>
9 References


Appendix A – Calibration Bore Hydrographs

Plots show the calibrated predicted water levels versus observed water levels. Generally there is a good correlation, indicating the model is well calibrated. Blue dots indicate observed data, the red lines indicate predicted data.

Bore hydrographs are taken from model slice 2, while pool hydrographs are taken from model slice 1.
Lower De Grey Groundwater Model
Appendix B – Scenario Comparison Hydrographs

Plots showing hydrographs at the observation bore locations are shown below for each of the 6 scenarios. Note that Scenario 6 (shown in orange) was terminated early due to the Pardoo Creek aquifer running dry.
Lower De Grey Groundwater Model

![Graphs showing groundwater levels over time for different scenarios.](image)

SINCLAIR KNIGHT MERZ