WATER FOR A HEALTHY COUNTRY FLAGSHIP
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Proposed project methods

A report to the West Australian Government and industry partners from the CSIRO Pilbara Water Resource Assessment

15 October 2012

Water for a Healthy Country Flagship Report series ISSN: 1835-095X

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Citation

CSIRO (2012) Proposed project methods. A report to the West Australian Government and industry partners from the CSIRO Pilbara Water Resource Assessment, CSIRO Water for a Healthy Country, Australia.

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Important disclaimer

Pilbara Water Resource Assessment acknowledgments

This report was prepared by CSIRO for the West Australian Government and industry partners – Department of Regional Development and Lands – Pilbara Cities Office, BHP Billiton, West Australian Department of Water and the Water Corporation. This report benefited from reviews by Mike Braimbridge (West Australian Department of Water), Jacqui Durrant (West Australian Department of Water), Gary Humphreys (West Australian Department of Water), Simon Rogers (West Australian Department of Water), Blair Douglas (BHP Billiton), Lucinda Ransom (BHP Billiton), Mahtab Ali (Bureau of Meteorology) and Mohammed Bari (Bureau of Meteorology).

Foreword

In 2007 and 2008, the CSIRO produced a series of reports examining the likely water yield of surface and groundwater catchments in the Murray-Darling Basin (MDB) as a result of future climate scenarios and land management changes such as afforestation and farm dams. On 26 March 2008, the Council of Australian Governments (COAG) expanded this assessment of 'sustainable yield' to northern Australia, Tasmania and south-west Western Australia. By late 2009 for the first time Australia had a comprehensive scientific assessment of water yields in all major water systems across the country. This allowed a consistent analytical framework for water policy decisions across the nation. More recently a water resource assessment has been undertaken by CSIRO and Geoscience Australia for the Great Artesian Basin.

This Pilbara Water Resources Assessment Project is therefore the sixth such assessment of regional water resources which will provide critical information on resources in a part of Australia that is experiencing rapid economic and social development in a variable climate. This information will help governments, industry and communities consider the environmental, social and economic aspects of the sustainable use and management of the water assets of the Pilbara. The project is expected to be completed by December 2014.

Determinations of the amount of water that can be safely diverted from streams and aquifers require choices by communities and governments about the balances of outcomes (environmental, economic and social) sought from water resource management and use. These choices are best made in the light of sound technical information and the fundamental underpinning information is a robust description of the extent and nature of the water resource.

While existing records of rainfall, streamflow and groundwater levels (and simulation models based on these data) provide a description of the resource from the past to the present, it is increasingly widely recognised that these data do not provide the best description of the likely extent and nature of the resource into the future, and thus no longer provide the best basis for planning. A careful examination of the likely implications of climate change on water resources is required as the basis for planning into the future. This includes a consideration of the direct effects (such as changes in rainfall and potential evaporation) and indirect effects (such as changes in mine dewatering and demand).

The required baseline information for determining future yields is thus an assessment of the current and likely future extent and variability of surface and groundwater resources. Before estimating what water resources may be available in future it is important to properly describe what currently exists and how it has responded to past and recent climates as well as development.

CSIRO is to conduct the Pilbara Water Resource Assessment to cover the water resources in the Fortescue, Port Hedland Coast, De Grey, Onslow Coast and Ashburton river basins with an emphasis on areas undergoing active mining and prospective for water supplies to coastal towns.

For this project, the CSIRO agreed to provide an overview of the current and future climate and water resources of the Pilbara to aid water planning and management and place local studies into a wider context.

The overall approach of the project includes:

- analysing the current climate and water resource status of the region including analysing and explaining historical trends where data allow them to be estimated;
- defining different climate scenarios and generating time series of climate data to describe these scenarios;
- spatial–temporal modelling of the implications of these climate scenarios for catchment runoff and aquifer recharge;

- propagating the runoff/recharge implications through river system and groundwater models including explicit consideration of the surface–groundwater exchanges and impacts on water dependent ecosystems; and
- assessing and reporting these findings so that they put local studies into a regional context and can be used by resource managers for assessing water availability under climate and development scenarios.

This report is a working document of the project that sets out the methods being adopted to deliver on the above terms of reference. These methods are similar to those used in the Murray-Darling Basin Sustainable Yields Project (CSIRO, 1 June 2007) so that national comparisons can be made between regions. However each time the methods have been applied, improvements have been incorporated (e.g. running groundwater models in predictive mode in the south-west Sustainable Yields project). This Pilbara Water Resource Assessment will also consider rainfall intensity-duration-frequencies under future climates for periods of less than one day (the time step used in Sustainable Yield assessments). This will enable an assessment of future flood impacts and well as water yields.

The methods need be approved by the project's Steering Committee before they are applied.

The overall approach of the project is to ensure a technically robust methodology appropriate to the available time frame and resources that draws on the best available skills, data, models and techniques, especially considering relevant work already undertaken and the existing expertise and capacity within the partner organisations.

Project methods

The overall approach of the project includes: (i) analysing and reporting on historical climate and hydrological trends; (ii) defining different climate scenarios and generating time series of climate data to describe these scenarios; (iii) spatio–temporal modelling of the implications of these climate scenarios for catchment runoff and aquifer recharge; (iv) propagating the runoff/recharge implications through river and groundwater models including explicit consideration of the surface–groundwater exchanges; and (v) assessing and reporting the findings so that they may be used to estimate current and future water resources by water managers and industry players (Figure 1).

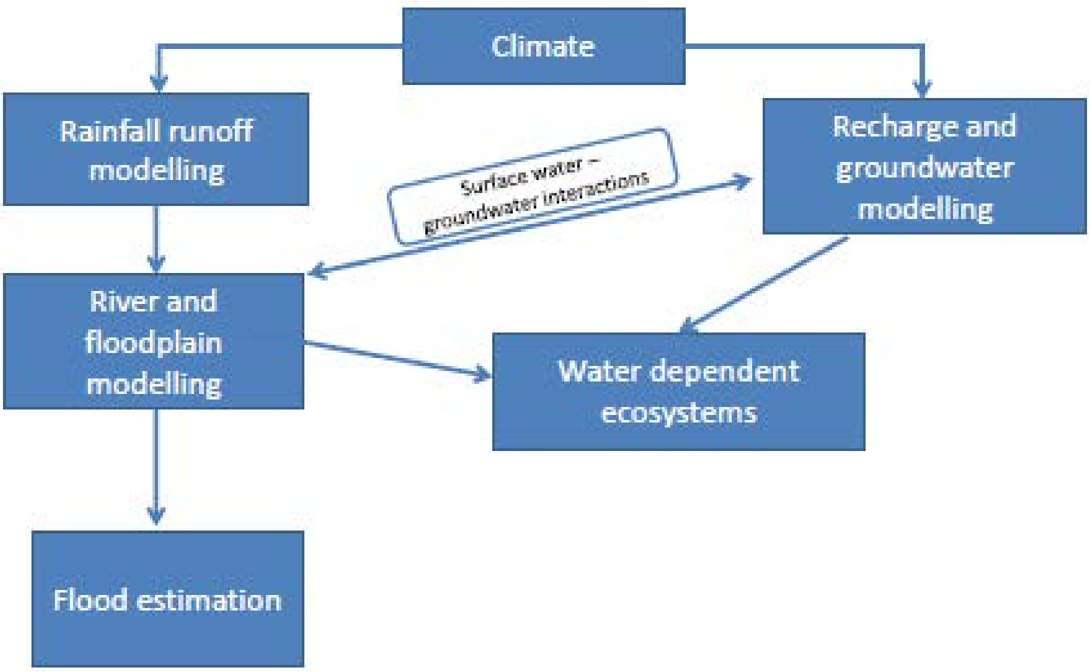

Figure 1 The overall project approach and the flow of information

This report is structured around the work areas within the project.

Chapter 1 describes some background to the work, the **geographic scope** and **main deliverables** of the project

Chapter 2 defines the methods used to **analyse the historical climate** and the **climate and development scenarios** that will be considered in the project, and then for each scenario describes the methods that will be used to define climate time series and other modelling inputs.

Chapter 3 describes the methods that will be used to **analyse historical runoff** and to translate the future scenarios into **catchment runoff, streamflows** and **river models** and discusses model uncertainty.

Chapter 4 describes the methods that will be used to summarise **current groundwater resources and use** and to translate the scenarios into **catchment recharge** and to assess and model **groundwater systems**, including a description of how **surface–groundwater interactions** will be assessed and incorporated into the modelling.

Chapter 5 describes the methods that will be used to assess the impact of past and projected surface and groundwater resources on significant **environmental values**.

Each section will include consideration of key aspects of **regional monitoring** opportunities and needs that arise from analysing the existing data and models for the region.

Chapter 6 examines the interrelationship between activities as shown in Figure 1, including a Gantt chart showing possible timelines for each activity.

Chapter 7 explains **data management and compilation** processes and systems used by the project including model output management and storage, and Chapter 8 describes **report management** and details the **reports** that will be developed as a result of the work.

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Shortened forms

AHD	Australian Height Datum
APET	areal potential evapotranspiration
BFI	baseflow index
BHPB	BHP-Billiton
CLW	CSIRO Division of Land and Water
CMAR	CSIRO Division of Marine and Atmospheric Research
CMB	chloride mass balance
CO_2	carbon dioxide
COAG	Council of Australian Governments
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	digital elevation model
DoW	Western Australian Department of Water
DRDL	Department of Regional Development and Lands
DTW	depth to watertable
GCM	global climate model
GDE	groundwater-dependent ecosystem
GRCI	groundwater resource condition indicator
IQQM	Integrated Quantity and Quality Model – a river systems model
IPCC AR5	The fifth assessment report of the Intergovernmental Panel on Climate Change
MSLP	mean sea level pressure
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Wetness Index
PDC	Pilbara Development Commission
Sacramento	A rainfall-runoff model
SAN	storage area network
SIMHYD	Simulated Hydrology, a rainfall-runoff model
SRN	streamflow reporting node
Water Corp	Water Corporation of Western Australia

Table of units

m^3/s	cubic metres per second or ‘cumecs’
mS/m	milli Siemens per metre
GL	Gigalitre or 1000 Megalitres (ML)
ML	Megalitre or 1000 kilolitres (kL)

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1 Introduction

1.1 Background

In early 2010 the Department of Water approached CSIRO to discuss the benefits of doing a water resource assessment of the Pilbara similar to that which had been carried out in south-west Western Australia (CSIRO 2009 a, b, c) and in Northern Australia (CSIRO 2009d). In these studies, CSIRO used the best available estimates of future climates (including extrapolations of historical and recent climates) and changes in development, to estimate potential surface water and groundwater yields in 2030 on a catchment and aquifer basis. This determined the sensitivity of water resources to climate and developmental drivers and indicated whether future water demands (environmental and consumptive) could be met. These projects also produced models and methods that have been used for water and developmental planning.

The Department of Water developed a draft regional water plan in 2008 and a final plan for the Pilbara two years later (DoW 2010a, b). The strategic level regional water plan recognises a variable future climate in the Pilbara in contrast to the more certain declines in the south west, but noted that there remains uncertainty in what the future climate may be which will effect other planning and regulatory decisions. This Assessment was developed to provide more certainty to Government and industry on the future effects of climate.

The regional plan identified that the West Pilbara water supply scheme operated by the Water Corporation had a demand greater than the area's long-term reliable supply. Water demand in the Port Hedland water supply scheme further east was close to available supply.

A water allocation plan for the Pilbara that sets allocation limits (mainly for alluvial aquifer) and groundwater management rules (mainly for fractured rock aquifers) is due for release in draft form in 2012. The development of this plan focuses on the key resources likely to support development. The plan will be based on over three years of scientific investigation and groundwater modelling of key aquifers required to help meet current and future water supplies. It estimated future climate impacts by scaling the historical climate record. Through this Assessment, future planning and allocation decisions will be refined using improved climate information from global circulation models (GCMs) as develop through the IPCC.

In recent years, iron ore mining companies have been asked by the Environmental Protection Agency (EPA) to assess the likely cumulative impacts of discharging dewatering flows into rivers and aquifers when mining below the watertable. The EPA also required companies to estimate long term impacts of mining and mine closure on the hydrology of areas and dependent ecosystems, often up to 2030 or 2050. In discussions about this Assessment, the EPA expressed a desire for there to be standardised methods for assessing hydrological impacts of different mining operations in these out years, as well as a larger regional understanding of cumulative impacts of mine development.

Independent of regulatory requirements, mining companies need to quantify the risk of intense rainfall and consequent flooding on their operations (e.g. inundation of mine pits). They also have their own water requirements to consider. While this can often be done on a mine-by-mine basis, sometimes there are advantages in looking at what is happening on a river basin scale because large patterns may not be obvious at the local level.

This research plan therefore tries to meet a number of different objectives held separately or jointly by state government departments, water service providers, mining companies and environmental agencies. Because there are uncertainties about what the future climate of the Pilbara may be, scenarios that include base cases of extensions of the past climate sequences are included in the Assessment as well as the current best estimates coming from the Intergovernmental Panel on Climate Change's Fifth Assessment Report (2012) and the Indian Ocean Climate Initiative's third phase.

The Assessment also includes an analysis of the regional hydrological properties of the region outside the already-assessed alluvial systems in response to past, current and possible climates.

1.2 Assessment objectives

The overall Assessment objective is to provide an authoritative analysis if the current and future water resources of the Pilbara region for use by state government agencies, water supply providers and mining companies for use in future water and land planning. The Assessment is also likely to produce new models and tools for water management.

There are a number of specific objectives agreed by the partners under different categories as detailed below:

1.2.1 CLIMATE

1. To provide a review of historical climate trends in the Pilbara based on available Bureau of Meteorology data and the Stage 3 Indian Ocean Climate Initiative (IOCI) findings, especially:
    a. climate extremes,
    b. intensity and frequency of tropical cyclones
    c. the drivers of changes to recent rainfalls; and
    d. drought frequency and duration
2. To develop 2030 and 2050 climate scenarios for all parameters that are required to run surface water and recharge / groundwater models (i.e. daily rainfall, temperature, relative humidity, aerial potential evapotranspiration)
3. To provide an assessment of the range of possible future climates of relevance to sectors outside hydrology where possible
4. To estimate future rainfall intensity-duration-frequencies for periods of less than one day where desired for flood runoff modelling

1.2.2 RUNOFF

1. To define rainfall-runoff relationship in the five basins and major catchments under historical, recent and projected future climates
2. To determine the intensity, duration, and frequencies of runoff under the historical climate and estimate changes to the rainfall-runoff relationship under recent and future climate scenarios
3. Derive runoff for all major streams of five river basins for 2030 and 2050 climate scenarios
4. Provide more detailed spatial and temporal data for priority catchments as identified by the Steering Committee

1.2.3 RIVER AND FLOODPLAIN MODELLING

1. To develop river systems models capable of simulating entire river systems under historical and future climate and development scenarios. Where supporting data are available these models can account for sub-catchment runoff, extractions, diversions, storages, floodplain inundation, transmission losses,

simple groundwater-surface water interactions and complex management, allocation and environmental flow rules.

2. To provide a high level assessment of the relative inputs of climate variability, climate change and dewatering discharges into river flows at different times of the year and in different parts of the Pilbara.
3. To provide an evaluation of local recharge mechanisms (loosing streams and/or overbank flooding), frequencies and rates for alluvial aquifers under different climate regimes and estimate recharge to, and discharge from, aquifers from river beds and floodplains.
4. To develop insights into recharge mechanisms and frequencies for alluvial aquifers under different rainfall regimes.
5. Provide the recharge and discharge from river beds and floodplains for groundwater modelling.
6. To provide data for assessing the separate and combined impacts of climate and development on surface water dependent ecosystems.

1.2.4 GROUNDWATER

1. To review the regional groundwater hydrology of the Pilbara, with an emphasis on the Central Pilbara
2. To provide improved estimated of recharge under future climate projections for existing Pilbara groundwater models
3. To better understand how fractured rock aquifers, chemically deposited aquifers (calcrete and limonite) and Tertiary alluvial-colluvial aquifer systems may respond to climate variability, climate change and development scenarios. This will include an assessment of the relative importance of diffuse and localised recharge.
4. Extend understanding of alluvial beyond currently modelled areas in areas likely to be useful for water supply
5. To better understand surface water – groundwater interactions in areas not presently covered by groundwater models

1.2.5 WATER DEPENDENT ECOSYSTEMS

1. To identify potential and where possible actual water dependent ecosystems, mainly Groundwater Dependent Ecosystems (GDEs) at a regional scale and determine any majors changes in past status and link past changes to climate history
2. Assess how changes to surface water regimes resulting from climate change and development scenarios will impact the occurrence and distribution (spatially and temporally) of dependent ecosystems.
3. Estimate possible future impacts on GDEs that result from changes in groundwater regimes driven by climate change and development scenarios.
4. To provide comparative data on how climate may be affecting streams, river pools and GDEs

1.2.6 REGIONAL MONITORING (REPORTED WITHIN EACH SECTION)

1. To provide advice on how additional or adapted climate, surface water gauging, groundwater monitoring and remote sensing may assist water resource assessment and management in the Pilbara.

1.3 Geographic scope of the Assessment

Deciding the geographic scope of the Assessment considered AWRC Drainage Basins 706 to 710 inclusive, the area covered by the Pilbara Regional Water Plan 2010-2030 (which extends to the state border but cuts across some southern river basins), the area likely to provide water to the Onslow, West Pilbara and Port Hedland water supply schemes and the main areas of mining activity. A combination of these was agreed as shown in Figure 1-1

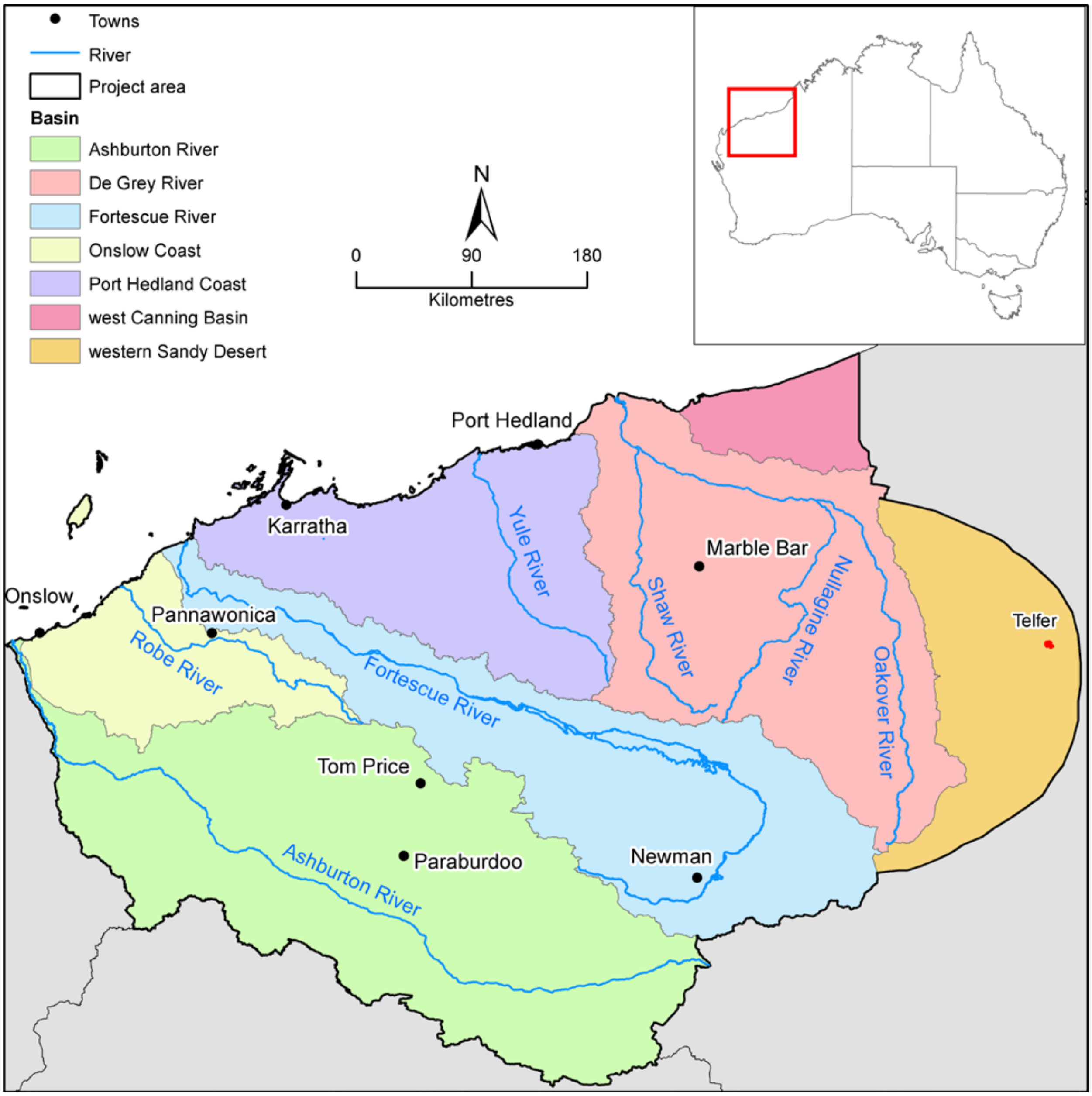

Figure 1.1 Geographic scope of the Assessment area

The region therefore includes all five AWRC Drainage Basins but extends to the east to include mining areas around Telfer and Kintyre (Rudall River) and to the north-east to include those parts of the west Canning Basin that are being explored for supplying the East Pilbara water supply scheme. The precise extent of these two eastern areas will be better refined when the Assessment is underway.

1.4 Surface water regions

The Assessment will cover the Ashburton River Basin (AWRC Drainage Basin 706); the Onslow Coast Basin (707) which includes the Cane and Robe Rivers; the Fortescue River Basin (708) ; the Port Hedland Coast Basin (709) which includes the Maitland, Harding, George, Sherlock, Peawah, Yule and Turners rivers; and the De Grey River Basin (710) which includes the De Grey, Strelley, Shaw, Coongan, Nullagine and Oakover rivers as described in Ruprecht and Ivanescu (2000).

Details on how these basins will be sub-divided for modelling and reporting purposes can be found in later sections of this report.

1.5 Groundwater regions

The main target areas for groundwater assessment are based on Department of Water priority areas as shown in Figure 1.1. Alluvial aquifers around coastal rivers, palaeochannels and the west Canning Basin contain most of the prospective groundwater in the region (shown as detailed assessment areas in Figure 1.2). Many of these areas have groundwater models as described later in this report. There are less prospective resources shown as 'risk-based assessment area' with remaining areas containing mainly fractured rock aquifers. The areas selected for further investigation will be made by the Steering Committee.

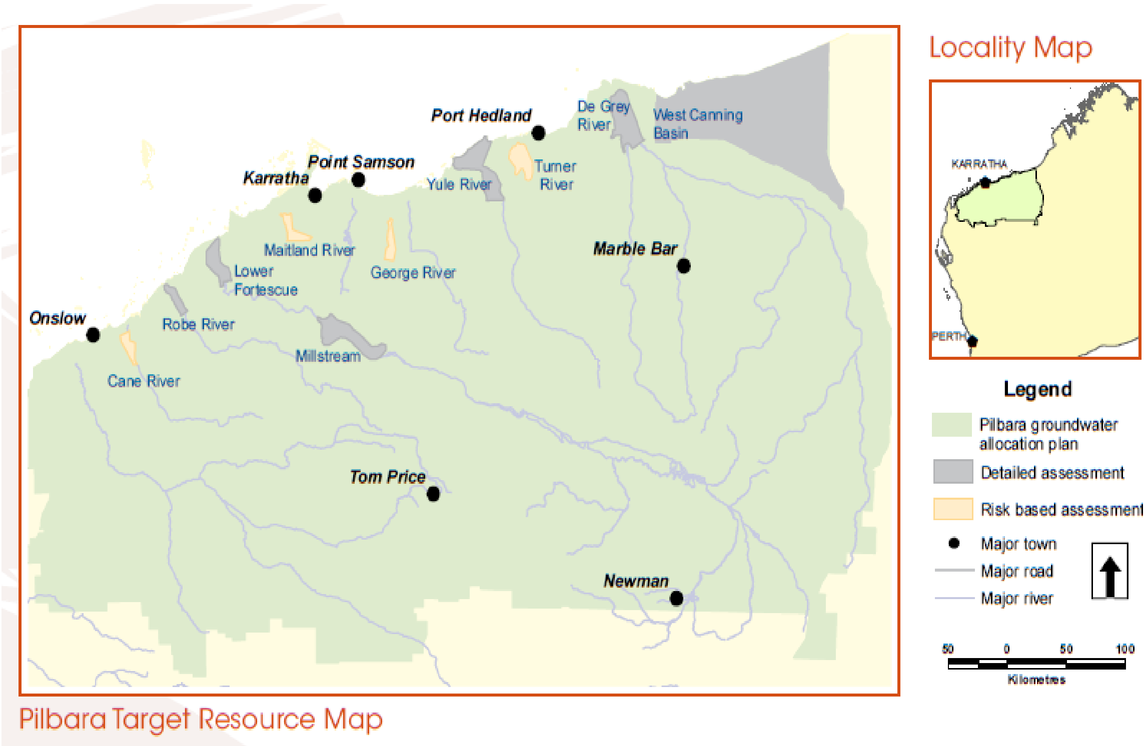

Figure 1.2 The main aquifers that will be addressed by detailed analysis in the Assessment (DoW 2011)

1.6 Subdivision of the Assessment area for reporting

Chapter 8 examines reporting options in some detail. At this stage it is intended to produce comprehensive reports covering climate, surface water and groundwater hydrology, and water dependent ecosystems for river basins either singly or grouped, depending on the amount of material to be covered in each basin and the likely target audience. This approach is similar to that adopted in the Murray-Darling Basin and

Northern Australia Sustainable Yields projects. In addition, region-wide summary reports will be produced for climate and water resources overall as detailed in the following section.

Most Sustainable Yield projects concentrated on likely future water resources under climate and development scenarios. The South-west Sustainable Yield project included a review chapter in each main report summarising the current state of knowledge about the area before doing these future projections. The Pilbara Water Resource Assessment will analyse past climate and hydrological responses as well as make future projections. This reflects the absence of recent hydrological reviews in this region compared with other regions. As well as considering water as a recourse the project considers dewatering activities to access iron ore deposits.

1.7 Deliverables

The Assessment is an analysis of climate, hydrology, geographic and remote sensing data and models into existing and new models to better define current water resources and identify future trends. The main deliverables are reports aimed at either at technical, management or community audiences. A list of proposed reports is provided in Chapter 6.2. The exact scope of each report is expected to evolve to better meet audience needs. Variations in deliverables will be made through the Steering Committee.

It is expected that datasets themselves will be a useful product of the analysis, providing input data for models used by third parties. For example, future climate datasets may be used in more detailed groundwater and river models than will be used in this Assessment.

New methods and models are also likely outcomes from this Assessment as has happened in past Sustainable Yield projects and Water Resource Assessments. These are often difficult to define at the start of each project. However the very limited amount of rainfall – runoff and river modelling in the region means that the results from this analysis are likely to be an important advance on current methods. Having a consistent climate set to run through groundwater models will be advantageous for making regional comparisons of how different types of aquifers may respond to climate variability and change.

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2 Climate

The climate activity will assess and summarise our current understanding of the climate of the Pilbara region and provide scenarios of current and future climate suitable for the hydrological modelling activities. This chapter describes the scope of the planned climate activity investigations and provides details of methods proposed to generate scenarios of climatic time-series for hydrological modelling.

2.1 Background

The future climate of any region will always be uncertain, a factor of both inherent natural climate variability and the irreducible uncertainties of climate model projections. When estimating the likely changes in future climate and the resulting climate impacts at the regional scale the aim is to create climate change scenarios that, where possible, encompass the full range of quantifiable uncertainties (Pittock, 1993). In the terminology of the Intergovernmental Panel on Climate Change (IPCC), a climate change scenario is simply the difference between a climate scenario (implicitly this is a scenario for the future) and the current climate, where the climate scenario is defined as a plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change. Climate scenarios are based on climate projections, defined as the response of the climate system (as simulated by global climate models, GCMs) to prescribed future greenhouse gas and aerosol emissions/concentrations or radiative forcings.

Climate scenarios will be constructed for the Pilbara region that account for the uncertainties due to both the projected range of global warming and the differences in GCM's regional responses to global warming. This scenario approach will facilitate a comparison of a baseline scenario 'future' representing current climate (Scenario A) with future scenarios (Scenario C) derived from the current best available science as incorporated in the Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports (IPCC, 2007; 2013) and the Indian Ocean Climate Initiative (IOCI) Stage Three (IOCI, 2012).

2.2 Objectives

The research undertaken within the climate activity will:

- provide a review of historical climate trends in the Pilbara, based predominantly on available Bureau of Meteorology station data and IOCI Stage 3 (IOCI3) findings, with a focus on:
    - climate extremes
    - intensity and frequency of tropical cyclones and rain-bearing low pressure systems
    - the drivers of changes to recent rainfalls
    - drought frequency and duration
- develop seasonal and daily scaled climate scenarios suitable for 2030 and 2050 planning horizons for the input parameters that are required by surface water and recharge / groundwater models, i.e. gridded daily rainfall and areal potential evapotranspiration (APET)
- provide summaries of daily rainfall and APET scenarios to sectors outside hydrology, such as mining (Loechel et al., 2011), agriculture and urban design (NB: not delivering sector-specific products)
- review available estimates of future rainfall intensity-duration-frequencies for periods of less than one day (i.e. review already available information, as no capacity to develop or apply new methods)

2.3 Review of Indian Ocean Climate Initiative research

The Indian Ocean Climate Initiative (IOCI) was a partnership between the Western Australia Government, CSIRO and the Bureau of Meteorology formed to investigate Western Australian climate, the factors that influence it, the causes of changes that have occurred since the 1970s, and develop climate projections to support informed decision making on climate variability and change. IOCI formally began its Stage 1 program in January 1998, Stage 2 commenced in July 2003 and Stage 3 in 2008. Stage 3 (IOCI3) research concluded in June 2012 and final reports are currently in preparation. IOCI3 was committed to establishing and maintaining state-of-the-art and regionally-specific knowledge of past and projected climate trends in Western Australia, and making such knowledge available in a policy-ready form and for public information processes (IOCI, 2012).

Research undertaken by IOCI3 of relevance to both historical climate trends and future climate projection in the Pilbara will be reviewed and summarised within the context of the hydrological modelling requirements of this project. Specific IOCI3 projects of relevance include:

Project 1.4: *Regionally Specific Climate Data and Monitoring for the North-West and South-West to Support the Understanding of Past, Present and Future Climate*

Project 2.1: *Observed and Modelled Climate for the North-West*

Project 2.2: *Tropical Cyclones in the North-West*

Project 2.3: *Statistical Downscaling for the North-West*

Project 2.4: *Physical-Statistical Modelling of Extreme Events*

In addition to IOCI research, the findings of recent paleo-climatological research using oxygen isotopes in tree-rings to investigate longer-term climate trends in the Pilbara will also be reviewed (Cullen and Grierson, 2007; Cullen et al., 2008). For example, for a study site in the Karijini National Park in the central Pilbara, Cullen and Grierson (2007) inferred relative humidity, rainfall and temperature trends spanning the last 80 years. Their results indicate relatively dry and warm summers between 1919 and 1955 followed by progressively more humid, wetter and cooler summers since 1955, with the 1980s and 1990s the wettest and coolest in this period.

2.4 Historical climate and recent trends

Both historical daily Bureau of Meteorology station data and gridded products based on this observed data network will be analysed to characterise past and current climate of the Pilbara. The project will investigate the suitability of the gridded AWAP (Australian Water Availability Project) daily data on a 0.05^{o} x 0.05^{o} (~ 5 km x 5 km) grid interpolated from point measurements made by the Bureau of Meteorology (<http://www.csiro.au/awap/>).

AWAP gridded data will be assessed against the Queensland Government Department of Environment and Resource Management's SILO Data Drill previously used in CSIRO Sustainable Yields Projects. Both AWAP and SILO Data Drill provide gridded daily climate data on the same 0.05° x 0.05° (~ 5 km x 5 km) grid interpolated from point measurements made by the Bureau of Meteorology. The variables we will assess are rainfall and, for the calculation of daily Morton's wet areal evapotranspiration (APET), total daily incoming shortwave solar radiation (Rs), daily mean vapour pressure (e_a), maximum air temperature (Tmax) and minimum air temperature (Tmin).

The observations used as input to AWAP and SILO Data Drill have been quality checked by the Bureau of Meteorology and Queensland Department of Environment and Resource Management, respectively. Nevertheless, it is inevitable that errors remain in the data and the interpolation routines can introduce further errors. In general, the data accuracy is expected to be higher in areas where the observation density is high and this will be more significant in areas with higher gradients in climate variables. In the Pilbara the observation density is low but fortunately the climate gradients are also generally low with the exception of rainfall which is highly variable both in time and space. Although rainfall is more spatially variable than the other climate variables, this is offset to some extent by the generally higher density of the rainfall observation network than of other parameter observations. Assessment of the quality of the Pilbara region observational data network in terms of length of record and density of coverage will thus underpin our confidence in the suitability of the gridded data. This will include comparisons with satellite-gauge blended products (Luigi Renzullo, pers. com.) that may allow determination of how 'wrong'/different the SILO and AWAP interpolations are for sparsely gauged areas of the Pilbara and the type of events that are missed by these interpolation routines.

Initial analysis has suggested that there has been a wetting trend through the last 20 to 30 years in the inland Pilbara (Grierson et al.,) but also that the trends across the region are far from uniform either in direction or in strength. We will assess the high quality BoM climate stations (<http://www.bom.gov.au/climate/change/hqsites/>) used for the AWAP and SILO surfaces as well as the rainfall stations in the region to determine trends and establish whether there are distinct rainfall trends in time and whether these are uniform across the region. Climate models can also be used to develop an understanding of drivers of observed trends by investigating how different combinations of model forcings result in simulations with trends similar to those observed. There has been a significant research effort undertaken to understand the drivers of long-term rainfall trends in the North-West using simulations from the CSIRO Mk3.6 GCM (Rotstayn et al., 2012). Additionally, statistical downscaling – linking large-scale atmospheric processes (observed and modelled) to station rainfall – has been undertaken over a network of Pilbara rainfall stations to understand recent observed rainfall trends and their meteorological drivers.

Historical trends in tropical cyclone frequency and intensity have also been a subject of interest in recent research (predominantly within the IOCI3 projects listed above), as have analysis of trends in rainfall (IFD changes) and temperature extremes. All relevant research in these areas will be synthesised and reported upon.

2.5 Current climate scenario (Scenario A)

The AWAP gridded data, as described in Raupach et al. (2009), will provide gridded daily rainfall and variables to calculate APET series for inputs to the hydrological models. APET series will be calculated from the AWAP temperature, solar radiation and vapour pressure series using Morton's wet environment evapotranspiration algorithms (Chiew and Leahy, 2003; Morton, 1983). AWAP data commences in 1900 and is available to 2011.

As station coverage for the Pilbara region would have been limited in the early decades of last century, an initial assessment will be undertaken to determine the earliest decade with sufficient data available to start the historical period. The period selected could also be chosen to complement currently used baseline periods used in management or policy for the region, e.g. for water allocation rules. Based on data quality and trend analysis of the observed station rainfall and APET series, and on other studies such as vegetation responses to climate, a 'Scenario A' period will be selected to represent an appropriate baseline. Unless there is strong evidence of a shift in climate (e.g. as experienced in south-west WA in the mid 1970s), it is recommended that the longest period of adequate quality data be chosen as the Scenario A baseline in order to incorporate as much climate variability as possible (Chiew, et al. 2012).

Previous CSIRO Sustainable Yields projects have used a Scenario B, a subset of the Scenario A period, to represent recent observed climate. Experience shows this can lead to confusing interpretations when comparing future scenarios to multiple baselines. A decision on whether and if so how best to define and utilise a climate scenario that captures observed recent trends will be made based on the analysis of trends and discontinuities in observed station rainfall and APET series.

2.6 Future climate scenario (Scenario C)

Scaling techniques are the simplest readily available techniques that can efficiently produce projected daily rainfall and APET scenarios for all 0.05° AWAP grid cells across the Pilbara project region, thus enabling hydrological scenario development across the full project domain. One such scaling technique is the daily scaling (DS) method as used in CSIRO Sustainable Yields projects (Chiew et al., 2009). DS uses pattern scaling (Mitchell, 2003) to calculate seasonal scaling factors for the variables required to estimate APET and for rainfall, with additional daily scaling factors to account for projected changes in daily rainfall intensity (Mpelasoka and Chiew, 2009).

In previous Sustainable Yields projects, the DS scenarios were developed on a 'per degree of global warming' basis. On a seasonal and GCM grid cell basis, monthly GCM rainfall and other climate variables (as used in APET calculation) for 1870-2100 were linearly regressed against simulated global average surface air temperature to produce seasonal scaling factors as percent change in each variable per degree of global warming (degree change, not percent change, for temperature). Additionally, also on a seasonal and GCM grid cell basis, daily scaling factors for rainfall percentiles were obtained from GCM simulated daily rainfall intensity changes and also expressed as percent change per degree of global warming (Chiew et al., 2009). To produce climate change scenarios from 'per degree of global warming' DS factors, the historical series of daily climate variables were scaled by daily and seasonal scaling factors (daily for rainfall and seasonal for other variables) multiplied by selected global warming scenarios representing the range of global warming uncertainty at selected periods in the future (e.g. the range across IPCC AR4 models).

A limitation of scaling techniques, such as DS, is that they do not change the sequencing of daily events. The PWRA Methods Workshop identified this as possibly detrimental to understanding how Pilbara hydrology will respond to projected climate change, as simply scaling the historical sequences of daily rainfall and APET will not address concerns that the frequency of significant rainfall events may change under a future climate. Given these concerns, while there is a need to use a DS approach in order to provide scenarios across the full project domain, we will also investigate and apply better ways to use climate projections and take advantage of the opportunities provided by the new Coupled Model Intercomparison Project phase 5 (CMIP5; cmip-pcmdi.llnl.gov/cmip5/) GCM results. CMIP5 is currently producing the GCM projections that will be used in the IPCC Assessment Report 5 (AR5) to be completed by September 2013.

Specifically, the CMIP5 transient runs will archive daily output for the full period from 1850 to 2100; compared to CMIP3/AR4 that only archived daily output for three periods: a historical 40-year period (1961-2000), and 20-year projections for mid-century (2046-2065) and end of century (2081-2100). This will provide the opportunity to apply DS techniques to utilise the continuous simulations available from CMIP5 GCMs, by calculating scaling factors for each CMIP5 GCM according to each GCM's simulation trajectory for 2030 and 2050, rather than applying DS on a 'per degree warming' basis to notionally represent 2030 and 2050 climates. Whether we can incorporate a stochastic component to change the sequencing of events, as reflected by the changes in the GCM simulations, will also be assessed. The climate change scenarios producing the 10th, 50th and 90th percentile average rainfall change for the region as a whole will be selected as Scenario C (Cdry, Cmid and Cwet scenarios, respectively) for use in hydrological modelling. The issue of changing frequencies of events will also be addressed by using statistical downscaling, as described in the following section.

The much larger number of GCMs in CMIP5 (Table 2.1) affords the opportunity to assess GCMs based on their ability to reproduce observed climatology or trends in key variables (e.g. rainfall). The main reason to do this would be to select a sub-set of better performing GCMs and to determine whether such a selection reduces the uncertainty, i.e. range, of projected rainfall change for the study region. Thus we will undertake a rigorous assessment of CMIP5 GCM historical performance over the Pilbara region, to determine whether selecting a sub-set of GCMs that better simulate Pilbara rainfall results in a smaller range of projected change.

2.7 Statistical downscaling

Statistical downscaling research undertaken in IOCI3 for networks of Pilbara stations has provided projections of how rainfall may change at the individual station scale, for the AR4 periods mentioned above, conditional on the atmospheric changes projected by five AR4 GCMs for SRES B1, A1B and A2 scenarios (IOCI, 2012). Statistical downscaling models relate large-scale climate variables ("predictors") to regional and local, often point scale, variables such as rainfall to bridge the gap between the coarse scales simulated by global and regional climate models and finer scales required by process models (Maraun et al., 2010). Statistical downscaling using atmospheric predictors from GCMs, rather than using GCM rainfall directly, can produce more consistent multi-GCM rainfall projections because projected changes to atmospheric states can converge even when precipitation projections diverge due to inadequate or inconsistent GCM precipitation parameterisation schemes (Hewitson and Crane, 2006).

The IOCI3 statistically downscaled projections were generated using the Nonhomogeneous Hidden Markov Model (NHMM, (Charles et al., 1999) (Kirshner, 2005)) that stochastically generates synthetic time-series of multi-site daily rainfalls conditional on input atmospheric predictor series. These predictors represent the key atmospheric processes influencing daily rainfall variability, such as the position and strength of pressure systems and the degree of saturation of the lower atmosphere, with the optimum combination of predictors determined during model calibration. The NHMM generates day to day sequences of the dominant spatial patterns of rainfall over a network of stations (termed 'weather states') conditional on the selected sets of predictors.

Statistical downscaling using the NHMM has previously found relevance in several sector-specific sensitivity studies in South-west WA. In the water sector, NHMM projections of changes in rainfall patterns over key water supply catchments have been used by the Department of Water in three reports to assess water supply vulnerability to climate change (Bates et al., 2010)(Charles et al., 2007)). The NHMM has also been used in an investigation quantifying the uncertainties in projections of groundwater recharge under climate change that included the Gnangara Groundwater System as a study site (Crosbie et al., 2011). In the agriculture sector, downscaled projections have been used to assess scenarios for changes to crop yields at several locations in the WA wheatbelt (Farre and Foster, 2009).

We will apply the NHMM to CMIP5 simulations, producing transient continuous daily rainfall projections at selected Pilbara stations, and investigate whether these simulations can be adequately interpolated to the AWAP grid to be in a form suitable for comparison with the DS Scenario C results. Comparison with Scenario C results will enable assessment of changes of sequencing of rainfall events, because while the DS approach maintains the observed sequencing of rainfall events statistical downscaling does not have this limitation. Hence statistically downscaled results will be analysed to determine projected changes to frequencies and lengths of wet and dry periods, i.e. drought statistics, under projected future climates. However, a caveat is that NHMM statistical downscaling is limited in its ability to infer how extreme daily rainfall may change in the future. This is because the NHMM is formulated to use large-scale predictors (typically in the order of several GCM grid cells) that may not incorporate the 'signal' of changes to local-scale dynamics and moisture sources (i.e. sub-grid scale features such as thunderstorms or intense lows) that may result from intensification of the hydrological cycle due to a warmer climate.

2.8 Extreme climate and sub-daily rainfall projections

Research that offers the potential to quantify projected changes in daily to sub-daily rainfall extremes will be reviewed. IOCI3 research that has modelled tropical cyclones and changes to daily rainfall intensities using dynamical and statistical methods will be reviewed to extract information on possible changes in daily and sub-daily intensity-frequency-duration (IFD) characteristics for the study region. The suitability of these research findings to inform hydrological modelling of extreme events (e.g. flood modelling) will be assessed. Correct simulation of flood intensity is non-trivial as there are many influencing factors, such as precipitation spatial extent, intensity and timing and basin antecedent conditions. In addition coastal flooding involves the interaction of river flows with tides and storm surge which can combine to exacerbate flooding. A comprehensive assessment of all of these factors is outside the scope of this project.

The work undertaken in IOCI3 towards quantifying daily and sub-daily IFD changes is limited to a single GCM and one scenario (IOCI, 2012). This means that the results will not represent the range of possible changes and hence will only be indicative. Research estimating climate change impacts on daily and sub-daily IFD changes is a complex and rapidly developing field and as such there are no 'off the shelf' methods of sufficient rigour available for implementation in this project. A recent research plan developed for Australian Rainfall and Runoff outlines a proposed four-year research initiative to develop methods and produce estimates of IFD curves for future climates using high resolution RCMs and advanced statistical techniques. The northwest of Western Australia is one of the proposed study regions for phase 2 of the project, potentially commencing in 2013/14. This research will involve dynamical (RCM) and statistical modelling of rainfall extremes for current and projected climates, in order to assess the impact of global warming on extremes, far beyond the capacity of anything we could attempt. It would be premature for the PWRA project to pre-empt the findings of such projects and attempt ad-hoc development of IFD scenarios, particularly given the limited resources and expertise available within the PWRA project. Thus continued dialogue with the relevant researchers (external to this project) is recommended to determine whether their results will be available in time to guide sensitivity analysis in this project's hydrological modelling.

2.9 Summary

Given the limited extent of the climate activity, it is important to make clear what will be delivered. So, to summarise, climate deliverables will be limited to the following:

- A report reviewing the state of current knowledge on historical hydroclimate trends in the Pilbara.
- Scenario A: baseline daily rainfall and APET gridded AWAP series (for period to be determined).
- Scenario B: a sub-set of Scenario A to represent a period with climate different to that of the full Scenario A period, if judged more representative of current conditions.
- Scenario C: For 2030 and 2050, Cdry, Cmid and Cwet scaled versions of Scenario A series representing the 10th, 50th and 90th percentile average rainfall change across the range of selected CMIP5 projections.
- Statistically downscaled station projections of rainfall produced by driving the NHMM with the same GCMs used to produce the Scenario C series.
- A final climate report summarising the projections in the context of current trends, and assessment of limitations and caveats.

2.10 Glossary

Climate model (spectrum or hierarchy)

A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.

Climate projection

A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate

projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Downscaling

Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Table 2.1 CMIP5 global climate models and institutions

GLOBAL CLIMATE MODEL	INSTITUTION	INSTITITION ID
ACCESS1.0 ACCESS1.3	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM
BCC-CSM1.1 BCC-CSM1.1(m)	Beijing Climate Center, China Meteorological Administration	BCC
BESM OA2.3	Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research)	INPE
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University	GCESS
CanESM2 CanCM4 CanAM4	Canadian Centre for Climate Modelling and Analysis	CCCMA
CCSM4(RSMAS)	University of Miami - RSMAS	RSMAS
CCSM4	National Center for Atmospheric Research	NCAR
CESM1(BGC) CESM1(CAM5) CESM1(CAM5.1,FV2) CESM1(FASTCHEM) CESM1(WACCM)	Community Earth System Model Contributors	NSF-DOE-NCAR
CFSv2-2011	National Centers for Environmental Prediction	NCEP
CMCC-CESM CMCC-CM CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC
CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
EC-EARTH	EC-EARTH consortium	EC-EARTH
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University	LASG-CESS
FGOALS-gl FGOALS-s2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP
FIO-ESM	The First Institute of Oceanography, SOA, China	FIO
GEOS-5	NASA Global Modeling and Assimilation Office	NASA GMAO
GFDL-CM2.1 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GFDL-HIRAM-C180 GFDL-HIRAM-C360	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
GISS-E2-H	NASA Goddard Institute for Space Studies	NASA GISS

GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC GISS-E2CS-H GISS-E2CS-R		
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA
HadCM3 HadCM3Q HadGEM2-CC HadGEM2-ES HadGEM2-A	Met Office Hadley Centre	MOHC
HiGEM1.2	Natural and Environmental Research Council/Met Office Hadley Centre	undeclared
INM-CM4	Institute for Numerical Mathematics	INM
IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	Institut Pierre-Simon Laplace	IPSL
MIROC-ESM MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC
MIROC4h MIROC4m MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
MPI-ESM-HR MPI-ESM-MR MPI-ESM-LR MPI-ESM-P	Max Planck Institute for Meteorology	MPI-M
MRI-AGCM3.2H MRI-AGCM3.2S MRI-CGCM3 MRI-ESM1	Meteorological Research Institute	MRI
NICAM.09	Nonhydrostatic Icosahedral Atmospheric Model Group	NICAM
NorESM1-M NorESM1-ME	Norwegian Climate Centre	NCC

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3 Surface water modelling

3.1 Introduction

The surface water modelling for the Pilbara Water Resource Assessment project deals with runoff and flood estimation in the five river basins in the region which includes rainfall-runoff, river and floodplain inundation modelling. Tropical cyclone events are the main causes of floods and contribute to major streamflow and groundwater recharge to aquifers surrounding the rivers (URS, 2008) in the Pilbara region (Figure 3.1). The average annual rainfall in the region ranges from 200 to 350 mm.

The objectives are:

1. to characterise the rainfall-runoff and streamflow characteristics of the Pilbara region under the historical climate,
2. to estimate and characterise likely changes in streamflow quantity, frequency and duration across the five river basins under historical, recent and future climates, accounting for possible changes in mining discharge to streams, and
3. to determine changes in these characteristics and periodic alluvial aquifer recharge relative to a baseline based on the historical dataset to support assessments of possible changes affecting water dependent ecosystems.

Catchment and river system modelling will be done in these catchments and flood plains to account for the flood propagation and estimate streamflow at defined catchment outflow points and along the river systems from the headwaters to the basin outlet. In some cases it does not occur, such as outflow from the Fortescue Marsh in the Fortescue River and from Ophthalmia Dam in the upper Fortescue Basin. The Harding Dam, in the Port Hedland Coast Basin, however can overflow during major rainfall events. The method will also account for floodplain flows and the ensuing recharge to riverine and adjacent aquifers. The methods used in this project are developments of those used in the earlier South-West Western Australia Sustainable Yields, the Northern Australia Sustainable Yields, Tasmania Sustainable Yields projects, as well as the current Flinders and Gilbert Agricultural Resource Assessment (CSIRO, 2010).

Specifically, the surface water modelling will be done to estimate runoff, streamflow and flood for base line conditions using historical climate and for conditions given by future climates representative of 2030 and 2050 in defined catchments. The following four climate scenarios are envisaged:

- historical climate (dates to be determined from climate analysis) and current development (Scenario A) – one single simulation based on the historical climate series
- if the climate analysis suggests this is required[1], a recent climate (dates to be determined) and current development and/or a possible 'previous' climate with current development
- future (~2030 and ~2050) climate and current development (Scenario C) – climate series (rainfall and APET) based on 15 GCMs for each of the low, medium and high global warming scenarios (from Climate Section) corresponding to wet, medium and dry climate sequences.
- future (~2030 and 2050) climate and future development (Scenario D) – three simulations based on selected climate sequences from Scenario C above and modifying the catchment inflows estimated in Scenario C to reflect ~2030 and 2050 developments in the Pilbara region. The 'developments' will be estimated mine dewatering discharge to streams, based on available or future mine development. As these will be largely unknown, low-, medium- and high-development scenarios will be modelled.

[1] Early analysis of climate trends suggests this will not be required

Scenario A simulations are the baseline against which all other simulations will be compared. The relative changes between modelled catchment streamflow under Scenario A and the other scenarios are used to assess the impacts of the changed climate and developments.

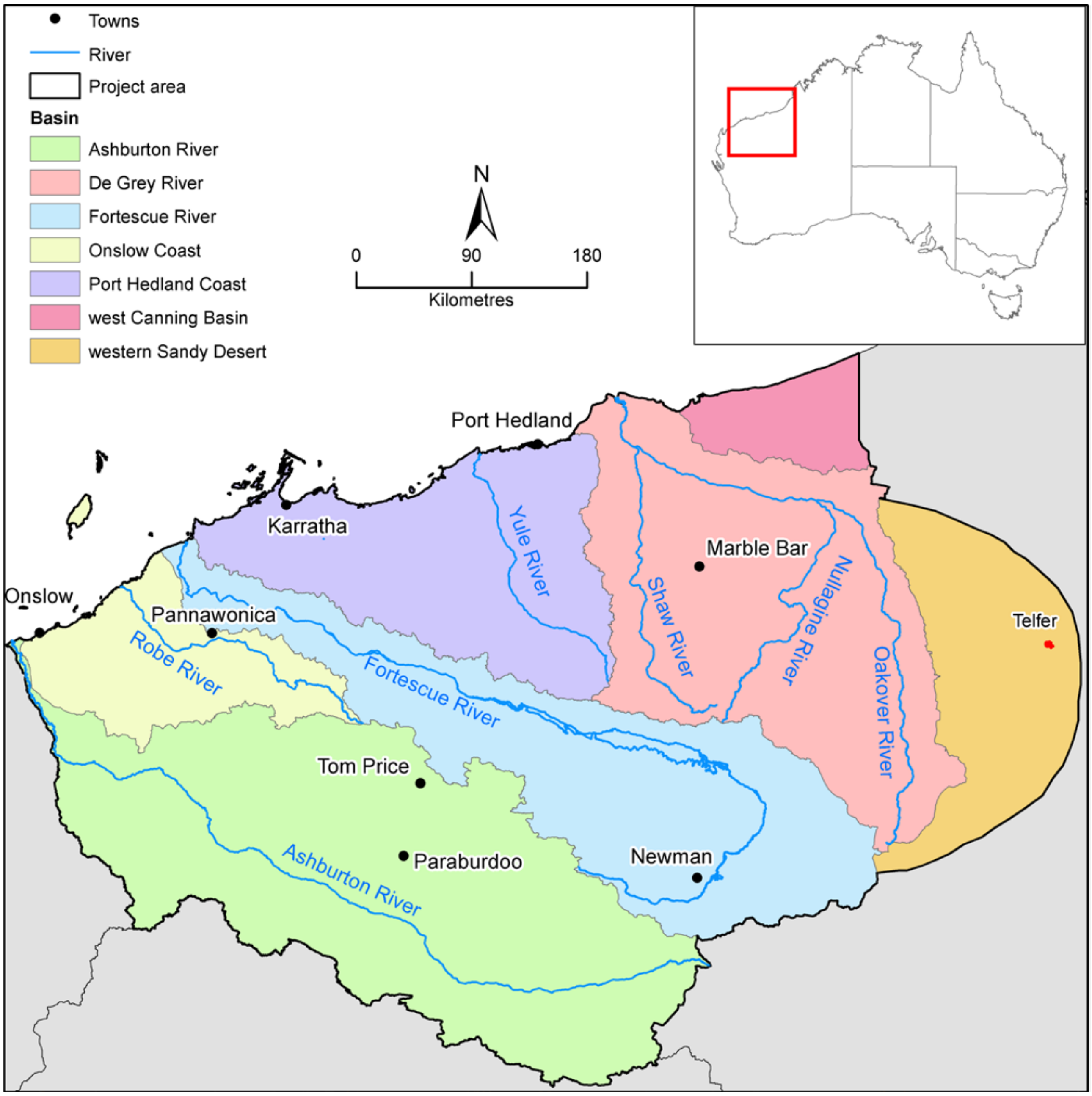

Figure 3.1 The five basins across which runoff and streamflow will be assessed

General Approach

The Pilbara lies in the dry interior of Western Australia at subtropical latitudes. The hydrology of the Pilbara is governed by those two factors and is marked by the domination of infrequent high intensity rainfall events comprising most of the average annual rainfall, and long dry periods with high potential evaporation rates. The intense events are the main cause of river flow in an otherwise dry region. The runoff generation of rainfall falling in less intense events is less clear. Therefore the initial focus of the project is to investigate the long term relationship between rainfall and runoff before adopting a modelling approach for the region. The Pilbara surface water modelling task will be done in three main steps:

4. Comprehensive analysis of rainfall and streamflow data, to characterise Pilbara river response to rainfall, assess climate and streamflow trends and develop an appropriate rainfall-runoff and streamflow modelling strategy for the project.

5. Based on the results of the data analysis and advice from the Technical Advisory Group, undertake catchment rainfall-runoff modelling at a regional scale
6. River system and floodplain modelling including flood propagation and flood inundation
7. Assess changes to flood frequency and wetland inundation projected as a result of future climate and mine dewatering trends

These steps will be carried out together with a range of associated tasks such as selection of gauging stations and climate data preparation. Data preparation includes analysis of data for their consistency with each other, identifying and treatment of any inconsistent, suspicious or missing data.

3.1.1 ANALYSIS OF HISTORICAL RAINFALL AND STREAMFLOW DATA

Because of the temporal and spatial sparseness of data the characteristics of flow and runoff at catchment scale are not clear. A comprehensive data analysis at daily (and if possible sub-daily), monthly and annual time scales will be undertaken to understand the characteristics of Pilbara streamflow generation and flood events. All available rainfall and streamflow data will be analysed to determine major response characteristics of the streamflow generation that occurs from local intense storms and from widespread regional climatic systems. Trends will be assessed for any seasonally specific mechanisms that need characterisation. Trends in rainfall, runoff and the rainfall-runoff relationship will be assessed. The modelling approach will be developed based on the results of this data analysis.

Development of spatial and temporal rainfall sequences

Early analysis of rainfall statistics (Fu *et al.*) indicates that rainfall trends are consistent across much of the study region and that the gridded DataDrill data from SILO are probably adequate for the modelling at daily timescales. However, if sub-daily timescales are required the satellite based blended rainfall products developed by the BoM and CSIRO under the WIRADA (Luigi Renzullo, CLW Canberra) will be assessed for use in the modelling. The surfaces used in previous similar projects may not meet the requirements and this will be assessed in combination with the project Climate Team (Charles *et al*.).

3.1.2 SELECT, ADAPT OR DEVELOP A RAINFALL RUNOFF MODEL

On the basis of the analysis and suitability of available data, the models used in previous CSIRO Resources Assessment projects (notably the Flinders and Gilbert Agricultural Resource Assessment, and Northern Australia Sustainable Yields and South-West Western Australia Sustainable Yields projects) will be assessed and adapted if necessary, or alternatives used. An eWater toolkit “Source”-style model (link-node with losses and other considerations) may provide the river system modelling linked to the adapted rainfall-runoff model or models. The rainfall runoff models are discussed in Appendix B.

3.1.3 RIVER FLOW AND FLOOD MODELLING

River modelling

The objective of the river modelling is to assess the effects of different river-related fluxes (such as extraction and addition) on river flows and to propagate these flows downstream where they may impact on floodplains, ecosystems and aquifers. River system models encapsulate descriptions of current infrastructure, water demands and water management and can be used to assess the implications of the changes in inflows described in the rainfall-runoff section on the reliability of streamflow. A number of river system models are available such as MIKE-BASIN (DHI, 2003), RiverWare (Zagona et al., 1998, 2001), IQQM (Simons et al. 1996), REALM (Perera et al. 2005) and MSM-Bigmod (Close and Sharma 2003). Recently the eWater Cooperative Research Centre (CRC) has developed a new integrated river system modelling software called ‘Source’ in collaboration with several of its research and industry partners to assist in decision making for operations of regulated river systems (Welsh et al. 2012). Source encompasses and enhances the key functionalities of the three widely used river system modelling tools in Australia: IQQM, REALM and MSM-Bigmod. It also incorporates several new components such as a suite of rainfall-runoff models, environmental and urban demand models. The key attributes that Source offers are an integrated package of calibratable runoff models with the river flows and automated optimization tools for calibration of catchment rainfall-runoff and river routing parameters.

Floodplain modelling

Most rivers of Pilbara are susceptible to irregular flooding due to tropical cyclones. Flooding can damage infrastructure and cause erosion and deposition. However, flooding also recharges the floodplains and allows off-stream wetlands to be connected to the main river channel. Both of those are vital to help sustain groundwater dependent ecosystems. The biodiversity found in floodplain systems in Australia are thought to be largely dependent upon the periodic floods that facilitates biophysical exchanges between the main channel and wetlands. Satellite based products (notably from MODIS and AVHRR) are available that indicate flooding and these will be included in the analysis to estimate the extent, frequency and persistence of flooding in the region, and assist the modelling and parameter estimation.

The Hydrologic Engineering Centers River Analysis System (HEC-RAS) hydrodynamic model will be used to simulate flood propagation and floodplain inundation under current and future climate and development scenarios. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full river network of natural and constructed channels including mixed flow regimes (USACE, 2002). HEC-RAS is most suitable for the task for a number of reasons: (i) it is suitable for simulating 1D flood wave propagation and associated flood inundation along the floodplains (need to be defined as extended cross-sections); (ii) it has a smaller run time than 2D models; and (iii) it is widely used and is available free of charge.

Preparation of contextual information

The contextual information relating to surface water resources, status of the resources, mine dewatering discharge and other land uses and water allocation and other key datasets is a prerequisite to the interpretation of the surface water assessment and modelling results.

Data assembly

1. Reports will be sourced from the following Western Australian agencies: DoW, Water Corporation, MRWA, Department of Agriculture and Food and other relevant agencies and mining companies on the hydrology of the catchments, water extraction and discharge data. These will provide the summary description of the hydrological setting, and trends in water management and flow statistics, and the basis on which projections of surface water management changes to 2050 will be made.
2. Based on the advice from DoW, explicit accounting for groundwater–surface water interactions is required only for selected areas. Furthermore, as the recharge of alluvial aquifers occurs during major flow events, the magnitude and frequency of this occurrence is also important.

3.2 Surface water modelling procedure

3.2.1 CATCHMENT SELECTION

Catchments from the five basins considered in the assessment (Table 3.11, Figure 3.1) will be selected for specific reporting. These catchments will be a mix of gauged and ungauged catchments. The results of surface modelling will be reported along with the groundwater and environment analyses in separate reports for each basin as defined in Chapter 6. The gauged catchments will be used to calibrate the rainfall-runoff models. Catchments will be selected that have at least 10 years of recent, good quality and continuous streamflow record.

The ungauged catchments will be selected based on where the flow records are required for surface water and groundwater based on environmental and other demands. Nodes from gauges and ungauged catchments for which streamflow values are reported are termed the ‘streamflow reporting nodes’ (SRNs). The SRNs are the locations at which flow estimates are required which can be either water supply dams, locations for ecological water requirement (EWR) calculations, outlets at the downstream end of each river basin, or gauged points used in the calibration process.

Table 3.1 List of river basins and Australian Water Resources Council code numbers

AWRC ID	Basin	Area (km^2)
706	Ashburton	77,040
707	Onslow Coast	17,560
708	Fortescue	47,920
709	Port Hedland Coast	35,190
710	De Grey	56,890
	Total	**234,600**

Input data

The historical daily rainfall and meteorological data required to calculate potential evaporation (APET) to drive the models is expected to be obtained from the Queensland Government Environmental Protection Agency SILO gridded data (Data Drill) (<http://www.longpaddock.qld.gov.au/silo>; (Jeffrey et al., 2001)). This provides gridded daily rainfall and other climate data interpolated from point measurements made by the Australian Bureau of Meteorology. APET is defined as the evaporation that would take place if there were unlimited water supply from a large area that has come to equilibrium with conditions in the overlying air. APET is calculated from the SILO daily climate surfaces using Morton’s wet environment evapotranspiration algorithms (Charles et al., 2010). The variables for the calculation of APET are incoming shortwave solar radiation, vapour pressure, maximum air temperature and minimum air temperature. In addition to rainfall and potential evaporation, LUCICAT and LASCAM also require land use data which may vary with time. One of the first tasks will be, undertaken with the Climate Team (see Chapter 2), to analyse the historical rainfall from recording stations for temporal trends and spatial variability. These data will be compared with the DataDrill data to check for inconsistencies in areas with sparse station density.

There is a general paucity of streamflow gauging stations in the region with only about 23 stations having up to date (to 2011) streamflow data as listed in the DoW Water Resources Information Catalogue (Table 3.2). The average data length is 31 years (median 36 years) with more than three quarters of the stations starting before 1985. Although the good quality data from the discontinued gauging will also be used in calibration to help obtain parameter values from observed data for as many catchments as possible, the lack of data will limit the number of SRNs for which projected flow data will be reported.

The quality of flow data for stations listed in Table 3.2 and other discontinued stations will be assessed in consultation with regional hydrographers responsible the collection, quality control and storage of those data.

Table 3.2 Gauged catchments with flow data up to present

AWRC ID	Catchment Gauging Station	Start
706003	Ashburton at Nanutarra	1972
706209	Ashburton at Capricorn Range	1968
707005	Cane River at Toolunga	1986
707002	Robe River at Yarraloula	1972
708001	Marillana Creek at Flat Rocks	1967
708002	Fortescue River at Gregory Rock	1968
702005	Fortescue River at Deep Reach	1972
708011	Fortescue River at Newman	1980
708012	Ophthalmia Dam at Mt. Newman	1981
708013	Weeli Wolli Creek at Waterloo Bore	1984
708014	Weeli Wolli Creek at Tarina	1985
709004	Maitland River - Miaree Pool	1972
709005	Yule River - Jelliabindina Well	1972
709008	Sherlock River at Sherlock River Bridge	1976
709010	Turner River at Pincunah	1985
710003	De Grey River at Coolenar Pool	1974
710004	Nallagine River at Nullagine	1997
710005	Oakover River at Ripon Hills Road	2001
710006	Coongan River at Marbal Bar Rd Crossing	2001
710007	Shaw River at Marble Bar Rd Crossing	2001
710008	Nullagine River at Tumbinna Pool	2002
710204	Coongan River at Marbal Bar	1966
710229	Shaw River at North Pole Mine	1967

3.2.2 MODEL CALIBRATION AND PARAMETER ESTIMATION

Model calibration

All hydrological models need calibration for a variety of reasons which involves selecting and adjusting model parameter values so that the model results agree with observed data to user-specified criteria. Manual or automatic calibration methods can be used (see below). The model calibration helps estimate the model parameters which are then used for scenario modelling using future climate series. All models will be calibrated against observed streamflow data, as hydrographs, as flow frequency distributions and/or flooding extent and duration. Since the length of streamflow records varies from catchment to catchment, the calibrations made using all available data for each catchment can result in the catchments being calibrated for non-concurrent periods. From the five basins in the project area, there are 23 gauged catchments to calibrate the models. Calibrations may be checked against non-WIN data where it can be collated (e.g. mining company records in accession reports). In addition, satellite derived flooding extent will be assessed for use.

Since the number of stations and length of record with observed streamflow in the Pilbara region are limited, it is proposed that all the available streamflow data is used for calibration to obtain a better estimate of parameter values. A 15-year warm-up period will be used prior to calibration and for all simulations to ensure initial conditions are not a factor in the model output. The calibration period is a compromise between a recent shorter period that would better represent current conditions and climate, and a longer period that would better account for climate variability. Streamflow in some of these catchments may include the effects of historical mine water discharges at some stage during the calibration period, but impacts of these in most cases will be minor relative to total streamflow and may be ignored in the regional assessment of runoff. It is assumed that the average impact of these activities will be included in the optimised parameter values. However if such discharge are high then discharge record would be sought to be incorporated in the calibration.

Calibration objective function

The rainfall-runoff models will be optimised using an automated optimiser (described in the following section) to maximise an objective function that incorporates the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) of daily, monthly or annual runoff together, the flow frequency distribution and the constraint that the total modelled runoff over the calibration period was within 10 percent of the total observed runoff (Silberstein et al., 2010).

NSE is a common measure in water resource modelling and is calculated as:

$$NSE = 1 - \frac{\Sigma\left(Q_O - Q_A\right)^2}{\Sigma\left(Q_O - \bar{Q}_O\right)^2}$$

where Q_O is the observed flow, $\bar{Q}_O$ is the mean of the observed flow and Q_A is the flow simulated by the model.

The NSE is an estimate of the variance in model error between simulated and observed data. Values can vary from $-\infty$ to 1, with 1 indicating a perfect fit and a value of zero indicating that the model is no better than assuming an average flow over the period. A negative NSE value implies a bad prediction which is hard to interpret, and is worse than simply assuming a fixed average flow. An undue influence of high flows can be an issue with this indicator; however the NSE is a reliable statistic for assessing the goodness of fit of hydrological models and is recommended for a variety of model types (ASCE, 1993; McCuen et al., 2006).

To improve the low flow and dry season flow calibrations, several alternative objective functions may be trialled in this project as needed and the ‘best’ overall set (i.e. wet season and dry season flow NSE measures) of model parameters selected for each calibration catchment. Through this process large improvements were made to the dry season and low flow NSE measures in the Northern Australia Sustainable Yields Project while only marginally sacrificing the wet season flow NSE measures. The team on the Northern Australia Sustainable Yields Project recommended the use of an appropriate objective function that encompasses both wet season and dry season flow objectives. This will be explored in the initial model testing phase.

Automatic optimisation

All models used in this project are amenable to automatic calibration for optimising the parameter values. The parameter set from the optimisation algorithm that gives the highest objective function value for each model will be chosen to run scenario modelling. Advances in computational resources have enabled the global optimum to be determined in a prescribed objective function by evaluating the response surface of the objective function (Duan et al., 1992). Model calibration in this project uses three optimisation algorithms followed by the Rosenbrock local optimisation:

- genetic
- shuffle complex evolution
- uniform random sampling.

The Source software includes automated optimisation of parameters and this will be complemented by the Differential Evolution Adaptive Metropolis (DREAM) method parameter estimation techniques (Vrugt et al., 2009) based on Monte-Carlo Markov Chain and genetic algorithms.

Selection of models for scenario modelling

Each model will be assessed for its ability to reproduce observed streamflow total and frequency distributions, based on the objective function score, to decide which models and calibration methods are to be used in the scenario simulations (Viney et al., 2005). Prior experience has shown that no model and no optimisation method gives universally the best calibration for all catchments. For each catchment, the model will be selected by using a comparison of combinations of model output with the calibration data and the best representation of observed flows will be used as the representative 'adopted model'.

Parameter estimation in ungauged catchments

The model parameter values are determined by the input climate and catchment characteristics on which they are calibrated. The calibrated parameter values of a catchment should not be transposed to other catchments without the reliability of the transposition being assessed. Since there is no proven method to adjust these parameters to other catchments, the streamflow for the uncalibrated catchments will be simulated using model parameters from calibrated catchments. In a series of sustainable yields projects the parameters were transferred to non-calibrated catchments based on the nearest neighbour to the calibrated catchments criterion (SKM, 2008; Silberstein et al., 2010). A comparison between the results generated using the similarity mapping and using the nearest neighbour parameter transfers found that the nearest neighbour transfer did better in more catchments than the similarity approach (Aryal and Silberstein, 2012). Further, in the Northern Australia Sustainable Yields Project it was found that where low flow metrics are required, regression approaches may be better employed. It is possible that catchment similarity approaches may be more appropriate for regionalising model parameters in northern Australia. This depends on the availability of suitable spatial data at an appropriate scale for the derivation of explanatory catchment attributes. The nearest neighbour and multiple donor catchment approaches will be tested for transposing model parameters to ungauged catchments for high flow estimates and for low flow estimates in northern Australia.

Scenario Modelling

All models will be used in predictive mode from July 2012 to estimating future surface water flows for the next 50 years of the scenarios, with results reported as representative of 2030 and 2050 conditions for all scenarios. Simulations will start before the start of the calibration period using the historical climate sequence to achieve the required 'spin up' prior to the first day of the simulation period, which, in the case of the 'historical' scenario (Scenario A) continues with the same climate sequence repeated. The reported catchment flows will be the ensemble model that best matches the observed streamflow as determined by maximising the objective function. The modelled daily runoff is assembled for the 'adopted model' and daily and mean annual flow statistics determined for all catchments for all scenarios. For each of the sequences, the daily modelled runoff for the 0.05º x 0.05º grid cells will be aggregated to obtain modelled streamflow for all catchments. The catchment runoff from all scenarios will be input to the river systems model.

Rainfall-runoff modelling for climate and development scenarios

Scenario A

As described in earlier chapters, results under Scenario A form the baseline against which the other results are compared to assess the impacts of climate variability and future climate and development on runoff. The modelled flow in all catchments using historical climate data will determine daily flows in all catchments.

As discussed in the climate chapter, rainfall in the Pilbara Region has shown drying and wetting trends through the last 80 years, with these trends varying in time and location. Although generally in north-western Australia the current trend is a wetting one, there is a forecast of a drying trend starting within the next 50 years (Cai et al., 2011). The available data will be analysed to determine the strength and direction of historical rainfall trends and on the basis of this analysis the scenario definition may be revised.

There is not expected to be a need for an intermediate scenario of recent climate that has been included in other similar projects, referred to as Scenario B, but the scenario labelling terminology has been kept common with those other projects for clarity for readers of previous reports.

Scenario C

1. For each of the catchments, each of the models will be run using the daily climate series for Scenario C (~2030 and 2050 climate scenarios, obtained from Section 1.6.3). This provides for each of the low, medium and high global warming scenarios.
2. For each of the low, medium and high global warming scenarios, the total annual runoff over the region modelled that gives the 2nd wettest of the low warming, the median of the medium warming and 2nd driest of the high global warming scenarios respectively is determined. These flows of the whole ensemble of results will be reported as the dry, median and wet (Cwet, Cmid, Cdry) future climate scenario runs. The order of wettest to driest scenario will be determined on the basis of average annual total rainfall of each scenario.

Scenario D

This task will report the combined effects of future water discharges and abstractions in addition to future climate scenarios on streamflows determined from Scenario C. The method is to modify the daily catchment flow time series for Cmid with low, medium and high development scenarios to reflect future (~2030 and 2050) diversions and discharges.

The results will be reported as the difference between these scenarios and Scenario A which gives changes to the catchment flow regimes and available resources due to future climate.

3.2.3 RIVER SYSTEM AND FLOODPLAIN MODELLING

River system modelling

The objectives of the river system modelling are:

- To simulate entire river systems under current and future climate and development scenarios. Where supporting data are available these models can account for sub-catchment runoff, extractions, diversions, storages, floodplain inundation, transmission losses, simple groundwater-surface water interactions and complex management, allocation and environmental flow rules; and
- To provide a high level assessment of the relative inputs of climate variability, climate change and dewatering discharges into river flows at different times of the year and in different parts of the Pilbara.

Figure 3.2 shows a schematic of a river network setup in Source for river system modelling. Inflow from the catchment can be either through the simple models (see Appendix B) that are built-into Source or as inflow data derived from those models calibrated separately. The flow is then routed through the channel and reservoirs. These can be done using simple linear or non-linear river routing and reservoir routing algorithms.

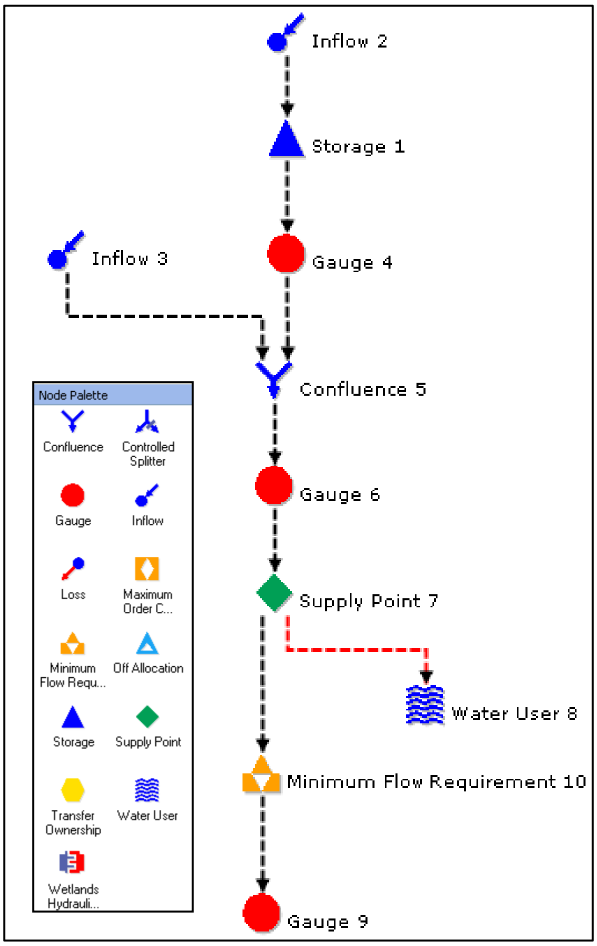

Figure 3.2 A schematic of a simple river network prepared in Source for river system modelling

With the exception of Ophthalmia and Harding dams there are no substantial diversions affecting end-of-system flows. However changes to the river flow regime due to local development or climate change may be locally important. For example, stream water may have been used for dust suppression or other activities. Therefore river system modelling will be carried out to determine effects of flow extraction, disposal of mine-water to the river, together with routing of river flow to determine attenuation and translation of flow peaks. Based on the need, appropriateness and availability of resources and data, one or more river system models will be selected for different basins. The inflow generated from rainfall runoff models will be used in the river system model.

In the Northern Australia Sustainable Yields Project, six river system models were used; a MIKE-BASIN model for the lower Ord River catchment, a simple single node reservoir model for the Darwin River Dam, and IQQM for the Leichhardt, Flinders, Gilbert and Mitchell river catchments. In those regions where information on infrastructure, water demand, water management or future development were not provided no river modelling assessment was undertaken. It is envisaged that a similar approach will be adopted in this project.

In the region, there are generally few suitable gauging stations in series to validate results of flow routing; therefore modelled ensemble runoff (see for example, Petheram et al. 2009a) will be used directly to determine streamflow at each SRN, and satellite imagery will be investigated for use in flood monitoring to complement the gauge data.

Where suitable gauging stations exist, streamflow will be modelled at that station using the ensemble results from the selected best models results and fed into river system models. Where a SRN does not coincide with a suitable gauging station, a runoff time series will be generated by aggregating the runoff values between the SRN and any upstream gauging stations.

All the rivers examined in the Northern Australia Sustainable Yields Project were gaining rivers, that is, their mean annual flow increased towards the coast and was highest at the end-of-system. This may not be the case in the Pilbara, and appropriate decisions will need to be taken accordingly.

Floodplain Modelling

Figure 3.2 shows a map of the Pilbara region with assessed inland flood hazard. De Grey, Yule, Fortescue and Ashburton River catchments contain areas of extreme and high flood hazard. Most notably the flood hazard covers larger areas upstream of Fortescue River around Fortescu Marsh and lower and coastal regions of Asburton, Robe, De Grey and Yule Rivers. Detailed topographic data of the flood prone areas (e.g. from LiDAR) will be sought from Landgate and other agencies including the 1” (~30 m) hydrologically enforced DEM data available from Geoscience Australia at:
<https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=72759>.

Where supporting data are available the HEC-RAS model can account for sub-catchment runoff, extractions, diversions and floodplain inundation along the river system. The simulated inflow from rainfall-runoff models for gauged and ungauged catchments can be used as lateral inflow for flood modelling using HEC-RAS.

The objectives of the floodplain modelling are to:

- provide an estimation of flood propagation and inundation to help evaluate local recharge mechanisms (losing streams and/or overbank flooding), frequencies and rates for alluvial aquifers under different climate regimes and estimate recharge to, and discharge from, aquifers from river beds and floodplains;
- supply flood inundation data for the recharge and discharge from river beds and floodplains for groundwater modelling. This can provide insights into recharge mechanisms and frequencies for alluvial aquifers under different rainfall regimes;
- provide data for assessing the separate and combined impacts of climate and development on water dependent ecosystems.
- quantify the hydrological connectivity (extent, timing and duration) of the main river channels to off-stream wetlands and assess how this connectivity may change as a result of changes to flow regimes; and

A finer scale topographic map is required to achieve some of the above objectives. For results to be transferred to the broader region a regionalisation of results, based on a coarser scale topographic data, may be needed.

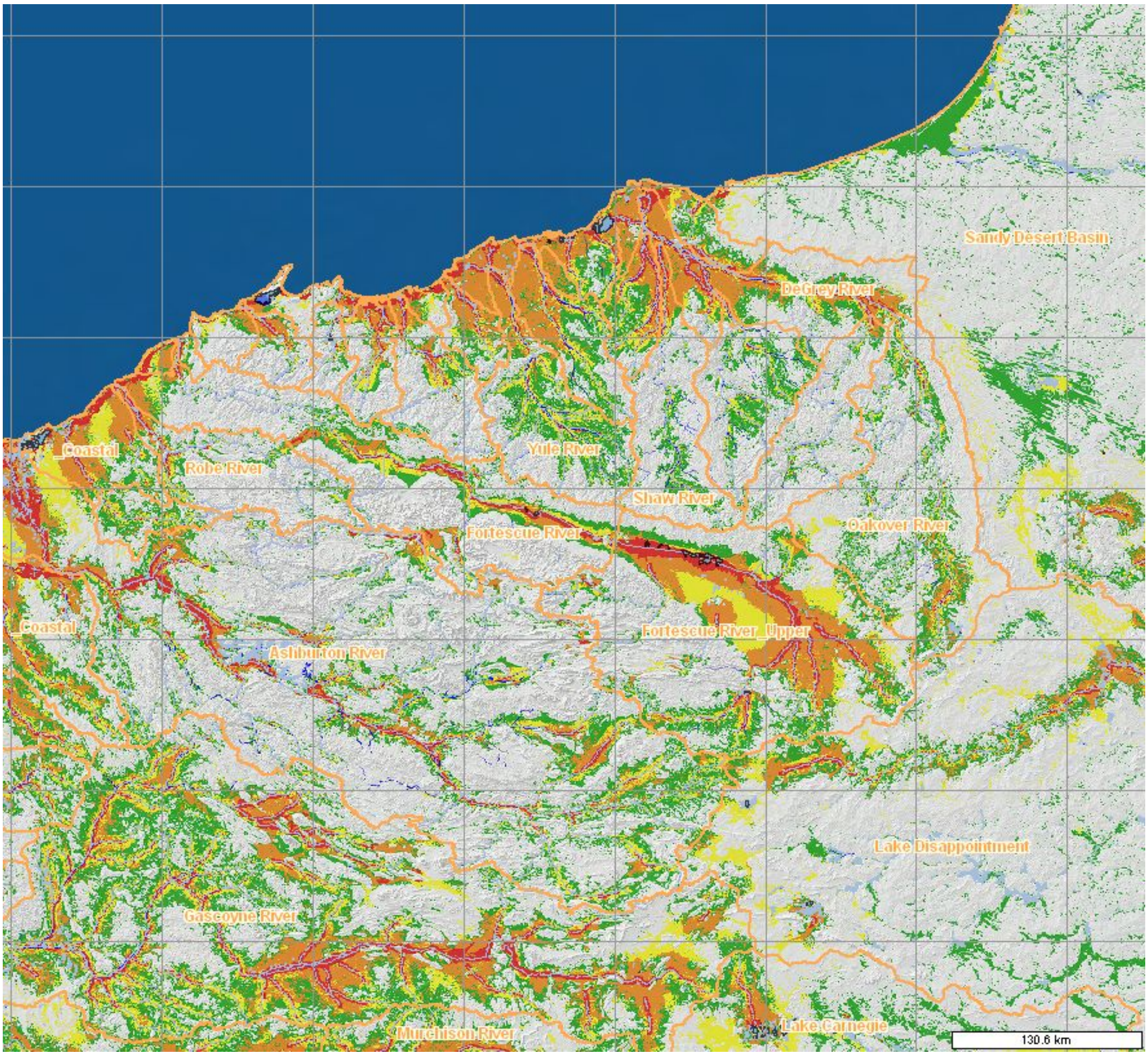

Figure 3.3 Map of Pilbara Region showing extreme (red), high (orange), moderate (yellow) and green (low) inland flood hazards (Source: floodmap.dli.wa.gov.au/landgate_floodmap_public.asp)

Flood modelling at a sub-daily time-scale

Most floods in rivers of Pilbara region are caused by intense tropical cyclonic activities and subtropical storms where a large quantity of rainfall can occur in a short duration. There may be a need for modelling the catchments at sub-daily time intervals to account for the rapid rise of floods. The simulation of cyclones and similar intense systems is notoriously difficult and there is no conclusive analysis on whether these are changing frequency or intensity in any systematic way. Changes to the frequency or intensity of rainfall projected by the GCMs will be captured in the future climate scenarios through the scaling process as discussed in Chapter 2, and hence will contribute to the future flood projections. Unless significant progress is made in intensity-frequency-duration (IFD) projections, the same scaling approach will be applied to historical sub-daily data to drive the future runoff projections using overland flow routing (Henderson and Wooding 1964) or RORB runoff routing software. RORB is freely available in the public domain for download <http://eng.monash.edu.au/civil/research/centres/water/rorb/>. Observed data from gauged stations will be used to calibrate the RORB model and its parameter will be regionalised to determine flow from other ungauged catchments.

3.2.4 LOWFLOW ANALYSIS

Frequency and duration of extended low flows

While the main focus of this report will be on the total runoff generation, flooding and the impact on water resources, changing climate also has implications for the intermittency of streams, with consequences for extended low flows (droughts) and low flow years. The extended low flows can have devastating effects on water dependent ecosystems as well as on town, port and mine water supplies. It can also affect the top soil condition and the microclimate. It is envisaged that under some climate scenarios all regions may show an increased number of days of low or zero flows. Frequencies of high and low flows will be reported for the baseline and a range of future climate change scenarios. For the purpose of this project, drought period may be defined as a number of consecutive years of below long term average flow or the lowest consecutive-year flows. Statistics that relate best to recharge of alluvial aquifers and/or the rejuvenation of river pools may be developed and reported in the assessment if they can be sufficiently well defined.

3.2.5 ANALYSIS AND PRESENTATION OF RESULTS

Aggregation of results

Modelled streamflows will be obtained by aggregating calculated runoff for all sub-catchments within each catchments multiplied by the appropriate catchment area to streamflow reporting nodes (SRNs) and input to the river models. The results will be presented in summary reports for each region that will include all surface water, groundwater and environmental results. For each catchment and each basin the following will be reported:

1. Hydrological Data Analysis:

   a. ***Rainfall and APET characteristics:*** Spatial and temporal plots of mean annual and seasonal rainfall and APET across the project area.
   b. ***Runoff characteristics:*** Spread and distribution of observed runoff in catchments by the way of box and scatter plots; area versus runoff plots and main runoff data statistics.

2. Modelling Results

A detailed report of model calibration performances based on daily, monthly and yearly flows. The following will be shown:

a. scatter plots of observed and modelled flows;
b. distribution of NSEs across the basin; and
c. residual curves showing the differences in observed and modelled runoffs.

3. Scenario Modelling Results

Key findings including changes in runoff and streamflow behaviour for all climate scenarios relative to the baseline Scenario A. These will be presented for all scenarios as:

a. daily, monthly and yearly flow duration curves;
b. average monthly flow under all scenarios;
c. spatial and temporal distribution of mean annual runoff across the project area;
d. low flow and ‘no flow’ analyses under future climate;
e. changes to flooding extent and duration
f. impact of future climate on dams; and
g. summary and discussion of the findings.

4. Report on Knowledge and Information Gap

A section on knowledge and information gaps will be presented and ways to address those will be discussed. This will discuss ways to improve the hydrological knowledge of the basin by further data collection. Advice on how additional climate, surface water gauging, groundwater monitoring and remote sensing may assist water resource assessment and management in the Pilbara will be provided. Suggestions will be provided for the installation of additional gauging and climate stations at different strategic locations.

3.2.6 MODEL PERFORMANCE ASSESSMENT

Surface water statistics

The surface water modelling results will be reported through the following output indicators of streamflows in each region:

- annual average flows;
- daily and annual flow frequency distribution;
- variability calculated as coefficient of variation; and
- daily and monthly runoff frequency distribution under scenarios C and D relative to scenario A.

If needed, the following additional statistics can be reported for river reaches:

- the percentage of time that the ecological water requirement is expected to be met under the climate scenarios and how this has changed from Scenario A; and
- low flow and high 'aquifer-fill' flows.

Surface water model uncertainty and error sources

If agreed by the Steering Committee, catchment model and data uncertainty can be assessed and reported regarding:

1. the adequacy of the water resource observation network;
2. uncertainty in gauge rating;
3. model structural uncertainties, including the manner in which key processes are described together with comparison of projected change versus model structural uncertainties; and
4. appropriateness of regionalisation of model parameters, including assessment during the calibration phase on the test catchments, and assessment of parameter uncertainty.

Uncertainty of model projections will be assessed by comparison of the objective function calculated for each scenario relative to the Scenario A.

3.3 Deliverables

While the details of the reported results will depend to some extent on the modelling approach adopted, a comprehensive surface water assessment report will be prepared that will include the following results for the five basins:

Calibrated catchment models, river and floodplain models ready for future scenario modelling.

- Catchment runoff from all gauged catchments used in calibration and from all other catchment outlets identified as streamflow reporting nodes (SRNs). These will be reported for current and future climate and development scenarios.

Depending on the capability of the models used, the results presented are likely to be:

- spatial runoff plots across all basins showing variations due to different climate scenarios
- flow duration curves for gauged and ungauged SRNs
- table comparing runoff and streamflows for all scenarios
- effects of individual GCMs on runoff
- monthly and seasonal plots of runoff
- table comparing effect of climate change on low flows across different basins including effects of those changes on the frequency, duration and timing of low flows.

- chart and table comparing the runoff change for all major streams, including changes in the frequency, duration and timing of drought
- table comparing effect of climate change on high flows across different basins including effects of those changes on frequency, duration and timing of high flows.
- floodplain model set up using HEC-RAS
- extent, timing and duration of floods in floodplains of the major rivers and areas under inundation and the inundation period.
- spatial maps of areas under inundation for major events
- stage-area relationship for the floodplain
- report on connectivity of the floodplain wetlands (extent, timing and duration).

3.4 Discussion

The lack of fine scale topographic data for floodplain modelling and the sparseness of rainfall and streamflow gauging stations were raised in the Methods workshop. To address the scale of topographic data a number of agencies (e.g. Landgate, Geoscience Australia) will be contacted seeking fine scale data including that available as LiDAR and 1” (~ 30m) hydrologically enforced DEMs. It is envisaged that finer scale topographic data may not be available for all locations in the study area and regionalisation of results may be needed to transfer findings from a finer scale to coarser scales.

The sparseness of gauging stations has given rise to the importance of uncertainty analysis on the results. As listed in Section 3.2.7, uncertainty and sensitivity analyses will be carried out in some detail in this study. These will help results to be reported with upper and lower bounds for a better understanding of the project results. The project also aims to suggest locations for additional streamflow and rainfall gauging stations in the region. This will be based on the data worth analysis done with the help of uncertainty analysis indicating the extent of reduction in uncertainty due to each additional gauging station.

Cumulative effects of excess discharge from mine dewatering on the rivers may be analogous to changes of hydrologic regimes due to river regulation in the Lower Ord River and rivers in the Murray Darling Basin (Simon Rogers, pers. comm.). It may be possible to draw experience from those systems to investigate effects of mine discharge on rivers in the Pilbara. Suggestions were also made for the use of National Water Commission and eWater guidelines on low flow and rainfall runoff modelling. These will be assessed and will be followed if practical.

The availability of sub-daily rainfall data for scenario modelling was also discussed. It is acknowledged that currently there is no well established method to predict sub-daily rainfall for scenario modelling and this is the subject of active work. If a suitable method becomes available during the project this may be applied for some scenarios.

Finally, as most of the recharge takes place during the large events, some additional calibration metrics, such as analysis of flow above a certain threshold, will also be implemented to ensure the larger events are modelled accurately.

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4 Groundwater methods

Mining and industrial development in the Pilbara region is likely to increase substantially over current levels. Population growth is also expected in the Pilbara due to the Pilbara Cities initiative. This will further increase pressure on groundwater resources because of expected increased demand for drinking and process water, dewatering as mining goes below the watertable and its disposal into surface environments, and a warmer, if not drier, climate. This component of the regional water resources assessment will assess the future availability of groundwater resources in the Pilbara region. This assessment will include a high level review of regional groundwater hydrology, estimation of diffuse recharge under current and future climates, improved understanding of the response in the fractured, chemically-deposited and Tertiary alluvial-colluvial aquifer systems to climate change, and an improved understanding of surface water – groundwater interactions.

The review of regional groundwater hydrology will focus on the central Pilbara in areas not presently covered by the previous groundwater review reports (Haig 2009; Johnson and Wright 2001; MWH 2010). Recharge-discharge estimation is a pre-requisite to groundwater modelling and the main flux relating to the system, along with an assessment of levels over time and key datasets such as rates of extraction and licensed allocations. The diffuse recharge estimation in areas covered with alluvial sediments will be conducted using the WAVES – VFM model. This model has previously been used in the sustainable yield projects and in a project on climate change impacts on groundwater recharge in Australia. Groundwater modelling will be conducted for areas covered by existing groundwater models including the quantification of surface water – groundwater interactions. For other areas (where surface water – groundwater interactions are important), conceptual models will be built to improve the understanding of surface water – groundwater interactions.

The following table lists major aquifers in the Pilbara region and their role as water supply or water disposal, the methods that will be used for their assessment and major location.

Table 4.1. Main aquifers of the Pilbara region and methods proposed for groundwater assessment

Aquifer	Geological unit	Objective	Methods	Location
Unconsolidated sedimentary aquifers 1. Coastal aquifers 2. Inland valley fill 3. Tertiary palaeochannel	Alluvium Colluvium	Water supply	Diffuse groundwater recharge estimation using WAVES; Climate – runoff – river / floodplain modelling Groundwater modelling of selected areas Surface water – groundwater interactions Discharge recharge relationships discharge > recharge GDEs?	Port Hedland coastal plain, Onslow coastal plain, Ashburton, Maitland, Yule, De Grey, Robe, Fortescue, Millstream, Cloudbreak, Sandy Creek, Mt Lewin, Normay, Marble Bar, Gold Spec, Golden Eagle, Wodgina,
1. Sedimentary rock aquifers 2. Northern Carnarvon Basin (NCB) 3. West Canning Basin (WCB)	NCB (Trealla Limestone; Yarraloola Conglomerate; Birdrong Sandstone; Nanutarra Formation; Lyons Group) WCB (Broome Sandstone; West Canning Basin Broome Sandstone, Wallal Sandstone)	Water supply	Waves for recharge estimation (for overlying superficial sediments); Groundwater model for climate change impacts on groundwater	West Canning Basin Carnarvon Basin
Chemically deposited aquifers	Calcrete, Dolomite, Pisolitic limonite	Water supply	Characterisation of Channel Iron Deposits (CIDs); flow, spatial distribution of CIDs in Pilbara; Recharge mechanism, Rejected recharge	Onslow plain, Upper Fortescue, Millstream, Robe, BHP Yandi, Telfer, Bungaroo, Marandoo?
Fractured sedimentary-rock aquifers Dolomite Sandstone	Fractured sedimentary Banded Iron Formations- BIF (Hamersley Basin: Brockman Iron Fm, Marra Mamba Iron Fm, Wittenoom Dolomite; Duck Creek Dolomite Hardey Sandstone Cliff Spring Fm	Low water use Short term water supply	Characterisation of Fractured Rock Aquifers (FRAs); spatial distribution of fractured sedimentary aquifers in Pilbara Recharge mechanism, rejected recharge?	Various
Fractured Igneous-rock aquifers	Fractured rock Granites and greenstones		Characterisation of FRAs; Recharge mechanism – rejected recharge	Coastal Plain, Bamboo Creek, Kintyre, Wodgina

4.1 Description of main aquifers

4.1.1 UNCONSOLIDATED SEDIMENTARY AQUIFERS

Unconsolidated sedimentary aquifers are major water bearing formations in the Pilbara. They are comprised of alluvium and colluvium. The alluvium is often clayey with interbedded sand and gravel lenses. The colluvium is comprised of cobble-sized detritals within a clay matrix. The thickness of the alluvium and colluvium is highly variable and can range from 20 to 150 m. The recharge mainly occurs through leakage from steam river beds following cyclonic and storm events. Estimates of localised recharge from stream and rivers beds to valley-fill aquifers range between 90 and 17,000 ML/year per km length of valley. It mainly depends on surface water flow rates, volume, duration and frequency of flow events. Groundwater flow is generally away from the recharge areas. Bore yields in the valley-fill aquifers vary from 50 to 2500 kL/day and groundwater is mostly fresh to brackish.

4.1.2 SEDIMENTARY ROCK AQUIFERS

The sedimentary rock aquifers occur in the West Canning Basin and Northern Carnarvon Basin. The West Canning Basin contains a multilayer aquifer system with the Broome and Wallal Sandstones being the main aquifer units. The Broome Sandstone is a major unconfined aquifer. The main source of recharge is via rainfall infiltration where it is outcropped or indirectly through thin layers of overlying sandy sediments. The Wallal Sandstone is mainly a confined aquifer which is separated from the overlying Broome Sandstone by the Jarlemai Siltstone. Recharge may occur where it outcrops or through the overlying Broome Sandstone where the Jarlemai siltstone is absent. The Wallal Sandstone is potentially a large source of groundwater with quality generally better than that from the Broome Sandstone.

The main aquifers of the North Carnarvon Basin include the Trealla Limestone Aquifer, Yarraloola Conglomerate Aquifer and the Lyons Group Aquifer. The Trealla Limestone Aquifer mainly occurs in the subsurface along the coastal plain from the Ashburton River to the Lower Robe River. Recharge is mainly via leakage from overlying alluvial sediments. It has little potential to supply significant volumes of water for drinking or agricultural use. The Yaraloola Conglomerate aquifer is comprised of the Yarraloola Conglomerate, the Birdrong Sandstone and the Nanutarra Formation. It is confined by the Murerong Shale over much of the coastal plain. Recharge to this aquifer is either through leakage from overlying alluvial aquifers or through direct rainfall infiltration where it outcrops. Bore yields from the Birdrong and the Yarraloola Conglomerate can exceed 1000 kL/day. The Lyons Group aquifer is a large confined aquifer and is comprised of Lyons Group sediments distributed over the subsurface of the Onslow coastal plain. Relatively small recharge occurs from overlying sediments. The resource potential is low because of its high salinity.

4.1.3 CHEMICALLY-DEPOSITED AQUIFERS

The calcrete and pisolitic limonite are chemically-deposited aquifers within Tertiary drainages or palaeodrainages. Calcrete occurs as localised exposed mounds near discharge zones. It is characterised by the secondary porosity with karstic features which were developed through partial dissolution of calcrete due to surface water percolation and groundwater movement. Recharge to calcrete aquifers is through leakage from stream beds. Bore yields from this aquifer range between 50 and 100 kL/day. Groundwater is mostly fresh to marginal. It can become brackish during prolonged dry periods. Pisolitic Limonite Aquifers are highly porous, vuggy and heterogeneous. Bore yields generally exceed 1500 kL/day. They do not outcrop extensively. It only constitutes an aquifer where it occupies channels incised into basement rocks by earlier drainages.

4.1.4 FRACTURED SEDIMENTARY-ROCK AQUIFERS

These aquifers occur in the Proterozoic Hamersley Basin and other sedimentary crystalline basement areas in the Pilbara.

Fractured sedimentary-rock aquifers exist within a host of different rock formations and occur extensively in Pilbara region. Dolomite, Banded iron-formation, and Sandstone are common fractured sedimentary rock aquifers in the Pilbara. In fractured rock aquifers groundwater may flow in both primary and secondary fracture systems. The rocks are tight in zones where there are few fractures. Fractures are planes along which stress has resulted in a partial loss of cohesion in the rock. Fractured rock aquifers are heterogeneous in nature and their hydraulic characterisation is one of the most difficult challenges in hydrogeology (Paillet et al. 2011). Extreme spatial variability in hydraulic conductivity and groundwater flow rate is the fundamental characteristic of fractured rock aquifers (Cook, 2003). Despite extremely high velocities through individual fractures the average flow rates through the aquifer can be quite low because fractures usually occupy only a small fraction of the aquifer.

Due to heterogeneity of the fractured rock aquifers a number of methods that are traditionally used for characterising porous media aquifer systems are of limited value in fractured rock aquifers. As fracture networks become complex, it is not practical to characterise the system properties as the sum of individual fractures. Characterisation of groundwater flow even for simple parallel plate model with identical planar fractures requires estimates of fracture orientation, fracture spacing, fracture aperture, matrix porosity and matrix diffusion coefficient, many of which are difficult to measure accurately. Because of this, approaches that are aimed at measuring large-scale properties integrating small-scale variability are expected to be more successful than the techniques that are aimed at characterising the small-scale variation.

Groundwater recharge occurs to these aquifers where rocks are fractured, jointed and weathered and exposed to the ground surface. Recharge also occurs through leakage from surface water bodies, where rocks with secondary porosity are exposed and through superficial sediments overlying the fractured rocks.

4.1.5 FRACTURED IGNEOUS AND METAMORPHIC-ROCK AQUIFERS

These aquifers form in the igneous and metamorphic crystalline basement areas such as the Achaean Pilbara Craton. They form in fractured granites and greenstones. Significant groundwater only occurs where secondary porosity is developed within fractured and weathered zones.

The methods listed in for each aquifer type will be used for its groundwater assessment. These methods are described in the remainder of this chapter.

The methods are detailed in the following order in this Chapter:

- Review of regional groundwater hydrology for selected areas in the Pilbara
- Preparation of contextual information on groundwater systems
- Estimation of diffuse rainfall recharge by modelling
- Characterisation of fractured sedimentary rock aquifers
- Groundwater scenario modelling and assessment
- Surface water – groundwater interactions

4.2 Review of regional groundwater hydrology

Previous regional groundwater hydrology review reports cover various parts of the Pilbara region. Johnson and Wright (2001) reviewed regional groundwater hydrology of the Central Pilbara Iron Ore Province extending from Jimblebar in the east to Robe River/Pannawonica in the west. It covers the Hamersley Range which includes most of the iron ore bearing rocks of the Hamersley Group between the Fortescue River in the north and the Ashburton River in the south. The Pilbara coast study by Haig (2009) extends along the Pilbara coast from the edge of the Carnarvon Basin to the West Canning Basin. The study area extends about 100 km inland from the coast. The east Pilbara groundwater review study by MWH (2010) covers parts of the east Pilbara region. In this study the regional groundwater hydrology review will focus on the upper half of the Hamersley Basin and parts of the east Pilbara shown in Figure 1. The review area boundary was selected after discussions with the Department of Water, Western Australia and can be modified further after consultation with other project partners. Following the selection of groundwater hydrology review area all relevant existing and available information and reports will be collated. This will include all hydrogeological related reports, groundwater investigation reports, annual borefield monitoring reviews, operating strategies, and environmental approval documents. All the electronic copies of the reports, investigations and other related information will be stored into location folders and then individual project areas.

The reports and all other collated information related to each location will be reviewed to extract the following key information

- Aquifer type and location
- Groundwater hydrogeological information
- Groundwater yield estimates and quality
- Groundwater allocation and use
- Groundwater system (aquifer) performance and status
- GDE issues

The extracted key information will be reviewed to summarise the groundwater hydrology together with any related issues and recommendations. This will be completed for all locations within the groundwater review study area, provided all required information and reports are available and accessible in a timely manner. From summary of all locations, the status of the regional groundwater hydrology will be summarised along with recommendations related to groundwater management, and any mining impacts and environmental risks

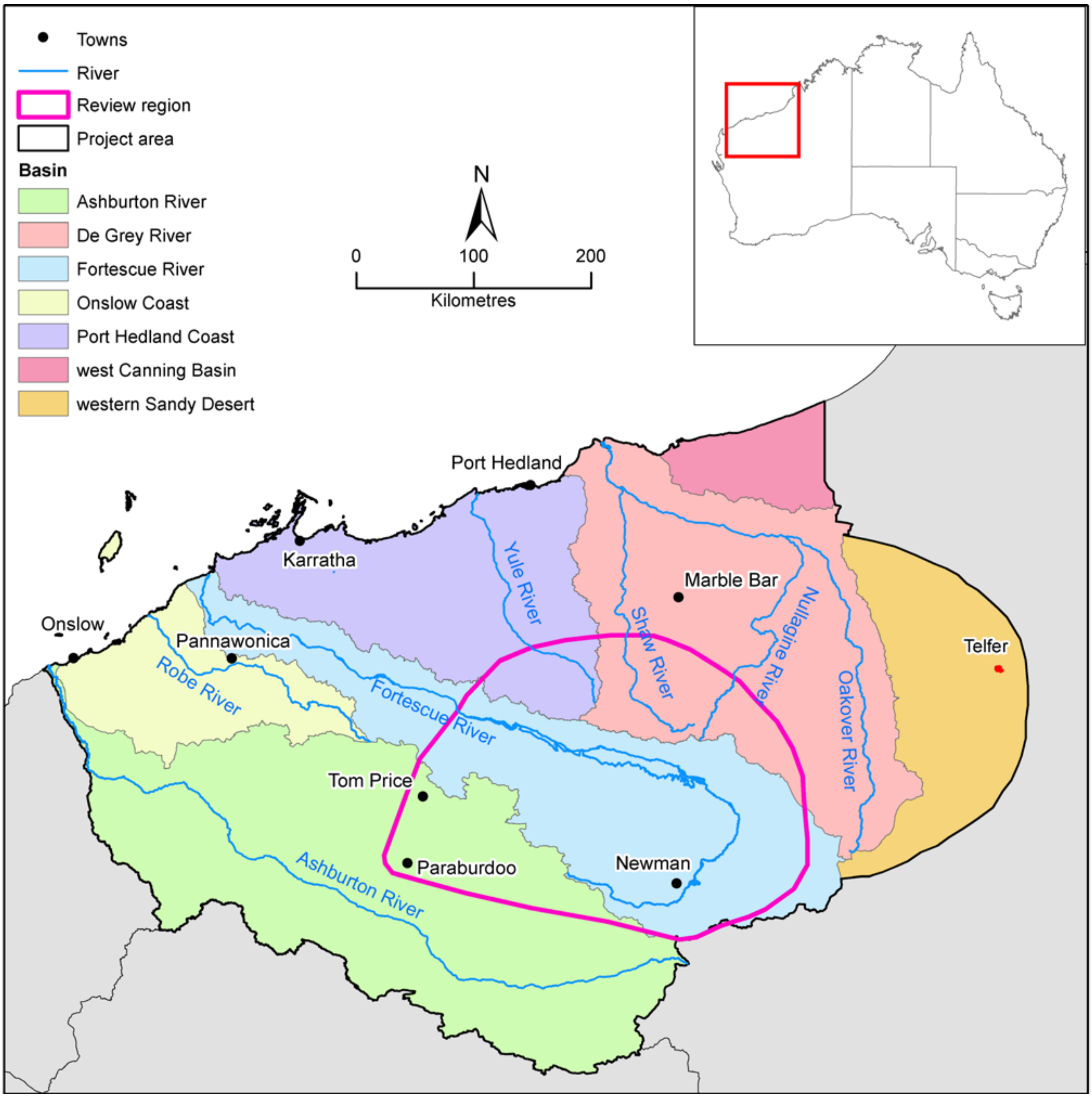

Figure 4.1. Pilbara water resources project area and regional groundwater hydrology review study area (shown with pink line)

4.3 Preparation of contextual information

All available information relating to the groundwater system such as the nature and status of the resource and data such as rates of extraction and allocation will be assembled for the whole project area.

Method

1. Subject to confidentiality and access restrictions, reports on hydrogeology, water sharing plans, groundwater extraction, extraction limits, entitlement data and information on groundwater status will be sourced from the DoW, mining companies, consultants and regional water service providers.
2. Summary description of the hydrogeological setting, surface water–groundwater interactions and trends in groundwater levels will be provided for seven groundwater basins: Ashburton River, De Grey River, Fortescue River, Onslow Coast, Port Hedland Coast, West Canning Basin and part of the Western Sandy Desert. The content in summary description will depend on the amount and type of available information for each groundwater/river basin.
3. Water management regimes including the pattern of historical groundwater extraction will be summarised for basins or parts of the basins for which groundwater extraction data are available.
4. The above summaries for each basin or parts of each basin will be included in each river basin report or a separate technical report where they are too detailed.

4.4 Rainfall-recharge modelling

4.4.1 INTRODUCTION

Diffuse groundwater recharge estimation will be carried out in unconsolidated sedimentary aquifers and in the superficial sediments of the sedimentary rock aquifers (West Canning Basin) as listed in . In the Northern Carnarvon Basin and West Canning Basin groundwater recharge occurs through rainfall infiltration in the unconfined portions of the sediments. In alluvial aquifers, diffuse groundwater recharge occurs via direct rainfall infiltration and localised groundwater recharge occurs via leakage from stream beds. Diffuse groundwater is thought to provide only 3 to 5 five percent of the total recharge in these aquifer systems.

The WAVES (Water, Atmosphere, Vegetation, Energy, Simulation) model (Zhang and Dawes, 1998) model will be used to estimate diffuse groundwater recharge from rainfall infiltration. . WAVES is a 1-dimensional biophysical model that simulates vertical water flow through soil and water uptake by vegetation. The model was developed by CSIRO (Zhang and Dawes, 1998) and is available in the public domain. It is described in detail in Hatton et al. (2001). The WAVES model has been used to estimate the diffuse groundwater recharge rates in Australia (Ali et al. 2012; Crosbie et al. 2011; Crosbie et al. 2010) under a range of future climate projections for different soil type and land cover conditions.

4.4.2 WAVES MODELLING

The WAVES model is a preferred tool for recharge estimation in bare ground areas as well as in vegetated areas with different soil types. It is not recommended for recharge estimation in wetlands and other areas where watertable is close to the ground surface. The WAVES estimates aquifer recharge or deep drainage based on four factors: i) climate, ii) land cover, iii) soil type, and iv) watertable depth.

It can estimate the deep drainage for each cell or combination of cells with the same climate, soil type, land cover and watertable depth. For this project the grid cells of similar attributes will be grouped together into units based on climate zone, soil type, land cover and depth of the watertable and the WAVES model run for each combination of units. For example, if an area or aquifer selected for diffuse recharge estimation is classified into 2 climate zones, 3 soil types, 3 land cover types and 3 watertable depth zones, the maximum possible number of units will be 54 (2 x 3 x 3 x 3). If there are six modelling scenarios (future climate projections) the total number of model runs will be 324 (54 x 6). Figure 4.2 shows a schematic diagram of assemblage of units and the recharge calculation for each modelling scenario (future climate).

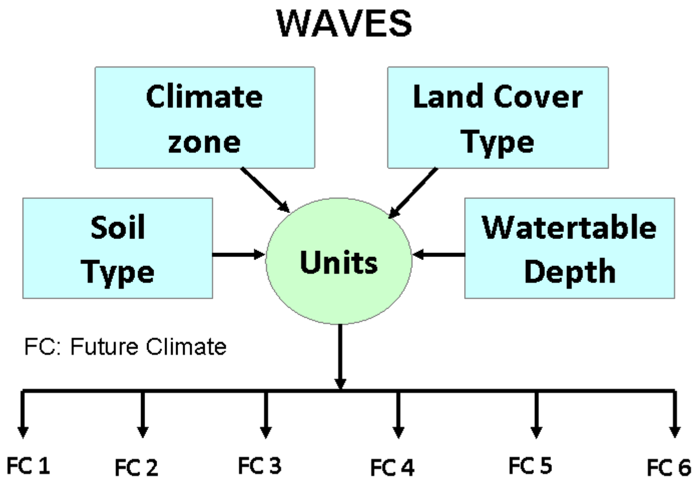

Figure 4.2. Flow diagram showing the grouping of cells of similar attributes into WAVES model units

4.4.3 METHODS FOR WAVES MODELLING

Climate zones

Based on rainfall and evaporation gradients, the project area will be divided into climate zones depending on spatial variation in rainfall and evaporation. Grouping the project area into many climate zones will result in a better prediction of recharge rates but at a cost of increased computation and data processing time. The total number of climate zones within the project area may range between 2 and 10. Averages of historical climate years (Scenario A) of rainfall, moisture index and evaporation data will be used to classify the Pilbara project area into these zones. The climate zones that lie within the area selected for diffuse groundwater recharge estimation will be used in the WAVES model.

Land cover classification

An ArcGIS model will be used for mapping the historical and current land cover for the project area. The methodology is based on previous work by a number of research studies (Ali et al. 2010; Furby et al. 2008; Hodgson et al. 2005; Silberstein et al. 2004; and Xu et al. 2004). The source data required for land cover mapping and classification includes satellite imagery, aerial photographs, geographic datasets and ground truth information. The model will be used to process the historical Landsat 5 Thematic Mapper (TM) data and will produce yearly or two yearly maps from the first year of availability of Landsat images to year 2011. In each map area covered by different types of native vegetation, open water bodies, urban, bare soil, mining and commercial use will be mapped. The exact number of land cover classes during a particular historical year will depend on the number of major land cover types within the project area. The land cover classification will be undertaken for the whole project area and the land cover classes that are within the area selected for diffuse groundwater recharge estimation using the WAVES model.

Soil classification

The soil data will be collated from the Australian Soils Resource Information System (ASRIS), the Department of Agriculture and Food, Western Australia and other sources. The suitability of these data for classification of the project area into various zones of similar soils and/or soil hydrological properties will be assessed. Recharge is most sensitive to annual rainfall, plant leaf area index, light extinction coefficient and depth of the watertable. Therefore the generalised nature of the soil hydraulic information in ASRIS seems adequate for soil descriptions. For the project area the soil units will be grouped into soil types of similar hydrological properties and texture based on ASRIS level 4 and other collated data. The soil classification will be done for the whole project area and major soil types within the area will be selected for diffuse groundwater recharge estimation by WAVES modelling.

Watertable depth

The fourth parameter required to classify the region into units is the depth of the watertable. Using available groundwater data the whole project areas will be grouped into areas of various watertable depths. If the watertable depth information is not available for some parts of the project area the WAVES modelling to estimate deep drainage or recharge rates will assume watertable depths in areas selected for the diffuse recharge estimation.

The above four parameters will be used to create units of similar attributes in each area selected for diffuse recharge estimation and the WAVES model run for each of those units under each modelling scenario or future climate projection to estimate deep drainage or recharge.

Method

1. A brief summary of the hydrogeological setting will be prepared and reported.
2. Information about previously-determined recharge estimates together with estimation methods will be collated.
3. The data about current and future abstraction and allocation limits will be collated.
4. Groundwater monitoring data, if available, will be collated and analysed to assess watertable depths in various parts of the project area particularly in areas selected for WAVES modelling.
5. Input files for soil and major land covers will be prepared for WAVES modelling. The climate files will be prepared for all modelling scenarios.
6. Use WAVES to estimate deep drainage rates under a defined set of climate and major land use conditions.
7. Compare WAVES modelled recharge estimates with those estimated by a chloride balance (CMB) method and also with those estimated previously.
8. Make groundwater assessments based on recharge estimates determined through WAVES modelling.
9. Assess changes in recharge in response to projected future climate scenarios.

4.4.4 DIFFUSE GROUNDWATER RECHARGE ANALYSIS

The recharge estimates under each future climate projection (scenario) will be analysed for each combination of soil, land cover, climate zone and watertable depth. The following will be estimated through this analysis.

- Spatial and temporal variability in diffuse recharge under future climate projections
- Effect of soil, climate and land cover on diffuse recharge
- Effect of aquifer type on diffuse recharge
- Relationships between aquifers and recharge (consolidated versus unconsolidated, coastal versus inland valley fill, inland valley fill versus palaeochannel)
- Relationships between rainfall and diffuse recharge
- Relationship between change in rainfall and change in diffuse groundwater recharge

4.5 Characterisation of chemically-deposited and fractured rock aquifers

Significant groundwater resources are contained within fractured rock aquifers in Australia. Both chemically deposited and fractured rock aquifers with mainly secondary porosity exist in the Pilbara region. To properly manage these resources the characteristics of these aquifer systems needs to be understood. While there are well developed and relatively robust procedures for characterising aquifers with primary porosity there are no well developed procedures for the characterisation of fractured rock aquifers, especially the characterisation of their spatial heterogeneity remains a significant problem (Cook, 2003; Krasny and Sharp, 2007). Some common characterisation methods include measurement of the orientation of fractures, spacing of fractures, fracture length, fracture connectivity, aperture, and surface roughness. Characterisation of the rock matrix such as measurement of matrix porosity and permeability may help determine the extent to which fractures are likely to dominate groundwater flow. A number of methods can be used for measuring the matrix porosity including the water saturation method and the mercury intrusion method. Matrix permeability can be measured in the laboratory using a permeameter. Matrix diffusion can be measured using the double reservoir method or the radial diffusion method (Cook, 2003). Measurement of variations in hydraulic head within individual boreholes or piezometer nests may provide important information on the connectivity of fracture networks. Methods such as pump tests, borehole flow meters, and tracer approaches can be used for estimating the hydraulic conductivity of fractured rock aquifers.

A number of methods can be applied for the calculation of volumetric groundwater flow and recharge rates in fractured rock systems. They include Darcy's Law, point and well dilution methods, Radon, applied tracer tests, groundwater dating, inferring recharge from hydrograph response, and chloride mass balance. Groundwater modelling approaches such as equivalent porous medium approach, dual porosity models, and discrete fracture network models, and stochastic models can be used for modelling flow in fractured rock aquifers. Each approach has some advantages and disadvantages.

The characterisation of fractured rock aquifer in the Pilbara region and application of methods for their characterisation will depend on the type, amount, density and availability of relevant geological, hydrological, GIS, geophysical and geochemical data. Since the type, amount and density of hydrogeological, geological and other data of chemically deposited aquifers, fractured sedimentary rock aquifers and fractured igneous and metamorphic rock aquifers of the Pilbara region is unclear at this stage it is difficult to propose aquifer characterisation methods for these aquifers. The first step therefore is to collate, analyse and review all available data and information

- Hydrogeological and geological (rock types and characteristics) maps and reports
- Accession reports
- Groundwater level and groundwater quality data
- Geophysical, remote sensing and seismic reports, lineament mapping
- Groundwater abstraction data
- Tracer, Radon and groundwater dating test data and reports, if available
- Information about fractures (number of sets, orientation, spacing, fracture length, fracture connectivity, aperture, surface roughness), solution channels (spatial distribution and variation with depth), if available
- Information about thickness and structure of fractured rock aquifers and their spatial distribution, especially their relationship with alluvial aquifers that may provide pathways for either recharge or discharge
- Information, data and reports about groundwater discharge from chemically deposited and fractured rock aquifers
- Work by mining companies involved in dewatering fractured rock and chemically deposited aquifers will be sought as they have many years experience with their management and response to rainfall and pumping.

A comprehensive review of all relevant and available data and analyses will inform the methods and models that can be applied for characterising fractured rock aquifers. Such a review will also help build conceptual models for improving our understanding of flow behaviour and controlling factors in different fractured sedimentary-rock aquifer systems in the Pilbara region.

Recharge mechanisms will also be evaluated using a suitable approach. The selection of recharge estimation method(s) will depend on the amount, density and availability of relevant data. The rainfall and groundwater monitoring data will be used to establish relationships between rainfall and recharge. This analysis will be conducted at various locations to account for variability in rainfall. The relationships developed at various locations will be compared to assess and map recharge characteristics in these aquifers.

4.6 Groundwater modelling

Groundwater modelling will be carried out for the alluvial coastal and inland systems in areas with existing groundwater models. The West Australian Department of Water (DoW) has developed five groundwater models for various parts of the coastal and inland alluvial systems: Lower De Grey groundwater model, Lower Fortescue groundwater model, Lower Robe groundwater model, Lower Yule groundwater model and the Millstream groundwater model. Groundwater modelling will also be carried out for the West Canning Basin (sedimentary rock aquifers overlain by the unconsolidated superficial sediments) for which a model has been developed by the DoW. The climate input data will be provided to the mining companies if they have groundwater models for other aquifer systems. These models, if any, will be run by the mining companies for scenario modelling.

4.6.1 DESCRIPTION OF GROUNDWATER MODELS

4.6.2 WEST CANNING BASIN GROUNDWATER MODEL

The Western Canning Basin groundwater model was developed by Aquaterra (2010) for the western most part of the Canning Basin and covers an area of about 9,400 km^2. The model domain (Figure 4.3) covers an area of about 228 km (east-west) by 255 km (north-south) and has 424 rows and 456 columns. This is a MODFLOW based model which operates under the Visual MODFLOW graphical user interface. It has five layers consisting of the surficial sediments (layer 1), Broome Sandstone (layer 2), Jarlemai Siltstone (layer 3), and Wallal Sandstone (layer 4 and 5). Groundwater flow direction is from south to north in the surficial sediments and Broome Sandstone. The flow is from the southeast to northwest in the Wallal Sandstone. The River package in Modflow is used to simulate the ocean boundary in layer 1 while lower layers are assumed as no flow. A fixed head boundary is used to simulate groundwater inflow to the Wallal Sandstone from the eastern parts of the West Canning Basin. The groundwater recharge mainly occurs via rainfall infiltration.

The main stratigraphic units are the Wallal Sandstone, Jarlemai Siltstone and Broome Sandstone which generally thickens to about 420 m and deepens to the northeast. The Wallal Sandstone is mainly comprised of very coarse to fine grained sands. A fine to medium grained sandstone and interbedded mudstone in the upper parts of the Wallal Sandstone is correlated to the Alexander Formation. The Wallal aquifer is confined by the overlying Jarlemai Siltstone over most of the West Canning Basin. Measured hydraulic conductivity ranges between 20 and 60 m/day. Groundwater salinity ranges between 250 mg/L TDS in the east to about 2,000 mg/L TDS in the west.

The Jarlemai Siltstone comprising of mainly black puggy clay and silty clay is present throughout the model area except in the southern and western areas where it pinches out. It acts as an aquitard and separates the groundwater flow systems of the Wallal Sandstone and Broome Sandstone aquifers. It has a maximum thickness of 200 m in the northwest of the model area.

The Broome Sandstone unconformably overlies the Jarlemai Siltstone over most of the model area. This is mostly an unconfined aquifer and has a maximum thickness of about 60 m in the West Canning Basin. The groundwater in the aquifer flows in a northwards direction towards the Indian Ocean. Its hydraulic conductivity ranges between 3 and 15 m/day. Rainfall infiltration is the main source of recharge to groundwater. Some throughflow also occurs. The salinity of the groundwater ranges between 380 mg/L in the east to over 10,000 mg/L in the west.

This model was calibrated to steady-state conditions using the groundwater level monitoring data and groundwater extraction data. The transient model calibration period was from 1975 to 2009. The calibration has a scaled RMS error of 5.23 percent. Surface water – groundwater interactions, particularly with regard to Mound springs and Baningarra, have not been included due to a lack of data required for calibration. There are no other significant surface water – groundwater interactions in the modelled area.

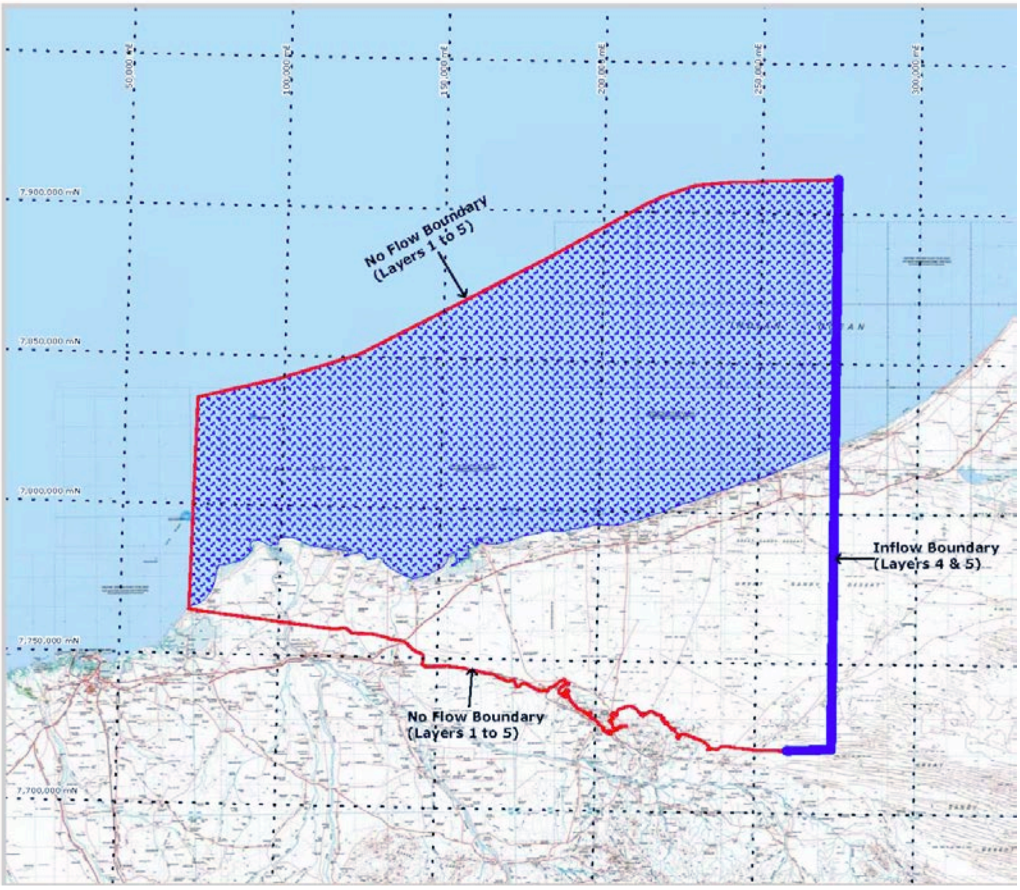

Figure 4.3 A map showing West Canning Basin groundwater model extent and boundary conditions Aquaterra, 2010)

4.6.3 MILLSTREAM GROUNDWATER MODEL

SKM (2009) recalibrated a MODFLOW based groundwater model of the Millstream Aquifer in the Pilbara region of Western Australia which was developed by URS (2007). The model domain is shown in Figure 4.4. This model in the Fortescue valley covers an area beneath the Fortescue River Plain between the Hamersley Range to the south and the Chichester Range to the north. The Western Fortescue Valley contains alluvial, colluvial and lacustrine sediments. The four major formations filling the valley include: the Millstream Dolomite, Robe Pisolite and Kumina Conglomerate, and the Kangiangi Clay (aquitard). The calcrete unit in the Millstream Aquifer is highly transmissive. The main recharge mechanism to this aquifer is the localised recharge from the Fortescue River as a result of floods from extreme rainfall events. Some diffuse recharge also occurs from direct rainfall infiltration on the outcropped areas of the aquifer. The ephemeral streams draining off the Hamersley Range also recharge this aquifer. Groundwater discharge is to Deep Reach Pool, Chinderwarrier Spring. Minor groundwater discharges also occur to the Woodley, Peters and Palm Springs. Evapotranspiration is the potential discharge mechanism in areas of shallow watertable. Groundwater abstraction from the northern parts of the valley is a significant groundwater discharge mechanism. Groundwater salinity is generally less than 1000 mg/L except beneath the Fortescue River where it exceeds 1250 mg/L. Groundwater recharge occurs by rainfall infiltration where unconfined aquifers outcrop, by seepage via small streams draining the Hamersley and Chichester Ranges and by seepage through the Fortescue River bed during river flow. Natural groundwater discharge is mainly to Deep Reach Pool and to Chinderwarriner Spring. Minor groundwater discharge also occurs to Woodley, Peters and Palm Springs. Groundwater discharge through evapotranspiration occurs where the watertable is shallow.

This model was calibrated from 1968 to 1995 and verified from 1995 to 2007. The calibrated model has a normalised RMS error of 8 percent. The RMS error was 0.15 m. The normalised error for the verified model was 11.1 percent. The transient model was used to investigate the impact of a range of future groundwater extraction regimes on groundwater levels.

Localised recharge and discharge

To estimate the exchange between river and groundwater it is necessary to know river water levels, flow duration and groundwater levels. MIKE11 can be used for estimate surface water levels and their temporal variation. MIKE 11 solves the Saint Venant hydrodynamic equations for open channel flow to calculate flow depth and flow velocity in open channels for given river discharges. In the previous modelling (SKM, 2009) the reach of the Fortescue River that traverses the groundwater model domain was represented as a series of cross sections. The river chainage (distance in the direction of flow) was defined at each cross section. River discharge data was provided from river gauging which for the Fortescue River is limited to a flow gauge at Gregory Gorge which has been monitored daily since 1969. The Gregory Gorge flow gauge is located downstream of the model domain. There were no upstream gauges that could be used to provide model input data at the time of previous modelling.

SKM (2009) extracted river cross sections from the Digital Terrain Model (DTM) which was derived from Shuttle Radar Topography Mission (SRTM) data supplied by the Department of Water. This data provided limited topographic detail of the Fortescue River channel and was the best available at the time of previous modelling. The MIKE 11 model was run using the recorded Gregory Gorge daily discharge as the upstream model boundary. Dynamic coupling of the Mike 11 and MODFLOW models was not attempted during the previous modelling due to lack of representative and accurate data required for MIKE11. The river recharge was modelled using the River Package the required information for which was obtained from MIKE11. Discharge to various springs was modelled by SKM (2009) by defining the springs as river cell boundaries. River stage elevations were assigned according to the measured water levels.

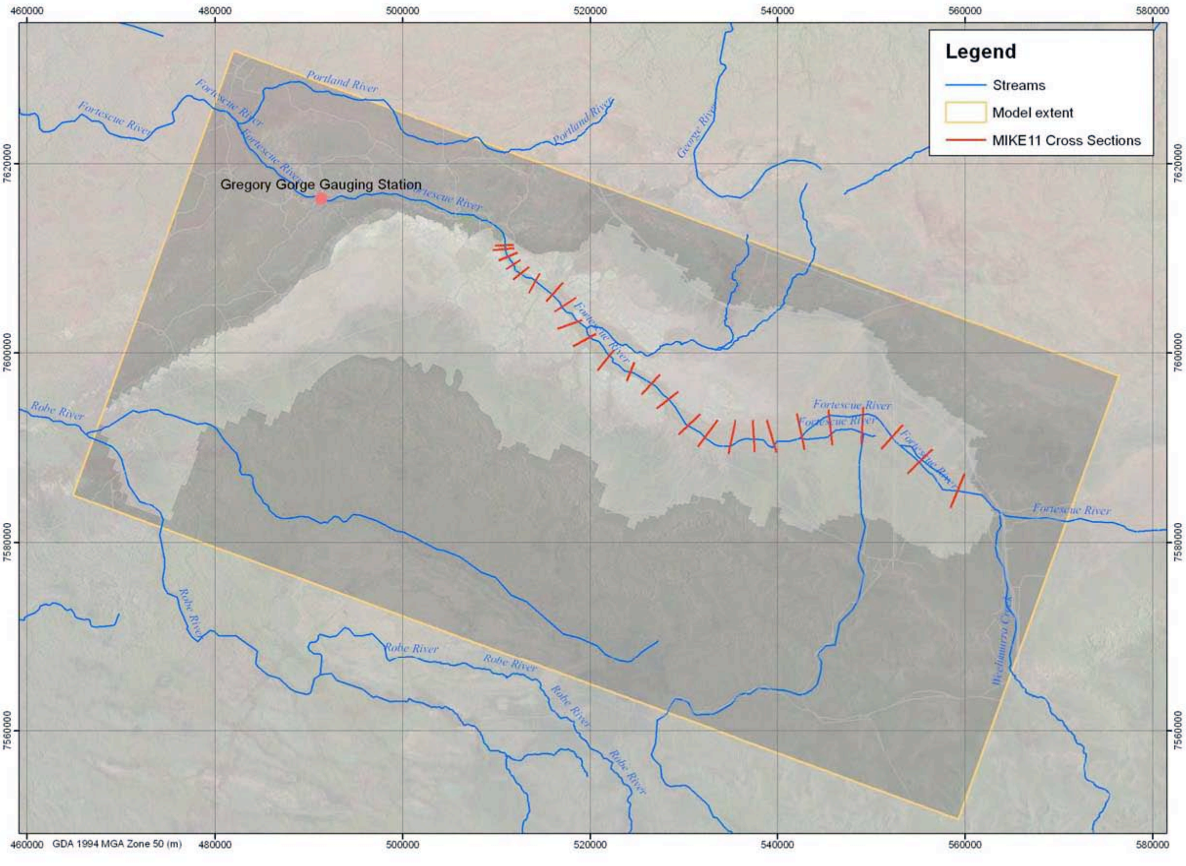

Figure 4.4 A map showing extent of the Millstream Aquifer groundwater model (SKM, 2009)

4.6.4 LOWER DE GREY GROUNDWATER MODEL

The Lower De Grey groundwater model was developed by SKM (2010) to quantify the potential groundwater resources in the study area. The model covers the alluvial aquifers in the De Grey catchment from upstream of the Namagoorie borefield to the ocean as shown in Figure 4.5. The Cainozoic (Quaternary and Tertiary) alluvium deposits are the primary water bearing formations in the De Grey area. These are underlain by the Mesozoic sandy shale and sandstone, and weathered clay. At some locations the Mesozoic clay of up to 80 m thickness separates the Cainozoic alluvial material from deeper Archaean bedrock.

The rainfall however is extremely variable and depends on cyclones with an average of 0.8 cyclones per year in the model area. Groundwater recharge via rainfall infiltration is about 3 percent of rainfall; about 91 percent of groundwater recharge is from the De Grey River (Davidson, 1974) which is the largest and most reliable of the Pilbara rivers. The De Grey River flows 2 to 3 times each summer on average. The flow duration is 2 to 4 weeks each time following a cyclone or storm event.

Phreatophytic vegetation exists across much of the aquifer due to the shallow watertable. The shallow alluvial aquifer supports groundwater dependent ecosystems during the dry parts of the year.

The FEFLOW package was used to develop this groundwater model. The model has three layers (four slices). This model was calibrated from 1983 to 2009 using the groundwater level monitoring data. The normalised RMS error of the calibrated model was 4.31 percent.

Localised recharge and discharge

In the previous modelling by SKM (2010) the recharge from the De Grey, Shaw and Ridley rivers was simulated using head boundaries. The nodes within the river banks were assigned time varying head conditions based on the river stage measured at the Coolenar river gauge. Since the river bed elevation rises gradually from 0 m AHD near the coast to about +50 m AHD at the upstream end of the model, the river gauge readings were adjusted to match river bed levels along the length of the river. The recharge from the Shaw and Ridley rivers was only modelled within the palaeochannel area due to lack of gauge data away from the De Grey River. Pardoo Creek was not modelled due to lack of gauge and observation data.

Previous modelling by SKM (2010) also modelled flooding when the flow overtopped the De Grey River banks (SKM, 2010). The Coolenar gauge data were used to determine the extent of flooding. It was assumed that the flooding will dry as soon as the river subsides. Flood water was an additional flux which was added to the rainfall. Further details about flood simulation in the Lower De Grey groundwater model can be found in SKM (2010).

Evaporation and flow from pools was modelled by SKM (2010) using the head boundary condition which allowed flux both in and from river nodes during river flow events. During dry periods the boundary condition only allowed water to leave the model (pool acted as a drain).

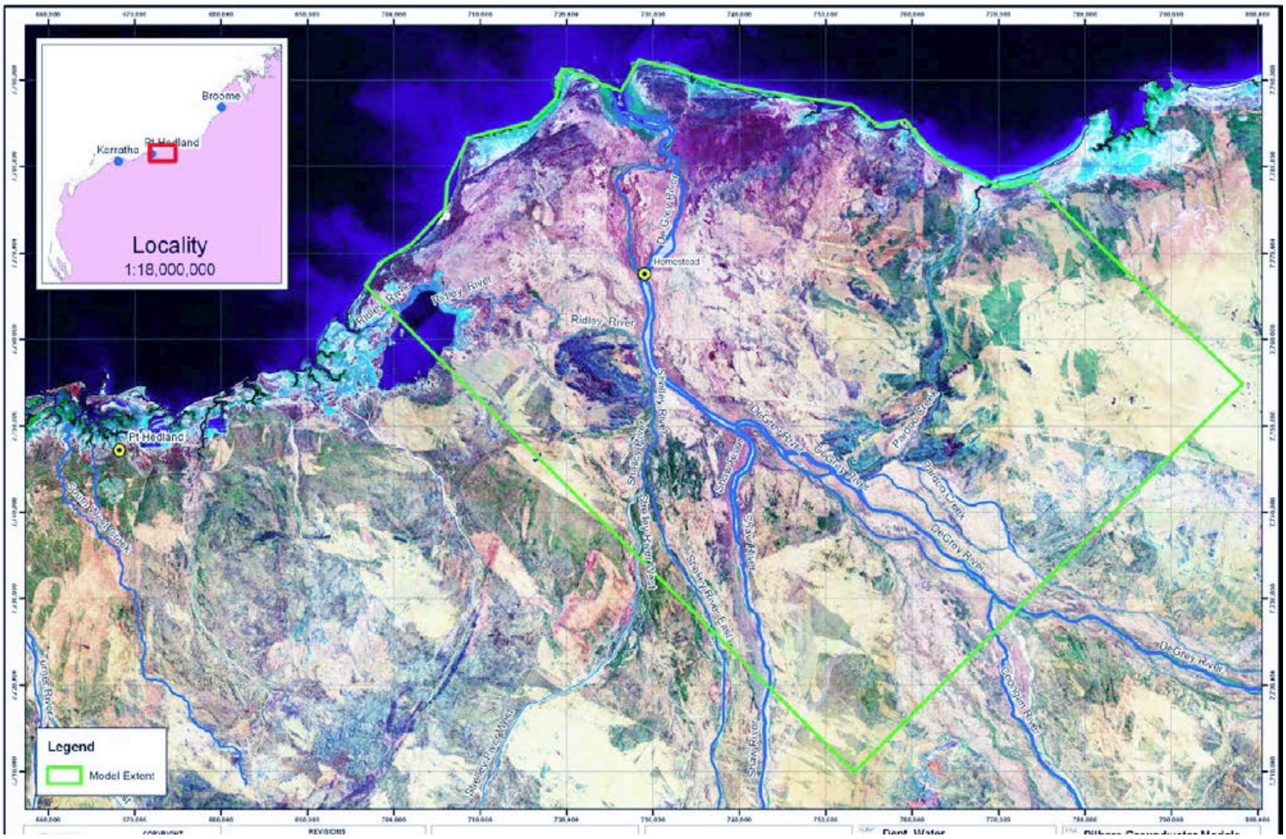

Figure 4.5 A locality map showing the extent of Lower De Grey Model

4.6.5 LOWER FORTESCUE RIVER GROUNDWATER MODEL

The Lower Fortescue River (LFR) groundwater model was developed by MWH (2010a) to understand the dynamics of aquifer system under natural conditions and to project the potential impacts of groundwater extraction on the environment. The LFR Alluvium is a part of the Fortescue Rive catchment as shown in Figure 4.6. Previously, Aquatarra developed a groundwater model of this area using MDOFLOW (Aquatarra, 2008). The MODFLOW River package was used to estimate the groundwater recharge.

The LFR area is underlain by the Peedamullah Shelf in the northern part of the Carnarvon Basin. The Peedamullah Shelf basement is up to 90 m thick and consists of a sequence of gently northwest-dipping Cretaceous strata. The Tertiary sediments overlie the Cretaceous sequences which are unconformably overlain by up to 30 m of Quaternary alluvial sediments associated with the Fortescue River (Haig, 2009). Proterozoic basement rocks outcrop on the hills along the eastern edge of the lower portion of the LFR. There are a series of ridges of branded iron formation, chert and shale of the Brockman Iron Formation, the Mt. McRae Shale and the Mt. Sylvia Formation to the east of the LFR.

The alluvial sediments form the major aquifers of the areas. It extends from the base of the scarp boarding the coastal plain to the coast. The alluvial layer is comprised of a sequence of recent clays and gravels and overlies the Trealla Limestone. The average thickness of alluvium clay is 6 m where present and average thickness of the gravel is 13.6 m. The Trealla Limestone and lower clay layer separates the alluvial aquifer from the underlying Yarraloola Conglomerate confined aquifer which has an average thickness of 23 m. The measured hydraulic conductivity of the alluvial aquifer ranges between 63 and 190 m/day. The alluvial aquifer is a major source of water supply from the area whereas the Yarraloola Conglomerate aquifer has a limited aerial extent. The alluvial aquifer is replenished via rainfall recharge and localised recharge from the Fortescue River.

The LFR groundwater model includes all above described aquifers. Their hydraulic properties are given in MWH (2010a). The LFR groundwater model (MWH, 2010a) was developed using FEFLOW and MIKE 11 and covers the whole of the LFR catchment. It has six layers that describe five geological formations. The Fortescue River flowing through the model area from south to north discharges over the tidal flats and into the Indian ocean. It has a constant head boundary in the northwest and no-flow boundary along the eastern and southern margins as well as the base of the model. The Fortescue River is a third type boundary with fluxes estimated by the head difference between the river stage height and the aquifer water level and the conductance of the river bed material. The watertable depth in the alluvial aquifer ranges between 3 and 10 m.

The FEFLOW 5.4 (Diersch, 2008) was used to construct the finite element model and MIKE 11 (DHI, 2008) was integrated with FELOW through a FELOW interface module called IFMMIKE 11. Hydraulic conductivity of the alluvial aquifer and river recharge rates were adjusted for the steady-state model calibration. The normalised RMS error of the steady-state calibration was 4.5 percent. Transient model calibration period spanned between 1983 and 2007 and normalised RMS of the transient calibration was 4.5 percent. The calibrated model was used to assess the impacts of various groundwater abstraction rates on groundwater flow dynamics in the area.

Localised recharge and discharge

Modelling of the surface water and groundwater interactions in the Lower Fortescue River groundwater model can be achieved through an integration between FEFLOW and MIKE11. MIKE 11 is a dynamic, user-friendly one-dimensional modelling tool for the simulation of flows, water quality and sediment transport in estuaries, rivers, irrigation systems, channels and other water bodies. Groundwater discharge to the river is not significant in this area, except some discharge to pools. In the previous modelling (MWH, 2010a) recharge from the river to groundwater was simulated using FEFLOW's 3rd kind boundary condition, which calculates the rate of water exchange between river and aquifer as the product of a transfer coefficient (river bed conductivity divided by river bed thickness, 1/day) and the head difference between the river and groundwater. Since there were no measurements on this key model parameter that controls the rate of river recharge to groundwater in the modelling area it was calibrated.

MIKE11 can be linked with FEFLOW by an InterFace Manager (IFM) module called IFMMIKE11. The IFMMIKE11 integrates FEFLOW and MIKE11 in a way that groundwater levels and river water levels are predicted sequentially. The IFMMIKE11 patches each 3rd kind boundary FEFLOW node to an HPoint of MIKE11. At each FEFLOW time step, discharge/recharge is estimated using MIKE11 predicted river water levels and then exported to MIKE11 as the input of an additional boundary condition (Q_base). MIKE11 calculates its time step as often as required to reach the actual time level of FEFLOW. Once this is done, the predicted river water levels of MIKE11 HPoints are exported to the FEFLOW coupling boundary nodes and FEFLOW starts its next time step.

Since groundwater recharge from the Lower Fortescue River was only a small portion of river flow and groundwater discharge to the river was not significant, the previous modelling (MWH, 2010a) assumed that river water levels were little affected by river recharge to groundwater. Based on this assumption the river water levels during the previous modelling were predicted separately by MIKE11 (MWH, 2010a). This saved computer time (since only one MIKE11 run was required) and avoided possible convergence problems which might have occurred if FEFLOW and MIKE11 were integrated.

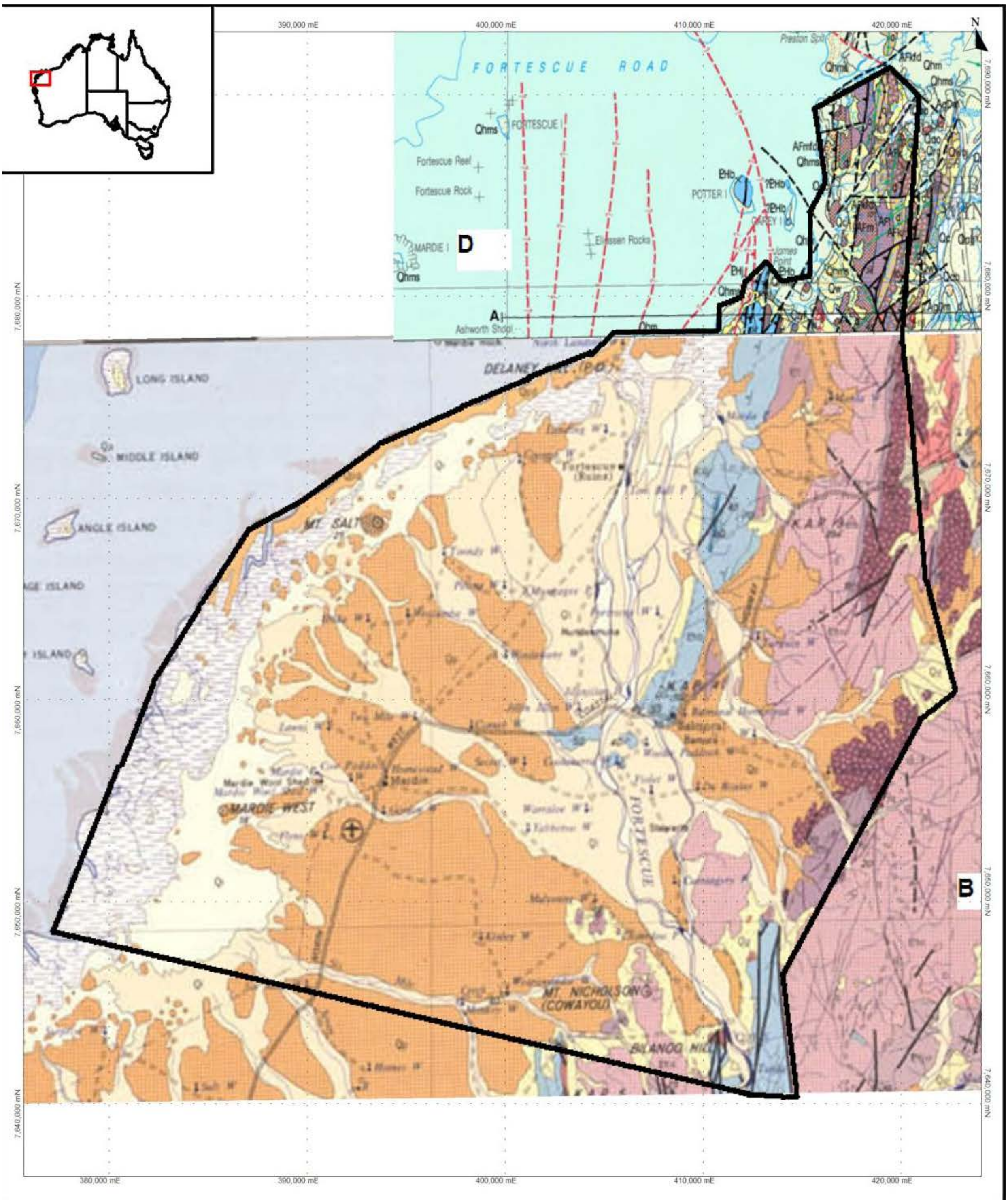

Figure 4.6 Surface geology of the Lower Fortescue River catchment and groundwater model boundary (MWH, 2010a)

4.6.6 LOWER ROBE RIVER GROUNDWATER MODEL

An overall aim of the Lower Robe River model was to quantify the potential groundwater resources of the study area and assess the long term sustainable yield of the alluvial aquifer under various future groundwater extraction regimes and climate. The Lower Robe River (LRR) groundwater model covers an area that contains the alluvial aquifer associated with the Robe River from upstream of the North West Coastal Highway to the ocean as shown in Figure 4.7 (SKM, 2010a).

The alluvium deposits, consisting of gravel and clay lenses, are the main water bearing formations in the Robe area following the model path of the Robe River. The watertable is between 5 and 10 m in the alluvium. A calcrete layer has been developed at some locations due to the rising and falling of the watertable. The alluvium sediments are underlain by the Tertiary Limestone and Robe Pisolite both acting as aquitards. The base of the alluvium is set as base of this model. The average horizontal hydraulic conductivity of the gravel is around 250 m/day according to Commander (1994).

The diffuse groundwater recharge via rainfall infiltration is about 3 percent of the annual rainfall. Most of groundwater recharge occurs locally. An estimated 24 GL and 10 GL groundwater recharge occurred during 1984 and 1985, respectively most of which was localised recharge from the river bed. Both permanent and semi-permanent groundwater dependent pools along the river bed and phreatophytic vegetation are supported by the shallow watertable during the dry periods.

The FEFLOW package was used to construct the LRR groundwater model. It has three layers with the first two layers covering the alluvial aquifer and the third layer represents the Trealla Limestone. The model has no-flow boundary on the eastern, western and southern margins and a constant head (0.2 m) boundary on the north-eastern coast. The model was calibrated from 1984 to 2008 by matching the calculated and observed groundwater levels. The calibrated model had a normalised RMS error of 8 percent. The calibrated model was used to assess the impacts of climate change and groundwater abstraction regimes on groundwater levels, water balance and potential impacts on GDEs of the LRR Alluvial Aquifer.

Localised recharge and discharge

The river recharge was simulated using a monthly time-varying head dependent 'transfer' boundary condition along the main Robe River as described in SKM (2010a). Flux constraints on the river boundary conditions were used to define the dry and flow conditions. The maximum flux constraint was zero in the case of no flow which means no flow could occur from the river to the aquifer. Water was always allowed to discharge to the river since no minimum flux was defined.

No specific inputs were required to model various groundwater pools along the Robe River. The river bed elevations were set by the high resolution Lidar data (SKM, 2010a). When groundwater levels were at or above the groundwater surface (at the pool) the evapotranspiration function was activated and evaporation from the pool occurred at defined maximum rate.

In the previous modelling by SKM (2010a) the flood plain infiltration was assumed to occur across the entire alluvial aquifer extent and was specified as a constant flux rate at the model surface. This rate was set at 0.002 m/day after testing through the calibration process. Floods were assumed to occur whenever the monthly flow exceeded 60 ML. Flows less than 60 ML per month were assumed to contain within the river channel.

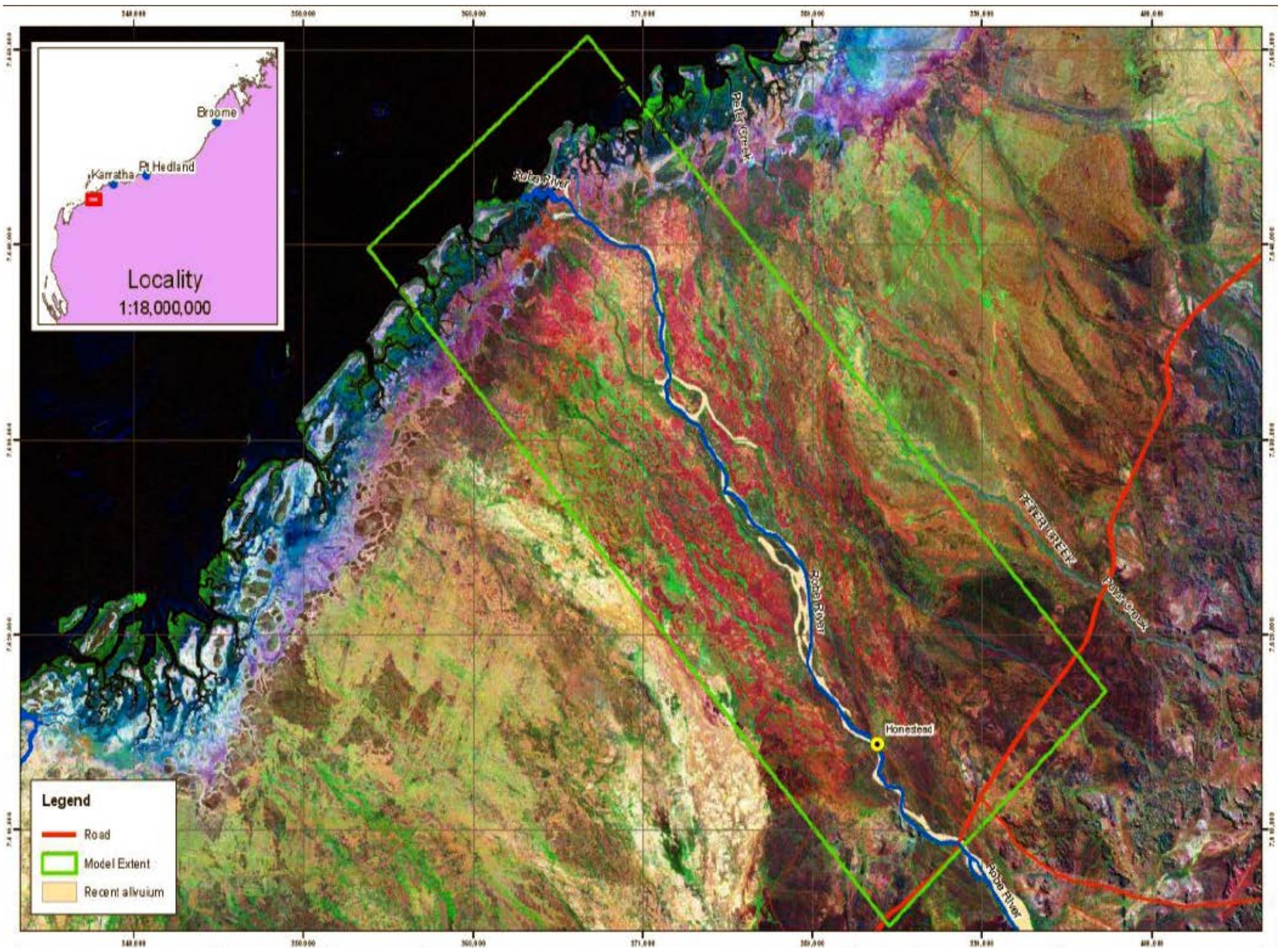

Figure 4.7 A locality map showing extent of the Lower Robe groundwater model (SKM, 2010a)

4.6.7 LOWER YULE CATCHMENT GROUNDWATER MODEL

The lower Yule catchment groundwater model was developed by MWH (2010b) to secure sustainable development of groundwater resources in the Pilbara. The Yule River is a major river within the Port Hedland Coast Drainage Basin. This groundwater model is for the Lower Yule Alluvium Aquifer which is located in the catchment of the Yule River north of the intersection with the North West Coastal Highway. The model domain is shown in Figure 4.8. The Yule River is the largest and the longest river in the Port Hedland Coast Drainage Basin. The Yule River in the model area consists of a large main channel flowing north which splits into a secondary channel and braided channels to the north of the North West Coastal Highway.

The alluvium is generally 12 to 22 m thick, apparently thinning to less than 12 m in the northwest adjacent to the coast. The superficial 10 to 20 m thick colluvium deposits overlie the remainder of the model area. Thick alluvium deposits (70 to 80 m) located along the northern side of the Yule River channel north of Jelliabidina Well are exploited for groundwater by the Water Corporation for the Port Hedland water supply. The basement consists of granite intrusions and meta-sediments.

The main recharge mechanism is localised recharge from river flow. Whincup (1967) and Forth (1972) estimated annual recharge from river flow of 13.4 to 14.6 GL which is 10 percent of the median annual flow. Very limited diffuse rainfall recharge also occurs.

The FEFLOW 5.4 (Diersch, 2008) and MIKE 11 2008 (DHI, 2008) were used for the construction of a numerical model. The model has 7 layers representing various aquifers and aquitards. The steady-state model calibration was reasonable with the standardised RMS of 3.65 percent. The transient model was calibrated for the period between 1972 and 2009 using the observed groundwater level monitoring data. The standardised RMS error for the transient model was 2.95 percent. The calibrated model was used to assess the impacts of climate change and various groundwater abstraction strategies on groundwater levels.

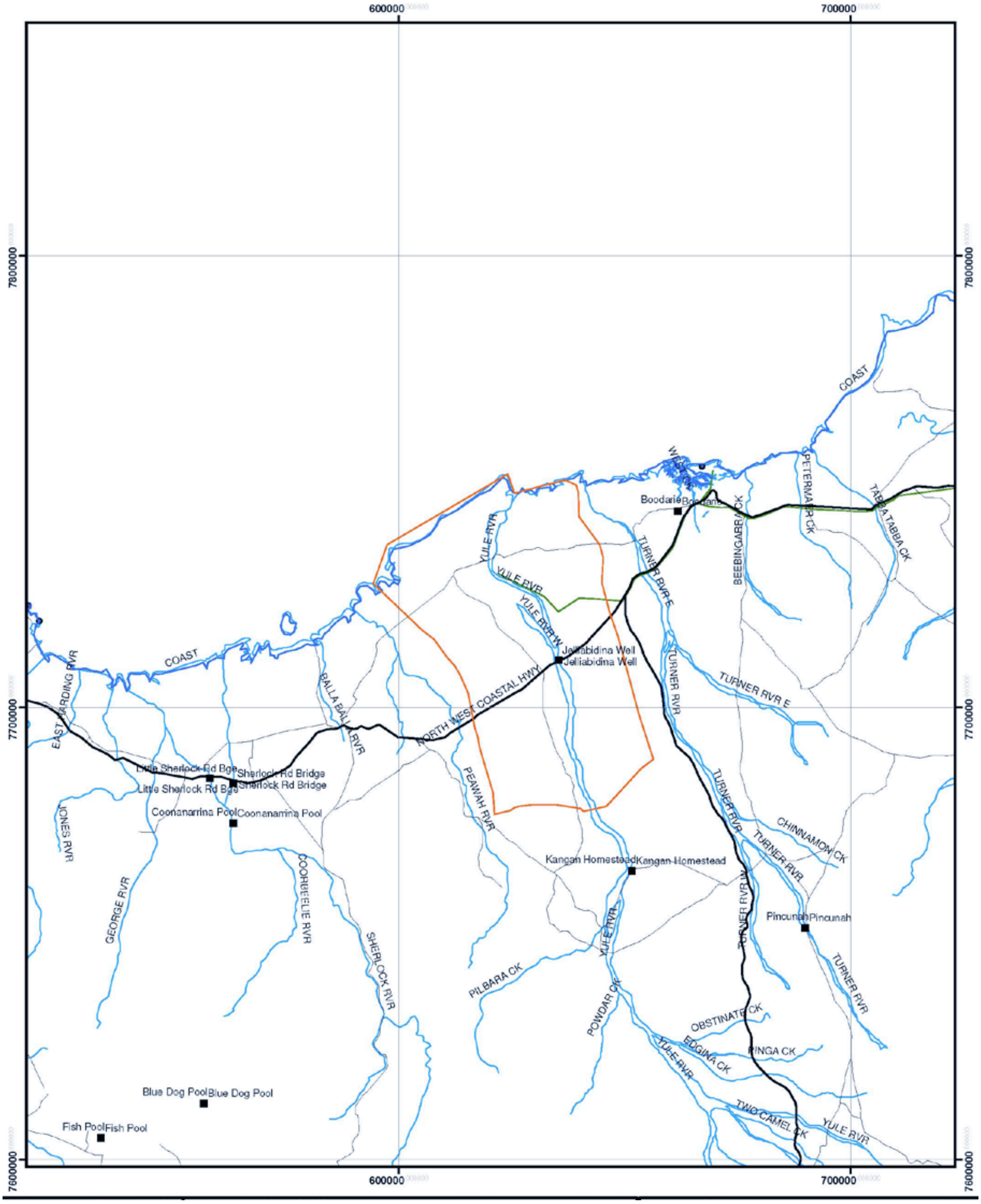

Figure 4.8. Location map showing the extent of Lower Yule groundwater model (MHW, 2010b)

Localised recharge and discharge

River recharge was simulated using the 3rd kind boundary condition of FEFLOW as described in MWH (2010b). Recharge was assigned through zones and rates within each zone were determined on a formulaic assumption using a transfer coefficient which was calibrated. In the model river recharge was estimated as a percentage of the total flow in the river channel divided by the area over which the recharge was calculated. Equations used for estimating the recharge from the surface water body, through the main and secondary river channels and by flooding between river channels on alluvium aquifer are given in MWH

(2010). Similarly an empirical formula was developed for simulating evapotranspiration. Lee Linn Pool had a recharge boundary condition during river flow and an evaporative boundary condition during no river flow.

These calibrated groundwater models will be used to project future groundwater levels under a range of future climate projections and assess the impacts on other parts of the water balance and on localised groundwater recharge provided the conceptualisation of surface water – groundwater interactions is adequate. The methods for quantifying and improving surface water – groundwater interactions in areas covered by existing groundwater models are described in Section 4.7. Groundwater models developed by the mining companies that are partner in this project will also be used for groundwater resource assessments. The modelling scenarios for groundwater modelling are described in the following section. Modelling scenarios

Using the calibrated and validated models the behaviour of groundwater systems across the modelled parts of the Pilbara water resources project area will be assessed under each of the following scenarios. Land use, soil type and groundwater abstractions will remain unchanged under all scenarios except the future land development (Scenario D) in which groundwater abstractions will increase to full allocation levels. Therefore climate will be the only variant among various scenarios except Scenario D.

Historical climate and current land development (Scenario A)

A review of historical climate trends in the Pilbara will be conducted to select the historical climate period (Scenario A) as described in Chapter 2 of this report. For the groundwater modelling, the selected historical period climate will be examined using consecutive sequences of y years duration from each representative weather station in each of the climate zones. The rainfall data from these sequences will be ranked from lowest to highest and the 50th percentile sequence selected. Once the 50th percentile sequence is selected, the remaining years (historical period – y years) of the climate data for that sequence will be added to make the historical climate Scenario A. The step-wise procedure is detailed below.

The y-year rainfall sequences will be ranked from lowest to highest across all climate zones. Ranking of sequences in this manner makes it possible to get a consistent climate series applicable to the whole project area, rather than different sequences for different climate zones.

A second analysis will use a Z-score, a measure of how far each value is from the mean value assuming a normal distribution. This measure is useful for comparing populations with different means and standard deviations, such as these data. The Z-scores will be summed over all climate zones for each climate sequence. The 50th percentile rainfall sequence will be selected. Comparison of the Z-score and absolute value rankings will help choose the 50th percentile rainfall sequence.

Recent climate and current land development (if required)

The historical climate data of the Pilbara will also be analysed to assess if this scenario is required and to select its climate period, if required. The analysis of the historical climate is described in chapter 2 of this report. Climate data for the selected period will be extended to 2050 if there is a valid justification for this scenario. The scenario climate data will be used as input in the VFM-coupled groundwater modelling to simulate groundwater levels until 2050 and in the WAVES modelling to estimate recharge rates until 2050 with the conditions in 2030 and 2050 being reported.

Future climate and current land development (Scenario C)

The climate sequences for the future climate will be derived from historical climate data modified by GCM predictions of the annual patterns and statistics for the year 2030 and 2050 under different future global warming trends. It will be based on 15 Global Climate Models (GCMs) and two global warming scenarios (1^{o}C and 2^{o}C) to account for IPCC AR4 (or AR5) projections representing median scenarios applicable to 2030 and 2050. In total there will be 30 (2 x 15) GCM series from which the future climate data will be derived. For each of the two global warming scenarios, the mean annual rainfall over the region for each of the 15 climate series will be determined. The resulting values from each of the 15 climates will be ranked separately for the two global warming scenarios. So there will be 15 recharge rankings in total (one for each

GCM) for 1°C global warming scenario (2030) and 15 for 2°C global warming scenario (2050). The procedure for the 2030 Cmid GCM and climate selection is detailed below. The same process will be used for determining the 2050 Cmid climate data.

The first step will be to select a representative GCM for the Cmid climate. For this, the annual rainfall will be determined for each of the 15 GCMs in each climate zone assuming +1°C global warming. An average of rainfall from all climate zones will be determined for each GCM. From the median ranked GCM and the GCM with rainfall closest to the overall average, a representative GCM will be selected.

Charles and Fu (2009) ranked the GCMs used in IPCC4 by their ability to reproduce various climate metrics across Australia, the Pacific and Indian Oceans, and globally against 10 criteria. For this project, all GCMs that fail more than half the criteria will be discarded, and a representative GCM for the region will be selected from the remainder.

The next step will be to select a historical climate sequence from which future climate will be derived by applying scaling factors. The annual rainfall will be determined for climate sequences modified by the selected GCM climate statistics of 2030 under +1°C global warming. The y-year sequence will be selected based on the full spread of values from best GCM.

Following the same procedure and based on rainfall rankings, the GCM will be selected for Cmid 2050 climate under +2°C global warming. Ranking y-year sequences of average rainfall, the modified climate of chosen y-year sequence will be selected as the representative period for simulation of the 2012 to 2050 for future climate scenarios.

Future climate and future land development

The climate data for this scenario will be the same as for Scenario Cmid. This future climate will be used with the future land development and defined as Scenario D. Any future land developments will be identified and implemented in the Scenario D. In the groundwater model areas where current groundwater abstraction is below 2011 allocation limits it will be increased to full allocation levels from the start of 2012.

4.6.8 SCENARIO DETAILS FOR GROUNDWATER MODELLING

The steps involved for the scenario modelling in areas of existing groundwater models are laid out below:

1. The accuracy of surface–groundwater exchanges will be assessed by reviewing all relevant data and conceptualisation of surface water – groundwater interactions in the existing models. An improved conceptualisation will be included if required and models recalibrated if relevant data and information are available.
2. The validated models will be used to carry out simulations for Scenarios A, B, C, and D.
3. The groundwater level data will be extracted from various layers of the models to make groundwater level difference maps between 2012 and 2030 and 2012 and 2050 to assess changes in groundwater levels under current and future climate and development conditions.
4. The water balance data will be extracted and all components of the water balance will be checked and compared between scenarios. Components of the water balance will be checked against data from various field and experimental studies.

The storage changes will be estimated in various model layers representing the unconfined and confined systems (if any) and these will then be compared between scenarios.

4.7 Surface water – groundwater interactions

Understanding of surface water – groundwater interactions is important in areas where significant water flux exchange occurs between surface water and groundwater. Their understanding and characterisation is necessary for managing water resources and groundwater dependent ecosystems, and for estimating climate change impacts on riparian systems. Quantification of fluxes to and from groundwater system is also necessary for an accurate account of both surface water and groundwater resources.

The term localised recharge refers to concentrated recharge to groundwater from depressions in surface topography, such as streams, lakes and depressions. The term localised discharge refers to discharge from groundwater to depressions in surface topography, such as streams, lakes and depressions.

There are extensive river and creek systems in the Pilbara region which only flow during and after major storm and cyclones. The frequency of these events varies greatly. For example, the De Grey River flows for about 2 to 4 weeks 2 to 3 times each summer. These events cause extensive flooding of the rivers and streams, and inundation of floodplains which recharges underlying alluvial aquifers. Due to the high permeability of the alluvial aquifers these are usually filled from localised recharge. The frequency, duration and volume of surface water flows often determine the timing and amount of recharge. At places these streams and rivers are incised into the alluvial aquifers. Due to shallow groundwater levels surrounding the streams and rivers. discharge occurs to many pools within the stream and river systems. Discharge also occurs via evapotranspiration by groundwater dependent vegetation in areas with shallow watertables. Understanding, characterising and quantifying surface water – groundwater interactions in these systems is critical to determine the nature of interactions, the frequency of aquifer filling, and the rate and volume of flux exchange. It is also necessary to estimate the river flow thresholds for full aquifer recharge, the impact of extensive droughts and no flow periods on localised recharge, the impact of flow duration, frequency and volume on the rate and volume of aquifer filling.

Groundwater models that account for surface water –groundwater interactions between rivers and streams and groundwater in alluvial aquifer systems have been developed for parts of some alluvial systems. It is unclear at this stage if the conceptual models from which surface water – groundwater interactions have been built have sufficient data and whether the knowledge and software platforms are able to accurately reproduce the interactions. An initial task will be to review the conceptualisation of surface water – groundwater exchanges in these systems based on the available data and information. We will then review the groundwater models to determine if they are adequate at representing the up-to-date conceptualisation and properly deal with hydraulic coupling. If it is found that they are accurate the models will be modified provided more recent data and information supports such a strategy. This will also require recalibration of these models. The final step will be to run these models suing the agreed climate and development scenarios.

In areas where no groundwater models are available, we will review all available historical data including flow gauging, flow duration, frequency and volume, groundwater monitoring, hydrochemistry to build conceptual models of the key surface water – groundwater interactions. Based on this review it may also be possible to select and apply suitable localised recharge and discharge estimation methods.

4.8 Groundwater assessment levels

Groundwater assessment levels are defined by considering the minimum standard required for different priorities and levels of confidence in the outputs.

The following criteria will be used for the assessment ranking:

- complexity of any numerical modelling used and whether it modelled the key processes which are operating
- nature of, and confidence in, any extraction data used
- distribution of observed data both in space and time
- availability of independent data to support parameterisation
- peer review

Based on the above criteria the following assessment standards will be used for various areas.

Very thorough –The areas covered by the complex groundwater models will qualify for the highest standard of analysis if they fulfil the following conditions otherwise a lower level of assessment will apply.

- The numerical groundwater models have been calibrated using spatially well distributed long-term historical data.
- The calibration period for the models is long enough to capture the major changes in hydraulic conditions within the model domains.
- Extraction data have been metered over a long period of time. The hydrogeological parameters used have been derived from sufficient field measurements.
- The information and data about surface-groundwater interactions is sufficiently accurate.
- The model has been extensively used and its outputs have been reviewed independently.

Thorough – This second level of assessment will be applied if the following conditions are fulfilled.

- Relatively less complex numerical models have been developed.
- The hydrogeology of most parts is well known and adequately represented in the numerical model.
- The extraction data are less reliable.
- The model calibration is generally good except few areas of poor calibration.
- The information and data about surface-groundwater interactions is reasonable.
- The model calibration is generally good.

Moderate – This level of assessment will be applied to the areas where there are no groundwater models. The groundwater models have not been developed due to a lack of hydrogeological and other necessary data. The groundwater resources have not been evaluated in any detail and the extraction data, where available, are less reliable. The moderate level of assessment will be based on groundwater recharge and discharge mechanisms (recharge modelling), conceptualisation of surface water –groundwater interactions, and aquifer characterisation.

4.8.1 CONFIDENCE IN GROUNDWATER MODELLING AND ASSESSMENT

The evaluation of the level of confidence in the groundwater modelling and assessment will also be undertaken by considering the following factors:

- Groundwater model availability
- Maturity and external review of a groundwater model
- Independent water balance data (groundwater abstraction, drain flows, hydrological data availability, accuracy, length of record, reliability)
- Level of understanding of the area's hydrogeology
- Adequacy of representation of the hydrogeology in the model
- Number of bores used for model calibration, their location and formation used for monitoring
- Measured and calculated water level difference and trends and Root Mean Square errors
- Comparison of modelled recharge with other independent studies
- Independent checks of model results

A confidence map will be prepared cumulating the input of all of the above factors.

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5 Groundwater dependent ecosystems

High variability in environmental water availability in Pilbara, both spatially and temporally, has led to the development of unique ecological systems in the region. The prolonged dry seasons and occasional floods resulted in a significant level of groundwater dependency of local vegetation, subterranean, in-steam and terrestrial fauna. Understanding of their ecological water requirements is particularly important in setting rules around water extraction, diversions and its disposal during mining activity, especially when mining takes place below the watertable.

This part of the project, Groundwater Dependent Ecosystems (GDEs), addresses the question "How sensitive are GDEs in the Pilbara region to climate variability and climate change" by assessing climate-induced environmental risks and impacts on the spatial extent of the GDEs occurrence. It is acknowledged that in some circumstances surface water may provide the water sources to ecosystems, and where relevant this will be investigated. However in the climate conditions such as in Pilbara, groundwater is likely to be the major environmental water sources, and as such a term "GDEs" will be used in the following section.

Within the project, GDEs are referred to as ecosystem associated with groundwater dependent terrestrial vegetation (GDV) and river pools, which metrics can be identified and monitored using remote sensing techniques. The methods of the assessment of climate-induced environmental risks and other impacts based on remote sensing (RS) techniques allows the analysis of historical satellite datasets covering large areas at low cost. Historical datasets can be used for investigating interaction between annual climatic cycles and flooding events and land cover dynamics in the past, allowing for analysis of their relationships. The GDEs metrics, which can be identified using remote sensing techniques, will include the area of GDE-related land cover classes, multispectral indices and other RS products, specific for those classes, and their temporal and spatial dynamics. Analysis of individual species response to the changing climatic or land sue conditions within the habitat falls outside the project scope, though were possible the critical thresholds can be introduced for an assessment of the ecological risks resulting from changes in those conditions.

The existing GDEs data for the region will be summarised with intent to collate sufficient information for RS GDEs metrics interpretation in terms of their ecological characteristics and dependency on water regime at selected locations. This will allow establishing the relationship between hydrological or hydrogeological observations (e.g. changes in groundwater depth or changing in river flow), RS metrics and the ecological thresholds, defining the risks to GDE habitats from changes in the water regime.

RS techniques are best used if their outputs can be validated by on-ground measurements or other data (e.g. model predictions). Groundwater modelling in selected aquifers as well as surface water modelling will facilitate the analysis of the historical changes in ecohydrological conditions, allowing development of a relationship between observed changes in terrestrial vegetation, pools persistence and changes in groundwater and surface water conditions. Such will be used to estimate projected climate change impacts on significant ecological assets. Following the discussion with the project partners, it is anticipated that methodology will be initially focused on the most ecologically significant regions (such as Fortescue Marsh, Mill Stream and Lower De Grey catchments). However data availability of GDEs ecohydrological characterises, describing the cause-effect relationship between the hydrological cycle and ecological systems, may limit the quantitative analysis at the regional scale. The project aims to explore the opportunities to extrapolate the local knowledge to a greater regional scale.

The research in this part of the project are closely linked with the other project activities (Figure 5.1) and will rely upon their results, particularly when ecohydrological conditions of identified ecosystems are assessed and when the climate change projection are made. The summary of the activities within this part of the project is illustrated in Figure 5.2, which cover four stages of the analysis. Those activities are described in the following section of this report, including regional GDEs assessments (Section 1), GDEs ecohydrological characteristics (Section 2) and inundation (Section 3), future climate change and development impacts on GDEs (Section 4), following by a discussion on the limitation and uncertainty of the proposed methods (Section 5) and main deliverables associated with this part of the project (Section 6).

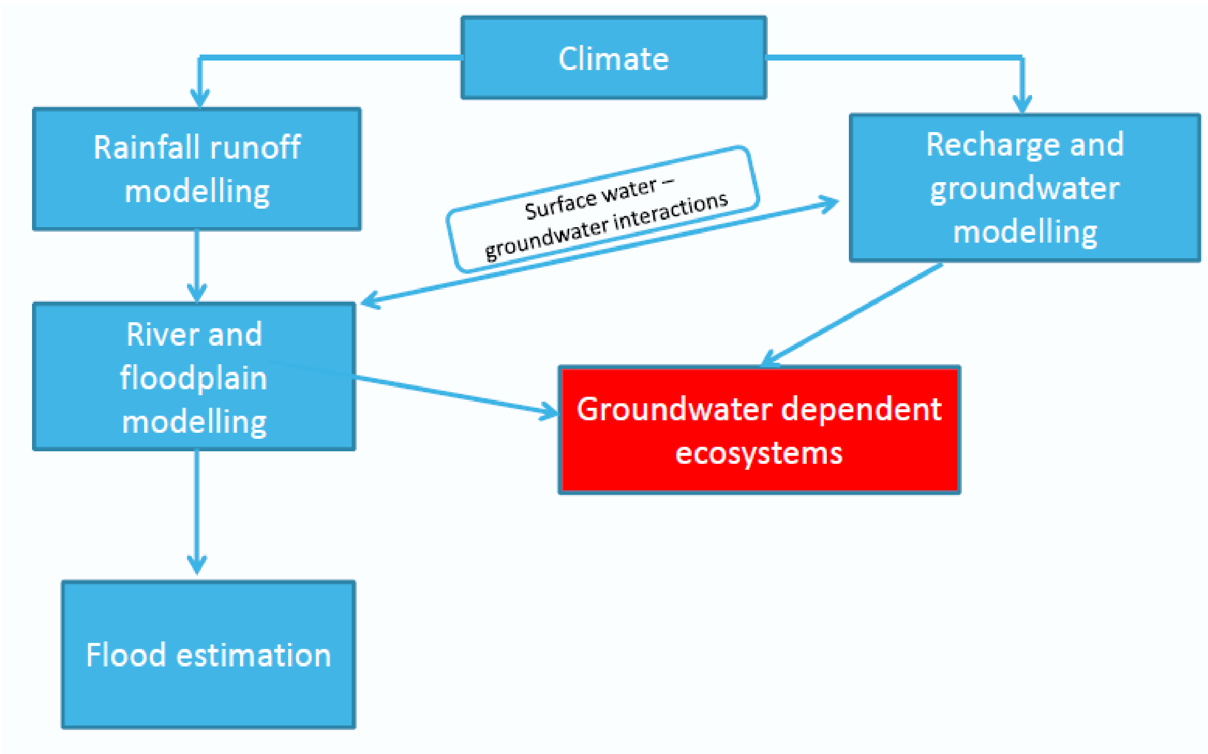

Figure 5.1 The relationship of this part of the Assessment to the rest of the Pilbara Water Resource Assessment

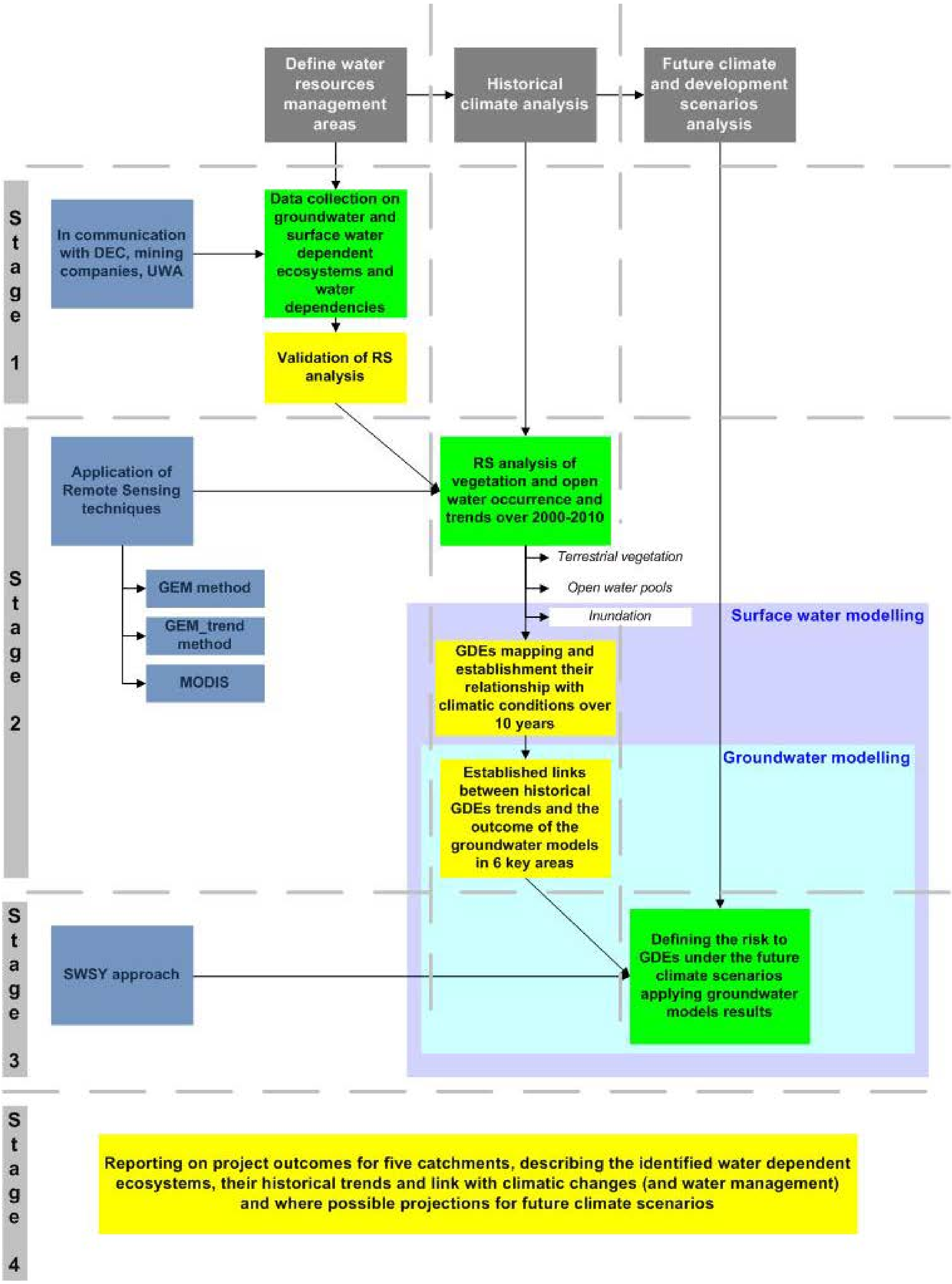

Figure 5.2 The framework of the WDEs assessment

5.1 Regional assessment of groundwater dependent ecosystems

Groundwater dependent ecosystems (GDEs) in the Pilbara region considered in this assessment include terrestrial and riparian vegetation and in-stream habitats, largely associated with the areas of localised groundwater discharge (e.g. springs) or diffuse groundwater discharge (as evaporation or evapotranspiration from shallow watertable). Streamflow in the Pilbara region is extremely seasonal and many species are restrained to refugia around riverine pools. The environmental stressors, associated with changes in groundwater levels, pool size and volume as well as changes in pool's water quality, may result in significant negative changes in aquatic habitat quality and suitability as well as terrestrial and riparian vegetation degradation.

One of the most important groundwater replenishing mechanisms in the region is floodplains inundation, which support the floodplain vegetation and their ecological functions over prolonged dry periods. The frequency and the extent of the flood related inundation area are important aspects of environmental water availability, which may be greatly affected by changing and variable climate. The dry periods between floods and inundation are also an important driver of ecosystems productivity.

In parts of the region mine dewatering is also affecting the availability of environmental water. Discharge of groundwater, generated by mining below the regional watertable, increases the connectivity of some river reaches. This can introduce otherwise uncommon species which can pose a threat to the local fish communities. On the other hand, dewatering may lead to reduction in groundwater discharge to rivers and lowering the watertables, affecting groundwater availability for environmental use. Therefore, both climate variability and mining operations of dewatering and mine water disposal may lead to alteration of water regime leading to changes in water availability for groundwater dependent ecosystems.

Therefore it is important to determine the extent and historical variability of groundwater dependent vegetation and pools. Understanding the spatial and temporal dynamics of these areas may help identify regions which are most resilient to climate variability (i.e. act as refugia). Focused on the above, this activity will not specifically include assessment of water quality and habitat suitability due to changes in water availability.

The main tasks of this activity are (Table 5.1):

- Task 1-1: summarise existing knowledge on groundwater dependent ecological assets in Pilbara;
- Task 1-2: map groundwater dependent ecological assets, using the existing data and employing remote sensing techniques;
- Task 1-3: define aspect of historical variability groundwater dependent ecological assets, both in-stream pools and terrestrial vegetation.

The outcomes of this activity will include:

- collated and mapped information available for the Pilbara region;
- a map of high likelihood of GDEs habitat occurrence (including GDVs and pools; inundation is discussed separately in Section 5.5.3); and
- a map of historical changes in GDEs habitat occurrence (including GDVs and pools; inundation will be discussed separately in Section 5.5.3).

The proposed methods for each of these tasks are described below.

5.1.1 SUMMARY OF GROUNDWATER DEPENDENT ECOLOGICAL ASSETS IN THE ASSESSMENT AREA

The current knowledge of GDEs in the Pilbara catchments will be reviewed; their occurrence and, where possible, their current and past status and condition. Important habitats will be located by searching for Ramsar wetlands, Directory of Important Wetlands, the Register of the National Estate, Fish Habitat Areas, National Parks and Nature Reserves, information available from Western Australia Department of Environment and Conservation, mining companies, universities and environmental consultants as well as by seeking expert and local knowledge of key ecological assets that warrant recognition. In collaboration with the project partners, we will summarise our findings on the GDE ecohydrological conditions (or relationship between ecological characteristics of GDE habitat with groundwater and surface water regime) in the study catchments, focusing on key environment assets.

Table 5.1 Input, scale, methods and outputs for regional GDEs assessment

KEY SCIENCE QUESTION	INPUT	SCALE	METHODS	OUTPUTS AND LINKS TO OTHER ACTIVITIES
What are the key environmental assets in the Pilbara? How can they be prioritised? What are the key refugia and their ecological values?	• Published data • www.website.com	Catchment	Literature review and collation of information	• List and map of known GDEs in Pilbara catchments
Where groundwater dependent vegetation occurs? How does the extent of these habitats change over time?	• Satellite imagery • Maps of the known GDEs	Catchment Landsat spatial resolution (25-30m)	Adaptation of groundwater ecosystem mapping (GEM) method	• Areas of likely GDEs occurrence • Inter-annual variability of GDEs extent
Where are the key refugia locations which persist year after year that need to be protected?	• Satellite imagery • Maps of the known GDEs	Full river length or just selected river reaches? Pools	Analysis of remotely sensed images	• Locations of pool refugia • Inter-annual variability of pool extent
What are the key water sources supporting GDEs (groundwater, surface water, flooding)?	• Published data • www.website.com	Catchment	Literature review and collation of information	• Developing of the database attributes for the identified WDEs

5.1.2 MAPPING OF GROUNDWATER DEPENDENT ECOSYSTEMS

The approach to GDEs mapping will be based on adaptation of known RS techniques to evaluate the likelihood of GDEs occurrence, employing analysis of the temporal and spatial changes in multispectral indices of the land classes in response to changing climatic conditions. Though more detail discussion on ecohydrological metric of the identified GDEs will be provided in the following section, some aspect will be used for their delineation at this initial stage of the research.

The ***G***roundwater dependent ***E***cosystem ***M***apping (GEM) method (Barron et al., 2012), a simplified version of which was adopted in the NWC GDE Atlas project (ref), defines vegetation and surface moisture response to seasonal drying conditions using a pair of Landsat images acquired at the end of the wet and dry seasons of a single year. The method is based on the assumption that due to limited precipitation over the dry period, soil moisture stores would be depleted and the areas that maintain high greenness and/or wetness are likely to have access to either groundwater or anthropogenic water sources. The general concept of the GEM method is summarised as follows:

- Areas where vegetation access to groundwater is permanent are likely to sustain comparatively high levels of greenness (amount of green vegetation) and wetness (surface moisture) even after a prolonged dry period. The multispectral indices Normalised Difference Vegetation Index (NDVI) and Normalised Difference Wetness Index (NDWI) derived from satellite images are used for indirect evaluation of greenness and wetness respectively. The areas of invariant greenness and wetness are mapped as GDE related.

- Areas where vegetation access to groundwater is diminishing due to lower annual watertables are likely to show some reduction in the level of greenness and wetness after a prolonged dry period; these areas are also GDE related.
- In areas where the root zone is never connected to groundwater, greenness and wetness measured at the surface can be dramatically reduced at the end of a prolonged drying period due to the complete depletion of soil moisture stores; these areas are not considered possible GDEs.
- Areas that exhibit no or low variation in water content and greenness (as was the case for the first point), but where wetness is consistently high and greenness is consistently low over the dry season are identified as permanent open water bodies. This may suggest that groundwater discharge to these water bodies is possible; and these areas are considered to be GDE related.

The GEM method is a two-step classification procedure. It includes unsupervised classification of remote sensing data applying the ISODATA algorithm (Ball and Hall, 1967; Tou and Gonzalez, 1974) which allows grouping land cover types into classes with similar spectral responses, described by NDVI and NDWI, to water limited conditions. This is followed by an analysis of the identified land cover classes' characteristics in terms of their relevance to GDEs in accordance with the concept described above. The advantage of this method is that it is allows multispectral indices to be used to interpret the temporal and spatial changes in land cover classes in response to limited atmospheric water availability defining those with an access to other water resources during dry seasons (e.g. groundwater or anthropogenic water resources).

Landsat 5 Thematic Mapper datasets will be used for this analysis. The advantage of this data product over other alternatives is that terrain-corrected data can be sourced from the United States Geological Survey archive at no cost (http://glovis.usgs.gov). However, a smaller number of scenes per calendar year is available for downloads prior to 2005 compared with later years. The spatial resolution of Landsat images is 30 m, which is a limitation for the proposed method as some GDEs can be smaller in size.

The Pilbara is covered by 18 Landsat scenes (represented by the following combinations of six paths and four rows in the global grid system (http://landsat.gsfc.nasa.gov/about/wrs.html) (Figure 5.3):

- Path 115 row 74*;*
- Path 114 rows 74, 75, 76;
- Path 113 rows 74, 75, 76, 77;
- Path 112 rows 74, 75, 76, 77,
- Path 111 rows 74, 75, 76, 77; and
- Path 110 rows 75, 76

An example of a land cover classification based on a single dry season analysis is shown in Figure 5.4. Two Landsat images were selected for this analysis: 30th April 2010 and 7th October 2010 from the scene of path 111 and row 76. The classes shown in this figure include vegetation established in gorges, vegetation which is likely to have access to intermittent flow (rivers) and vegetation with more consistent access to water (groundwater). In addition, it also shows the area covered with water during the wet season (*e.g*., Ophthalmia Dam). The results of this classification can be improved by defining the water sources and the level of GDEs dependencies using information about local hydrogeological and hydrological conditions if available. Such analyses will be repeated for selected years to identify the changes in the defined land cover classes' extents.

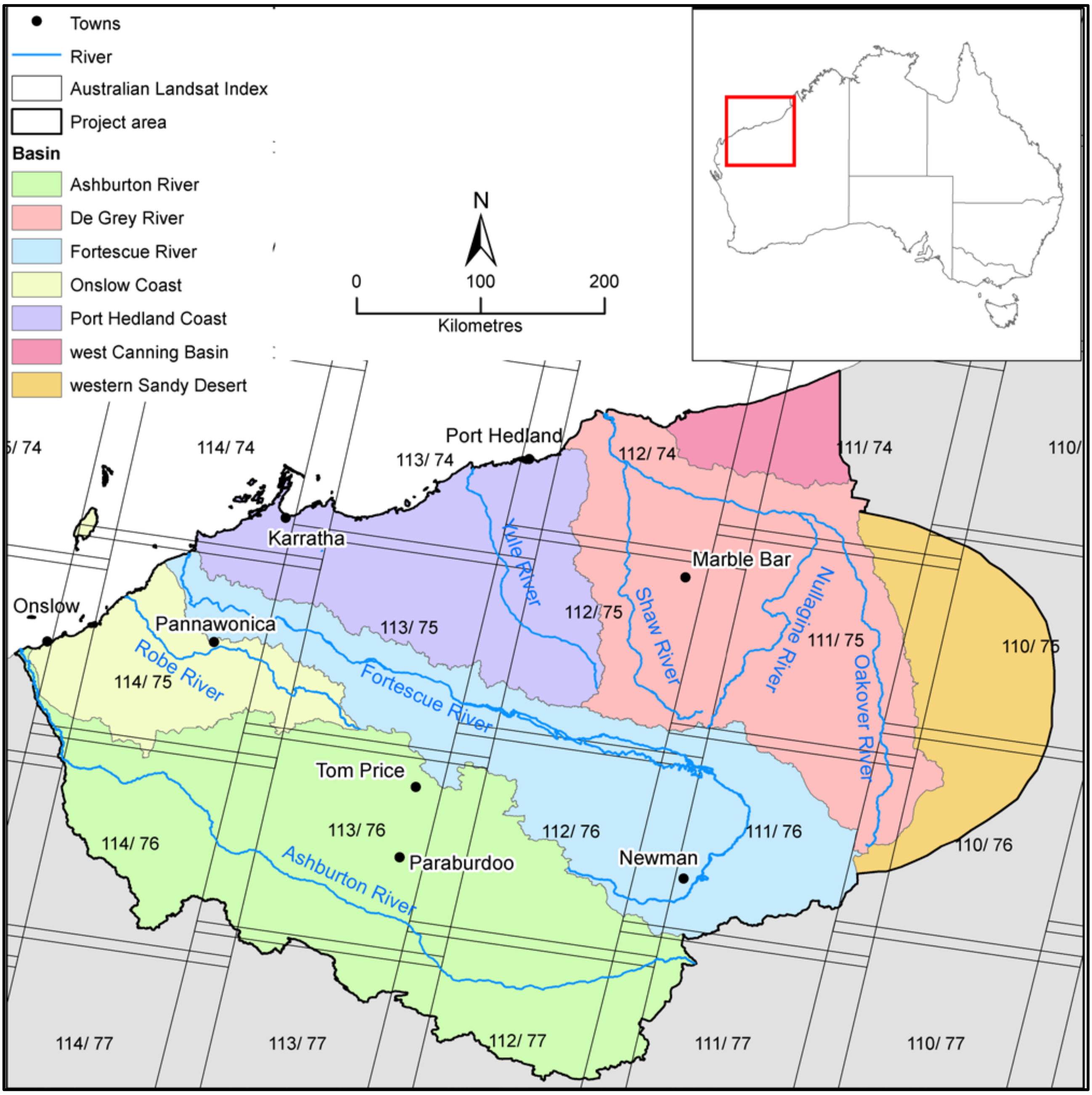

Figure 5.3 Study region and the extent of Landsat coverage

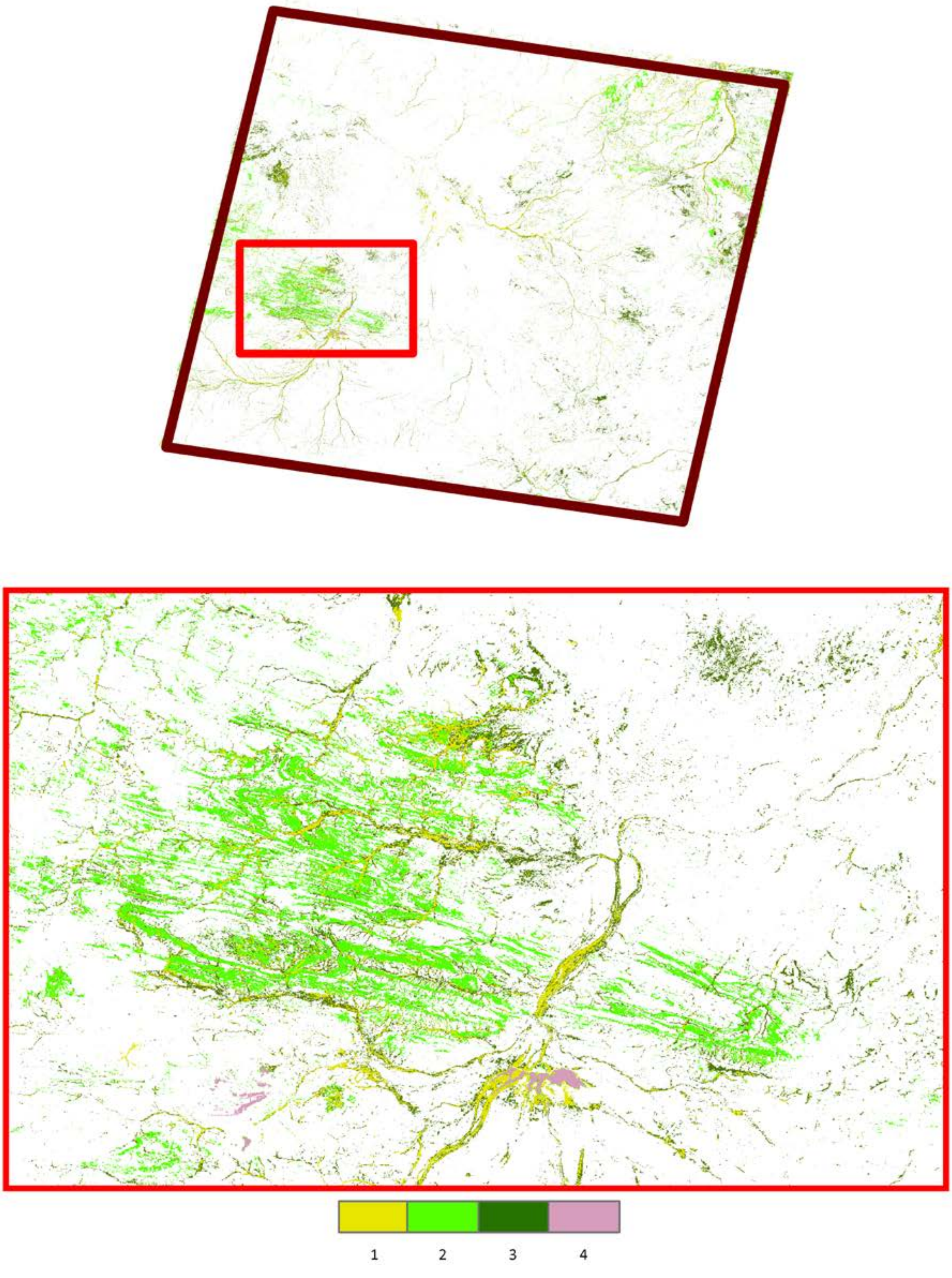

Figure 5.4 Classification example for Landsat scene (Path 111, row 76) showing selected land classes with specific ecohydrological conditions: vegetation which is likely to have access to intermittent flow (rivers) (1), vegetation established in gorges (2), vegetation with more consistent access to water (groundwater) (3), and the area covered with water in the wet season (e.g. Ophthalmia Dam) (4)

Phenological characteristics of the major vegetation types will be also used to generate additional information on the land classes' responses to variability in annual meteorological conditions. This will be assessed using NDVI and NDWI (Gu et al., 2007; Bradley and Mustard, 2008) as well as Evapotranspiration (ET) data (Guerschman et al., 2009) all derived from available MODIS products. Due to MODIS having a lower spatial resolution (>250 m) compared with Landsat, analysis is more suited to GDE land cover classes with comparatively large extents.

Figure 5.5 illustrates the vegetation phenophases as approximated by seasonal variations in monthly averaged MODIS-based NDVI time series. Such time series allow exploring differences in vegetation phenology with and without access to groundwater (Bradley and Mustard, 2008). Time series of NDVI and NDWI derived from MODIS can be used for the analysis of long-term trends in various vegetation land cover classes due to climate variability.

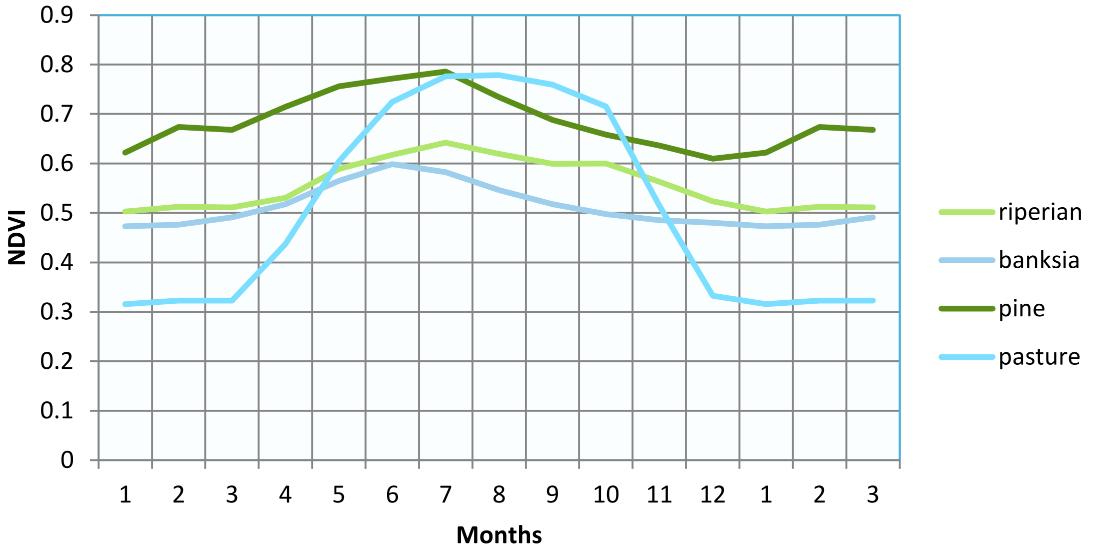

Figure 5.5 Monthly mean NDVI for selected vegetation types in Swan Coastal Plains (from Barron et al., 2012)

5.1.3 HISTORICAL VARIABILITY OF GROUNDWATER DEPENDENT ECOLOGICAL ASSETS

Application of RS techniques allows an analysis of historical variability of the identified GDEs. Considering limitations of RS techniques only two aspects of the GDEs changes will be investigated:

- changes in spatial extents of the identified GDEs (and transition from one land cover class to another); and
- changes in trends of multispectral indices (NDVI, NDWI or others) or other RS products (e.g. evapotranspiration derived from MODIS) which can be linked to the observed changes in GDEs.

The outcome of both analyses will be used to define ecohydrological characteristics of the selected GDEs, where the links can be established between the detected changes and climatic characteristics, ecological monitoring data, groundwater and surface water observations and modelling results, as described in Section 5.2.

Spatial statistical analysis methods will be used to identify the temporal/spatial changes in the extent of GDEs occurrence. To illustrate the approach, Figure 5.6 shows the areas of three GDEs classes in Perth South in 2000-2001 and 2010-2011. Significant reductions in GDE-related land classes was caused by drier climatic conditions and greater groundwater use during these period. According to these results, the areas of vegetation with consistent access to groundwater, vegetation with diminishing access to groundwater, and open waters (wetlands) were reduced by 26%, 56% and 28% respectively, compared to 2000-2001.

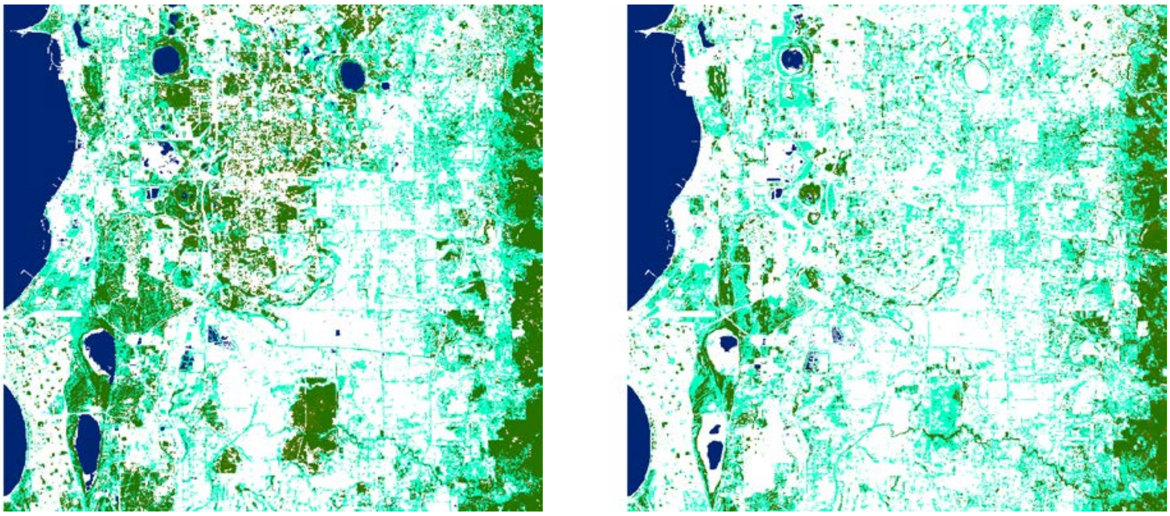

Figure 5.6 Changes in GDE related areas occurred from 2000-2001 to 2010-2011 (South of Perth)

Changes in temporal patterns of multispectral indices may be interpreted as an early warning that the GDEs are under stress and further changes may occur even if the current extents of the GDE-related land cover classes remain unchanged. For instance, changes in NDVI and NDWI for some vegetation land cover classes shown in

Figure 5.7 indicate different responses of tree plantations to climate variability and land use changes in the southeast of South Australia over more than 10 years period.

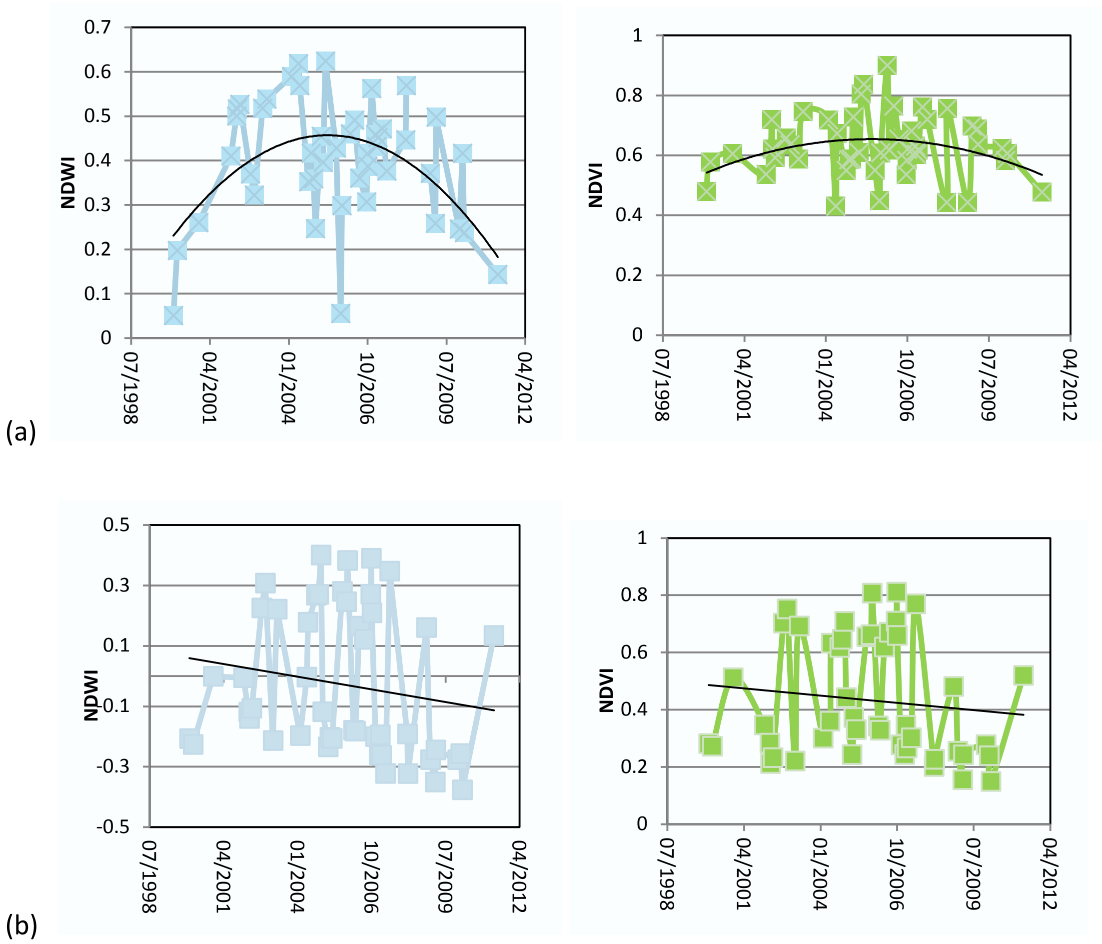

Figure 5.7 Time series of NDWI and NDVI (Landsat derived) estimated for two sites (a and b) located in the Green Triangular, South Australia indicate changes in GDEs by showing consistent negative trends in both indices starting from 2005 (a) and 2000 (b)

5.1.4 RIVER POOLS MAPPING

The GEM method also allows delineating the areas of consistent open water. Other RS based methods available for mapping water bodies will also be evaluated, and the most suitable method for the conditions in the Pilbara region will be selected for the analysis. The areas where previous investigations identified river pools and their importance in maintaining local ecosystems will be analysed. These will likely include the coast aquifers where a river pool analysis using Landsat data was undertaken by the Department of Water.

The first step in in-stream pools mapping within selected river reaches will include identification of the time period when the flow within the channel is close to 'bankfull' and the selection of relevant satellite images. At the bankfull stage, the river channel is essentially a single continuous pool and, as such, its satellite image can be used as a reference for comparison with images of the area acquired at different times. Next, a series of Landsat images observed during dry periods will be selected for analysis of land cover classes associated with open water and identifying as in-stream pools for each image. Finally, an area of in-stream pools will be estimated for each observation, which will be further analysed to define the dynamic of the pools area over dry seasons (and linked with groundwater level or river flow observations where available as described in Section 5.2). This analysis will be repeated for a number of years with contrasting meteorological conditions to identify ranges of the historical variability in these metrics.

An example of pool identification using the GEM method is shown in Figure 5.8 for the lower reaches of the Fortescue River.

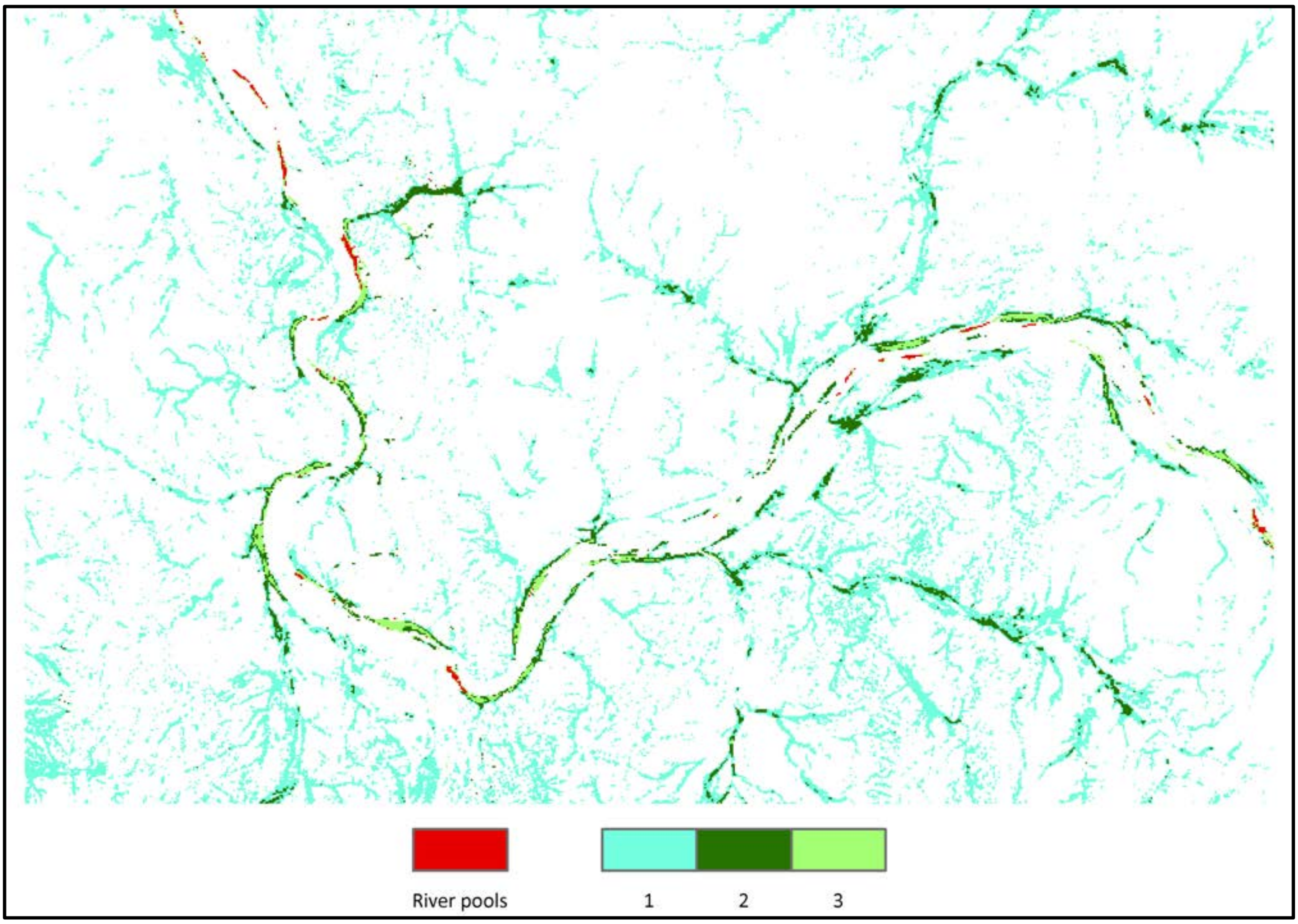

Figure 5.8 Identified GDEs along the lower reaches of Fortescue River; 1-3 – various GDE-related areas, mainly associated with riparian vegetation

5.2 Ecohydrological characteristics of groundwater dependant ecosystems

Following the regional assessment of groundwater dependent ecosystems, this task will be designed to establish the relationship between water regime and identified GDEs and to understand their ecohydrological characteristics. GDE types to be considered under this task include: (1) groundwater dependent vegetation (GDVs) - terrestrial and riparian vegetation; and (2) river pools. Floodplains inundation, especially in coastal areas, is a separate task discussed in a later section.

Water sources available for the regional ecological systems can be seasonal, driven by rainfall, causing seasonal increase in soil moisture and streamflow as well as more consistent and related to groundwater discharge zones (e.g. springs or groundwater from shallow alluvial aquifers). In the absence of other water sources during the prolonged dry season, the latter supports terrestrial or riparian vegetation as well as the river pools. The availability of various water sources leads to different phenological characteristics of the vegetation types dependent on them, which can be determined from time series of RS images.

Spatial and temporal changes in phenological characteristics of the vegetation land cover classes determined from RS data can be verified for known GDVs and linked to the water system supporting these GDVs. When inter-annual availability of those changes is linked to other information (e.g. hydrogeological or ecological), quantitative analysis of ecohydrological characteristics of land classes (or their metrics) can be undertaken.

The natural pattern of the water regime can also be affected by mining water management, when, for instance, mine dewatering leads to a reduction in groundwater discharge to the springs, or to increases in streamflow and downstream groundwater levels when surplus water is discharged to the streams.

The analysis within this activity will be based on identified historical changes in GDEs RS metrics, which will be further linked to the identified changes in rainfall patterns, groundwater or surface water regimes. The main tasks of this activity are (Table 5.2):

- Task 2-1: define the relationship between historical changes in GDVs and climate characteristics, groundwater regime and potentially mining activities; and
- Task 2-2: define the relationship between historical changes in river pools and climate characteristics, surface water and groundwater regime and potentially mining activities.

The outcomes of this research tasks will include the key identified:

- GDV RS metrics and their variability due to the changes in the water regime over the historical period in the Pilbara region; and
- river pools metrics and their variability due to the changes in water regime over the historical period in Pilbara region.

The proposed methods for each of these tasks are described below.

5.2.1 RELATIONSHIP BETWEEN HISTORICAL CHANGES IN GDVS, CLIMATE CHARACTERISTICS, SURFACE WATER AND GROUNDWATER REGIME

RS methods are best used when their outputs can be validated by on-ground measurements. It is likely that sufficient information on both the types of GDVs and their water use sources do not exist on a regional scale. However, it is expected that at some locations such information may become available and an effort will be made to validate the proposed approach for those locations. The initial areas of analysis will include the coastal alluvial aquifers, where groundwater observations and modelling results are available at selected locations associated with inland GDVs in the mining region of Pilbara.

Table 5.2 Input, scale, methods and outputs for ecohydrological GDEs characterisation

KEY SCIENCE QUESTION	INPUT	SCALE	METHODS	OUTPUTS AND LINKS TO OTHER ACTIVITIES
How are the observed changes in GDVs related to groundwater regime? Can such relationship be applied to the future climate and development scenarios?	• Time-series of satellite images • Data generated in activity 1 • Time series of APET, temperature and rainfall • Groundwater and surface water observation data • Groundwater and surface water modelling results	• Landsat scene • Groundwater model domain	• Develop a relationship between the historical variability of GDVs, climate characteristics and groundwater/surface water observations • Develop a relationship between the historical variability of GDVs, climate characteristics, surface water and groundwater modelling results	• Relationship between the historical variability of GDVs, climate characteristics, surface water and groundwater regime • This relationship will also be used for climate change projections
Can the available RS methods assist with identification of the resilience and vulnerability assessment of GDVs?	• Time-series of satellite images • Data generated in activity 1 • Time series of APET, temperature and rainfall	• Landsat scene • Selected GDVs • Groundwater model domain	• Define thresholds in GDVs response to prolonged dry period for selected sites with a particularly high environmental significance • Define thresholds in GDVs recovery after the prolonged dry periods and significant rainfall events for selected sites with a particularly high environmental significance	• This relationship will also be used for climate change projections
Are there relationships that exist between streamflow and pool persistence within a reach? Can these be applied to climate changes and development scenarios?	• Time-series of satellite images • Data generated in activity 1 • Time series of APET, temperature and rainfall • Surface water modelling results	• Landsat scene • Groundwater model domain • Selected river reaches (?)	• Develop a relationship between the historical variability of pools extents, climate characteristics and groundwater and surface water information	• Relationship between the historical variability of pools extents, climate characteristics and groundwater and surface water regime • This relationship will also be used for climate change projections
Can the available methods assist with identification of the resilience and vulnerability assessment for in-pool refugia?	• Time-series of satellite images • Data generated in activity 1 • Time series of APET, temperature and rainfall	• Selected pools • Selected river reaches (?)	• Define thresholds in pools size response to prolonged dry periods for selected sites with a particularly high environmental significance	• This relationship will also be used for climate change projections

Combined analysis of time series of multispectral indices and ET data, derived from both Landsat and MODIS, will be used to identify the relationship between phenological characteristics of the selected vegetation types and their seasonal and inter-annual variability between 2000 and 2012.

This approach can be illustrated using the examples of cumulative MODIS-derived ET over a single year presented in Figure 5.9 for different vegetation types. The plots show that for some vegetation types ET estimates can be greater than for the other by up to 30%. Particularly significant differences in cumulative ET estimates are during dry seasons (here from October to April), where these differences can be increased by up to 50%.

Figure 5.10 illustrates inter-annual variability of the ratio of MODIS-derived annual ET to annual Pan Evaporation for the period from 2000 to 2011. At the start of the observation period the ratio indicates that annual ET comprised up to 50% of the annual Pan Evaporation. Towards the end of the observation period the ratio for vegetation types 1, 4 and 5 has reduced significantly. Such changes are indicative of the changes in land cover, which could be related to alteration in water availability or land use practice.

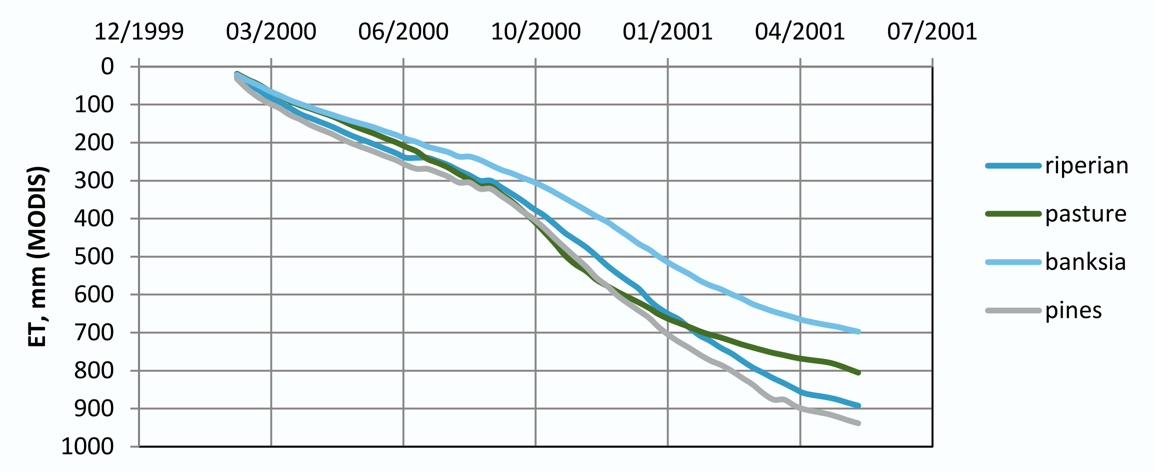

Figure 5.9 Cumulative ET for selected vegetation types (as also shown Figure 5.5)

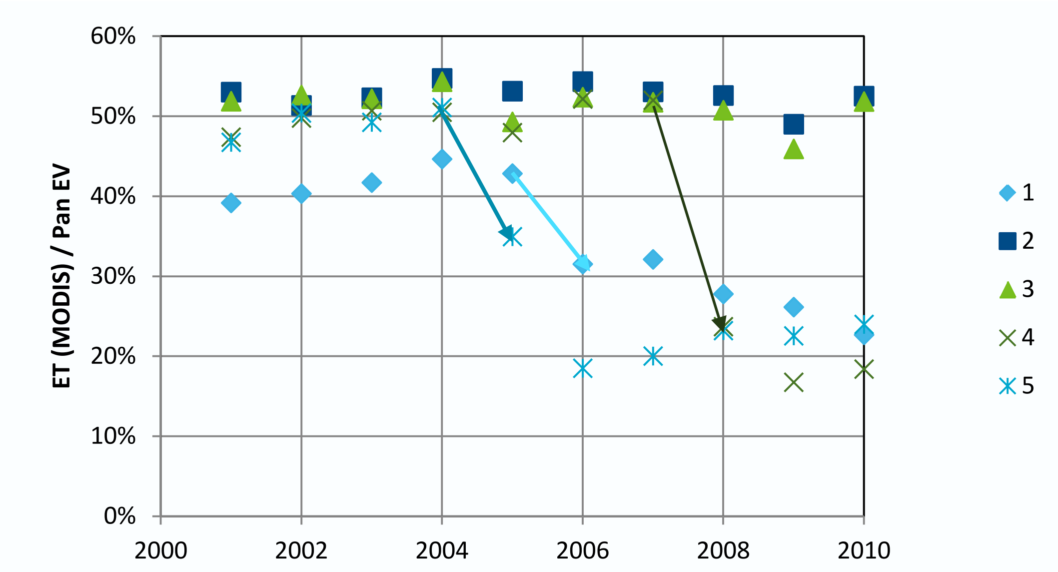

Figure 5.10 Annual ratio of MODIS-derived ET to Pan Evaporation for a selection of vegetation land cover classes; the arrows indicate periods of significant reduction in this ratio

The results of the analysis will be used to assess selected GDVs metrics and changes in these metrics in response to the external stressors: alteration in water availability or land use. These relationships will be further evaluated to define if they are applicable for investigating climate change and development scenario impacts on GDVs and an analysis of the potential risk to GDVs associated with such changes. This will be based on the identification of key changes in GDV characteristics in response to changing water regimes over an agreed historical period (proposed to be at least 12 years from 2000).

5.2.2 RELATIONSHIP BETWEEN HISTORICAL CHANGES IN RIVER POOLS AND CLIMATE CHARACTERISTICS, SURFACE WATER AND GROUNDWATER REGIMES

Similarly to GDVs, on-ground observations of the extent of river pools and their dependency on groundwater or surface water at selected locations is required to interpret and validate the RS data analysis. It is expected that at some locations such information will be available and these will be used to validate the approach in these locations. The areas selected for analysis will include coastal alluvial aquifers where groundwater observation and modelling results are available.

The extents of pool areas identified using RS methods will be summarised for all dates where Landsat images are available, such as illustrated in Figure 5.8. The key parameters for defining the relationships between river flow, groundwater levels and pool metrics will be the pool area, number of pools and length of pools. Similarly, these metrics were used by Close et al. (2012) for analysis of dry-season pool characteristics of the Fitzroy, Daly and Mitchell rivers. Figure 5.11 shows an example of such a relationship.

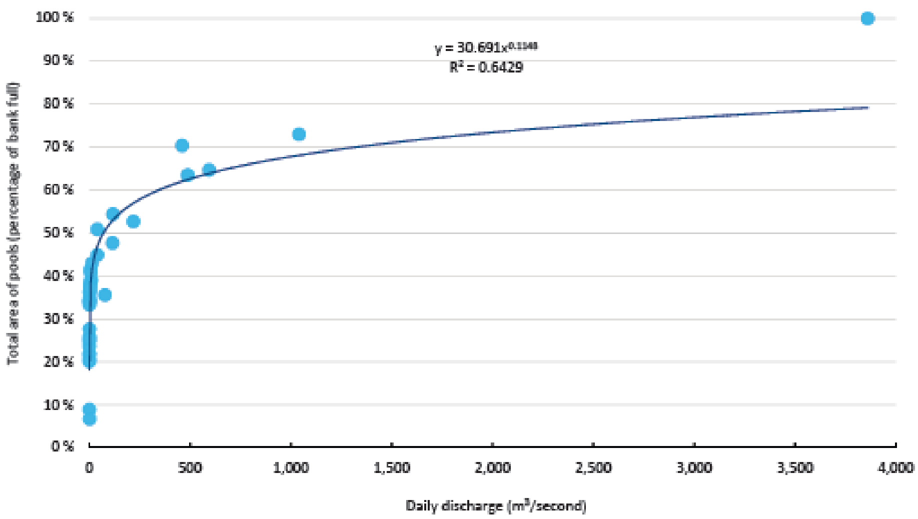

Figure 5.11 The relationship between the total pool area and the streamflow identified at the Fitzroy Barrage during years 2005, 2006 and 2008 (Close et al., 2012)

Where flow data or groundwater level observations are available the relationships between flow, groundwater levels and pool metrics will be quantified for individual years which will then be used to determine if common relationships apply across years. As streams in the Pilbara are highly seasonal, some additional pool metrics may be needed, especially the time since cessation of flow, which can also be used to separate pools mainly dependent on surface water from pools dependent on groundwater. Where observation data are not available, the pools response to variability in climate alone will be analysed using rainfall and evaporation data.

Emphasis will be made on the identification of 'key refugia' within selected river reaches, which are defined as the pools in the river reach, that persist through most or all years. If key refugia exist within these river systems, then it is highly likely that these sites are very important for the survival of many species. It is also possible that such sites are important Indigenous sites. The identification of key refugia can help indicate the area where groundwater management should consider protection of such ecologically significant sites.

The presence of riparian vegetation is important for pool biota as it provides shelter, shading and organic matter input. Hence, riparian vegetation can be considered as a key measure of habitat quality, and therefore additional work will involve identifying vegetation land cover classes that are adjacent to these pools.

The results of the analysis and identified GDE metrics will be assessed in terms of their applicability for investigation in climate change and land development scenarios impact on the key river pools.

5.3 Inundation

Pilbara Rivers can flood during summer. Though flooding can be hazardous for mining and road infrastructure, floodplains inundations provide localised recharge to alluvial aquifers as well as connecting off-stream wetlands to the main river channel. This activity aims to map floods in the selected rivers reaches, initially in the catchments of the coastal alluvial aquifers.

The flood mapping will be based on the RS methods, and where possible, linked to the flood modelling. The main tasks of this activity are:

- Task 3-1: map the extent of the flooding for the areas of the coastal alluvial aquifers, and elsewhere if required;
- Task 3-2: define the effect of flooding on the river pools persistence and other off-stream wetlands (if applicable); and
- Task 3-3: assist the flood and localised recharge modelling in the selected areas.

The results will also be used for river flood modelling, assisting the high flow discharge estimations by the river system models. The proposed methods for each of these tasks are described below.

5.3.1 FLOOD INUNDATION MAPPING USING REMOTELY SENSED DATA

Flood mapping will be undertaken across selected catchments using remotely sensed data which can provide a long-term record of inundation variability (Smith, 1997; Brivio et al., 2002; Overton, 2005; Guerschmann et al., 2009). The main emphasis will be made on coastal aquifers, but similar analyses may be undertaken for other sites.

Daily MODIS satellite imagery (~250 m spatial resolution on the TERRA satellite -called MOD09GA, and (~500 m spatial resolution on the AQUA satellite - called MYD09GA) will be used to produce historical flood maps for the region. These flood maps will be produced using the Open Water Likelihood (OWL) algorithm (Guerschmann et. al., 2009) which estimates the fraction of standing water. Alternatively this can be interpreted as the likelihood that a pixel contains surface water. Where available, Landsat satellite imagery will also be used to assess the extent of inundation within the investigation areas. Landsat provides better information on inundation primarily due to its finer spatial resolution (~30 m). However, Landsat is only available at 16 days frequency, reducing the probability of acquiring an image during peak flooding. Cloud cover during flood events is also an issue.

MODIS imagery will be used to generate individual flood maps for every day in months likely to have a flood (i.e. 1st November to 30th April) between 1st January 2000 and 2012 (e.g. as in Figure 5.12). For each month, daily images will be combined and the OWL algorithm applied. Pixel values range from 0, meaning there is no water in the pixel during the month, to 100, meaning the pixel was completely flooded at some time during the month. Monthly flood maps from those months containing large flood events (e.g. March 2009 or January 2011) will be combined to produce a single map of maximum flood inundation for the region.

This analysis will facilitate quantitative analysis of the hydrological characteristics of floods in terms of the flooding extent, flood frequency, timing and duration. This will provide an input to both the estimation of the localised recharge to the coastal aquifers and to flood modelling.

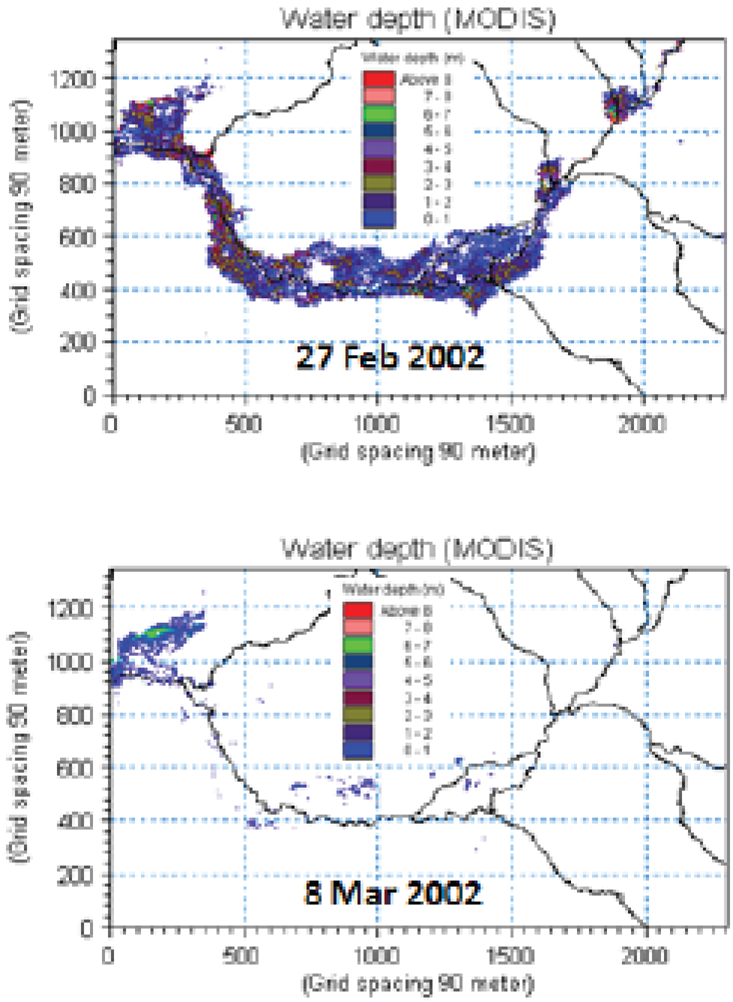

Figure 5.12 MODIS detected inundations in the central Fitzroy (WA) floodplain on 27 Feb 2002 and 8 Mar 2002 (ref)

5.3.2 THE EFFECT OF FLOODING ON THE RIVER POOLS PERSISTENCE AND OTHER OFF-STREAM WETLANDS

Flood analysis using RS methods (Smith, 1997) will assist investigation of the effect of flooding on river pools and other refugia such as off-stream wetlands, and the identification of changes due to variations in the flow regime.

Comparative analyses of river pool persistence after a river flow period with and without extreme events will be undertaken to clarify the effect of floodplain inundation on the pool durativity (Overton, 2005). The key parameters of the river pool dynamics, as described in the previous section, will be tested over dry seasons after flooding and after a wet season without extreme rainfall events. Additionally the examination of the floods effect on pool locations (particularly on coastal plain areas) will be undertaken. It was observed that river beds morphology can be altered due to mobilisation of sand beds during flood events. This may lead to pools sedimentation and "migration" of pools to other locations.

Once the difference (or their absence) is identified and quantified, the effect of this additional component of the catchment water balance on the pools persistency will be adopted for further analysis of climate change events on ecological significant refugia.

5.3.3 CONTRIBUTION TO THE FLOOD AND LOCALISED RECHARGE MODELLING IN THE SELECTED AREAS DATA

The results of this activity will be used to facilitate an analysis of localised recharge in alluvial aquifers to:

- provide an evaluation of local recharge mechanisms (loosing streams and/or overbank flooding), frequencies of flooding and the rates for alluvial aquifers recharge under different climate regimes; and
- develop insights into recharge mechanisms and frequencies for alluvial aquifers replenishment under different rainfall regimes.

5.4 Future climate change and development impacts on GDEs

The identified ecohydrological characteristics of GDEs and their dependency on climatic conditions will be used for an analysis of possible climate change impacts on GDEs. The analysis will be largely based on the results of other project outputs (i.e. projected climate changes and modelled impacts on surface water and groundwater regimes) and on the results of the preceding activities in the regional GDEs assessment. Possible climate change impact on GDEs will be investigated for: (1) groundwater dependent vegetation (GDVs) - terrestrial and riparian vegetation; (2) river pools; and (3) floodplains inundation.

The main tasks of this activity are (Table 5.3):

- Task 4-1: the relationship between GDVs ecohydrological characteristics and climatic characteristics identified in task 2-1 will be adopted for projections of GDVs responses to climate change for the area covered by groundwater models;
- Task 4-2: for groundwater modelled areas, the relationship between total pools area and climatic characteristics identified in tasks 2-2 and 3-2 will be adopted for projections of their responses to climate change. Where surface water is identified as the main water sources for river pools, the links with surface water modelling will be made under future climate scenarios;
- Task 4-3: define the climate change impact on the frequency, duration and the extent of floodplain inundation identified in tasks 3-1 and 3-3.

The outcomes of these research tasks will include:

- adaptation of the key ecohydrological characteristics in the identified GDVs under the historical water regime for the risk assessment of the climate change impact on GDVs for Pilbara region;
- adaptation of the key ecohydrological characteristics in the identified river pools under the historical water regime for the risk assessment of the climate change impact on river pools; and
- a risk assessment associated with the climate change impact on GDEs in the regions where groundwater models or surface water models are available.

The proposed methods for each of these tasks are described below.

5.4.1 CLIMATE CHANGE IMPACT ON GDVS

The approach to estimate possible climate change impacts on GDVs will be based on the identified historical relationship between key GDVs metrics (e.g. total area) and the water regime.

The analysis will allow extrapolation of the identified relationship between GDVs response to climate variability in the past to climate change projections, using groundwater model results in coastal aquifers. This will mainly be based on a risk metric, similar to those adopted in SWSY project, but identified using available information for the region and the results of the Pilbara assessment.

Table 5.3 Input, scale, methods and outputs climate changes and development impact on GDEs

KEY SCIENCE QUESTION	INPUT	SCALE	METHODS	OUTPUTS AND LINKS TO OTHER ACTIVITIES
What are the likely impacts of climate change and development scenarios on GDVs?	• The identified relationship between GDVs ecohydrological response and climate variability • Groundwater modelling results for future climate scenarios	• Groundwater models domain	• The extrapolation of the identified relationship between GDVs response to climate variability in the past to climate change projections, using groundwater model results in coastal aquifers	• Risk maps
What are the likely impacts of climate change and development scenarios on river pools?	• The identified relationship between pools total area and climate variability • Groundwater modelling results for future climate scenarios • Surface water model results for future climate scenarios	• Groundwater models domain • Selected river reaches	• The extrapolation of the identified relationship between pool metrics and groundwater levels or streamflow to climate variability in the past to climate change projections, using groundwater and surface water model results	• Risk maps
What are the likely impacts of climate change and development scenarios on floodplains inundation?	• The identified relationship between frequency, area and duration of floodplain inundation, climate variability and the river flow • Surface water model results for future climate scenarios • Selected groundwater modelling results for future climate scenarios	• Selected floodplains • Groundwater models domain	• The flood modelling will be used under the climate condition projected for the future climate scenario and under various development scenarios.	• Risk maps

5.4.2 CLIMATE CHANGE IMPACT ON RIVER POOLS

A relationship between pool metrics and groundwater levels or streamflow, if developed using the approaches discussed in previous sections, will be used to determine the impact of changed groundwater levels or flows under different climate and development scenarios on dry-season pools. This analysis will simply involve applying the developed relationships to the ensemble of water levels or flows modelled under the various climate scenarios. Increased or decreased flows should manifest themselves in different pool metrics at the end of the dry season.

This analysis will be undertaken for those regions where groundwater models are available (e.g. coastal alluvial aquifers and Millstream, providing pools occurrence has been established for those areas). Where surface water is identified as the main water source maintaining the river pools, the surface water modelling results will be adopted for the risk assessment of climate changes on key river pools under the future climate scenarios. Particular emphasis will be made on 'key refugia'. This will be mainly based on risk metrics, using available information for the region and results from elsewhere in the assessment.

5.4.3 CLIMATE CHANGE IMPACT ON FLOODPLAINS INUNDATION

The historical flood inundation mapping will be used for the calibration and validation of flood modelling (Chapter 3). Under future climate scenarios, simulated streamflow data from the river system models and rainfall-runoff models will be used as input to the hydrodynamic model. This model will be used to project the frequency, extent and duration of floodplain inundation under future climate scenarios. Where the role of groundwater in the inundation process is established (fill-and-spill scenario) groundwater model results will be also adopted to inform flood analysis.

5.5 Limitation and uncertainty of the proposed methods

The results of the proposed analysis will be reported within the likely limitations and uncertainties, defined by the following factors.

- The limitation of the available information suitable for validation of the RS analysis results. This is mainly associated with the extent of known GDEs and quantitative measures of their dependency on groundwater.
- Climate data, both historical and projected. The climate conditions in the region are monitored at the limited number of meteorological stations. Highly variable rainfall, both specially and temporally, limits the accuracy of meteorological data extrapolation. Future climate projections are also challenging in the region, as described in Chapter 2.
- Resolution of RS data and the frequency of their acquisition may also limit the accuracy of the proposed methods, as the highest resolution of the proposed RS data (Landsat) is 30 x 30 m, while MODIS has 250 x 250 m or lesser resolution. It is therefore infeasible that the proposed methods will be applicable for analysis of the land features of smaller areas. Landsat data is also acquire on 16-days basis and is affected by cloud cover.
- The adaptation of the historical ecohydrological conditions within a relatively short time period of historical observation (within the RS data availability) to the analysis of the climate change impact on GDEs may have limitation. Some unforseen impacts associated with the climate changes may be possible.
- Groundwater and surface water modelling uncertainties and limitations may lead to uncertainties in the modelling result adaptation to regional GDEs anlaysis.

5.6 Deliverables

The proposed activities will yield the following deliverables:

- Sections on the possible impact of climate variability, climate change and development on ecologically significant water regime for surface water and groundwater dependent ecosystems in the five river basin reports, the regional summary report and factsheets ;
- Regional methods will be developed that may be applicable at the local scale and used for further monitoring of water dependent ecosystem in the region; and
- Regional mapping of GDEs, river pools and the inundated areas associated with the flooding.

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6 Integration of results into basin-wide reports

6.1 Report structures

The main deliverables in the Assessment will be three to five (depending on how basins are grouped) basin-wide reports which integrate the main findings from the different work areas of climate, rainfall-runoff, river modelling, groundwater and water dependent ecosystems with pre-existing material on each basin (i.e. its geographical setting, land and water use, demographics etc).

Each work area will also have a component of literature review, an analysis of historical data and future hydrological projections. It will also include suggestions about methods that could improve the regional monitoring in each basin. Detailed methodological descriptions and detailed results will be included in technical reports that will be made available on the web.

The strength of basin-wide reports should be the integrative nature of the material in that there are currently no similar reports available for any Pilbara basins. The target audience is well informed non-experts so they need to be relatively easy to read but will include a number of technical terms which will be defined where necessary.

The structure of the reports will evolve as material becomes available but an indicative list of section headings is shown in Table 6.1 to enable comments to be made on their form.

Table 6.1 Generalised structure of basin-wide reports

Cover, Foreword, Table of Contents, List of Figures, List of Tables, List of Abbreviations, Definitions		
Executive Summary		
1	Introduction	
	1.1	Background to the Assessment
	1.2	Objectives
2	Overview of the basin(s)	
	2.1	Climate
	2.2	Physiography
	2.3	Soil-landscapes
	2.4	Land use, water use and demographics
	2.5	Vegetation
	2.6	Water dependent environmental assets
3	Climate	
	3.1	Analysis of past climate and trends
	3.2	Climate drivers
	3.3	Future climate scenarios
	3.3	Drought frequencies and durations
	3.4	Intensity-frequency-duration estimates
4	Rainfall-runoff	
	4.1	Catchment characteristics
	4.2	Review of previous rainfall-runoff analyses
	4.3	Rainfall-runoff models
	4.4	Model inputs and calibrations
	4.5	Rainfall-runoff results, synthesis and discussion
	4.6	Knowledge and information gaps; regional monitoring needs

5 River modelling

- 5.1 River channel and floodplain characteristics
- 4.2 Review of previous river modelling analyses
- 4.3 Basin models
- 4.4 Model inputs and calibrations
- 4.5 River modelling results, synthesis and discussion
- 4.6 Knowledge and information gaps; regional monitoring needs

6 Groundwater

- 6.1 Aquifer characteristics
- 6.2 Review of previous groundwater analyses
- 6.3 Groundwater models
- 6.4 Model inputs and calibrations
- 6.5 Surface water – groundwater interactions
- 6.6 Groundwater results, synthesis and discussion
- 6.7 Knowledge and information gaps; regional monitoring needs

7 Groundwater dependent ecosystems

- 7.1 Ecosystem characteristics
- 7.2 Review of previous analyses of GDEs
- 7.3 Analysis of historical trends in GDE conditions
- 7.4 River and groundwater model inputs
- 7.5 Future projections of GDE status and condition
- 7.6 Knowledge and information gaps; regional monitoring needs

8 Basin-wide synthesis and discussion

- 8.1 Basin-wide trends in hydrology
- 8.2 Cumulative impacts from development
- 8.3 A comparison of projected climate and development impacts
- 8.4 Future drought impacts
- 8.5 Future flood impacts
- 8.6 Discussion

9 Knowledge and information gaps; regional monitoring summary

APPENDICES

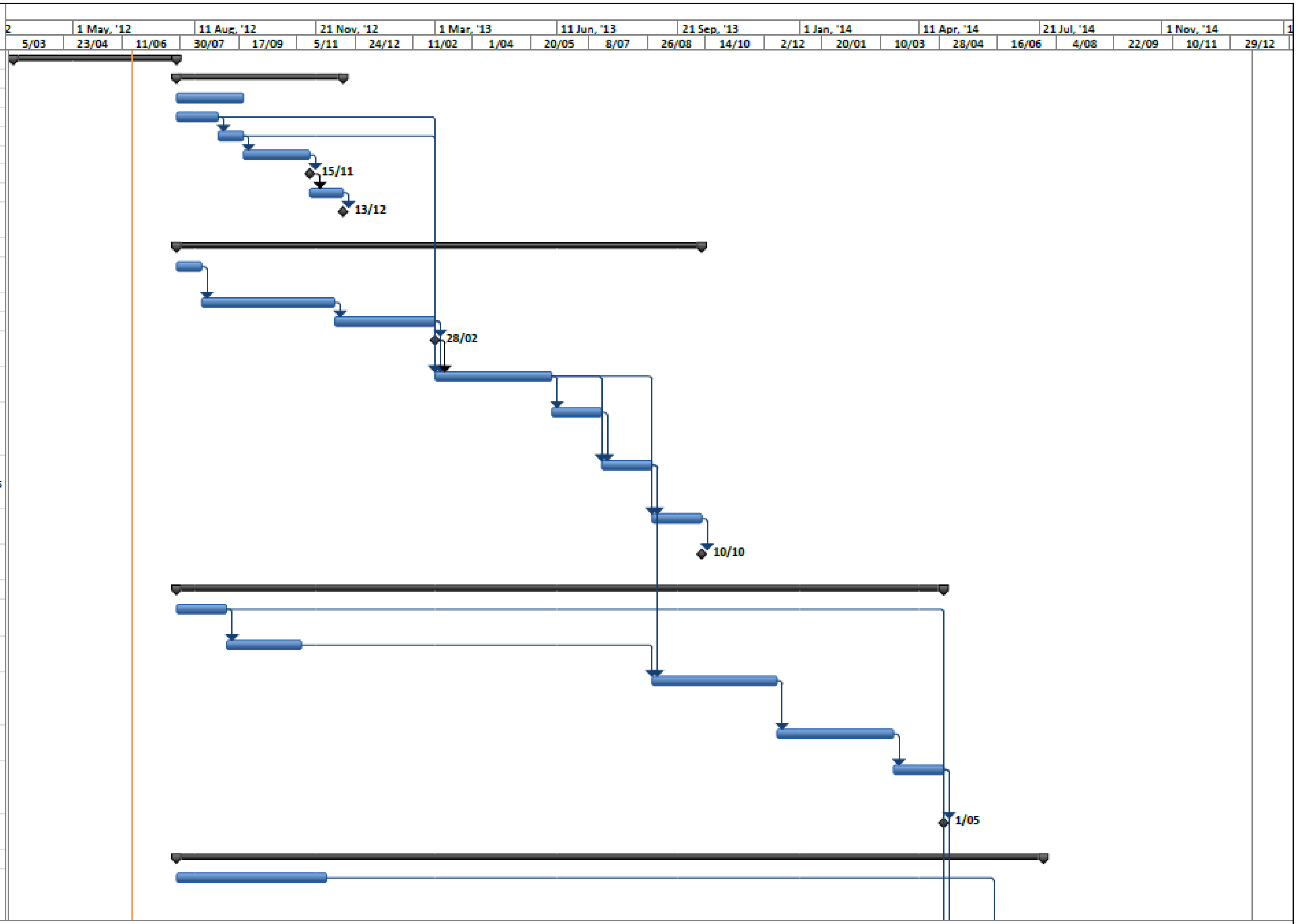
Technical data on climate, rainfall-runoff, river modelling, groundwater and GDEs

6.2 Assessment timeline

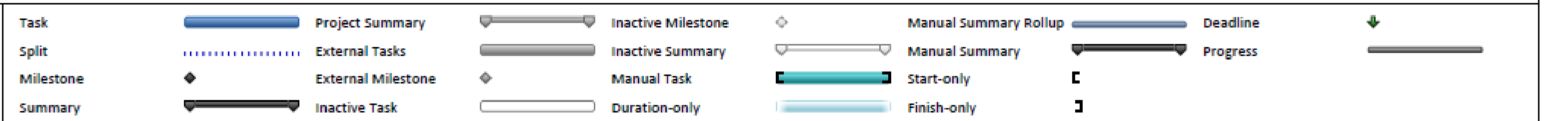
The Assessment requires timely delivery of different products to enable later analysis to be undertaken. The most important is the development of climate scenarios to be used in the rainfall-runoff, river and groundwater models, and the output from the river and groundwater models for analysis of the impacts on the groundwater dependent ecosystems.

A preliminary GANTT chart has been prepared showing the major steps in the Assessment (Figure 7.1). It assumes that the Assessment will be completed by late 2014. It will be important that interim milestones will be met over this period given the interdependencies.

ID	Task Mode	Task Name
1		1 Methods Report
8		2 Pilbara Climate
9		2.1 Historical climate review
10		2.2 Develop scenario datasets
11		2.3 Estimate IDF impacts
12		2.4 Draft report on Pilbara climate
13		2.5 Workshop on climate report
14		2.6 Finalise climate report
15		2.7 Steering Committee approval to release climate report
16		3 Surface water hydrology
17		3.1 Terrain analysis to define catchments and floodplains
18		3.2 Rainfall runoff modelling
19		3.3 River and floodplain modelling
20		3.4 Report on historical hydrology and calibration
21		3.5 Run climate and development scenarios
22		3.6 Report streamflows to compare with dewatering flows and effects on SWD ecosystems
23		3.7 Report floodplain inundation for estimating recharge and GDE impacts
24		3.8 Report sub-daily flood flows for key reaches
25		3.9 Report on surface water hydrology to Steering Committee
26		4 Groundwater hydrology
27		4.1 Define landuse from Landsat TM and soil types
28		4.2 Refine WAVES modelling for Pilbara
29		4.3 Calibrate six DoW groundwater models with WAVES/VFM and floodplain estimates of recharge
30		4.4 Run climate and development scenarios
31		4.5 Report groundwater levels to compare with dewatering impacts and effects on GDEs
32		4.6 Report on groundwater hydrology to Steering Committee
33		5 Water dependent ecosystems
34		5.1 Estimate change in condition of SWDEs from climate and development scenarios



Project: Pilbara WRA Time Plan fo
Date: Tue 19/06/12



Page 1

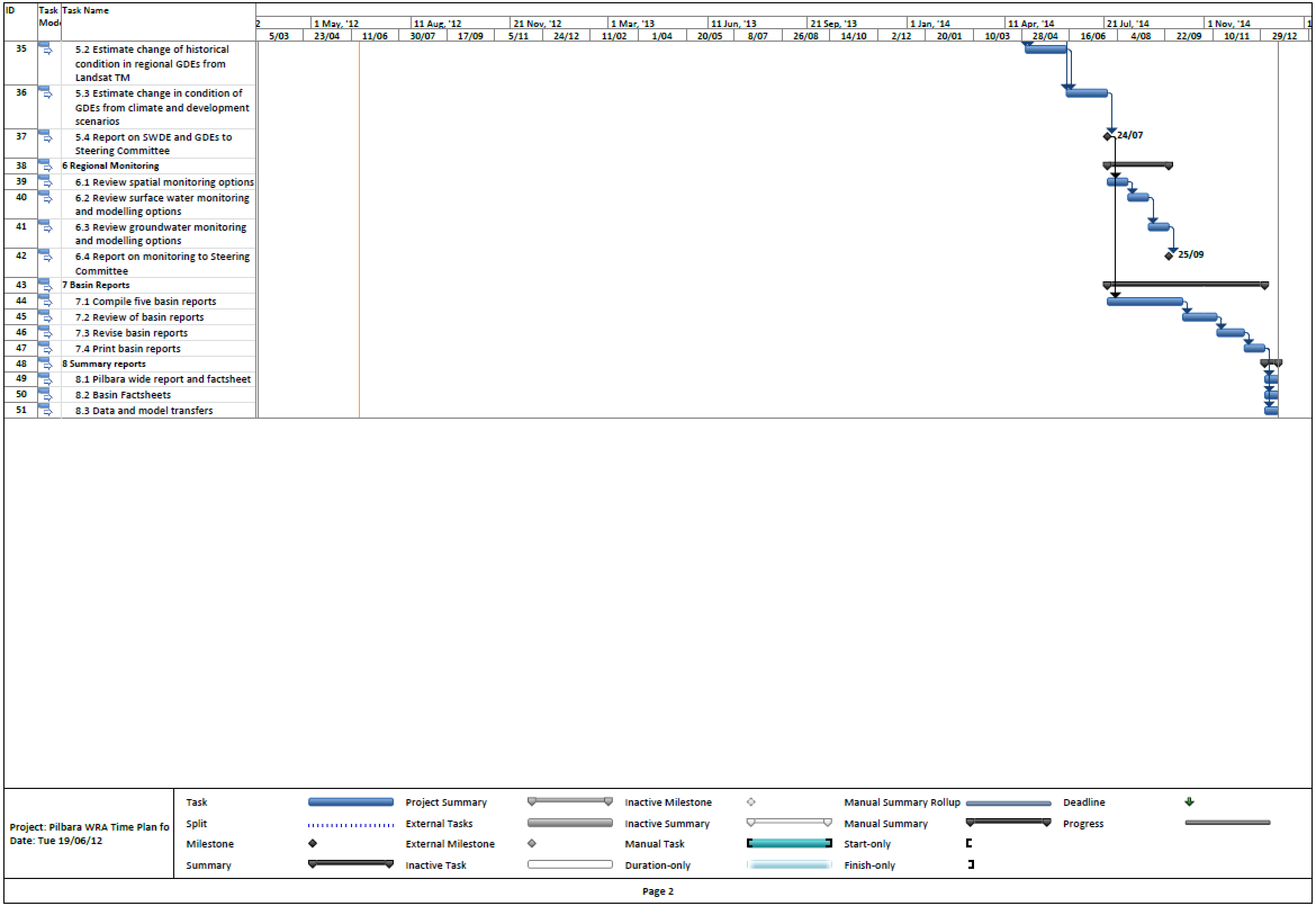


Figure 6.1 Preliminary gantt chart for the Pilbara Water Resource Assessment

7 Data Management

7.1 Introduction

A structured approach to data management is necessary to ensure that all project data is secure, accessible, and maintained in a logical and consistent manner. A Data Management (DM) team structure is allocated with defined protocols and workflow processes coupled with appropriate storage and processing resources, along with DM tools, to create a concise and consistent data management solution.

The DM team works in collaboration with the Project Team using the Project data archive and DM tools to ensure that all Project data is archived and documented and that a complete audit trail exists. The Project Archive has appropriate permissions applied to ensure data security and all data that is acquired for a project undergoes a data license risk assessment via Legal Services to ensure that all legal requirements are met.

7.2 People

7.2.1 TEAM STRUCTURE

The approach that has been taken involves having a Project Data Manager (PDM) and a series of Data Coordinators (DCO – Team Leaders) and/or Data Custodians (DCU – project team member).

7.2.2 ROLES AND RESPONSIBILITIES

The PDM overseas all data management issues and is responsible for ensuring that storage and cataloguing resources are available as well as facilitating the data licensing process with Legal Services and providing information to the Project team, which explains the DM environment. The DCO is responsible for ensuring that teams are archiving data correctly, datasets are defined appropriately, and metadata is entered for all project datasets. There is typically one DCU for each project team and they are responsible for supplying the data to the archive and the content for the metadata. The DCO works with the DCU’s to assist with the archive construction and may be involved in entering metadata.

The data management team will consist of all Assessment team members who will be involved in collating and/or generating data and models. The roles and responsibilities of the data management team are listed in Table 7.1.

Table 7.1 Roles and responsibilities of the reporting team

PERSON	ROLE	RESPONSIBILITIES
Geoff Hodgson	Data management team leader (PDM)	• Ensure core project data is sourced, obtained and stored securely, and is accessible by members of the Assessment team • facilitate the data licensing process with Legal Services for externally sourced data • ensure maps and figures adhere to the reporting processes, standards and templates • Assist the reporting team to ensure other non text elements adhere to the reporting processes, standards and templates • provide input into development of timelines • oversee the cataloguing and metadata process to ensure capture of data and metadata is completed within project lifetime • be the contact person for data requests after project completion
Steve Charles	Climate Team Leader (DCO)	• Coordinate the collation and analysis of the climate data storing key input and output data sets on the WRON • assist with figure production • coordinate the cataloguing of data sets and metadata entry
Richard Silberstein	Surface Water Team Leader (DCO)	• Coordinate the collation and analysis of the surface water data storing key input and output data sets on the WRON • assist with figure production • coordinate the cataloguing of data sets and metadata entry
Riasat Ali	Groundwater Team Leader (DCO)	• Coordinate the collation and analysis of the groundwater data storing key input and output data sets on the WRON • assist with figure production • coordinate the cataloguing of data sets and metadata entry
Olga Barron	Environment Team Leader (DCO)	• Coordinate the collation and analysis of the environmental data storing key input and output data sets on the WRON • assist with figure production • coordinate the cataloguing of data sets and metadata entry

7.3 Resources

The WRON server houses key storage volumes, which are coupled closely with high-end processing servers. There are also a series of data reference libraries as follows: \\wron\GIS, \\wron\RemoteSensing, \\wron\TimeSeries. These contain key data sources that can be utilised by projects. There is also a project volume at \\wron\Project and each new project will have a directory created on this volume, which will be used as the location for that project's data archive.

7.4 Tools

7.4.1 METADATA CATALOGUE

A Regional Water Data Management System (RWDMS) has been built specifically to address data archiving and the development of data audit trails. It consists of a web interface for metadata entry and searching, and a SQL server database, which stores the metadata content. The RWDMS also provides functionality for creating linkages between parent and child datasets so that audit trails can be established for all reported results. The audit trails are also portrayed in diagrams, which can be exported as an image for reporting.

7.4.2 FTP DATA EXCHANGE

An FTP site can be initiated for each project as a provision for exchanging data between the WRON server and external project partners, collaborators, and data suppliers. A 'DataFTP' folder will appear within the project directory and will contain both an 'Incoming' (data coming from external supplier to the WRON) and 'Outgoing' (data going from the WRON to external source) directory. A username and password will be allocated for each project-specific FTP site.

7.4.3 SUB-VERSION

Code used for developing models/data will be stored within the Project archive but also registered within the 'Sub-version' code repository.

7.4.4 SHAREPOINT

A 'Sharepoint' site has been set up for project document storage and sharing. A series of Information sheets containing details of data management protocols, processes, and tools, are stored on the 'Sharepoint' site. The 'Sharepoint' site will not be used for data archiving, or as a data exchange mechanism. At the completion of the project the 'Sharepoint' documents will be stored within the Project directory so that they are archived for future reference if necessary.

7.5 Data Archiving

7.5.1 PROJECT ARCHIVE DIRECTORY

The location dedicated to data archiving for projects is the \\wron\Project volume. Within the project-specific directory the archive and working space for the project is to be clearly separated. The working space is for Assessment team members to develop data/models and when they are completed they must then be migrated into the appropriate archive directory.

7.5.2 ARCHIVE STRUCTURE

The project archive will have a directory for each of the Project teams and may well incorporate reporting region directories. The structure of the archive will be demarcated by project teams and reporting regions, and by differentiating data from reporting documents. Examples from previous projects, such as the MDBSY and SWSY will be used as a basis for deciding the best structure.

7.5.3 ARCHIVING

Archiving will occur throughout the project. When new datasets are created they will be stored within a dataset directory with an underscore at the start of the directory name, e.g. '_ScenarioA' will contain the dataset for Scenario A. The underscore is necessary so that the metadata 'robot' script can discover the datasets and create an entry in the metadata database, which can then be populated with metadata content. A series of archiving milestones will be defined and included in the project delivery schedule in order to encourage archiving throughout the project, rather than it all happening at the end of a project. The milestones may be divided, for example, as follows:

DM Milestone 1 – All source data and models are archived and catalogued

DM Milestone 2 – All intermediate data/models/results are archived and catalogued

DM Milestone 3 – All final data/models/results/reports are archived and catalogued

7.6 Data Cataloguing

Once a dataset has been defined within the archive it can then be discovered by the metadata 'robot' script. The 'robot' scans the project archive every 60 minutes and upon discovering a dataset it creates a record for it in the metadata SQL server database. At this point the metadata can be entered via the RWDMS tool. The DCU's should enter the metadata for their respective project team although they may require team members to enter some individually.

7.7 Security

Email enabled security groups are applied to the project's archive directory with one administrator, within the project, assigned to manage the group.

7.8 Data Management Environment

The details defined above are illustrated in a flow diagram in Figure 7.1 below.

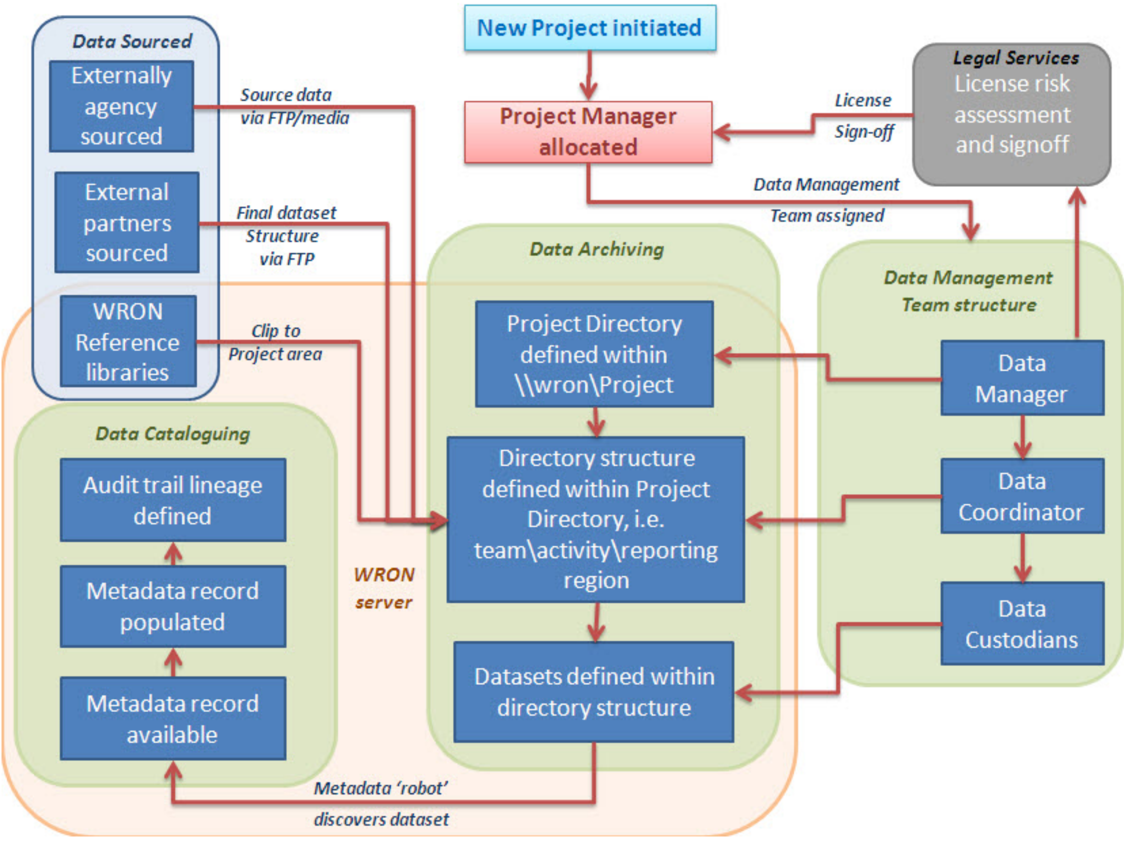


Figure 7.1 Data management process to be followed in the Pilbara Water Resource Assessment

7.9 Preliminary data list

Data List	Custodian	Comments
a. Catchment boundaries, DEMs	DoW, DLI, CMIS	Held but need approval to use
b. Streamlines	DoW	Held but need approval to use
c. Hydrogeological maps, GSoWA Bulletins, Groundwater resource locations (aerial outcrops for recharge estimation especially)	DoW	Needed ASAP for groundwater team to begin defining hydrogeology.
d. Management boundaries for groundwater – GMA, GM sub-areas	DoW, Watercorp	NLWRA mapping Other?
e. Historical climate data (SILO etc)	BoM (SILO), DoW	SILO gridded data to drive hydrological models
f. Climate prediction data	GCM's, CSIRO	Steven Charles and Francis Chiew
g. Soil types; landforms	NRAG or ASRIS	CSIRO ASRIS custodian
h. Landuses - recharge response units to run WAVES under various climates	DAFWA,	Need to derive RRUs for some GMU's using existing landuse maps, soil maps and remote sensing. Need to discuss future landuse – how to guestimate?
i. Irrigation areas – current and planned	various	May be part of landuse mapping
j. Aerial photography and satellite image access	DLI, CMIS	
k. Stream hydrographs	DoW Mining Companies	WIN database Site monitoring databases
l. Groundwater hydrographs	DoW Mining Companies	WIN database Site monitoring databases
m. Licensed allocations from surface and groundwater resources	DoW	Water Resource Licensing (WRL) database
n. Environmental Flows – EWR/ EWPS; GDE locations	DoW, DEC	Only broad analysis in scope of PWRA project.

8 Reporting

The objective of the reporting team is to provide quality assurance for reports produced from the Pilbara Water Resource Assessment. To meet this objective, the team will:

- provide templates, standards, processes and workflows for reporting
- advise and assist the Project Leader in integration and consistency, both within the Assessment and with respect to other projects and programs
- edit and produce basin and technical reports.

SharePoint is a website that provides a central storage and collaboration space for the team to share documents and information. The Assessment team will store all report documents on the CSIRO SharePoint <http://teams.csiro.au/sites/Pilbara%20WRA/default.aspx>.

8.1 People

The roles and responsibilities of the reporting team are listed in Table 8.1.

The reporting team will work closely with other Assessment team members in other aspects of the Assessment. Table 8.2 indicates the responsibilities of the reporting team and others with respect to these tasks.

Table 8.1 Roles and responsibilities of the reporting team

PERSON	ROLE	RESPONSIBILITIES
Maryam Ahmad	Reporting team leader	• ensure editorial quality of reports • provide reporting processes, standards and templates • provide input into development of timelines • final editorial approval (Project Leader has final technical approval) • produce reports (PDFs)
Becky Schmidt	Reporting manager	• advise and assist Project Leader on consistency with respect to other relevant projects (Flinders and Gilbert Agricultural Resource Assessment, Great Artesian Basin Water Resource Assessment and previous Sustainable Yields projects) • review summary reports • edit executive summaries
TBC	Editor	• edit • assist with report production
Simon Gallant / Audrey Wallbrink	Production assistant	• editorial assistance • advise and assist authors with plotting and formatting • produce reports (PDFs)

Table 8.2 Roles and responsibilities for other tasks in conjunction with other Assessment team members

TASK	REPORTING TEAM RESPONSIBILITIES	AFFILIATED PEOPLE AND THEIR RESPONSIBILITIES
ePublish approval	• advise and assist as needed	• Project Leader submits basin and summary reports to ePublish • Team Leaders submit their technical reports to ePublish
Communication	• proofread factsheets • proofread text for web page	Communication Advisor • branding and logos • three public-audience factsheets (at beginning, middle and end of Assessment) • communication protocol (if required) • ministerial briefings • media releases • text for CSIRO web page • upload reports to CSIRO web page • issues and media management
Design and layup summary reports	• provide content • proofread after layup	Creative Services Team (CSIRO) • design and layup summary reports
Printing		Project Coordinator (in conjunction with Creative Services Team) • identify printer and coordinate printing
References	• provide standards • proofread • identify missing references	Authors • provide properly formatted list of references that have been properly cited in text
Review	• enact changes in response to editorial comments by reviewers (but authors revise in response to technical comments) • edit *after* response to review	Project Leader • lead overall approach of response to review, including resolving conflicting review comments. Project Coordinator • coordinates review process • contacts reviewers, adjusts timelines if delays, collates review comments, coordinates authors' revisions. Authors • revise documents in response to review
SharePoint	• file relevant documents (e.g. reporting tools) • archive documents when appropriate (e.g. superseded versions of report documents)	Project Coordinator • general administration, including PUMA accounts for external people • file relevant documents (general and management)
Timeline	• provide Project Coordinator with reporting timelines	Project Coordinator • devise, update, monitor and adjust overall timeline • direct traffic
Write	• assist Project Leader with writing summary reports • advise on integration and consistency, both internally and with respect to relevant projects and programs	Authors (Team Leaders and Project Leader) • write reports

8.2 Reports

The Assessment will produce the following reports:

- this report (*Proposed project methods*) (audience: technical)
- between three and five 150- to 250-page basin reports depending on how the basins are grouped (audience: well-informed non-experts)
- between three and five 12-16 page basin summary reports depending on how the basins are grouped (audience: public)
- one whole-of-region report
- one whole-of-region summary report
- five 20- to 100-page technical reports (audience: technical) (climate, runoff, river modelling, groundwater, water-dependent ecosystems.

The reporting team will focus their efforts on the basin and summary reports, and will have limited involvement with the technical reports.

8.2.1 GROUPING THE BASIN REPORTS

There are several options for how the Basin reports are grouped. The first option is to base the reports on the Australian Water Resources Council Drainage Basins 706 to 710 (inclusive) as shown in Figure 1.1. Another option is to include the Upper Fortescue in a separate report with the cut off being the bottom of the Fortescue Marshes. This may enable the Lower Fortescue to be included with the Port Hedland Coast (Yule etc). For this option, the final breakdown would be:

1. Ashburton-Onslow
2. Lower Fortescue – Port Hedland Coast
3. Upper Fortescue
4. De Grey + /- West Canning – Great Sandy Desert.

Advice is currently being sought regarding these options and other options will also be considered.

8.3 Standards

The reporting team will define editorial standards to guide authors in reporting the findings of the Assessment. These standards will be available in a document entitled *Reporting standards* which will be available to the Assessment team on the SharePoint in the following folder:

Gulf Agricultural Resource Assessment > GARA_Authors > Shared Documents > ReportingTools

These standards are based on:

- the *Australian Government style manual for authors, editors and printers*
- *CSIRO brand identity guidelines*
- standards used in the Sustainable Yields projects, particularly the Northern Australia Sustainable Yields Project
- the *Australian Oxford dictionary*.

Many specialist terms are not found in these resources, however, and thus additional conventions specific to the Assessment will be developed in consultation with the Assessment team.

Reporting standards will be a 'living document' that changes as the Assessment progresses to document decisions on language and formatting. Conventions specified in early drafts, however, will not be changed unless absolutely necessary; the aim is to *add* conventions, not to backtrack on earlier decisions. *Reporting standards* will be published as a report at the end of the Assessment.

8.4 Processes

The reporting team will use previously developed processes to assist the Assessment team to collaborate and write multi-authored documents efficiently. An overview of the processes is provided in this section. Further detail will be provided in infosheets which will be available to the Assessment team on the SharePoint in the following folder:

Gulf Agricultural Resource Assessment > GARA_Authors > Shared Documents > ReportingTools

All reports will be written using Microsoft Word 2007 or 2010, and the format of the files will be *.docx (not *.doc). When writing first drafts, authors do not need to track changes. After the first drafts are submitted to the Project Leader and reporting team for review and editing, however, changes will be subsequently tracked. The reporting team will accept these changes at certain stages (for example, before submitting the reports for review), but authors should *not* accept any tracked changes.

Authors are required to adhere to language conventions provided in *Reporting standards* and according to the instructions provided in the templates.

Generally, technical reports will be one Microsoft Word document, whereas basin reports will be multiple Microsoft Word documents (one for each chapter).

There will be no shared Endnote database for references, but an Endnote style will be provided for authors who would like to use their personal Endnote database.

The 'check-out' facility of SharePoint will be used for version control. If a document is 'checked in' on SharePoint, then it is available for an author or edit or to revise. The following procedure should be followed, using the filename 'PilbaraWRA-example-v01.docx' as an example:

1. Check out 'PilbaraWRA-example-v01.docx' on SharePoint. While it is checked out, only the person who has checked it out can work on it.
2. Save 'PilbaraWRA-example-v02.docx' to a local hard drive.
3. Enter information in the table 'History of this document' in 'PilbaraWRA-example-v02.docx': date, name and nature of changes.
4. Revise and edit 'PilbaraWRA-example-v02.docx'.
5. Note issues in the table 'Log of issues and comments' in 'PilbaraWRA-example-v02.docx'.
6. Refresh fields (by selecting all of the text in the document and pressing F9) and then save the document 'PilbaraWRA-example-v02.docx'.
7. Upload 'PilbaraWRA-example-v02.docx' to SharePoint.
8. Discard check out of 'PilbaraWRA-example-v01.docx'. (Later, the reporting team will move this document to an archive folder.)

Plots are most simply drawn using Microsoft Excel, and the reporting team will provide templates. Other programs (R, CorelDraw) can be used as long as the result adheres to the standards defined in *Reporting standards*.

Maps are created using ArcGIS, and the reporting team will provide map templates.

Microsoft Excel workbooks will be used to hold all non-text elements (tables, figures, maps, plots and diagrams). These workbooks will be stored on the SharePoint, but will include links to the source data, which will be stored on the WRON. Each non-text element will be assigned a unique 'element number' which is noted in both the Microsoft Word document and the Microsoft Excel workbook and which forms an essential link to the audit trail.

Reports will be submitted to ePublish (CSIRO's publications approval and reporting system) for review. Reports will be submitted for review as PDF files; Microsoft Word documents will not be provided. Reviewers will be requested to fill in a Microsoft Excel spreadsheet to provide comments. These comments will be collated into a master document which includes all comments as well as the Assessment team's responses to review. The ePublish approver and client will use this master document in assessing the review of the reports.

Technical reports will not be printed, but instead will be available as a PDF on the CSIRO website. Basin and summary reports will be printed and will also be available as a PDF on the CSIRO website.

8.5 Workflows

There will be two general workflows – and hence timelines – for two groups of reports.

The first group is the technical reports, which will each be authored by one team and will be edited and produced by the authors. The review and response to review will be coordinated by the Team Leader via ePublish. For more detail see Table 8.3.

The second group is the basin and summary reports, which will be authored by multiple activities. These reports require more integration than the technical reports, and thus will be edited and produced by the reporting team. The review and response to review will be coordinated by Project Leader via ePublish. For more detail see Table 8.4.

The Project Leader will develop an overall timeline based on workflows for each individual report.

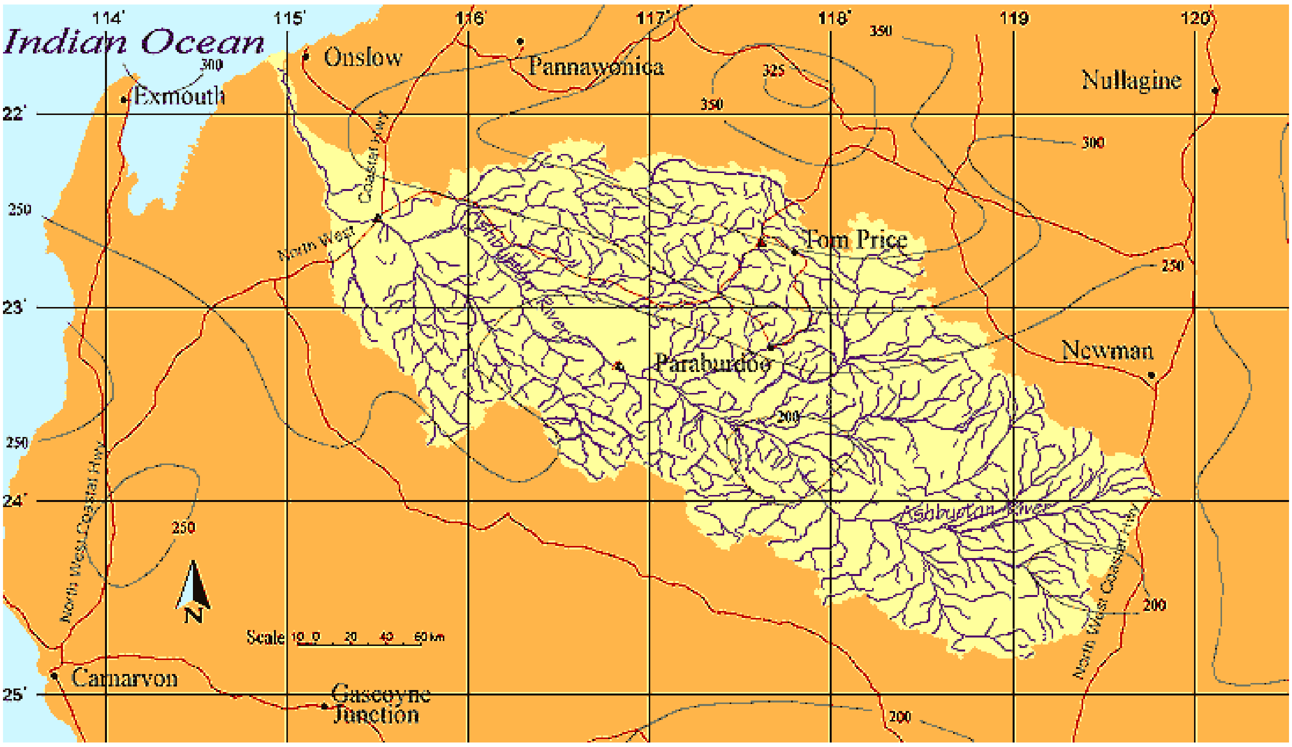
Table 8.3 Workflow for technical reports

WHO	DOES WHAT?	FOR HOW LONG?
Reporting team	• provide templates and standards	
Authors	• decide on outline • write report • create maps, plots, tables and/or other non-text elements	
Project Leader	• approve report to go to ePublish (using checklist to assess editorial quality)	2 days
Reviewers: 2 specialists (internal or external to CSIRO)	• review via ePublish, submitted by Team Leader • project Leader provides feedback in parallel	3 weeks
Authors	• respond to review • final ePublish approval	2 weeks
Client	• approve, but do not review	2 weeks
Authors	• final minor revisions	1 week
Reporting team	• final report production	2 days
TOTAL		**9 weeks**

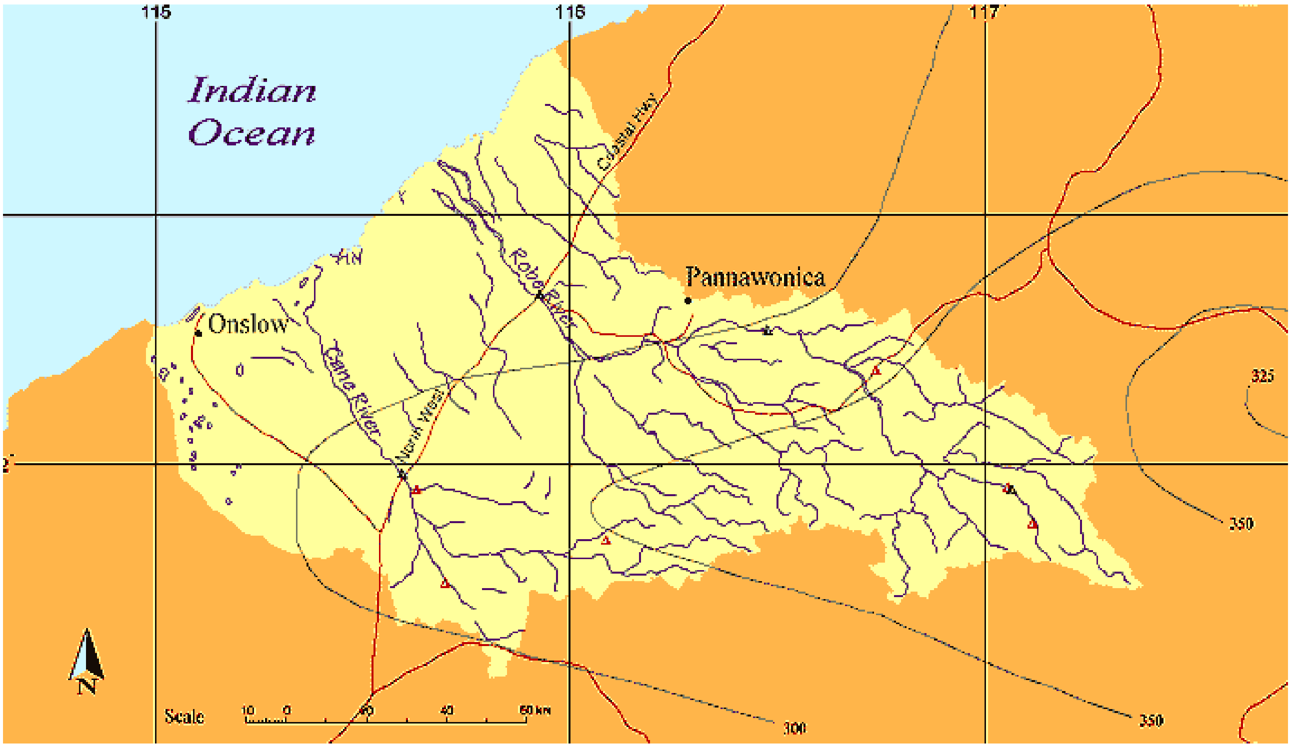
Table 8.4 Workflow for basin and summary reports

WHO	DOES WHAT?	FOR HOW LONG?
Reporting team	• provide templates and standards • assist team in devising outline	
Authors	• write chapters and sections • create maps, plots, tables and other non-text elements	
Reporting team and Project Leader	• Project Leader integrates and writes executive summary and other general material • reporting team edits	4 weeks
Reviewers: Steering and Governance Committees	• review via ePublish, submitted by Project Leader	3 weeks
Authors and reporting team	• respond to review • re-edit • final ePublish approval	4 weeks
Client	• approve, but do not review	2 weeks
Authors	• final minor revisions	1 week
TOTAL		**14 weeks**

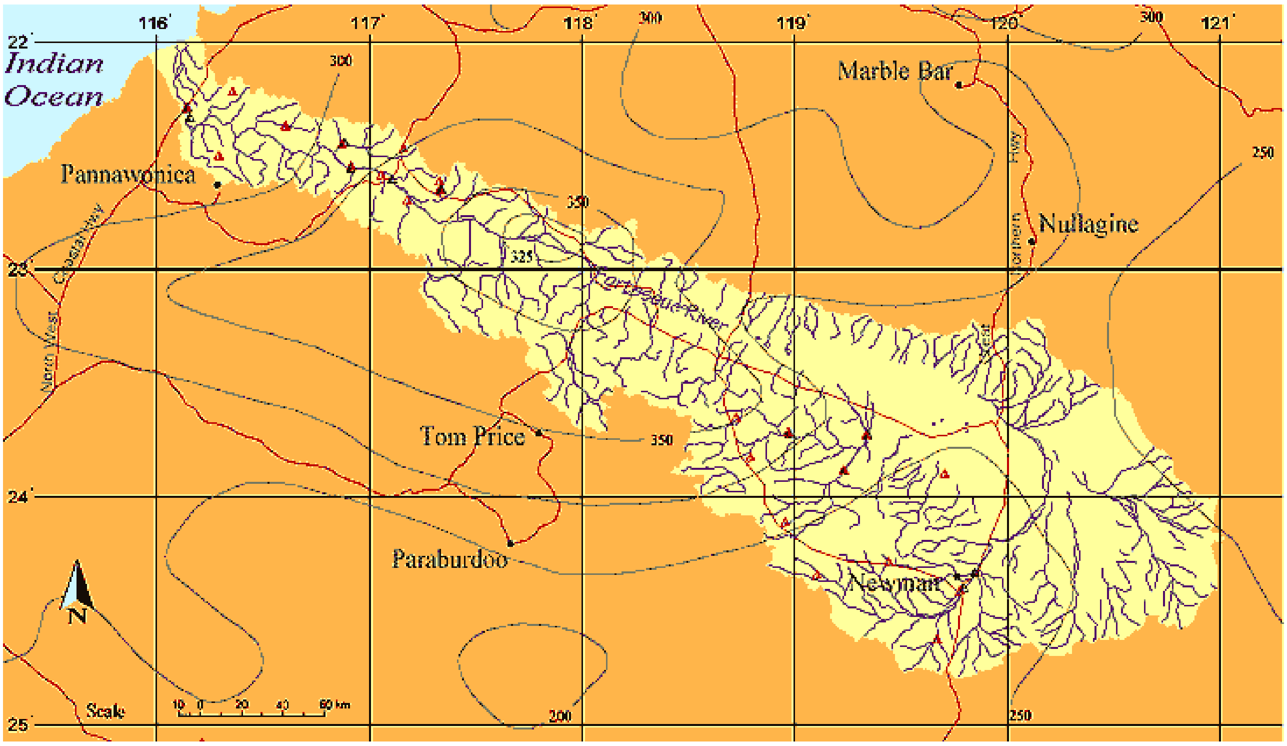
Appendix A Five river basins in the assessment area



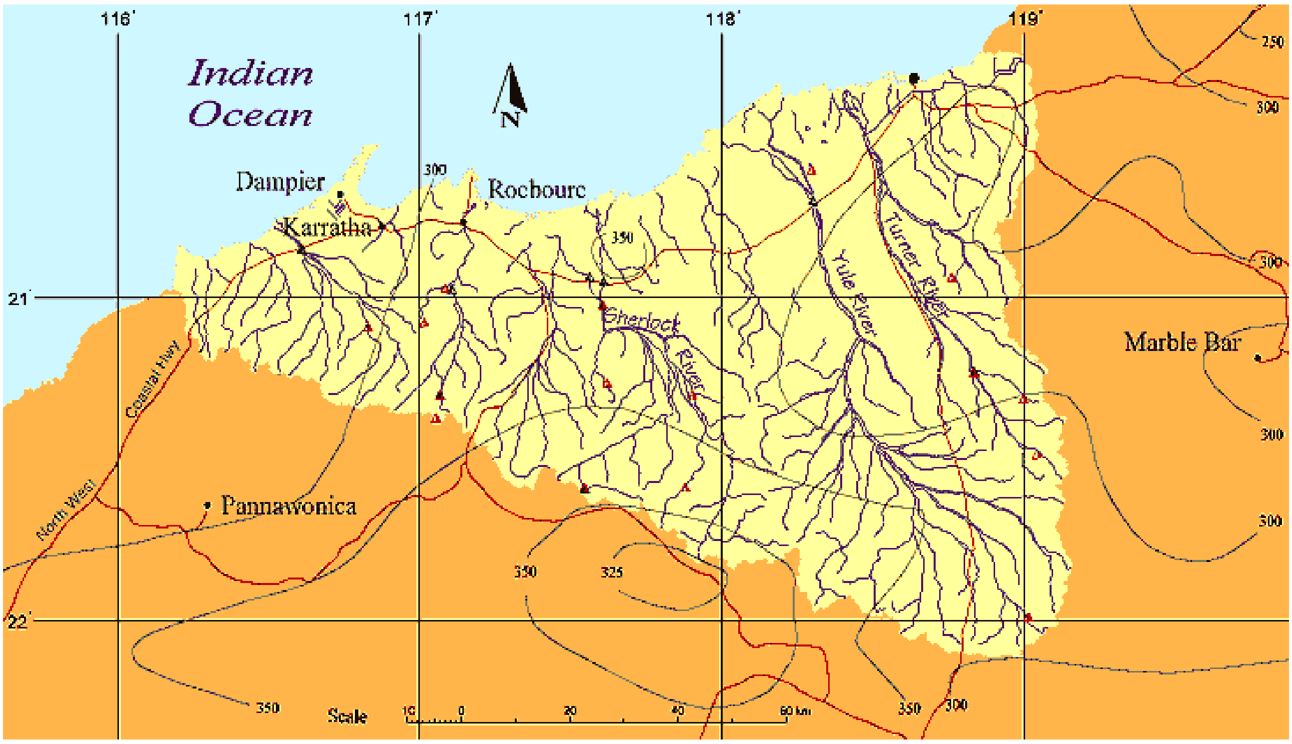
Apx Figure A.1 Ashburton River Basin (source: DoW, 2006)



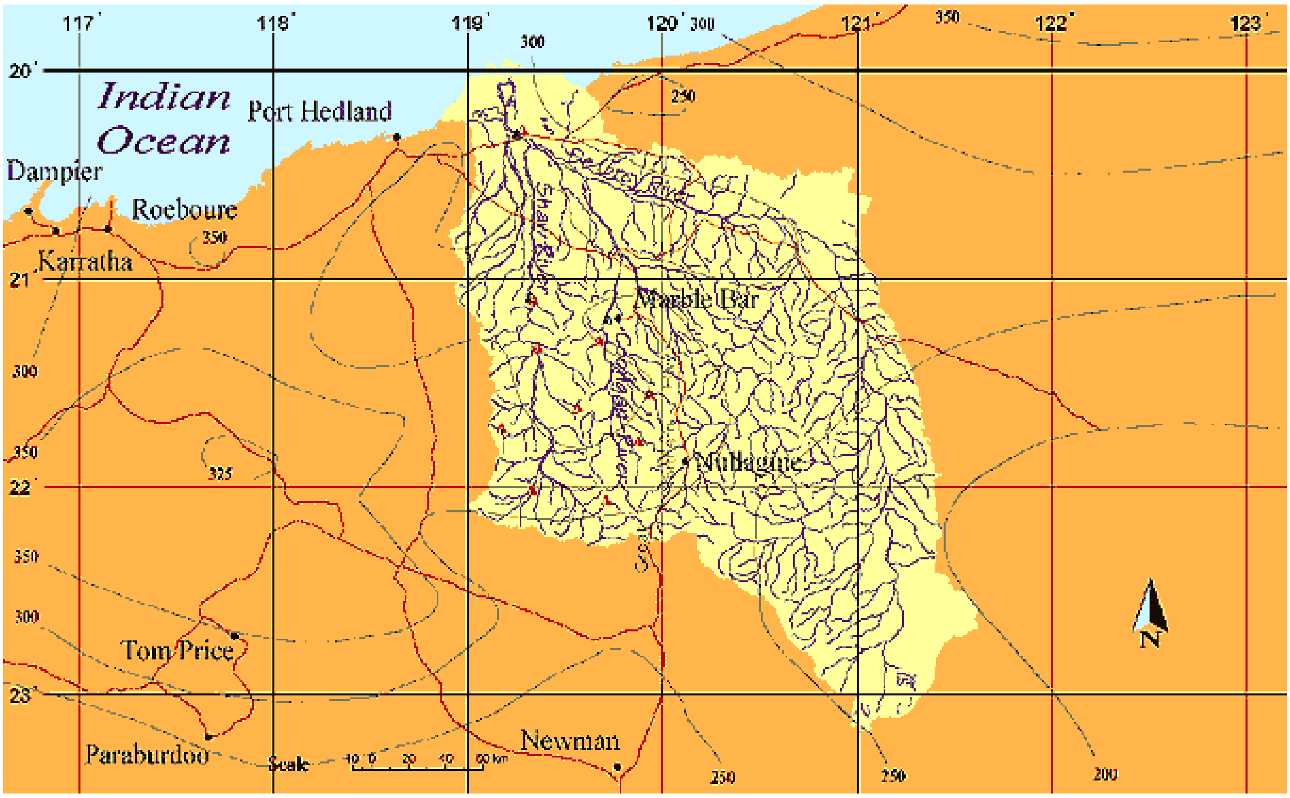
Apx Figure A.2 Onslow Coast



Apx Figure A.3 Fortescue River Basin



Apx Figure A.4 Yule River Basin



Apx Figure A.5 De Grey River Basin

A.1 References

DoW (2006) Water resources information catalogue, Department of Water, Western Australia. Accessed 16 October 2012, <http://kumina.water.wa.gov.au/waterinformation/wric/wric.asp>.

Appendix B Surface water models

B.1 Rainfall-runoff models

Simple conceptual rainfall-runoff models embedded in the modelling platform called the 'Source' will be used in all catchments. The framework allows use of a different model for each sub-catchment, if needed. The eWater Source platform is being further developed and now includes LASCAM, a distributed rainfall runoff and catchment flow routing model, which may be used to compare the results from two different genre of models making sure that all important hydrologic processes are considered in modelling. If available within a suitable timeframe and with sufficient resources to support it, the LUCICAT catchment model may also be assessed for this activity. The model(s) will be selected on performance, suitability and resource requirements during calibration and comparison with available expert knowledge, particularly from the Department of Water (DoW) and Main Roads WA (MRWA). Use will also be made of remote sensing to estimate flood extent and flow volumes. Implementation of all the models will be done through independent land unit 'cells' distributed across catchments on a grid or on terrain based Hydrological Response Units (HRUs) contributing to subcatchments. In the simple models runoff is calculated for each cell or HRU and cascaded from one cell or HRU to another or directly contributed to the stream without routing. For these, flow routing is handled in the river models.

The fully conceptual models selected are SIMHYD, Sacramento, IHACRES, AWBM, SMARG and GR4J. All except GR4J were used in the South-west Western Australia, Northern Australia and Tasmania Sustainable Yield projects. The Sacramento and IHACRES models performed best in both the South-west Western Australia and Northern Australia Sustainable Yields projects. The six simple models will be used because they are amenable to automatic optimisation and modelling runs. This provides a basis for calculation that is consistent from one model run to the other model run and reproducible for entire project area for modelling the base case and for assessing the potential impacts of climate change and development scenarios on future runoff.

Description of the six simple conceptual rainfall-runoff models are available in the RRL (Rainfall-Runoff Library) in the Catchment Modelling Toolkit (<www.toolkit.net.au/rrl>). These models are implemented through a CSIRO inbuilt modelling framework, the CYMF. The models are described below.

B.1.1   SIMHYD

SIMHYD is a lumped conceptual daily rainfall runoff model with seven parameters (Chiew et al., 2002; Tan et al., 2005), which for this project has a Muskingum routing method. It has been tested and used successfully in the National Land and Water Resources Audit (Peel et al., 2000) and in the Murray-Darling Basin Sustainable Yields Project (CSIRO, 2008). SIMHYD simulates daily runoff (surface runoff and baseflow) using daily precipitation and potential evaporation (PE) as input data.

B.1.2   SMARG

SMAR (Kachroo RK, 1992; O'Connell et al., 1970; Tuteja and Cunnane, 1999) is a lumped conceptual rainfall–runoff water balance model with soil moisture as a central theme. The model provides daily estimates of runoff, groundwater discharge, evapotranspiration and leakage from the soil profile for the catchment as a whole. The surface runoff component comprises overland flow, saturation excess runoff and saturated through-flow from perched groundwater conditions with a quick response time. The SMAR model consists of two components in sequence, a water balance component and a routing component. A groundwater component was added by Goswami et al. (2002, 2007). The model utilises time series of rainfall and pan evaporation data to simulate streamflow at the catchment outlet. The model is calibrated against observed daily streamflow.

B.1.3 IHACRES

IHACRES (Jakeman et al., 1990; Littlewood et al., 1997; Ye et al., 1997) is a time series transfer function model in which there is no attempt to represent physical processes but the catchment is represented as a 'black box' and the output is simply a function of the input forcing data. IHACRES stands for Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow. It has developed with a number of variations using different numbers of parameters. It has been used in many applications to explore impacts of changes in forcing conditions on catchment responses. IHACRES is a catchment-scale rainfall-streamflow modelling methodology whose purpose is to characterise the dynamic relationship between rainfall and streamflow, using rainfall and temperature (or potential evaporation) data, and to predict streamflow. IHACRES uses unit hydrograph theory which conceptualises the catchment as a configuration of linear storages acting in series and/or parallel. Non-linearity commonly observed between rainfall and streamflow is accommodated in a non-linear loss module which converts rainfall to effective rainfall. The model requires only a small number of parameters, typically six (three for the non-linear loss module and three for the linear unit hydrograph module). Current versions of IHACRES allow use of multiple catchment water 'storages' arranged either in series or in parallel. In the version used in this project there will be only one storage that generates flow as two components, 'quick flow' conceptually equivalent to storm generated flow, and 'slow flow' conceptually equivalent to groundwater discharge or 'baseflow'.

B.1.4 SACRAMENTO

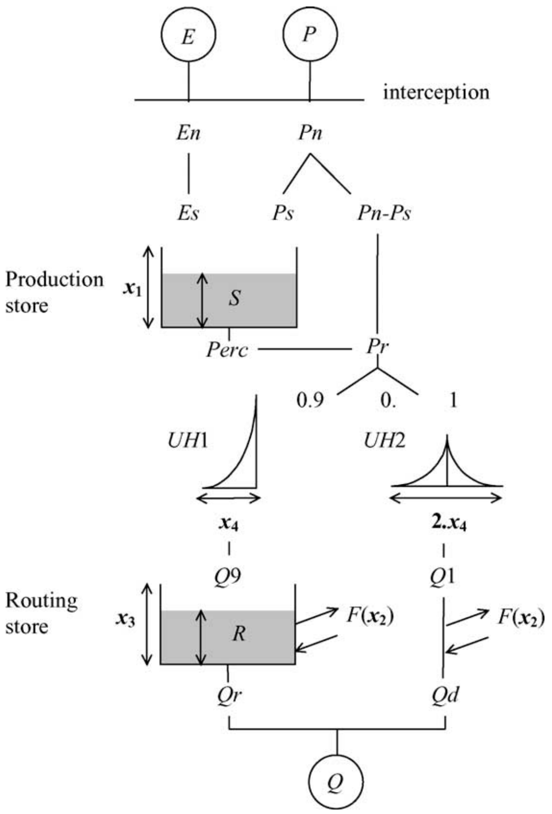
The Sacramento model (Burnash et al., 1973) is also a lumped conceptual daily rainfall-runoff model with 17 parameters and five moisture stores. The Sacramento model is used as part of IQQM implementations in New South Wales and Queensland. This model uses soil moisture accounting to simulate the water balance within the catchment, with flows between stores and out of catchment elements which are dependent on the size and relative wetness of the different stores. Moisture storage is increased by rainfall and reduced by evaporation and by flow of water out of storage. Rainfall in excess of the soil's infiltration capacity becomes runoff, and combined with lateral flow from soil moisture storage becomes the generated streamflow. Streamflow generated with the Sacramento model is made up of three flow components surface runoff, interflow, and baseflow.

B.1.5 AWBM

AWBM (Boughton, 1996) is a catchment water balance model that has three surface stores to simulate partial areas of runoff. The water balance of each surface store is calculated independently of the others. The model calculates the water balance of each partial area at each time step. When runoff occurs from any store, part of the runoff becomes recharge of the base flow store if there is base flow in the streamflow. Surface runoff routing can be represented if needed in a medium to large catchment.

B.1.6 GR4J

The GR4J model has been applied over a wide range of hydro-climatic conditions (Perrin et al., 2003; Vaze et al., 2010) and used in the MOPEX experiment of rainfall-runoff models inter-comparison (Andreassian et al., 2006). Streamflows are calculated from mean areal rainfall and potential evaporation (PE) time sequences. Apx Figure B.1 presents the overall model scheme. Perrin et al. (2003) provide further mathematical details. It has got considerably fewer parameters to be calibrated then most models described above. The four parameters to be calibrated are the following: (1) S, the capacity of the soil moisture store (mm), (2) IGF, the parameter that controls the inter-catchment groundwater flows (mm/day). Positive values indicate water imports from groundwater or neighbouring catchments; negative values indicate water exports, (3) R, the capacity of the routing store (mm), and (4) TB, the time base of the unit hydrograph (days). This parameter controls the time lag between the effective rainfall and the runoff peak.



Apx Figure B.1 Schematic of the GR4J model (Perrin, 2003)

B.1.7 LUCICAT

LUCICAT (Land Use Change Incorporated Catchment model) was developed for Western Australian catchments and has been applied to many of those listed in (Bari, 2005; Bari and Smettem, 2006)). LUCICAT is a semi-conceptual model with four moisture stores and inbuilt flow routing, based on disaggregating a catchment into a limited number (up to a few hundred) of sub-catchments, made up of terrain-derived Hydrological Response Units (HRUs). LUCICAT uses explicit river routing to account for the time delay of flows from remote parts to reach the catchment outlet. Each HRU has a defined vegetation density and many parameters can be set on the basis of prior experience in similar catchments. While in principle there could be hundreds of parameter values distributed across a catchment with each HRU having a different value, in practice only a small number are varied, and each HRU within a specified sub-catchment has the same parameter values. Only a few parameters are used in calibration. Because of the greater complexity, data requirement and difficulty in calibration, it may not be possible to implement an automatic calibration for this model within this project and as a consequence manual calibrations may used in catchments where calibrations from previous work were available.

B.1.8 LASCAM

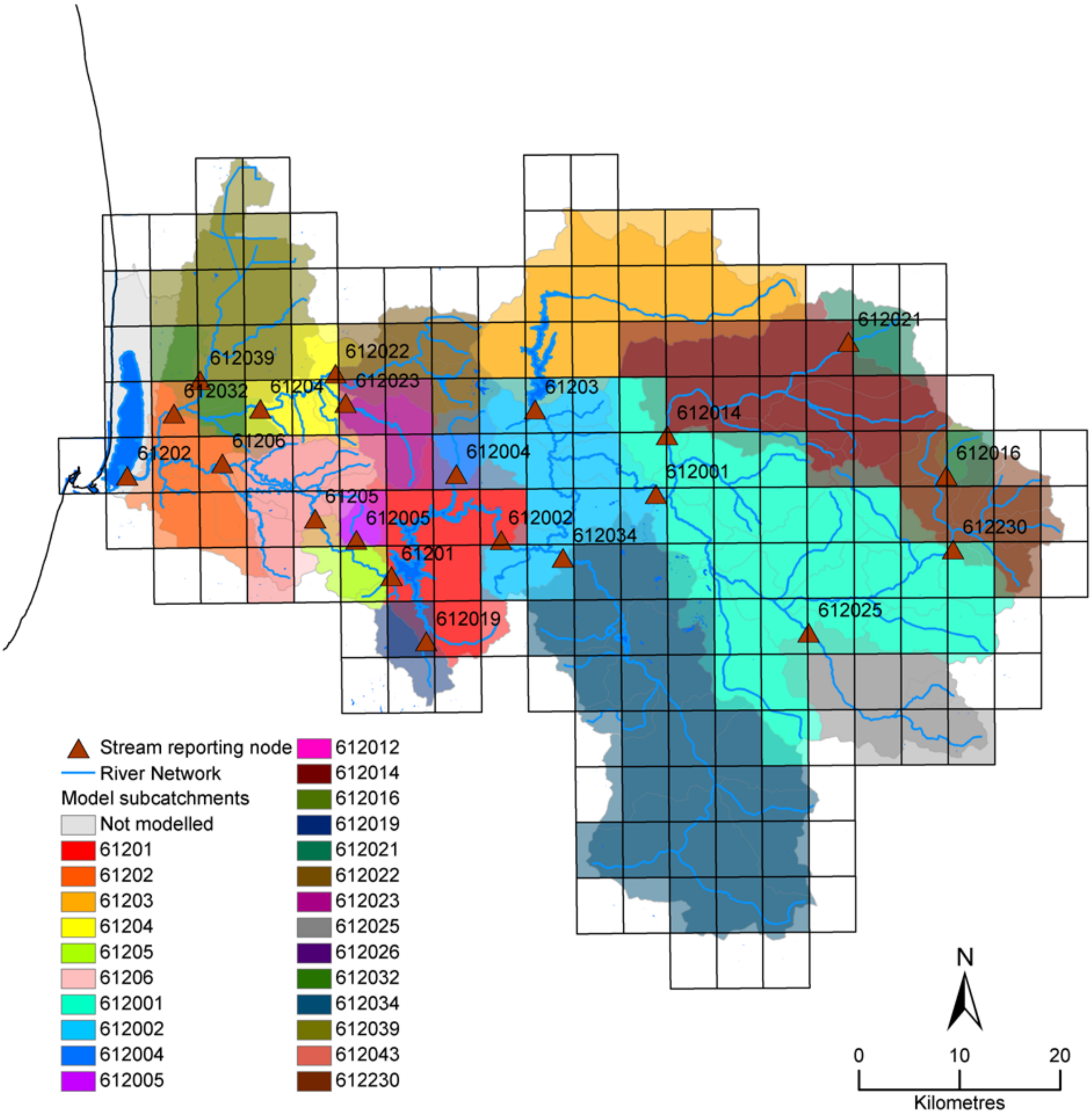
LASCAM is a complex conceptual model, the basic building blocks being subcatchments organised around the river network. All hydrological and water quality processes are modelled at the subcatchment scale, before being aggregated via stream network routing, to yield to the response of the catchment at the main outlet and at any number of intermediate points on the stream network (Sivapalan et al., 2002).

B.2 Application of the models

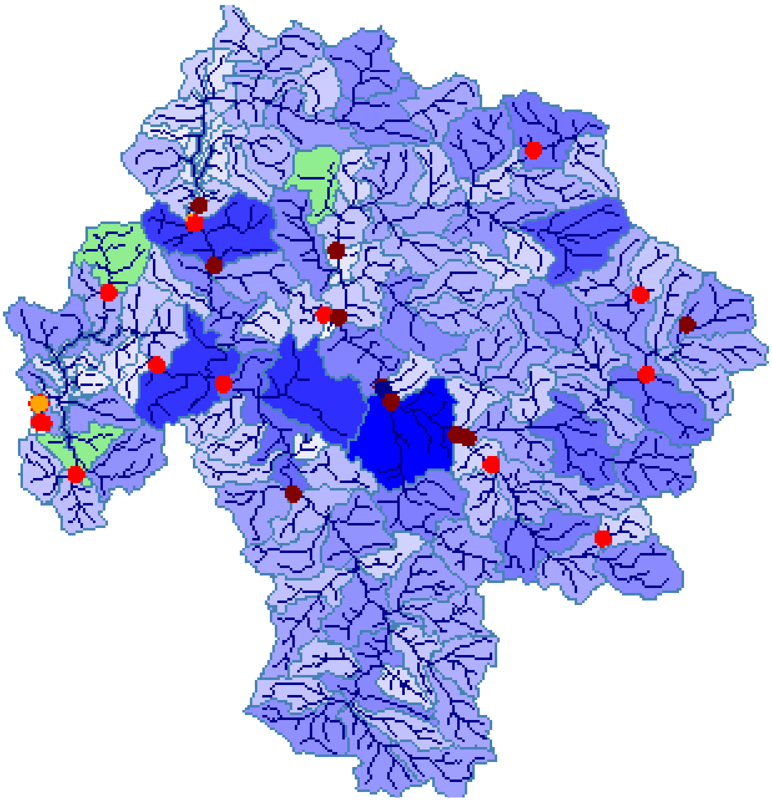
The rainfall-runoff models will be applied to gauged catchments from the basins considered in the assessment (Table 3.1). The models will be distributed across the catchments on grid based nodes. All these models will be set up to run on square grids across all catchments with gridded daily rainfall and areal potential evaporation (APET) data across the region. In earlier regional studies (e.g. CSIRO, 2009a) the grid size 0.05º x 0.05º (~ 5 x 5 km) were used, however given the sparseness of rainfall and streamflow gauging stations in the Pilbara a larger grid size is envisaged which will be determined during the model calibration. The daily modelled runoff for the grid cells will then be aggregated to obtain modelled runoff for gauged catchments.

Application of the rectangular grid approach used in previous SY projects may not be appropriate for catchments with large ungauged areas in this project. Therefore two approaches will be assessed for suitability from catchment to catchment with some catchments modelled on terrain-based HRUs.

As an example, shows the grid cells assigned to catchments of the Collie catchment as illustrated by the colours. The discretisation into sub-units allows rainfall and potential evaporation inputs to vary spatially across the catchments. Within each catchment the parameter values in each cell or HRU of the semi-distributed models (Apx Figure B.2) are the same and only climate inputs vary. Using the same approach for all models minimises the influence of different model formulations or calibration approaches and therefore limits the differences modelled under the scenarios to differences in climate and development. Use of a suite of models with different formulations improves the likelihood that the full range of simulated responses were covered.



Apx Figure B.2 Example of 0.05 x 0.05 degree (~ 5 x 5 km) grid cells over the catchments of the Collie catchment. The runoff for each catchment is calculated as the average runoff from all cells mapped into it as illustrated by the colours



Apx Figure B.3 Example of hydrological response units (HRUs) from LUCICAT. The runoff for each HRU, illustrated by the colours, is routed to the catchment outlet using a Muskingham method. The reporting nodes, catchment outlet and dams are indicated by dots of different colours

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