Australian Government
Department of the Environment, Water, Heritage and the Arts

National Research FLAGSHIPS
Water for a Healthy Country

CSIRO

Water yields and demands in south-west Western Australia

A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project

December 2009

Report 3

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South-West Western Australia Sustainable Yields Project acknowledgments

The South-West Western Australia Sustainable Yields Project was undertaken by CSIRO under the direction of the Australian Government Department of the Environment, Water, Heritage and the Arts. Important aspects of the work were undertaken by the Department of Water Western Australia. The Water Corporation and the Western Australia Department of Agriculture and Food provided expert advice and data. A contract to develop a groundwater model for part of the region was undertaken by URS Australia Pty Ltd. Additional technical input was provided by CyMod Systems, Jim Davies and Associates, Resource Economics Unit and Geographic Information Analysis. Valuable feedback was received during the review process from Tony Jakeman, Andy Pitman, Don Armstrong, Peter Davies and Murray Peel.

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Cover photograph: Irrigation at a dairy farm near Harvey, Western Australia. Photo: Robert Garvey. Copyright: CSIRO.

Director’s Foreword

Following the November 2006 Summit on the southern Murray-Darling Basin (MDB), the then Prime Minister and MDB state Premiers commissioned CSIRO to undertake an assessment of sustainable yields of surface and groundwater systems within the MDB. The project set an international benchmark for rigorous and detailed basin-scale assessment of the anticipated impacts of climate change, catchment development and increasing groundwater extraction on the availability and use of water resources.

On 26 March 2008, the Council of Australian Governments (COAG) agreed to expand the CSIRO assessments of sustainable yield so that, for the first time, Australia would have a comprehensive scientific assessment of water yield in all major water systems across the country. This would allow a consistent analytical framework for water policy decisions across the nation. The South-West Western Australia Sustainable Yields Project, together with allied projects for Tasmania and northern Australia, will provide a nation-wide expansion of the assessments.

The CSIRO South-West Western Australia Sustainable Yields Project is providing critical information on current and likely future water availability. This information will help governments, industry and communities consider the environmental, social and economic aspects of the sustainable use and management of the precious water assets of south-west Western Australia.

The projects are the first rigorous attempt for the regions to estimate the impacts of catchment development, changing groundwater extraction, climate variability and anticipated climate change on water resources at a whole-of-region scale, explicitly considering the connectivity of surface and groundwater systems. To do this, we are undertaking the most comprehensive hydrological modelling ever attempted for the region, using rainfall-runoff models, groundwater recharge models, river system models and groundwater models, and considering all upstream-downstream and surface-subsurface connections.

To deliver on the projects CSIRO is drawing on the scientific leadership and technical expertise of national and state government agencies in Queensland, Tasmania, the Northern Territory and Western Australia, as well as Australia’s leading industry consultants. The projects are dependent on the cooperative participation of over 50 government and private sector organisations. The projects have established a comprehensive but efficient process of internal and external quality assurance on all the work performed and all the results delivered, including advice from senior academic, industry and government experts.

The projects are led by the Water for a Healthy Country Flagship, a CSIRO-led research initiative established to deliver the science required for sustainable management of water resources in Australia. By building the capacity and capability required to deliver on this ambitious goal, the Flagship is ideally positioned to accept the challenge presented by this complex integrative project.

CSIRO has given the Sustainable Yields Projects its highest priority. It is in that context that I am very pleased and proud to commend this report to the Australian Government.

Dr Tom Hatton

Director, Water for a Healthy Country

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Executive summary

About the project

In 2007 and 2008, CSIRO produced a series of reports examining the likely water yield of surface water and groundwater catchments in the Murray-Darling Basin as a result of future climate changes and possible land management changes such as afforestation and farm dams.

On 26 March 2008, the Council of Australian Governments (COAG) agreed to expand the CSIRO assessments of sustainable yields to northern Australia, Tasmania and south-west Western Australia (SWWA). For the first time, Australia will have a comprehensive scientific assessment of water yields in all major water systems across the country, which allows a consistent analytical framework for water policy decisions.

The CSIRO South-West Western Australia Sustainable Yields Project has estimated the likely water yields of all major fresh, marginal and brackish surface water and groundwater systems between Geraldton and Albany under the same climate and development scenarios as used in the other three projects, except that the historical climate data were of shorter length (the 33-year period from 1975 to 2007). The project has also estimated future water demands and compared these with likely future yields from all water resources under all scenarios.

For the first time:

- A consistent set of future climate inputs has been compiled for use in surface water and groundwater models over the main water catchments in SWWA.
- The possible impacts of climate change and development on water dependent ecosystems has been estimated at a regional scale.
- Possible gaps between the estimated yields and demands have been identified under climate scenarios, which is in addition to what has been carried out in the other Sustainable Yields Projects.

The project has reported the results in three main reports:

- Surface water yields in south-west Western Australia
- Groundwater yields in south-west Western Australia
- Water yields and demands in south-west Western Australia.

This report presents water yields and demands for the South-West Western Australia Sustainable Yields Project area. The groundwater report presents modelled groundwater yields across the project area. In the surface water report, daily runoff projections under the future climate are presented for every major stream, and projected inflows to all major dams across the project area are reported. Companion technical reports provide more detail on the methods and results.

The assessments reported here have been reviewed by expert staff within the Department of Water Western Australia, a Technical Reference Panel, external reviewers and a Steering Committee with representatives from the Australian and Western Australian governments.

Key findings

- Modelling has projected that future surface water yields in the project area will be on average 24 percent lower than current yields by 2030, with a possible range of 4 to 49 percent lower. In terms of irrigation areas, greater reductions are likely in the Donnelly and Warren surface water basins than in the Harvey and Collie surface water basins.
- Runoff is projected to reduce by 20 to 30 percent under the median future climate and by 40 to 50 percent under the dry extreme future climate which would affect surface water dependent ecosystems, especially those that require high flows.
- Groundwater yields may decrease by between 2 percent under the median future climate and 7 percent under the dry extreme future climate. Yield declines may be greater than one-third in the Gnangara, Blackwood and Albany sub-areas, all of which have native vegetation overlying the aquifers.
- Groundwater is less impacted by reduced rainfalls in areas with high watertables because there may be reduced groundwater flow to drains and evaporation losses when these watertables fall.
- The decreased evaporative losses associated with falling groundwater levels will result in groundwater dependent ecosystems such as wetlands being impacted and current abstractions may need to be adjusted accordingly.
- About 20 percent of the area where groundwater dependent ecosystems may occur (based on depth to watertable) could be affected under the dry extreme future climate in the southern half of the Perth Basin.
- Consumptive water demand in the region is expected to increase by about 35 percent by 2030, with an increase ranging between 10 and 57 percent depending on population and economic growth factors.
- The project area is unusual in that over 70 percent of water is self-supplied (rather than through schemes), three-quarters is groundwater, irrigation only uses 35 percent of all water (in most other states it is over two-thirds), and most is used for irrigating high-value horticultural crops and not pastures.
- The greatest deficits between future water demands and water yields are expected to develop in the Harvey and Warren surface water basins and in the groundwater areas around Perth and Albany.
- If water quality and transportation costs are ignored, the region has enough water overall to meet all except high demands until 2030 under the median future climate.
- However, under the dry extreme climate and under the high demand scenario the region may have an overall deficit of about 250 gigalitres per year (GL/year).

Overview of the project area

The geographic extent of the South-West Western Australia Sustainable Yields Project includes all fresh, brackish and marginal surface water basins from Gingin Brook, north of Perth, to Albany, and groundwater resources between the Perth Basin, north-east of Geraldton, down the west coast and across to Albany in the south-east (Figure 1). This area covers all current and anticipated future water resources in SWWA suitable for irrigation, domestic water supplies and industries that require low salinity water. Inland water supplies are either limited or too saline for these uses. As a result these areas are supplied with water from the project area.

The project area occupies about 62,500 km^2 and contains over 1.9 million people or 89 percent of the population of Western Australia. It is concentrated over the highest rainfall part of the south-west of the state and includes all of the state's irrigation areas with the exception of the Gascoyne (Carnarvon) and the Ord (Kimberley).

Groundwater is a major source of water in the Perth and Collie groundwater basins and near Albany. The Perth Basin comprises flat sandy coastal plains and more elevated and clayey plateaux. The western Darling Plateau contains most of the usable surface water resources. Groundwater in this area is contained in clayey weathering zones and becomes more saline to the east. Significant interactions between surface water and groundwater occur in both the Collie and Perth basins.

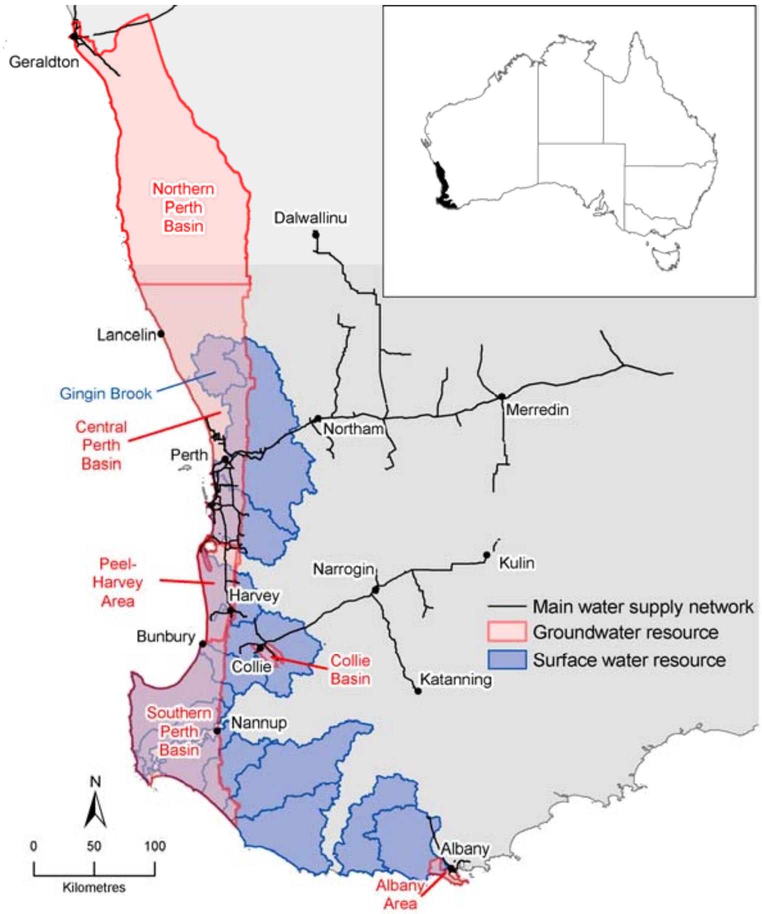

Figure 1. Groundwater resources and surface water resources in the project area

Scenarios assessed

The assessments of current and future water availability have been undertaken by considering a range of climate and development scenarios. All scenarios were defined by daily time series of climate variables based on different scaling of the observed climate from 1 January 1975 to 31 December 2007. This period was chosen because it follows a significant post-1974 climate shift which resulted in substantially reduced streamflows. All models were used in predictive mode – that is, estimating future water yields in 2030 based on scaling past climate sequences.

The **historical climate** scenario (Scenario A) was based on the climate of the historical past (1 January 1975 to 31 December 2007). This scenario was used to assess water yields should the climate in the future prove to be similar to that of the historical past. This scenario is used as the baseline against which other scenarios are compared. Current levels of surface water and groundwater development were used.

The **recent climate** scenario (Scenario B) was based on the climate of the recent past (1 January 1997 to 31 December 2007). This scenario was used to assess water yields should the climate in the future prove to be similar to that of the recent past. Current levels of surface water and groundwater development were used.

The **future climate** scenario (Scenario C) used 15 global climate models with three estimates of temperature changes (due to global warming) to provide a spectrum of possible ~2030 climates. From this spectrum three were selected for reporting, representing a wet extreme, median and dry extreme future climate (scenarios Cwet, Cmid and Cdry respectively). Current levels of surface water and groundwater development were used.

The **future climate with future development** scenario (Scenario D) used the same climate time series as the median future climate scenario, but future levels of development were used (~2030 projections of commercial forestry plantations, farm dams and likely future irrigation developments; and increased groundwater abstractions to full allocation limits).

Climate

Up to 80 percent of the annual rainfall occurs between May and October when temperatures are also at their lowest, which enables more rainfall to become runoff or recharge. There is a strong south-west to north-east gradient in rainfall. Annually, rainfall exceeds 1200 mm in the south-west and is less than 350 mm in the north-east (Figure 2a).

The mean annual areal potential evapotranspiration (APET) varies from 1650 mm in the north to 1180 mm in the south (Figure 2b). When rainfall in excess of APET is summed on a monthly basis, almost all except the extreme south of the project area has a negative value (Figure 2c).

All climate data are for the period 1975 to 2007 because a climate shift occurred in SWWA in the mid-1970s with post-1975 rainfalls being 10 to 15 percent lower than the long-term mean. The rainfall during this period is currently used by Western Australian water managers and suppliers for planning.

This part of the project aims to:

- provide a scientific platform in facilitating advancement in regional water plans to account for climate and development impacts on future water yields by using a regionally consistent approach
- help managers to identify the areas where there is potential risks for water dependent ecosystems associated with an impact of drying climate and development
- identify parts of SWWA which could develop significant gaps between future water yields and demands between 2008 and 2030.

The climate and development data were used in runoff models to estimate the amount of runoff needed to support surface water dependent ecosystems and water for consumptive use (Figure 3). Similarly the climate and development data were used in vertical flux models and groundwater flow models to estimate the amount of recharge needed to support groundwater dependent ecosystems and water for consumptive use. Future water demands by major user groups were estimated and compared with surface water and groundwater yields under climate and development scenarios.

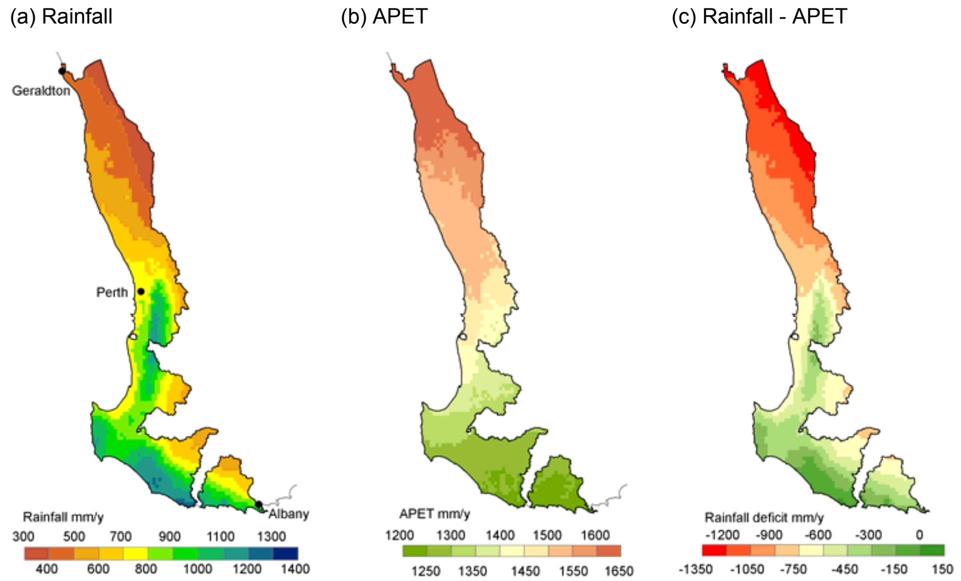

Figure 2. Mean annual (a) rainfall; (b) areal potential evapotranspiration; and (c) rainfall deficit (rainfall less areal potential evapotranspiration)

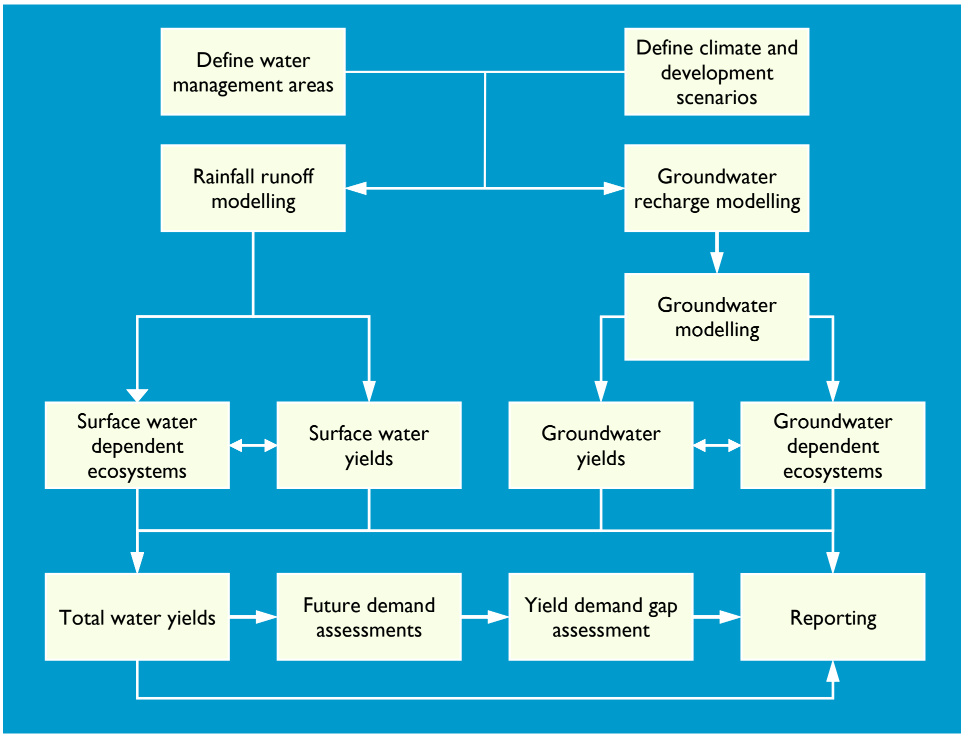

Figure 3. Process used to estimate gaps between future surface water and groundwater yields and demands in the project area

Surface water dependent ecosystems

The impact of climate change on surface water dependent ecosystems was assessed for 33 rivers for a 'winterfill period' between 15 June and 15 October, when gully dams are filling and intercept streamflow until they spill; and for the 'rest of the year' (16 October to 14 June) when biota require water over summer for their survival.

About half of the rivers are expected to have a 5 to 20 percent reduction in winterfill and rest-of-the-year flows compared to the historical climate if the climate of the recent (1997 to 2007) past continues until 2030. Under the median future climate, about 60 percent of rivers may have a 20 to 30 percent reduction (Table 1). Under the wet and dry extreme future climate, winter runoff is more affected than is summer runoff. Climate impacts are greatest in the southern Kent and Denmark rivers, and in the most northern river, Gingin Brook. The latter is affected by baseflow from a surrounding unconfined aquifer so further work may be required to be sure of this estimate. Under the median future climate, the reduction in runoff in these rivers during both the winter and the rest of the year is 40 to 65 percent relative to the historical climate, while it falls between 20 and 30 percent for other rivers.

Climate impacts are most significant for ecological river functions that require high river flows. The decrease in rainfall intensity that has accompanied the decrease in rainfall amounts in SWWA has already affected flood flows.

Table 1. Variations in median runoff during two periods of the year under climate scenarios

Scenario	Winterfill period (15 June to 15 October)		The rest of the year (16 October to 14 June)	
	Percent change from the historical climate	Number of rivers (out of total 33)	Percent change from the historical climate	Number of rivers (out of total 33)
Recent climate	-5% to -20%	15	-5% to -20%	16
Wet extreme future climate	-5% to -20%	30	-5% to -20%	23
Median future climate	-20% to -30%	20	-20% to -30%	20
Dry extreme future climate	-40% to -50%	19	-40% to -50%	13

Groundwater dependent ecosystems

Groundwater dependent ecosystems (GDEs) are uniquely adapted features of the Western Australian landscape, especially on the Swan and Scott coastal plains. Groundwater levels are within 10 m of the soil surface (the limit for GDEs) over about 3540 km^2 or about 18 percent of the southern half of the Perth Basin. Many areas have been cleared of native vegetation, however, so their ecological values have been affected. However only future risks associated with climate changes were considered, and the impact of recent climate and development was not included in analysis.

The risk to GDEs was assessed using the groundwater models and relationships between the level of vegetation stress and the amount and rate of fall in groundwater levels. Four types of GDEs were evaluated: wetlands and GDEs with three different depths to watertable (zero to 3 m, 3 to 6 m, and 6 to 10 m).

Under both the wettest (historical) and driest (dry extreme future) climates, the risk of reductions in groundwater levels for GDEs with a depth to watertable between zero and 3 m is greatest along the eastern Swan Coastal Plain and on the Scott Coastal Plain (Figure 5). Many areas with a shallow watertable in the western Swan Coastal Plain south-east of the Peel-Harvey Inlet have low or no risks which may be due to groundwater levels being buffered by drainage and evapotranspirational losses offsetting declines in rainfall. Many of these areas have been cleared.

The percentage of the areas with each GDE type that have different degrees of risk under each climate scenario in the southern half of the Perth Basin is shown in Figure 4. About half of all GDEs of all types may be affected to some extent by falling groundwater levels under the dry extreme future climate and under future development. About 40 percent may be affected even if the recent climate continues until 2030 and there is no increase in groundwater abstraction which indicates their sensitivity to change. GDEs with a depth to watertable of 6 to 10 m may be the most severely affected. However, a response to these changes may be in the form of a groundwater-dependent native Banksia tree being replaced by another Banksia species that is more drought tolerant. Such a change is not as noticeable as the loss of a wetland. The area at high to severe risk is relatively small under the wetter climate scenarios (historical, wet extreme future) but increases markedly under the dry extreme future climate and under future development.

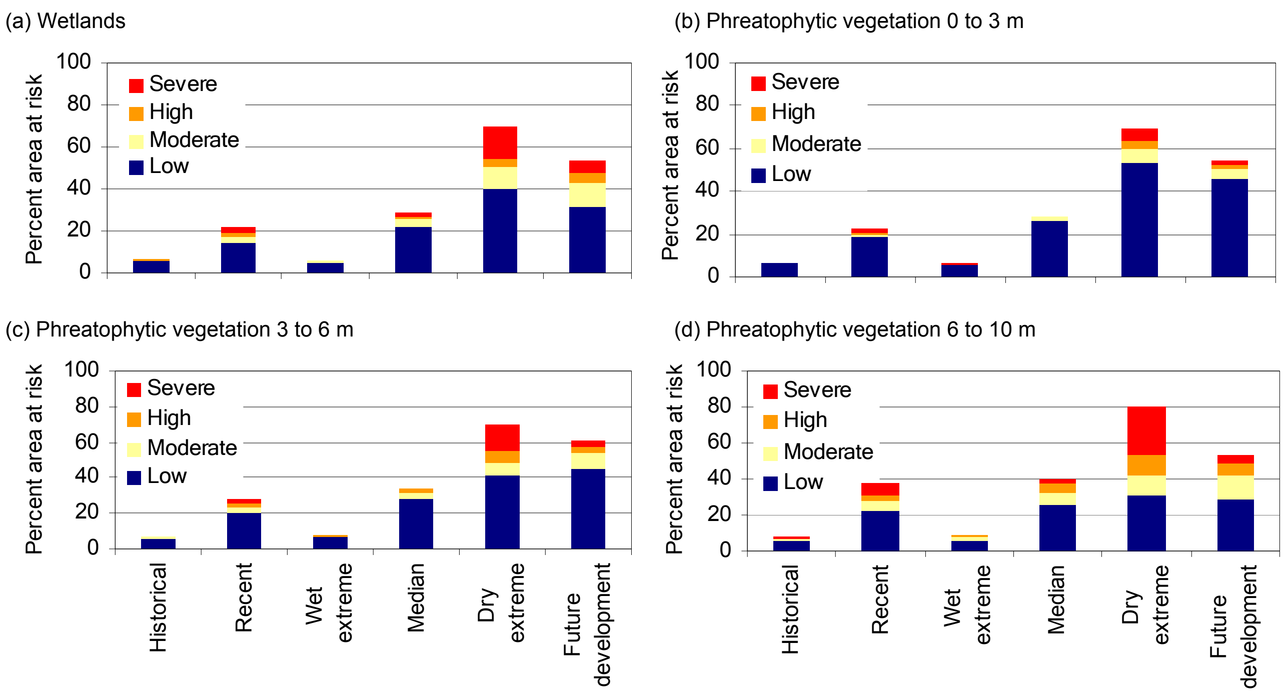

Figure 4. Percentage of the total area in specified risk category for each type of groundwater dependent ecosystem in the southern half of the Perth Basin: (a) wetlands, and phreatophytic vegetation with depths to watertable of (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m

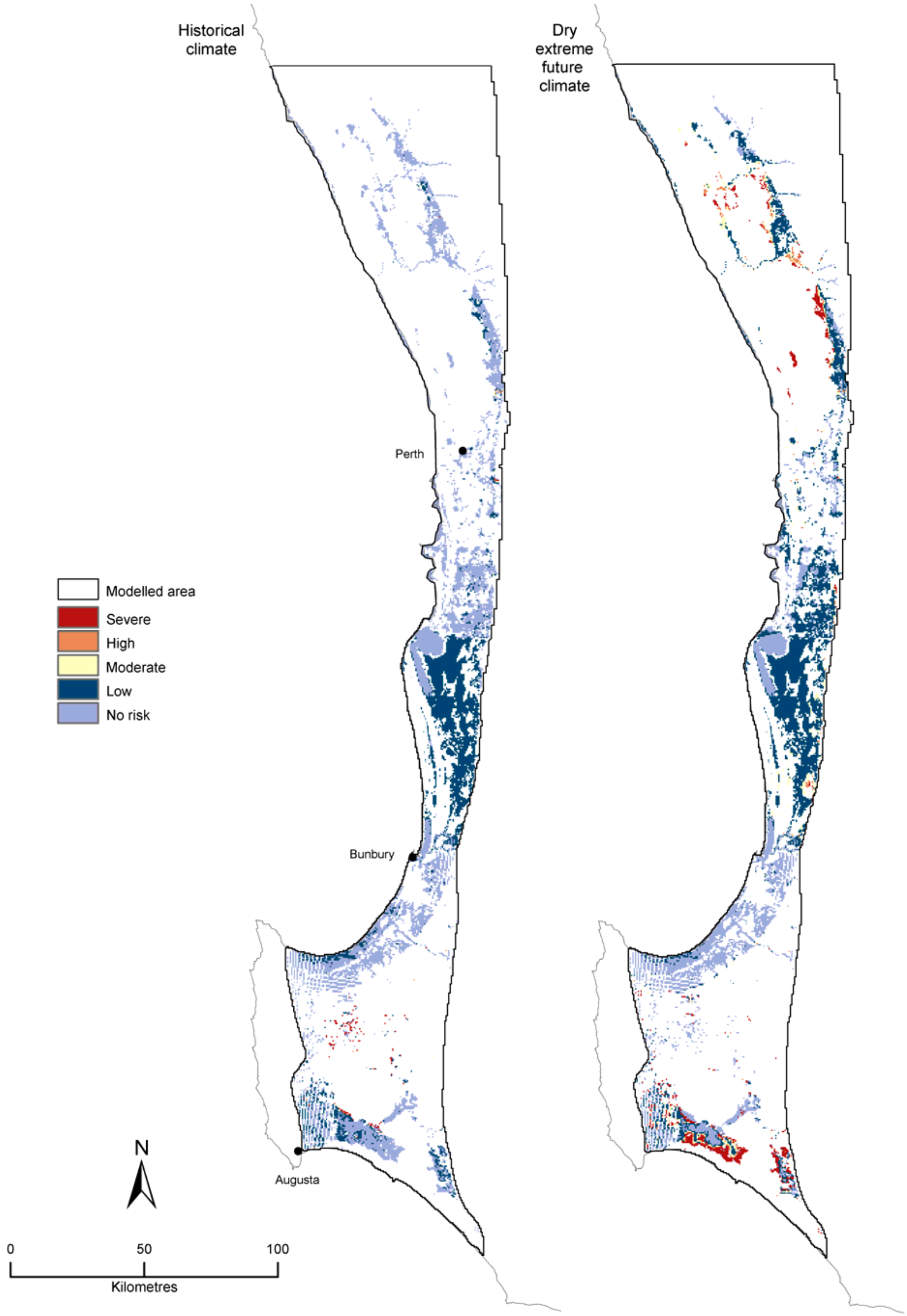

Figure 5. The risk category associated with groundwater dependent ecosystems (with a depth to watertable between zero and 3 m) in the southern half of the Perth Basin under the historical and dry extreme future climate

Future demands for surface water

Current demands for surface water are highest in the irrigation districts in the Harvey and Collie surface water management areas and these are expected to grow in future, along with the Warren basin under the high demand scenario (Figure 6). These estimates of demand include exports of water to the Integrated Water Supply Scheme (IWSS) that supplies drinking water to Perth, Mandurah and inland areas (Figure 1). The areas with small increases in demands by 2030 include areas that are already fully developed and areas where access to streams is limited by the occurrence of state forest, nature reserves or national parks.

Future demands for groundwater

Demand for groundwater is concentrated in the Perth area, especially when the volumes are considered relative to the small management areas near Perth (Figure 7). Demands are also expeceted to grow in the future in the vicinity of Perth for industry; self-supply irrigation for peri-urban horticulture; and public open space and private irrigation of lawns and gardens. Groundwater for the IWSS may also increase through the development of further coastal wellfields. These may intensify the competition between private users and IWSS which relied on groundwater resources.

Future surface water and groundwater yields

Future changes in surface water and groundwater yields are estimated as shown in Figure 8 and Figure 9. Water resources in the Harvey and Collie surface water management areas have high yields and are relatively less sensitive to climate change compared with the other main surface water irrigation areas in the Donnelly and Warren areas further south. However under the dry extreme future climate most surface water yields are significantly affected.

Groundwater areas also lose significant yields under this climate but due to the larger volumes of these groundwater resources the percentage changes in groundwater yields are overall smaller than yields of surface water. The southern half of the Perth Basin is most affected, along with the Collie Basin and Albany Area.

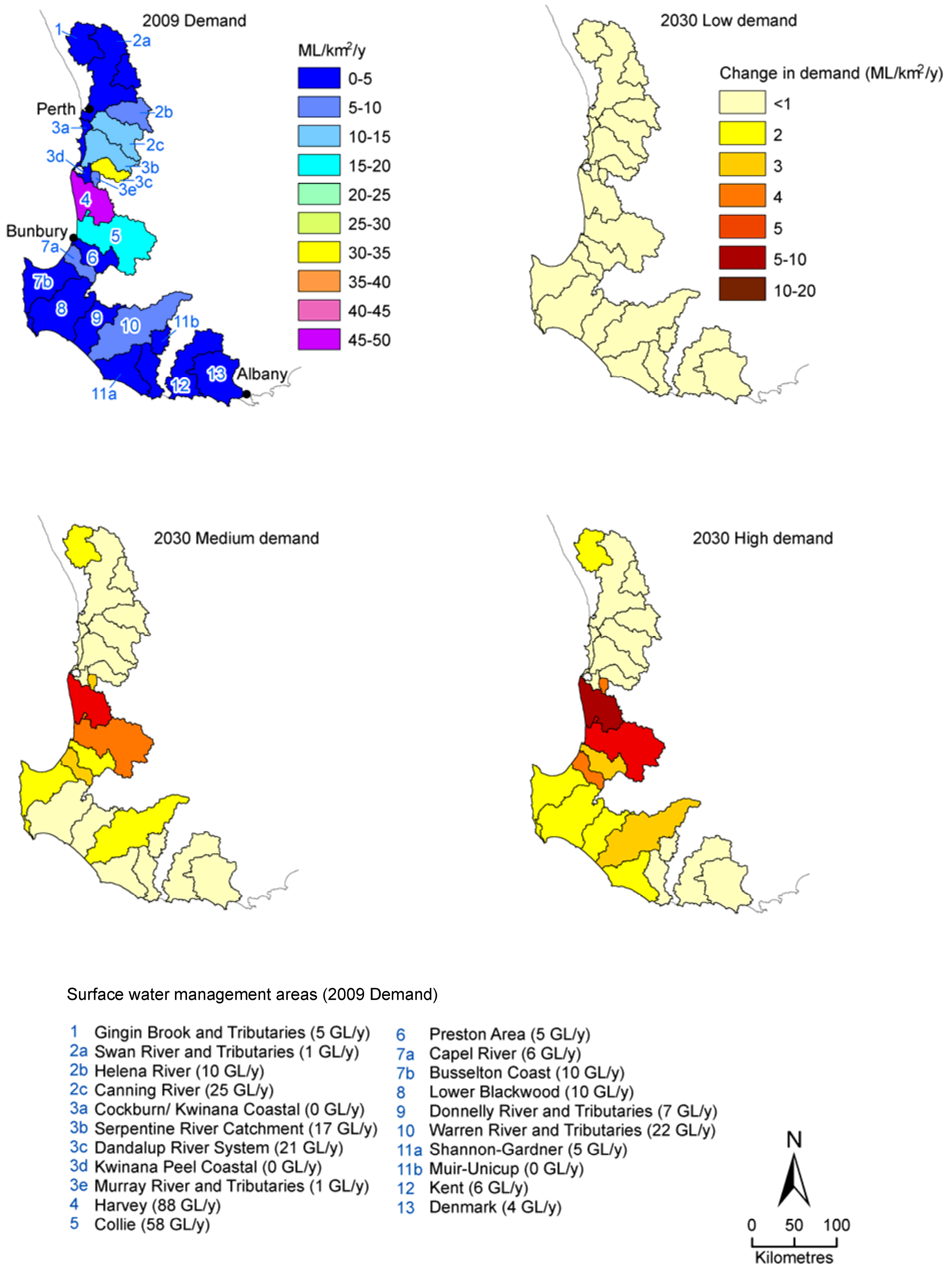

Figure 6. Current demand and change in demand under the low, medium and high demand scenarios by surface water management area

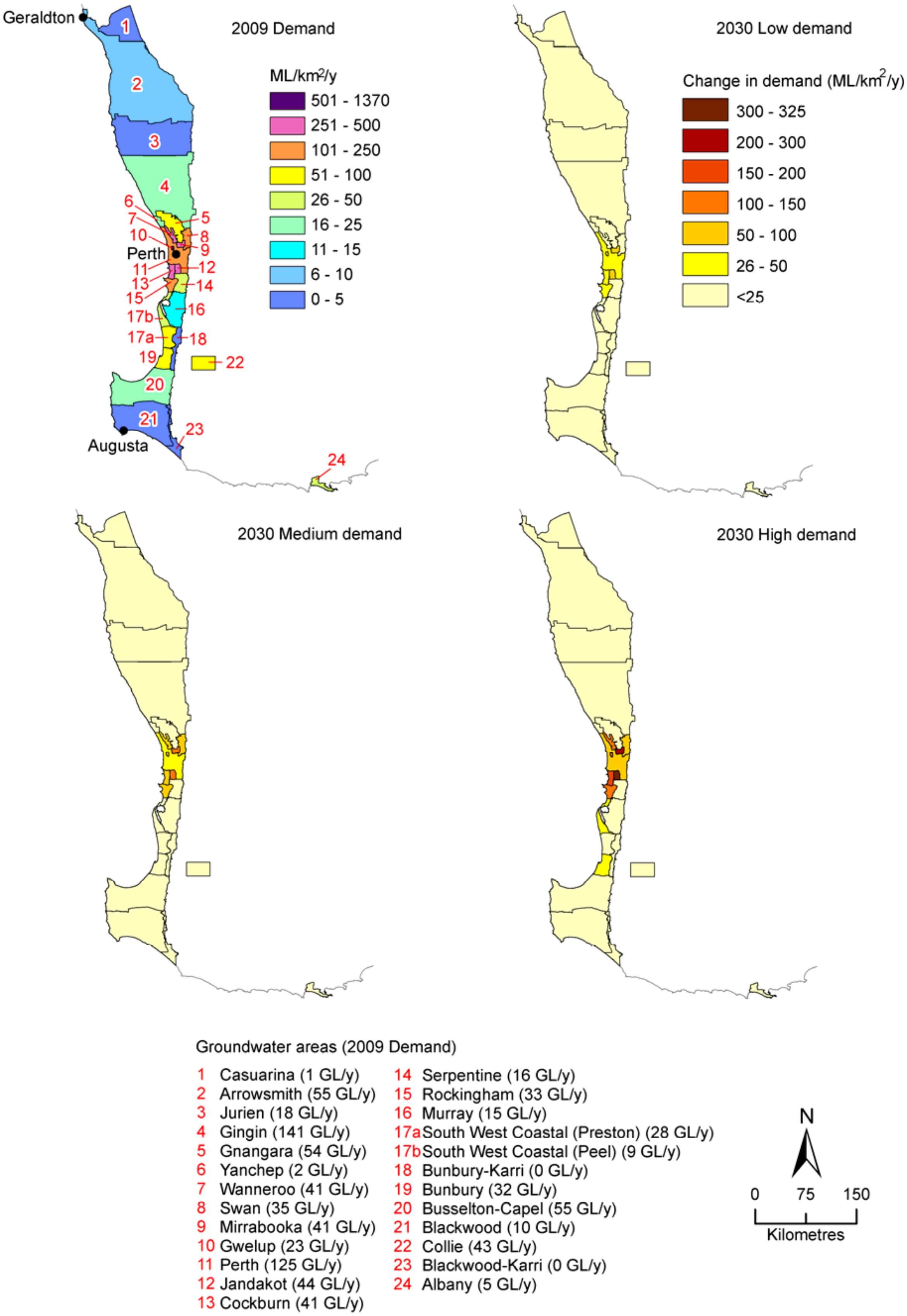

Figure 7. Current demand and change in demand under the low, medium and high demand scenarios by groundwater area

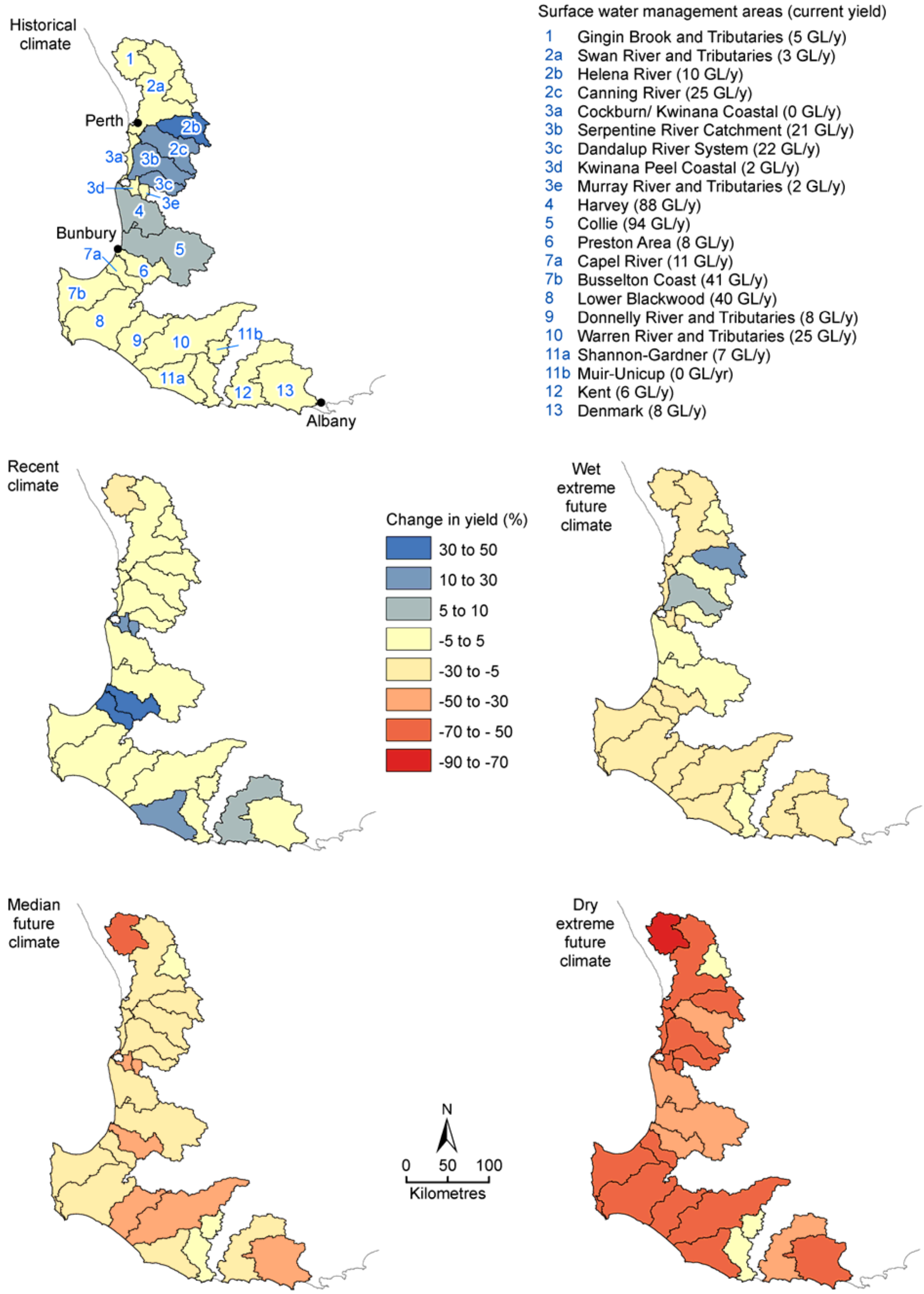

Figure 8. Estimated changes in surface water yields

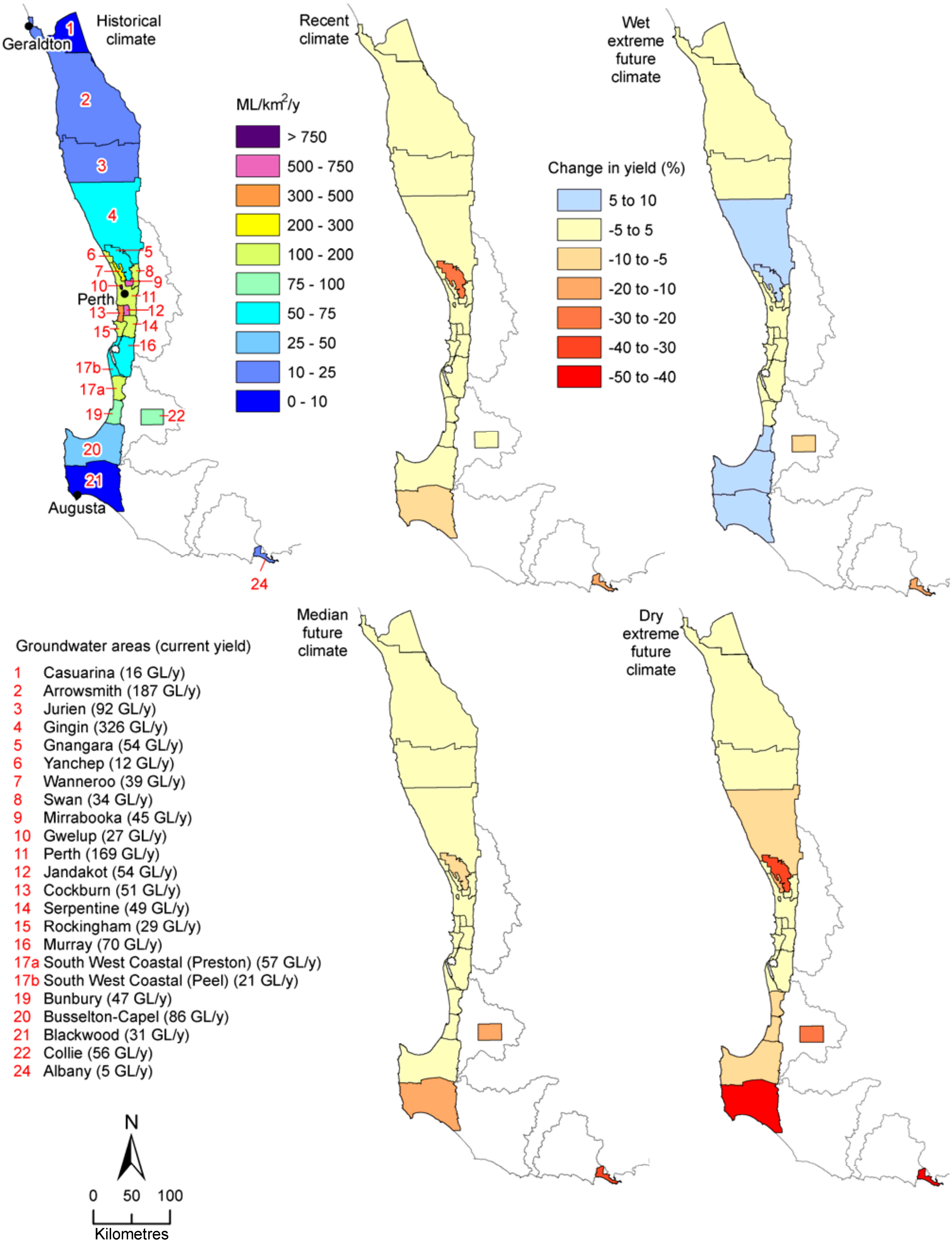

Figure 9. Estimated changes in groundwater yields

Gaps between water yield and water demand

While integrated water resources use of both surface water and groundwater is possible in some areas, especially where water is piped over long distances, for the purpose of this analysis the gaps between water yield and water demand are presented separately for groundwater and surface water resources. Figure 10 shows gaps between surface water yield and demand under the medium demand and climate scenarios. Table 2. Summary of gap analysis for the project area Figure 11 shows the equivalent gap for groundwater.

The Harvey and Collie surface water management areas have a high likelihood of developing a gap between yields and demands, despite their relative resilience to climate change. Potential growth in horticulture and industrial demands cause this gap. Similarly a gap between yields and demands is likely to develop in the Warren surface water management area.

The areas around Perth, Collie and Albany are likely to have the highest gaps between future groundwater yields and demands. Despite the Northern Perth Basin having the lowest rainfall in the project area, water is likely to remain available in 2030 unless significant new mining, horticultural or industrial demands develop. Such growth in demands is feasible before 2030 but the demand estimation method used cannot predict demands.

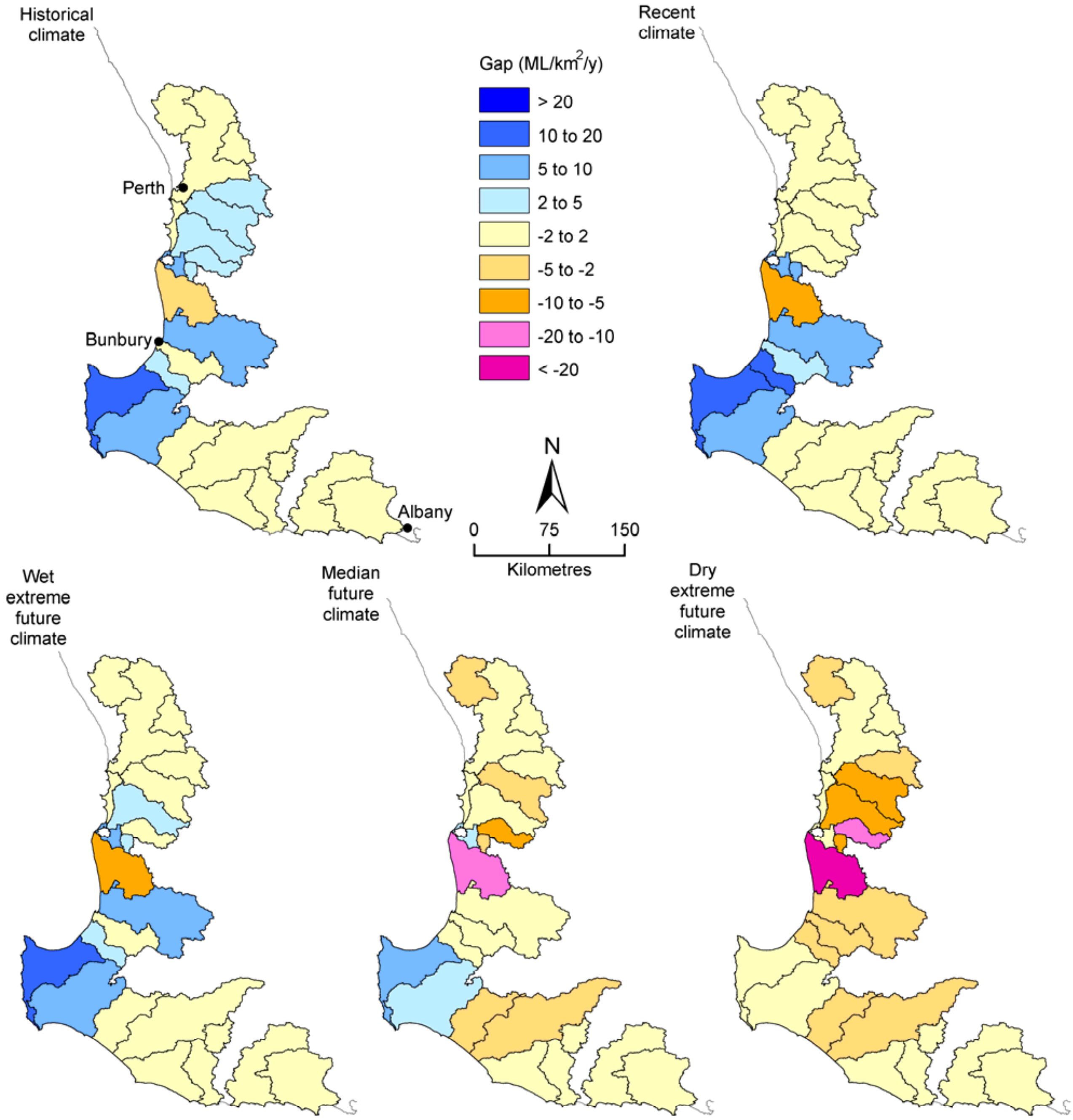

Figure 10. Gap between surface water yield and water demand under the medium demand scenario

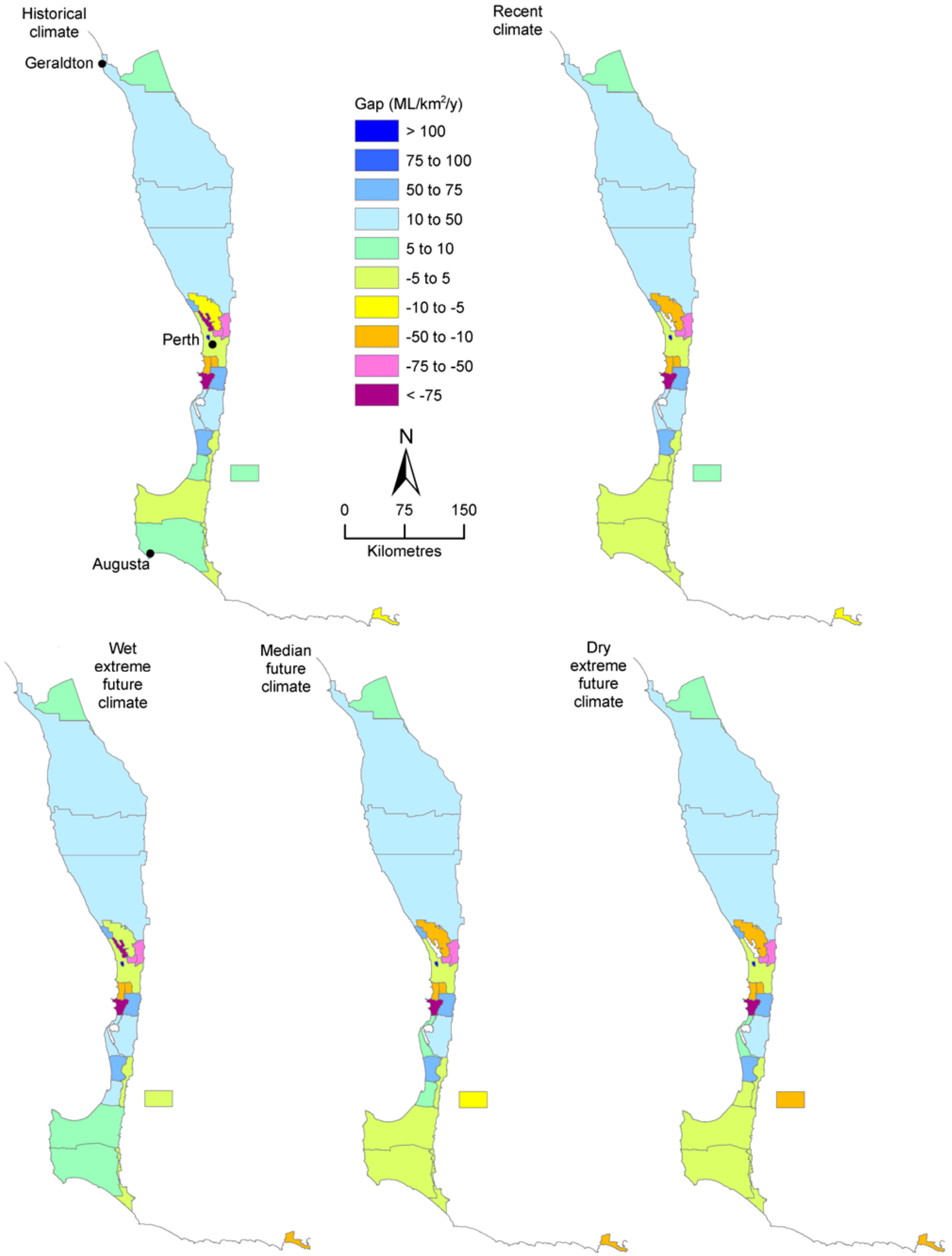

Figure 11. Gap between groundwater yield and water demand under the medium demand scenario

Gaps between total water yield and demand

In the Australian context, water use is unusual in the project area because 71 percent of all water is self-supplied, three-quarters is groundwater, and irrigated agriculture uses only 35 percent. Also, almost all irrigated agricultural use is for high value products rather than for irrigating pastures. Water deficits cannot be easily met by transporting water from low to high value self-supply uses because the ability to move the water may not be present as is possible in riverine irrigation systems such as the Murray-Darling Basin.

Figure 12 and Table 2 show the results of the combined water yield and demand gap analysis for the project area for all water resources. In overall terms, the area has a surplus of water to meet demands to 2030, except under the high demand scenario, and under the median future and dry extreme future climate. This scenario combination is feasible if rapid population and economic growth continue until 2030 and the climate gets much hotter and drier. Under the median future climate and the medium demand scenario, an overall surplus of 266 GL/year is estimated.

Figure 12 shows that it is mainly surface water yields that are likely to decline under the future climate scenarios. However, the total yield of the Superficial Aquifer is expected to also be impacted, especially under the dry extreme future climate.

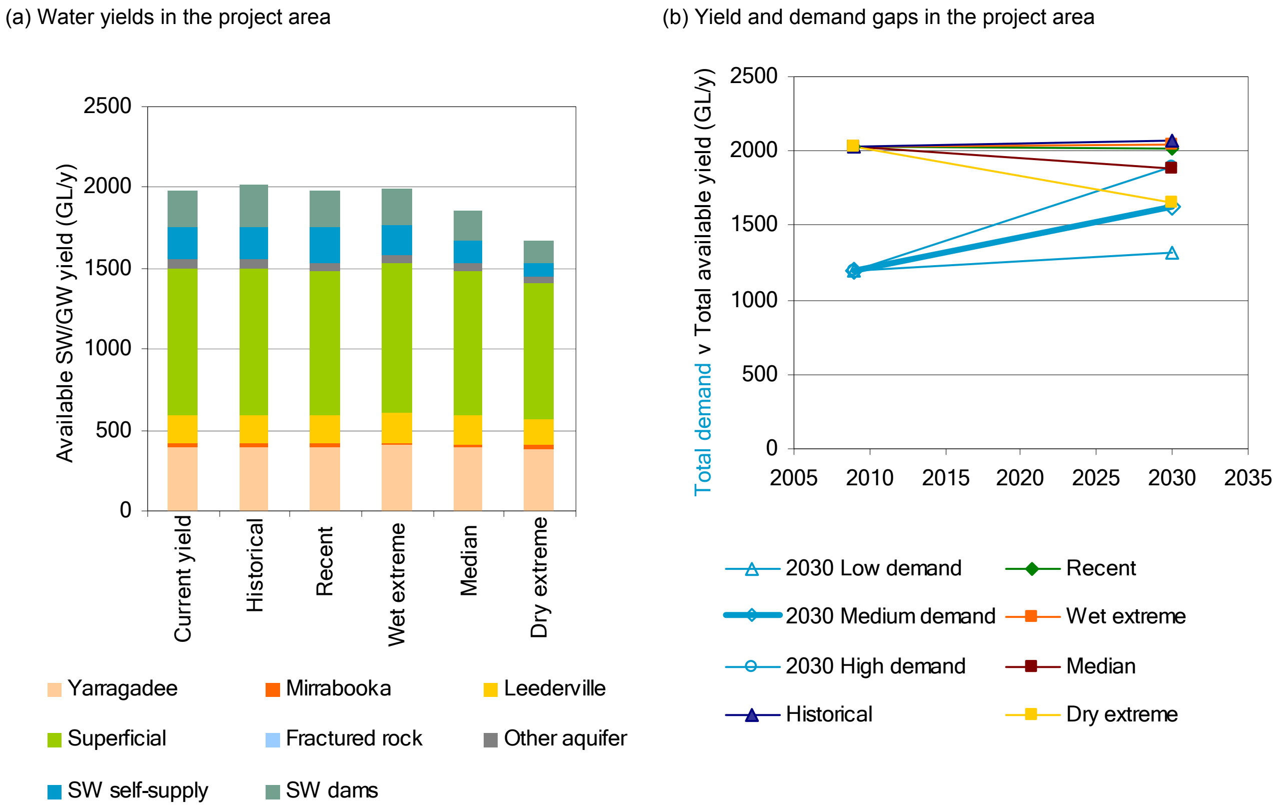

Figure 12. (a) Water yields in the whole project area for surface water (SW) and major aquifers combined; (b) gaps between yields and demands under climate and demand scenarios

Table 2. Summary of gap analysis for the project area

Climate scenario	Gap			
	Current demand	Low demand (2030)	Medium demand (2030)	High demand (2030)
	GL/y			
Current available yield	825	709	400	126
Historical climate	875	760	450	176
Recent climate	818	702	393	119
Wet extreme future climate	848	732	423	149
Median future climate	677	561	252	-22
Dry extreme future climate	451	336	26	-248

Limitations

The methods used in this project are suitable for regional estimates but to assess local impacts on water dependent ecosystems and water yields, more fine-scale modelling and analysis would be required. This project provides guidance on where this additional management effort is needed.

The estimates of future groundwater yields in the Northern Perth Basin and Albany Area were limited because of the lack of a suitable groundwater model for simulating the impacts of climate change and development.

Water demands from industries that are not currently in the area but may be introduced in the future cannot be anticipated. There may, for example, be mining developments that require significant groundwater in the Northern Perth Basin which can not be estimated by the method adopted. The method also does not take account of whether the water is suited to the demand (for example, brackish water is not suited for drinking water demands), nor does it take account of the cost of transferring water from areas of surplus to areas of deficit. The IWSS imports surface water from as far south as the Collie catchment and transfers it as far as the goldfields and is a case where water can be transferred across management areas.

Where to from here

The areas with potential regional risks to GDEs need to be further investigated al local scale to assess if there are any ecological values that may be affected if the potential groundwater levels change under drying climate.

The reductions in yields projected for groundwater resources are much less than those for surface water resources. This is understandable because groundwater systems appear to be more resilient and robust in the area of shallow groundwater occurrence where increased proportions of rainfall become recharge as watertables fall. Decreases in surface runoff are more closely related to rainfall reduction. However the differences estimated in priority areas need to be better evaluated, deploying the process-based hydrological models that take account of groundwater and surface water stores, thus allowing assessment of the effects of climate on wetlands and streams on a local scale.

Based on the undertaken analysis and within the constraints of modelling framework, it appears that surface water sources will increasingly be replaced by groundwater sources in many areas, with Albany a possible exception due to the relative paucity of groundwater in this area.

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1 Introduction

1.1 Background

In 2007 and 2008, CSIRO produced a series of reports examining the likely water yield of surface water and groundwater systems in the Murray-Darling Basin under future climate and development scenarios. Development included possible land management changes such as afforestation and farm dams.

To allow a consistent analytical framework for water policy decisions across the nation, the Council of Australian Governments (COAG) agreed in March 2008 to expand this assessment of 'sustainable yield' to cover the major water systems across the country thus providing a comprehensive scientific assessment of water yield in northern Australia, Tasmania and south-west Western Australia (SWWA).

The information collected and analysed in this project addresses water resources in SWWA which will assist water managers and users in the region to incorporate the effects of climate change and development in their estimates of future water yields.

The project aims to:

- provide scientific information to improve the way that climate change is handled in water allocation plans and thereby reduce the likelihood of over-allocation of water resources
- help managers identify and manage water dependent ecosystems that are under threat from a drying climate and growing water demands that threaten their ecological functioning
- highlight the areas of SWWA which could develop significant gaps between water yields and demands between 2008 and 2030 so that management priorities can be better identified
- identify areas that may be less sensitive to climate change and areas that may allow more development of water resources than are currently planned.

The geographic extent of the South-West Western Australia Sustainable Yields Project was chosen to include all fresh (<500 mg/L total dissolved solids (TDS)), marginal (500 to 1500 mg/L TDS) and brackish (1500 to 3000 mg/L TDS) surface water and groundwater resources from east of Geraldton down the west coast and across to Albany in the south-east (Figure 1-1). This area covers all current and anticipated future water resources in SWWA suitable for irrigation, domestic water supplies and industries that require low salinity water. The SWWA region also supplies reticulated fresh water to much of the Wheatbelt, Great Southern and Goldfields regions because inland water resources are either limited or too saline for these uses. The SWWA water resources support almost two million people and many important industries.

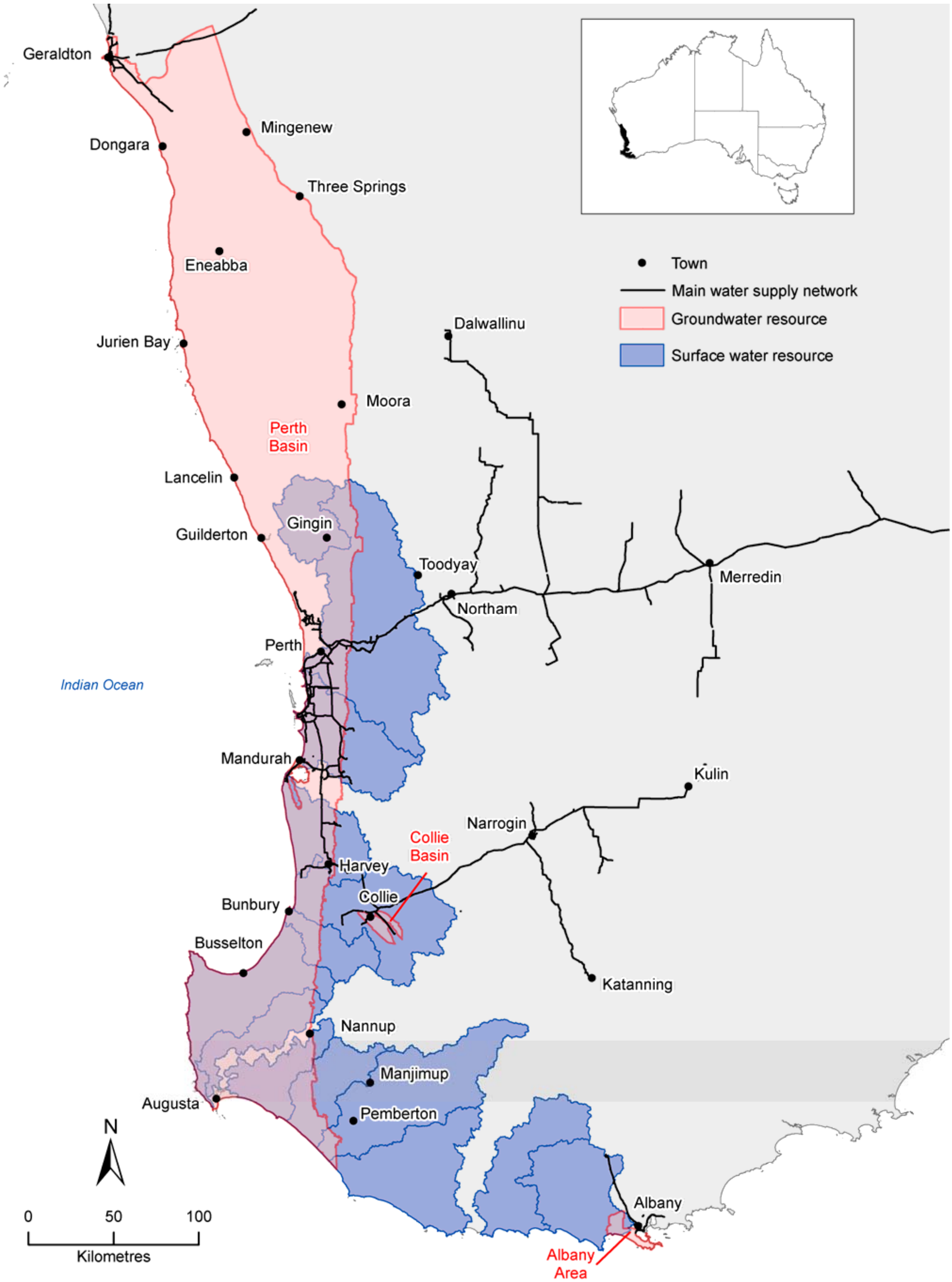


Figure 1-1. Groundwater resources, surface water resources and the reticulated supply network to inland areas supplied by the reservoirs and aquifers in the project area

The South-West Western Australia Sustainable Yields Project provides information on current and likely future water yields in a part of Australia that has experienced a drying climate since about 1975 (Appendix C). Since this time, SWWA has experienced a climate shift as severe as anywhere in the world (Bryson Bates, pers. comm. 2009; Hennessy et al., 2007). In addition to a decline in rainfall amounts, rainfall intensities – when measured over periods of hours to days – have decreased throughout the region and it is these major events and exceptionally wet seasons that often generate the most surface water runoff and groundwater recharge. At the same time, rising temperatures have been most marked in the latter part of the 20th century and may have exacerbated the hydrological response to the reduced rainfall, although studies of their combined effects are rare.

Reduced runoff into the Water Corporation's Integrated Water Supply Scheme (IWSS) surface water storages is internationally recognised as an instance of the impact of climate change on water resources (IPCC, 2007). Less well known, but as important, has been the gradual decrease in groundwater levels both in the surface water catchments in the hills east of Perth and in coastal plain aquifers used for water supplies. The marked reduction in runoff required the Water Corporation of Western Australia to fast track new water source developments for Perth and the surrounding regions from 1996. As a result of these reduced yields the amount of water available to be licensed for extraction from both surface and groundwater resources has decreased in recent water allocation plans.

Almost all global climate models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC) predict that SWWA will experience an even warmer and drier future. These models have been applied as a basis for estimating future water yields in surface and groundwater catchments in this project.

The determination of sustainable yields requires choices by communities and governments about the balances of outcomes (environmental, economic and social) sought from water resource management and use (Figure 1-2). These choices are best made in the light of sound technical knowledge and the most important need is a robust understanding of the extent and nature of the water resource. This project undertook to better define future water yields and demands so that the estimation of how much water may be available to future needs is better known by water managers.

While existing records of rainfall, streamflow and groundwater levels provide a description of the resource from the past to the present, it is possible that predictive models calibrated and validated on these data may not provide the best description of the extent of the resource in the future if input data for future scenarios are outside the historical bounds and if hydrological processes change under extreme conditions. A careful examination of the implications of future climate on water resources is required as the basis for water management and planning. This includes a consideration of the direct effects (such as changes in rainfall and potential evapotranspiration) and indirect effects (such as changes in vegetation and water demand).

The required baseline information for determining sustainable yields is thus an assessment of the current and likely future extent and variability of surface and groundwater resources and comparison of these to the current levels of resource commitment as expressed by the Department of Water Western Australia (DoW) in allocation plans and estimates of future demand by industry sectors.

The Terms of Reference for the South-West Western Australia Sustainable Yields Project required CSIRO to:

1. Develop transparent, consistent and robust methodologies for determining the extent of available water resources in the catchments/aquifers of the study area, including guidance on:
    a. how to utilise the historical flow records used in surface water models and the recharge assumptions used in groundwater models, to factor in climate change and other risks
    b. how to address the interaction between surface and groundwater systems
    c. appropriate models/methodologies to use in regions which do not have existing surface water or groundwater models and/or which do not have comprehensive water resource data
    d. ensuring that models/methodologies are capable of incorporating a range of ‘development’ scenarios or land use change activities
    e. identifying significant knowledge and information gaps.

2. In the application of the methodologies, use existing legislation, water plans or other arrangements to guide the assessment. For catchments or aquifers either without current water resource arrangements or with plans for which environmental outcomes and/or levels of extractive use are not clear, these parameters may be inferred and any assumptions clearly stated.
3. Apply the above methodology to estimate water availability and demand in 2030 in the light of climate change and other risks to provide:
    a. Estimates of water resources on an individual catchment and aquifer basis using four different scenarios:
        i. historical climate and current development
        ii. recent climate (of the last 11 years) and current development
        iii. 2030 climate change and current development
        iv. 2030 climate change and 2030 development of farm dams, plantations, groundwater systems and proposed irrigation development.
    b. For each of the scenarios (i) to (iv) above, provide an assessment of the impact of current and future predicted water resource development on water dependent ecosystems as defined under Section 4 of the *Water Act 2007*.
4. Address groundwater resources and particularly aquifer interconnectivity.
5. Address areas of significant direct groundwater or surface water irrigation activity (i.e. individual operators) as well as covering areas where significant irrigation already occurs.
6. Provide output in a fashion suitable to inform development and water management planning for those catchments.
7. Work will be guided by a Steering Committee chaired by the Australian Government, with membership from the government of WA and CSIRO, and include appropriate consultative arrangements to address environment and industry concerns. CSIRO's role will be to technically support the communication process.
8. The project will be completed by the end of December 2009.

This report collates runoff and groundwater yield data from two companion reports from this project: 'Groundwater yields in south-west Western Australia' (CSIRO, 2009a) and 'Surface water yields in south-west Western Australia' (CSIRO, 2009b). This data are then combined with information on water dependent ecosystems and consumptive demands to address the requirements in the Terms of Reference to 'estimate water availability and demand in 2030 in the light of climate change and other risks', to 'provide an assessment of the impact of current and future predicted water resource development on water dependent ecosystems' and to 'provide output in a fashion suitable to inform development and water management planning for those catchments'.

This project's contribution to the determination of how much water may be available for licensing is therefore an assessment of current and future water yields and demands, as shown by the left box in Figure 1-2. The project does not recommend or evaluate alternative allocation regimes and their impacts on environmental, social or economic values. However, future allocations may be based on better estimates of future water yields and demands at a regional level as a result of this project.

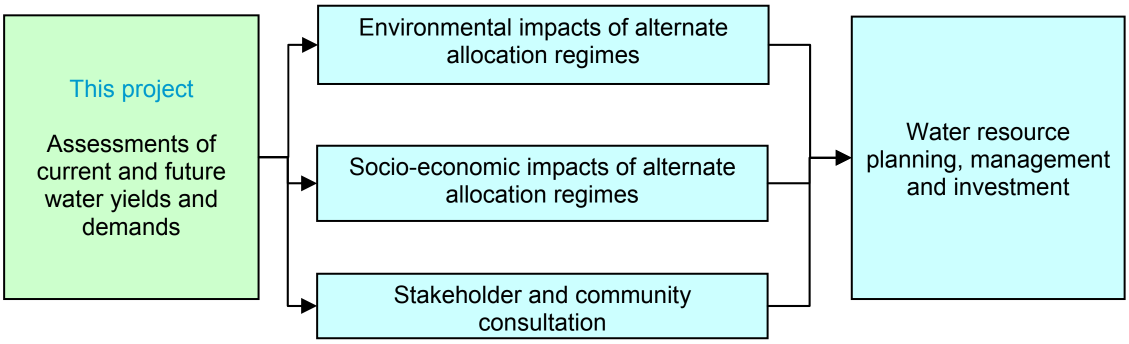


Figure 1-2. Project context

1.2 Methodological framework

1.2.1 Water resources reporting

Almost all surface water diversions occur in catchments east of the Darling Scarp and on the Leeuwin-Naturaliste Ridge (Chapter 2, Figure 2-12) where the topography enables storage dams to be constructed. Almost all groundwater extractions occur on the flat Swan and Scott coastal plains (Perth Basin), the Collie Basin and the western Bremer Basin near Albany (see Figure 2-11 and Figure 2-12, Chapter 2) where sedimentary aquifers are substantial and the water is usually fresh or brackish. The management areas for both surface and groundwater resources are shown in Figure 1-3.

There are a few areas where the simultaneous assessment of river and groundwater extractions needs to be considered. Most rivers that cross the coastal plains are gaining streams that receive groundwater discharge from the adjacent unconfined aquifers. However groundwater is the preferred water resource in these areas because groundwater is usually available and surface water impoundments are difficult.

Almost all water allocation plans developed by the DoW consider surface and groundwater resources separately due to this geographical separation of water resource catchments and major aquifers. However considerations of their interactions are taken into account within each plan. Both water resources are considered in regional water plans which provide a broader and often longer planning context, but do not specify water allocations.

For the above reasons this project provides separate reports on surface water and groundwater yields under future climate and development scenarios. Important surface–groundwater interactions are analysed in the groundwater report (CSIRO, 2009a.

1.3 Climate and development scenarios

The assessments of current and future water availability have been undertaken by considering four climate and development scenarios. All scenarios were defined by daily time series of climate variables based on different scaling of the observed climate from 1 January 1975 to 31 December 2007. This period was chosen because it follows a significant post-1974 climate shift which resulted in substantially reduced streamflows (Appendix C). All models were used in predictive mode – that is, estimating future water yields out to 2030 (for groundwater) or to 2040 (for surface water) based on the 33-year climate series from 1975 to 2007, with results reported as representative of 2030 conditions.

The four scenarios are defined generally below. More details are provided in the methods report (CSIRO, 2008) and in the companion groundwater and surface water reports (CSIRO, 2009a; CSIRO, 2009b).

1.3.1 Historical climate and current development (Scenario A)

The historical climate scenario (Scenario A) was based on the climate of the historical past (1 January 1975 to 31 December 2007). This scenario was used to assess water yields should the climate in the future prove to be similar to that of the historical past. Scenario A was used as the baseline against which other scenarios are compared. Current levels of surface water and groundwater development were used.

1.3.2 Recent climate and current development (Scenario B)

The recent climate scenario (Scenario B) was based on the climate of the recent past (1 January 1997 to 31 December 2007). This 11-year period aligns with the recent dry period and is used in the Water Corporation's Integrated Water Supply Scheme (IWSS) planning (Water Corporation, 2005) and is also the base case projection for groundwater management in the Gnangara Sustainability Strategy (DoW, 2008). Scenario B was used to assess water yields should the climate in the future prove to be similar to that of the recent past. Current levels of surface water and groundwater development were used.

1.3.3 Future climate and current development (Scenario C)

The future climate scenario (Scenario C) used 15 global climate models with three estimates of temperature changes (due to global warming) to provide a spectrum of possible ~2030 climates. From this spectrum three were selected for reporting, representing a wet extreme, median and dry extreme future climate (scenarios Cwet, Cmid and Cdry respectively). Current levels of surface water and groundwater development were used.

1.3.4 Future climate and future development (Scenario D)

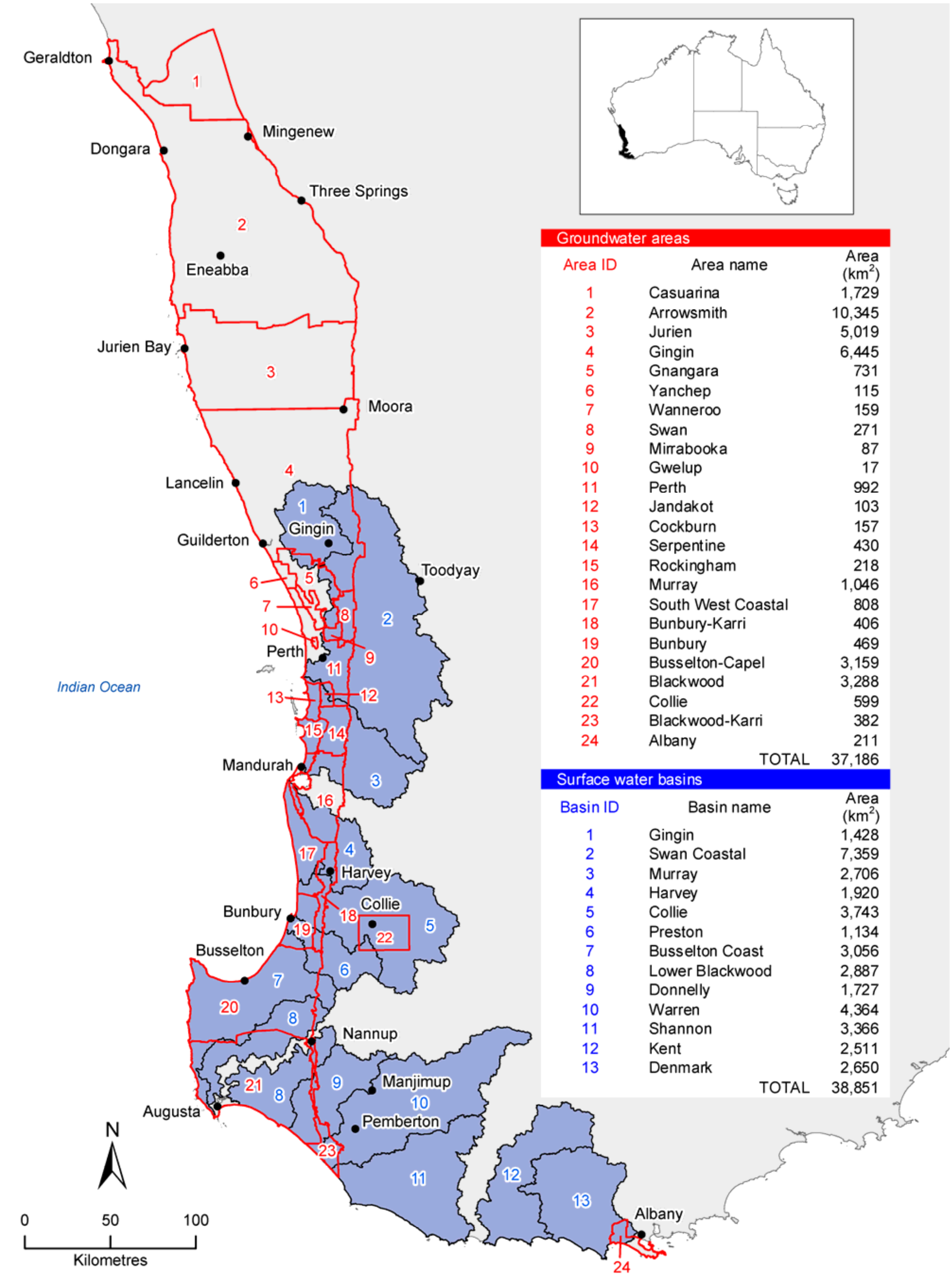
The future climate with future development scenario (Scenario D) used the same climate time series as the future climate scenario (Scenario C), but future levels of development were used. Future development was limited to a consideration of ~2030 projections of commercial forestry plantations, farm dams and likely future irrigation developments.

1.4 Report framework

This report is one of three main reports emerging from this project. This report uses the combined surface water and groundwater yield estimations to determine whether the resources have the ability to meet future demands and environmental needs in the project area under future climate and development scenarios. Companion reports estimate future yields from the groundwater and surface water modelling (CSIRO, 2009a); (CSIRO, 2009b). These three main reports are accompanied by technical reports, summary reports and factsheets. A list of all project reports is included in Appendix A.

The structure of this report is illustrated in Figure 1-4. An overview of the region (Chapter 2) outlines the climate, physiography, soil-landscapes, vegetation, land use, demographics and major water dependent assets. This chapter provides background material for interpreting both the yield and demand results. SWWA has a number of unique features with regards to water resources and demands and therefore this chapter provides useful context. Chapter 3 reviews relevant legislation and water plans which guide water allocation in the region. Chapter 4 defines the important surface water environments in the region and draws information from the project's surface water report about how water yields may change as a result of climate and development and how these changes may impact on environmental assets. In Chapter 5 outputs from the groundwater models in the project's groundwater report are used to assess how important regional groundwater dependent ecosystems may be impacted by climate and development.

Future water demand in the project area is estimated in Chapter 6. Data from the surface water and groundwater reports, as well as from Chapters 3, 4, 5 and 6, are used to estimate the gaps between water yield and demand under a number of yield and demand scenarios in Chapter 7. All of these results are discussed in Chapter 8. Finally, as required under the Terms of Reference, knowledge and information gaps are identified in Chapter 9.



Groundwater areas

Area ID	Area name	Area (km^2)
1	Casuarina	1,729
2	Arrowsmith	10,345
3	Jurien	5,019
4	Gingin	6,445
5	Gnangara	731
6	Yanchep	115
7	Wanneroo	159
8	Swan	271
9	Mirrabooka	87
10	Gwelup	17
11	Perth	992
12	Jandakot	103
13	Cockburn	157
14	Serpentine	430
15	Rockingham	218
16	Murray	1,046
17	South West Coastal	808
18	Bunbury-Karri	406
19	Bunbury	469
20	Busselton-Capel	3,159
21	Blackwood	3,288
22	Collie	599
23	Blackwood-Karri	382
24	Albany	211
	TOTAL	37,186

Surface water basins

Basin ID	Basin name	Area (km^2)
1	Gingin	1,428
2	Swan Coastal	7,359
3	Murray	2,706
4	Harvey	1,920
5	Collie	3,743
6	Preston	1,134
7	Busselton Coast	3,056
8	Lower Blackwood	2,887
9	Donnelly	1,727
10	Warren	4,364
11	Shannon	3,366
12	Kent	2,511
13	Denmark	2,650
	TOTAL	38,851

Figure 1-3. Geographic scope of the project area showing the water reporting regions

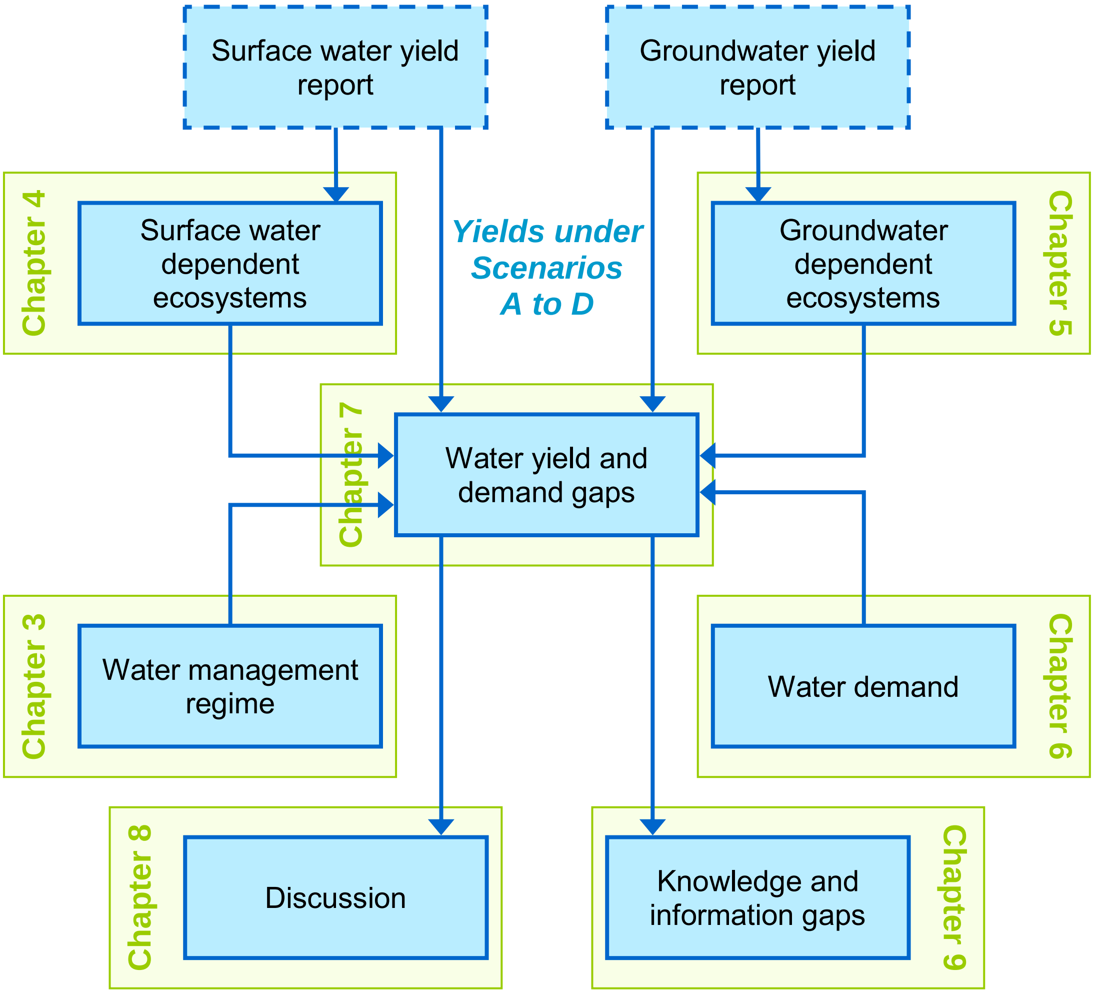


Figure 1-4. Framework for this report

1.5 Expectations, limitations and uncertainty

The project assessed future surface yields under a number of scenarios and compared these yields with environmental water requirements and estimated future water demands. There is still uncertainty about the ability of climate models to predict future conditions and therefore extrapolations from the past were included (scenarios A and B) as well as outcomes of all available daily global climate models (Scenario C). One option was to use only a subset of climate models. Instead, in order to better assess future water resources, particularly with uncertainty in future climate variability, results are reported for the 10th, 50th and 90th percentile runoff/recharge inputs as scenarios Cdry, Cmid and Cwet.

Six rainfall-runoff models and three calibration methods were used to obtain the best estimates of surface water yields.

While only one groundwater model was used in each region, an independent hydrograph analysis method was used to estimate groundwater levels at 2030 under each scenario and compare these estimates with the groundwater model results for the same point.

The level of confidence in the surface water and groundwater models used to estimate yields is variable and reported in CSIRO (2009a, b). The levels of confidence are usually higher in fully developed systems that have required an intensive management response.

Three possible future water demand projections were used to compare with results under the climate scenarios.

The assumptions used in all assessments are clearly stated so that managers can decide which of the yield and demand scenarios they consider when making specific water management decisions.

Additional sources of uncertainty are related to currently available information on ecological responses to changes in the water regime on groundwater dependent ecosystems and surface water dependent ecosystems. In many situations the need for ecological data is important, particularly since it is often the main constraint on water resource development. There is a need to more clearly define ecosystems' resilience to variations in water regime, both in terms of ecological community composition and their functionality. Currently limited data are available to identify those at only a few specific sites, increasing the level of uncertainty when analyses of these data are extrapolated to the regional scale.

1.6 References

Bates, Bryson (2009) Personal communication

Charles et al. (2010) Climate analyses for the South-West Western Australia Sustainable Yields Project. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. *In prep.*

Chiew F, Teng J, Kirono D, Frost A, Bathols J, Vaze J, Viney N, Hennessy K and Cai W (2008) Climate data for hydrologic scenario modelling across the Murray-Darling Basin. A report to the Australian government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

CSIRO (2008) Description of Project Methods, South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 70 pp.

CSIRO (2009a) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

CSIRO (2009b) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

DoW (2008) Gnangara Sustainability Strategy. Department of Water, Perth, Western Australia. Available at < http://portal.water.wa.gov.au/portal/page/portal/gss >

Hennessy K, Fitzharris B, Bates B, Harvey N, Howden S, Hughes L, Warrick S and Warrick R (Eds.) (2007) Australia and New Zealand. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 507-540.: 34pp.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contributions of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Water Corporation (2005) Integrated water supply scheme, security through diversity, 2005-2050 : an overview. Water Corporation, Perth, Western Australia, 12 pp.

2 Overview of the project area

The South-West Western Australia Sustainable Yields Project covers an area of about 62,500 km^2, which includes about 38,800 km^2 of surface water catchments and about 37,200 km^2 of groundwater areas (GWAs), 13,500 km^2 of which overlap (Figure 1-3 in Chapter 1). The area extends from east of Geraldton, about 450 km north of Perth, to Albany, 410 km south-east of Perth.

To put the hydrological results obtained in this project into a regional perspective, the following sections provide an overview of south-west Western Australia (SWWA) with respect to climate, geology, physiography, soil-landscapes, land use, demographics, water use, vegetation and water dependent environmental assets.

2.1 Subdivision of the project area for reporting

For the purposes of reporting, the surface water basins were grouped into three regions (Figure 2-1):

- the northern (Gingin to Murray) region which includes the northern Jarrah-forested catchments and most of the Water Corporation's Integrated Water Supply Scheme (IWSS) reservoirs
- the central (Harvey to Preston) region which includes the surface water irrigation scheme areas associated with the Harvey, Collie and Preston basins
- the southern (Busselton Coast to Denmark) region which covers the southern drainages between the Busselton Coast and the Denmark basin.

Within each surface water basin there are numerous catchments, many of which were used for surface water model calibration, and others for which projected surface water flows were assessed.

Likewise, for the purposes of reporting, 24 groundwater areas (GWAs) were grouped into six groundwater regions, most of which align with groundwater model domains (Figure 2-2).

There are eight water demand regions within the project area which are aligned with statistical reporting regions such as Local Government and Regional Development Authorities. Some demand regions extended outside the boundaries of the project area but these areas usually have very small water demands in comparison with the project area (Figure 2-3). For comparison with surface and groundwater yields, these demand regions were broken into 45 water management areas which align with surface water basins and GWAs as detailed in Chapters 6 and 7.

In this report, the 'project area' refers to the extent of the surface water basins (Figure 2-1) and the GWAs (Figure 2-2). The rest of this chapter summarises information across this entire area.

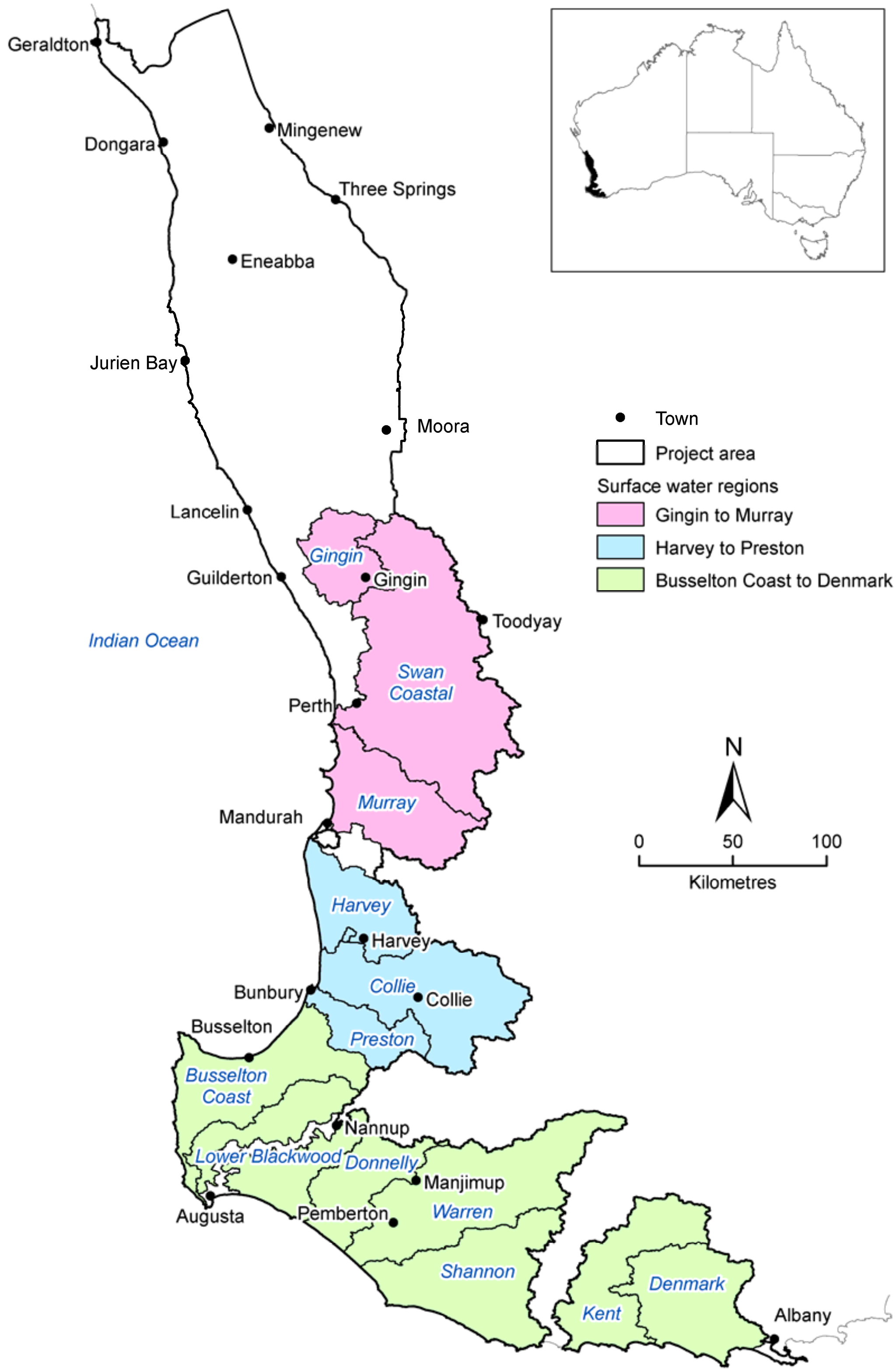


Figure 2-1. Surface water basins and regions reported in this project

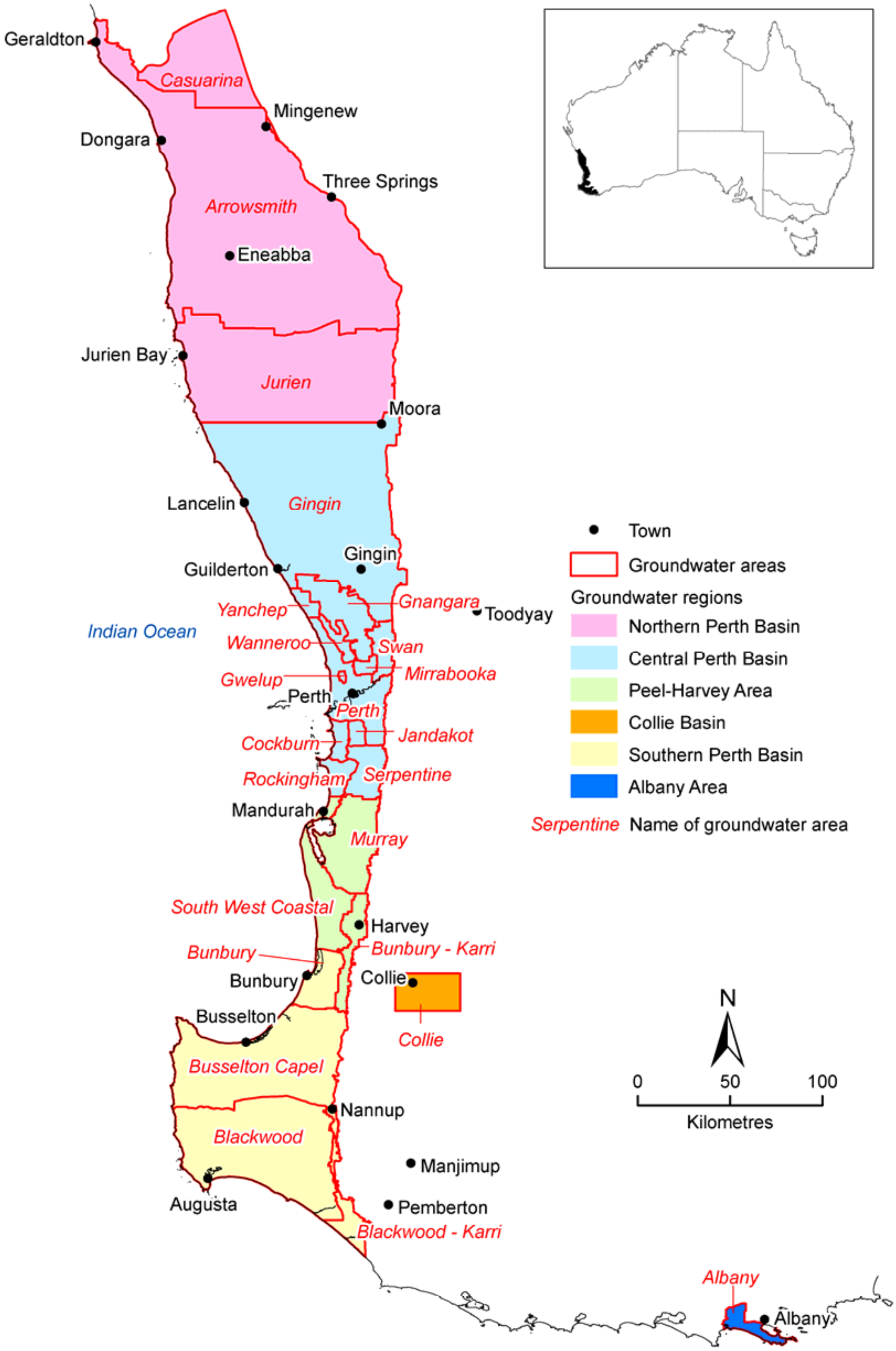


Figure 2-2. Groundwater regions reported in this project

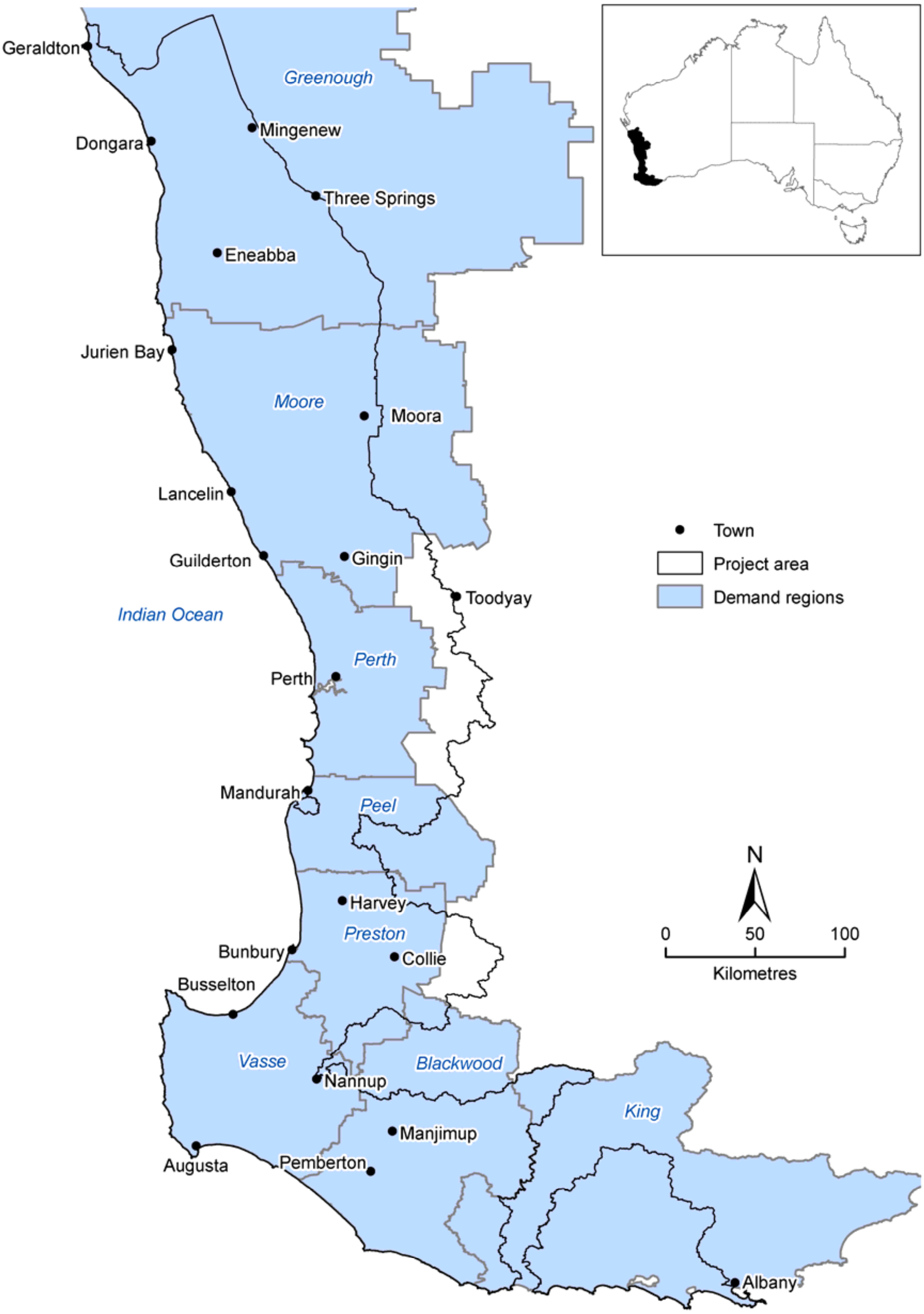


Figure 2-3. Demand regions reported in this project

2.2 Climate

2.2.1 Rainfall

SWWA experiences a Mediterranean type climate with a Köppen Classification as temperate in the south and sub-tropical in the north of the project area (http://www.bom.gov.au/cgi-bin/climate/cgi_bin_scripts/clim_classification.cgi). Up to 80 percent of mean annual rainfall occurs from May to October, with the majority produced by cold fronts that come through in the middle latitudes. The annual cycle in the procession of troughs, lows and highs produces marked rainfall seasonality as well as a strong south-west to north-east gradient. Figure 2-4 shows the spatial distribution in mean annual, summer (December to February), autumn (March to May), winter (June to August) and spring (September to November) rainfall across the project area for the period 1975 to 2007 referred to in this report as the historical period. Rainfall is highest both in south-west coastal parts of the project area and along the Darling Ranges (see Section 2.3.2, Topography) where there is a maximum mean annual rainfall of 1290 mm. It is lowest in the north-east where there is a minimum mean annual rainfall of 305 mm.

In SWWA winter rainfall was previously considered the most consistent and reliable in Australia: plentiful and with low inter-annual variability compared to any other region of the continent (Nicholls et al., 1997). However SWWA (south-west of a line joining 30ºS, 115ºE and 35ºS, 120ºE, see Bates et al., 2008) has experienced a substantial and prolonged rainfall decline since the early-1970s (Figure 2-5 and Appendix C; CSIRO and Australian Bureau of Meteorology, 2008). The 10 to 15 percent rainfall decline has severely reduced runoff, with inflow to major reservoirs in SWWA declining by 70 percent over the same period (Water Corporation, 2008).

The overall rainfall trend in SWWA can be assessed by considering individual stations (Figure 2-6 and Figure 2-7). Ten meteorological stations distributed throughout the project area were selected based on their high data quality with few missing records. All ten stations have negative linear trends in their annual and winter rainfall for the 1960 to 2007 period.

Concurrently, temperature in SWWA has risen in recent decades (Figure 2-8) which has increased water demand, while also contributing to reduced water yields from the associated higher evaporation rates. Further analysis of these trends is presented in the Climate Technical Report (Charles et al., 2010).

Understanding of the mid-1970s climate shift has increased rapidly over the last decade, and there is now a considerable body of research with consistent findings discounting the likelihood for a return to the wetter conditions experienced previously (Appendix C). Thus climate conditions over the historical period were considered a justifiable baseline for current climate which is characterised by a marked decline in mean annual rainfall, winter rainfall, and a decline in extreme rainfall events (Appendix C).

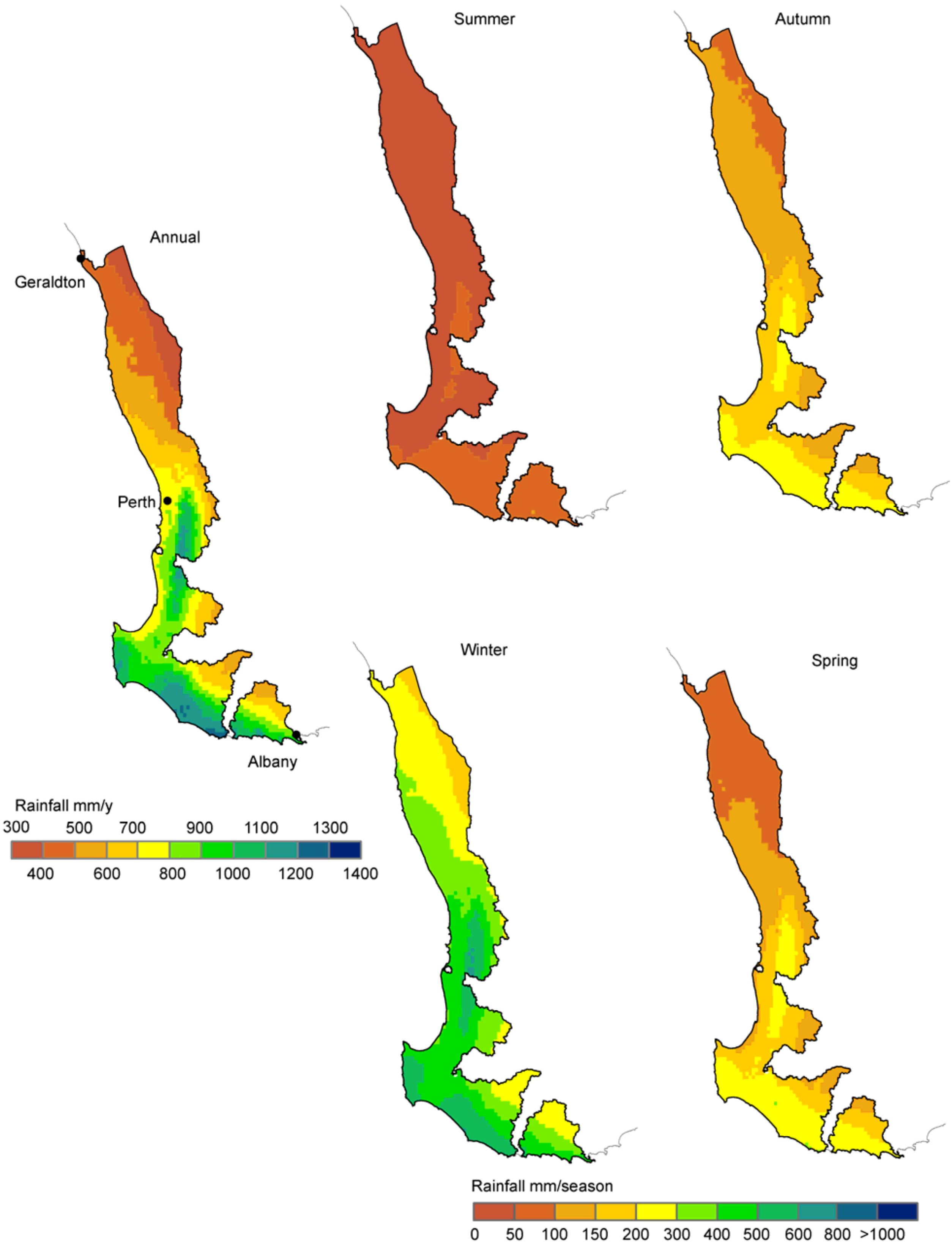


Figure 2-4. Spatial distribution of mean annual and seasonal historical (1975 to 2007) rainfall across the project area

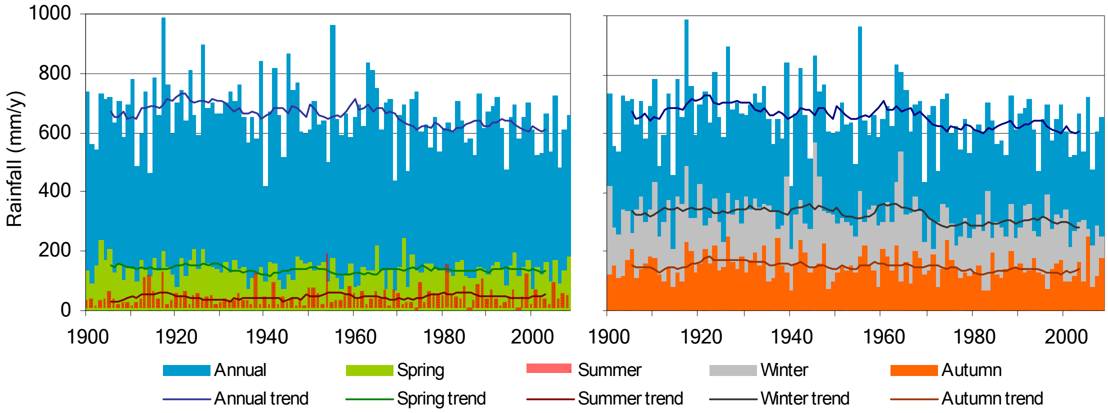


Figure 2-5. Annual and seasonal historical (1900 to 2007) rainfall, averaged across south-west Western Australia (Indian Ocean Climate Initiative region shown in Figure 2-7). Trend lines are 11-year running means (Source: Bureau of Meteorology data)

2.2.2 Areal potential evapotranspiration

Time series of daily Morton's wet environment areal evapotranspiration (APET) were produced for input into the surface and groundwater models used in this project (<http://www.longpaddock.qld.gov.au/silo/ >; Morton, 1983; Chiew and Leahy, 2003). APET is defined as the evapotranspiration that would take place if there were unlimited water supply, from an area large enough that the effects of any upwind boundary transitions are negligible, with local variations integrated to an areal average. APET is therefore conceptually the upper limit to actual evapotranspiration used in surface and groundwater modelling.

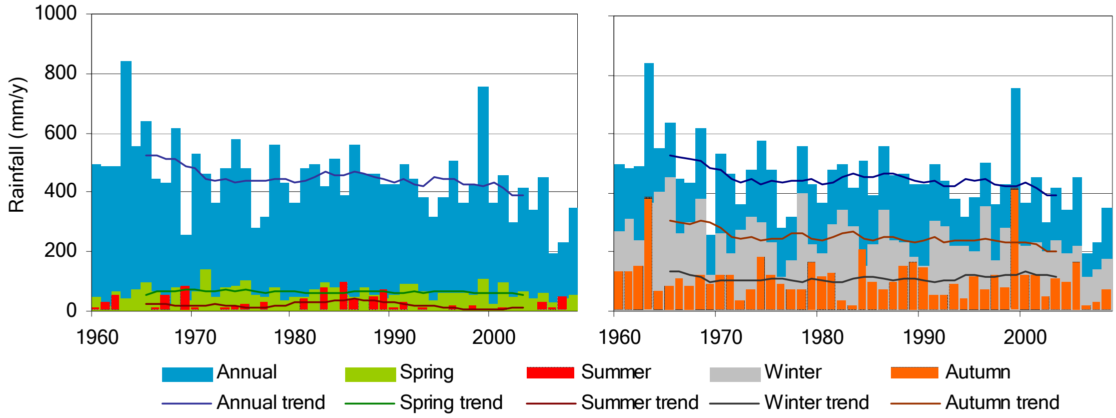
Rainfall-runoff modelling results are much less sensitive to errors in APET estimation than to errors in rainfall data. It is also easier to provide reliable APET data than rainfall, because APET is less variable in both space and time.

The mean annual APET averaged across the project area is 1420 mm, varying from 1650 mm in the north to 1180 mm in the south. The spatial and seasonal variations are shown in Figure 2-9; a strongly decreasing north–south gradient is apparent. APET was calculated using SILO data as outlined in Charles et al. (2010).

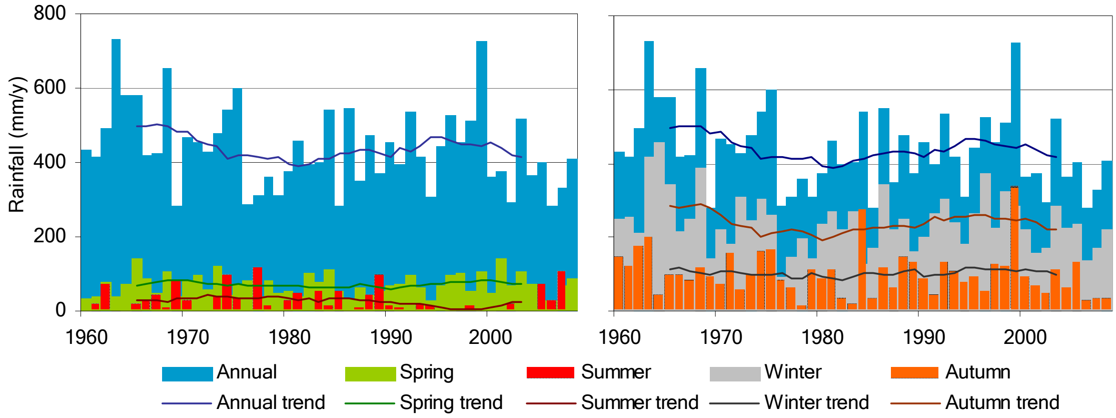
2.2.3 Rainfall deficit

The rainfall deficit, expressed as rainfall less APET on an annual and seasonal basis, highlights the extent to which the region is water-limited (Figure 2-10). Mean seasonal rainfall exceeds APET only in winter. The combined effect of declining rainfall (Figure 2-5) and increasing APET (Figure 2-9) contributes to the observed continuing decline in streamflow. An increase in rainfall deficit also results in increased irrigation demands to meet agricultural needs.

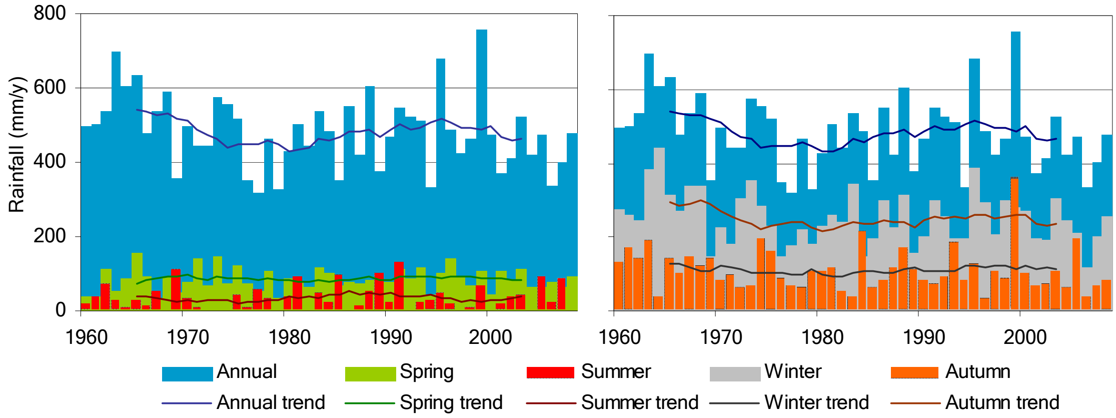
Geraldton Airport



Strawberry North



Chelsea



Perth Airport

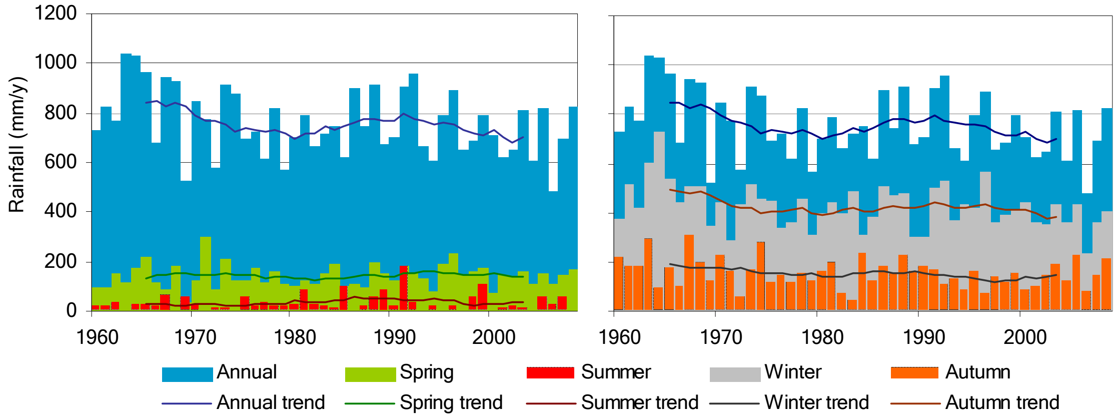
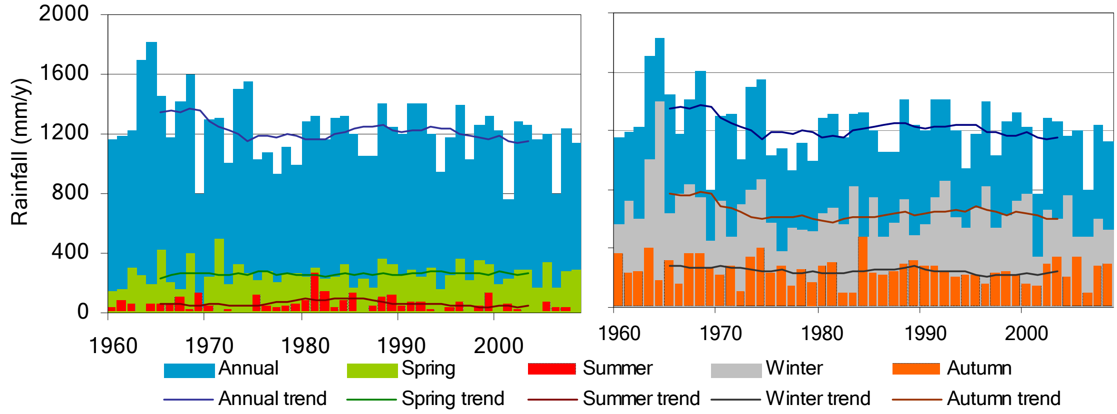
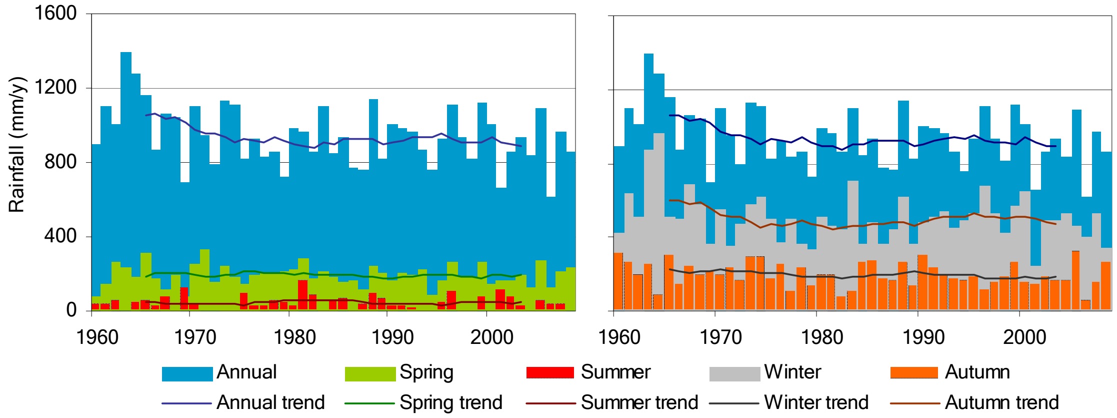


Figure 2-6. Time series of annual and seasonal rainfall for ten climate stations (locations shown in Figure 2-7)

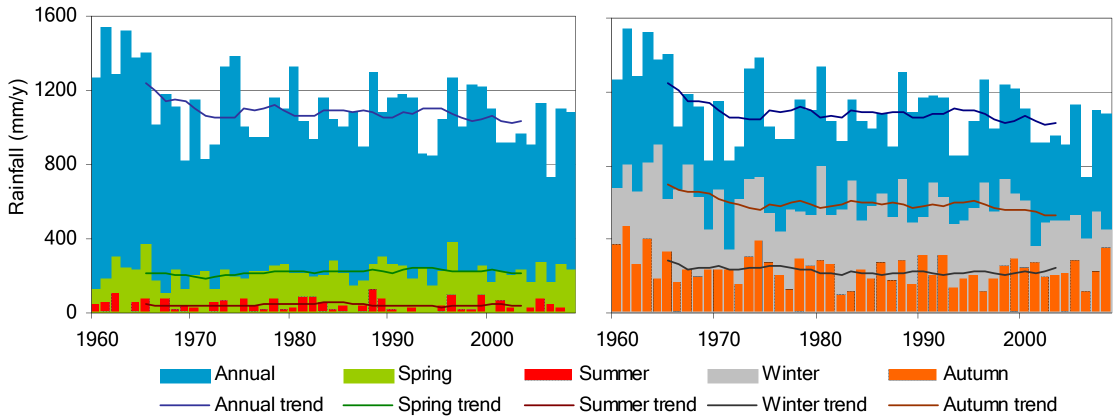
Dwellingup



Donnybrook



Cowaramup



Cape Leeuwin

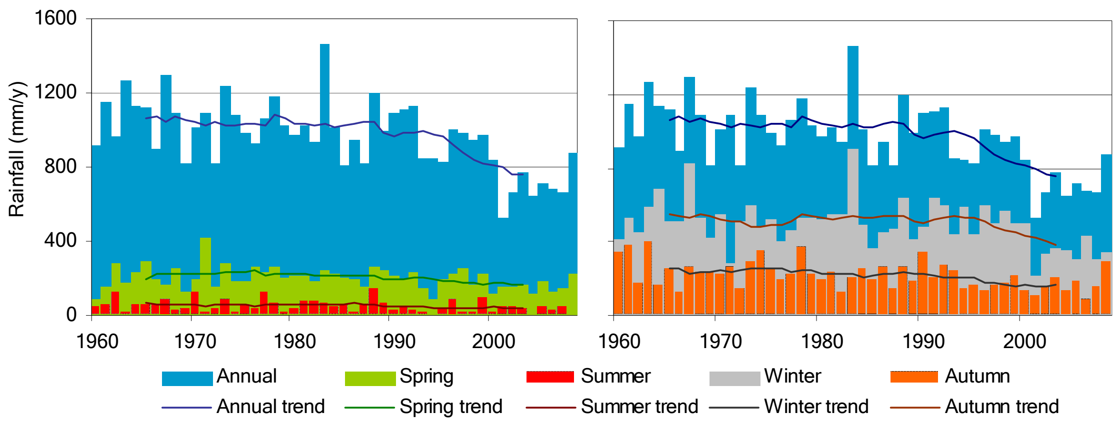
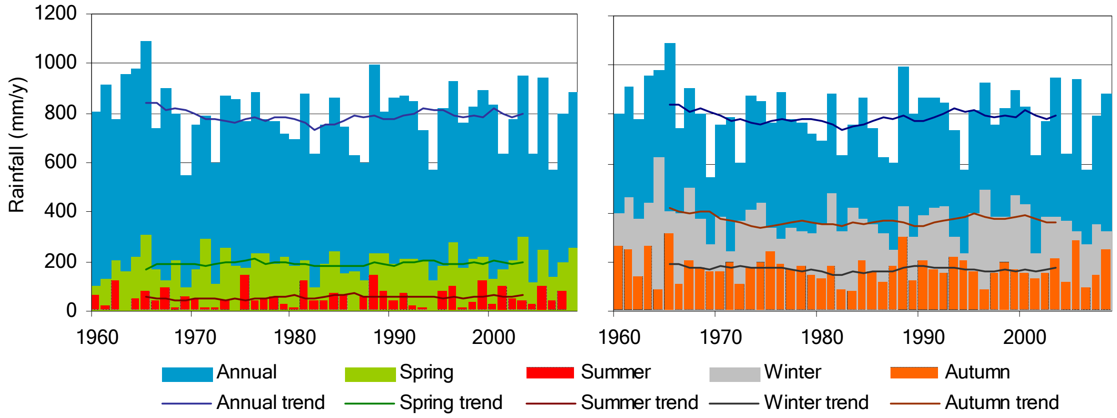


Figure 2-6. (cont'd) Time series of annual and seasonal rainfall for ten climate stations (locations shown in Figure 2-7)

Deeside



Mount Barker

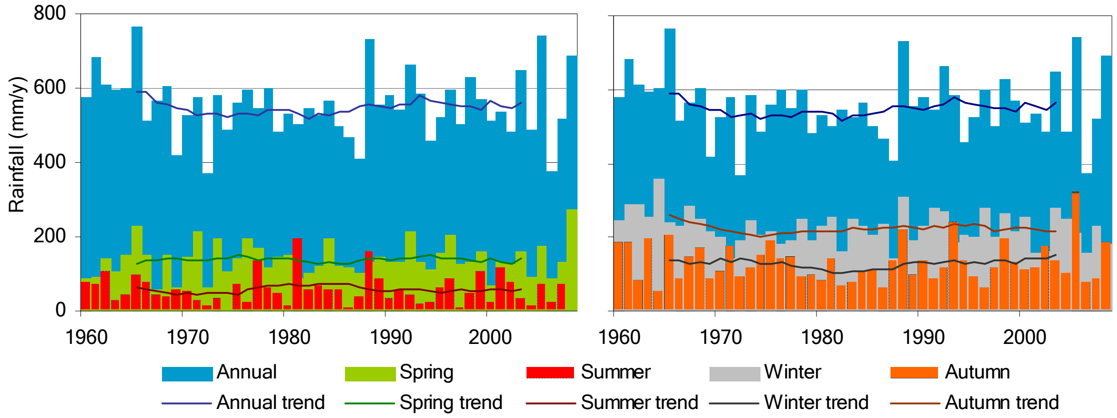


Figure 2-6 (cont'd) Time series of annual and seasonal rainfall for ten climate stations (locations shown in Figure 2-7)

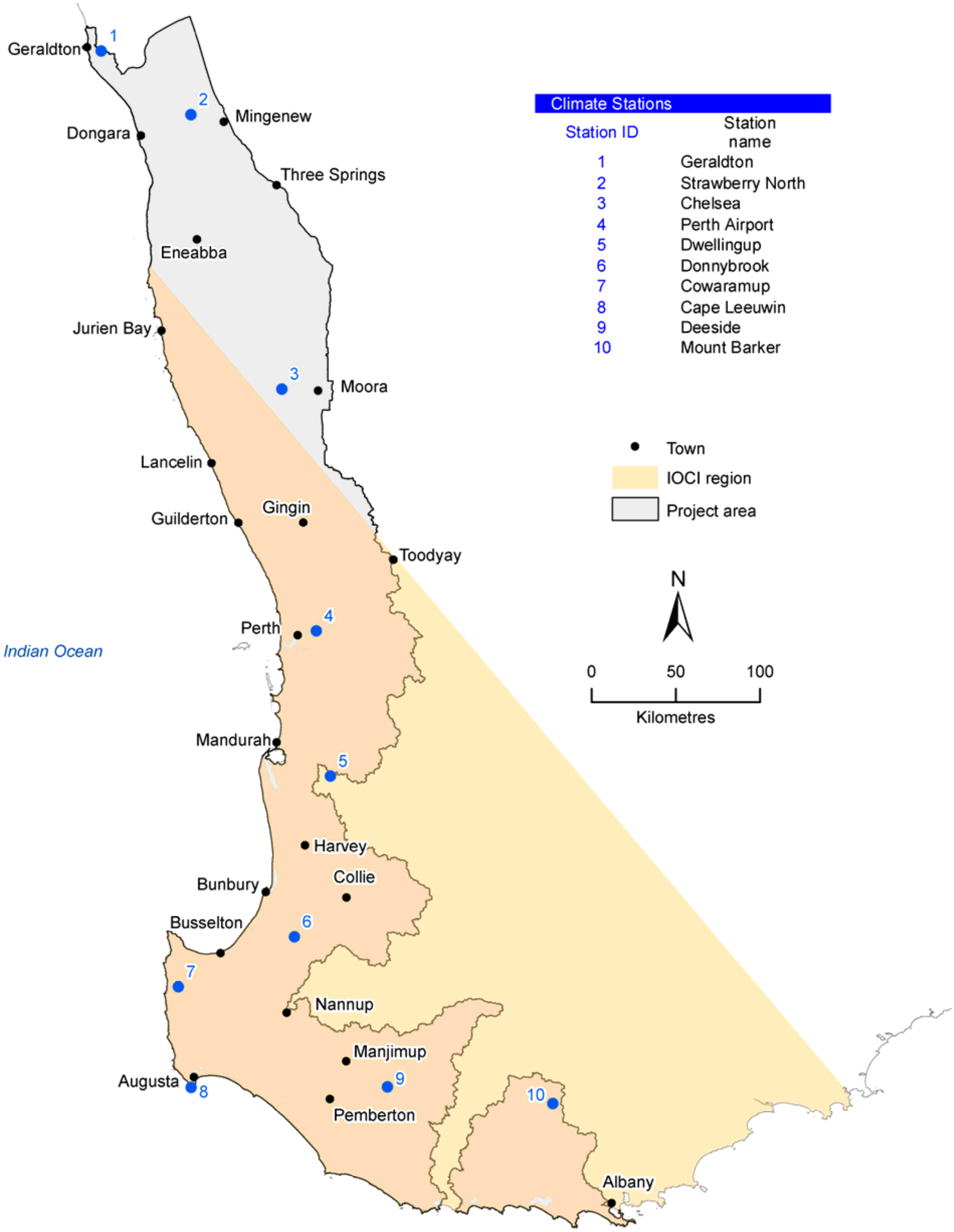


Figure 2-7. Location of the ten climate stations reported in Figure 2-6. The shaded Indian Ocean Climate Initiative region is used to produce the mean rainfall and temperature in south-west Western Australia shown in Figure 2-5 and Figure 2-8

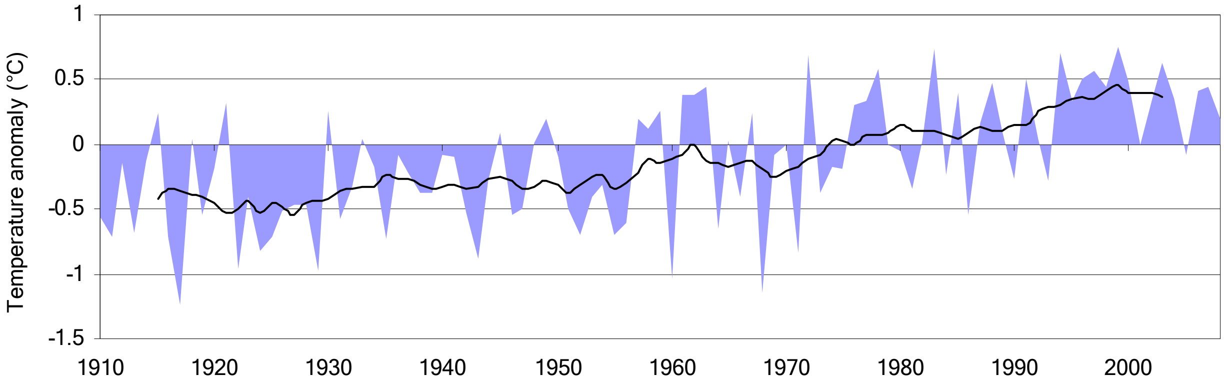


Figure 2-8. Mean annual temperature difference from the 1961 to 1990 mean averaged over south-west Western Australia (Indian Ocean Climate Initiative region in Figure 2-7). The trend line is an 11-year running mean (Source: Bureau of Meteorology)

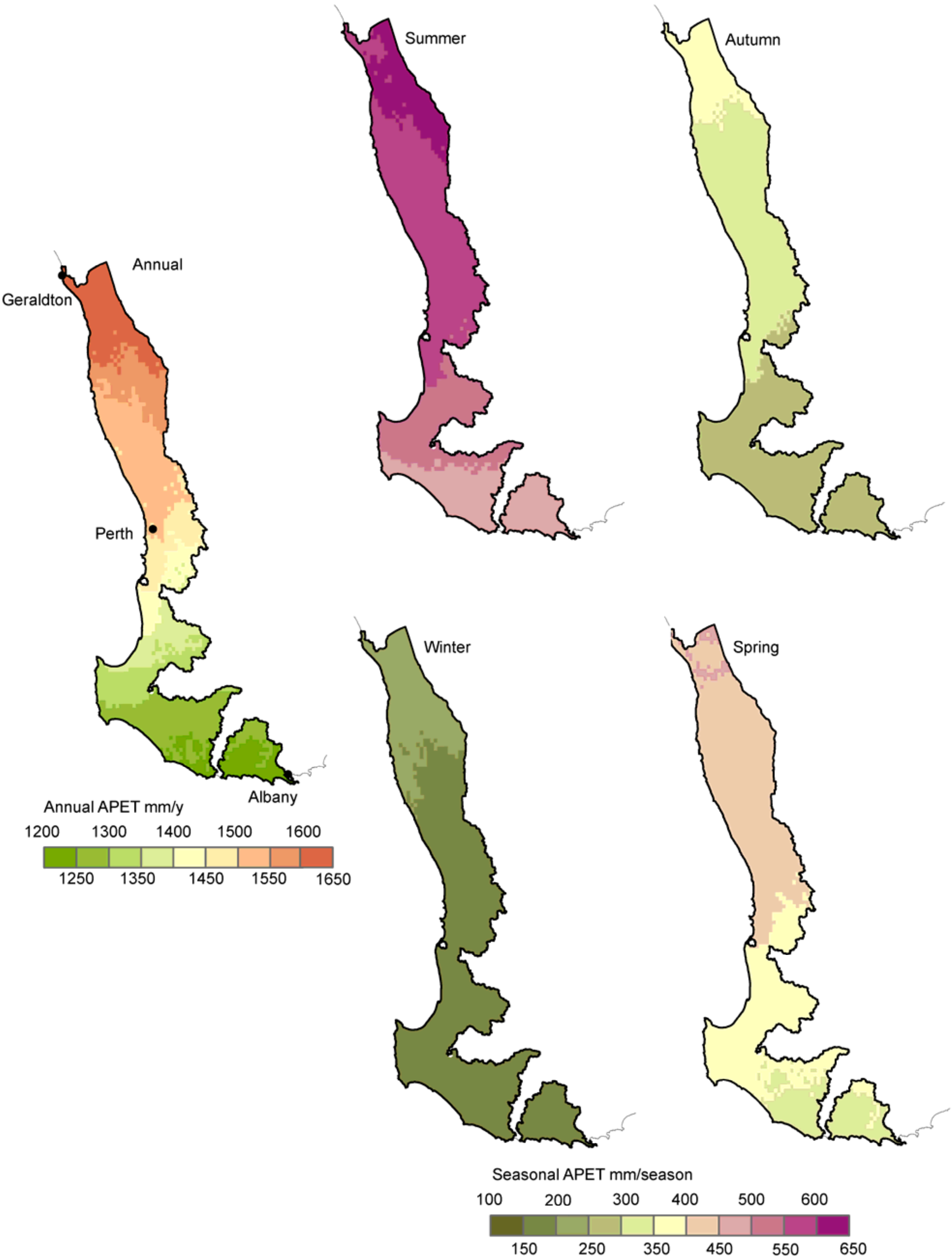


Figure 2-9. Spatial distribution of mean annual and seasonal historical (1975 to 2007) areal potential evapotranspiration across the project area

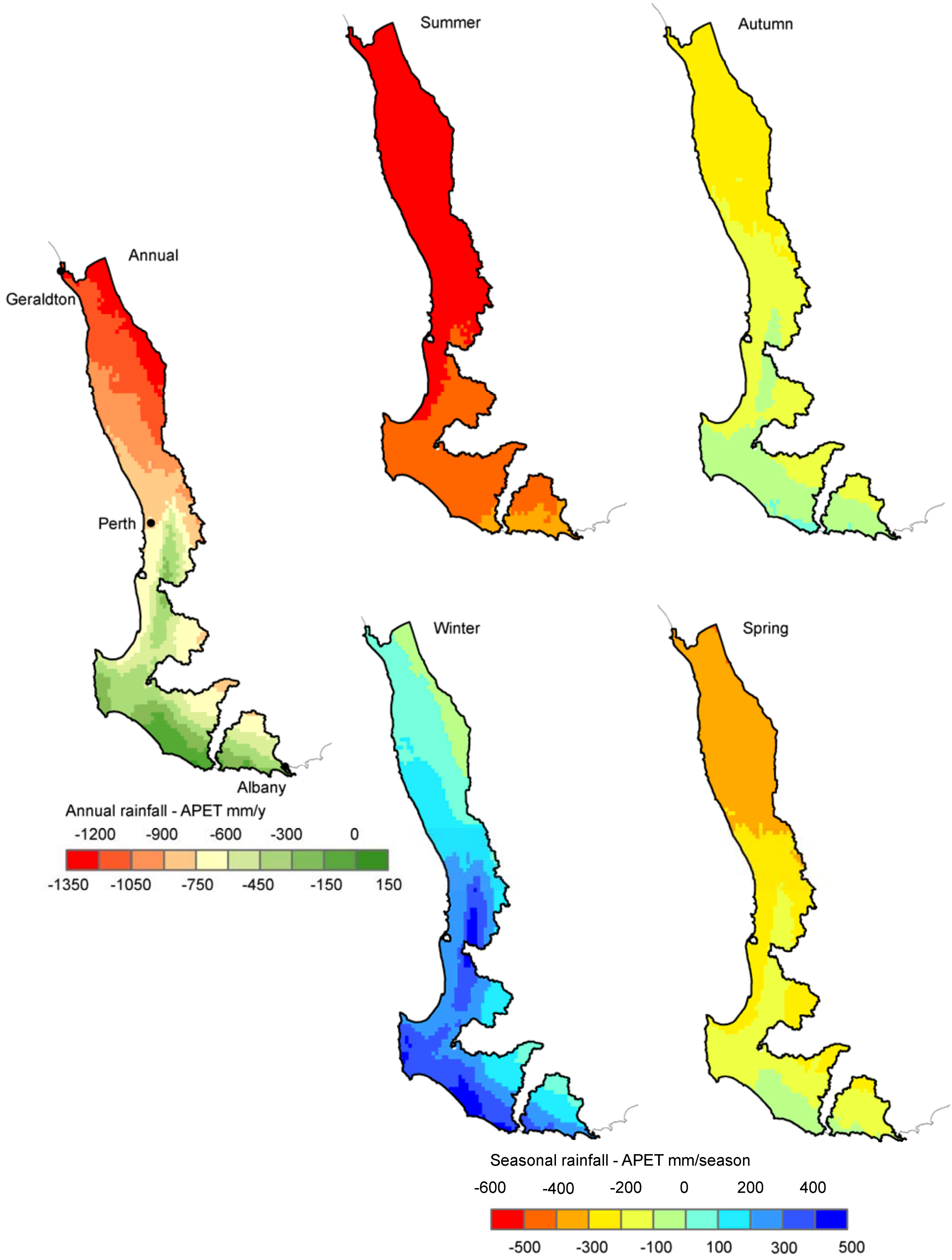


Figure 2-10. Spatial distribution of mean annual and seasonal historical (1975 to 2007) rainfall deficit (rainfall less areal potential evapotranspiration) across the project area

2.3 Physiography

2.3.1 Geology

SWWA has some of the oldest rocks in the world and has a complex geology. The geology greatly affects the topography, soils and therefore hydrology of the project area, which is briefly described in this section to support interpretation of this project results. In general, the study area is geologically built by Archean crystalline formations in the east and much younger sedimentary formations in the west. The crystalline basement rocks largely overlain by weathered clays, forms hills with rivers incising the areas and yields most of the project area's surface water resources. On the margin of these rocks lie the Perth and Bremer sedimentary basins which contain almost all of the usable groundwater in the project area (Figure 2-11).

The main geological subdivisions in SWWA are, in order of oldest to youngest, the South-West and Murchison terranes (blocks or fragments that have a geologic history different from surrounding areas) of the Yilgarn Craton; the Albany-Fraser Orogen (mountain building); the Northampton, Mullingarra and Leeuwin complexes of the Pinjarra Orogen; and the Perth and Bremer basins (Myers and Hocking, 1998; Figure 2-11). Major faults are the Darling, Urella, Busselton and Dunsborough faults (Figure 2-11 and Figure 2-12).

The South-West and Murchison Terranes are part of the Precambrian Yilgarn Craton which forms the Darling Plateau (Figure 2-12). The plateau forms the eastern part of the project area and is separated from the Perth Basin by the Darling Fault. The rocks are mainly granite and granodiorite with intruded dolerite dykes. The Craton has been remarkably stable for hundreds of millions of years having not been below the sea or experienced widespread glaciation or vulcanism. Therefore any mountain ranges have been eroded and the plateau often has a deep clayey weathering profile, tens of metres thick, associated with gravel and siliceous weathered remnants (Hocking and Cockbain, 1990; Tille, 2006).

The younger Albany-Fraser Orogen is exposed along the southern and south-eastern margin of the Yilgarn Craton and contains granite and metamorphic rocks (Myers, 1990). It also has been weathered but generally not as deeply as the western and central parts of the Yilgarn Craton.

The Northampton, Mullingarra and Leeuwin complexes are crystalline rocks which outcrop within the Perth Basin and therefore do not contain significant groundwater resources.

The project area contains the onshore Perth Basin which is a 30 to 100 km wide and 1000 km long strip from Geraldton along the western coastline down to the south-west corner of Western Australia. The basin contains arguably Australia's most important groundwater resources. The Perth Basin is a sedimentary trough up to 15 km thick containing sediments of Silurian to Pleistocene age (Iasky and Mory, 1993). It was formed during periods of rifting and sagging along the continental margin of south-west Australia which culminated in separation from the rest of Gondwana during the early Cretaceous period. This resulted in a faulted sedimentary sequence which is bounded to the east by the Darling Fault and overlain by comparatively undeformed sediments deposited during the tectonically quiet period following separation. Prior to breakup, continental sedimentation prevailed through to the late Jurassic and into the Cretaceous. During the Neocomian and following breakup, marine incursion resulted in periods of both continental and marine sedimentation (Davidson, 1995).

Several outliers of Permian strata of the Perth Basin sediments lie within the Yilgarn Craton, with the largest being the Collie Basin (Figure 2-12). The onshore Bremer Basin lies along the south-eastern margin of the project area and consists of numerous small sediment-filled depressions of Eocene age with a thickness of less than 200 m (Hocking, 1990). The basin formed and was inundated by the ocean after Antarctica separated from Australia in the Tertiary and the southern part of Australia sagged.

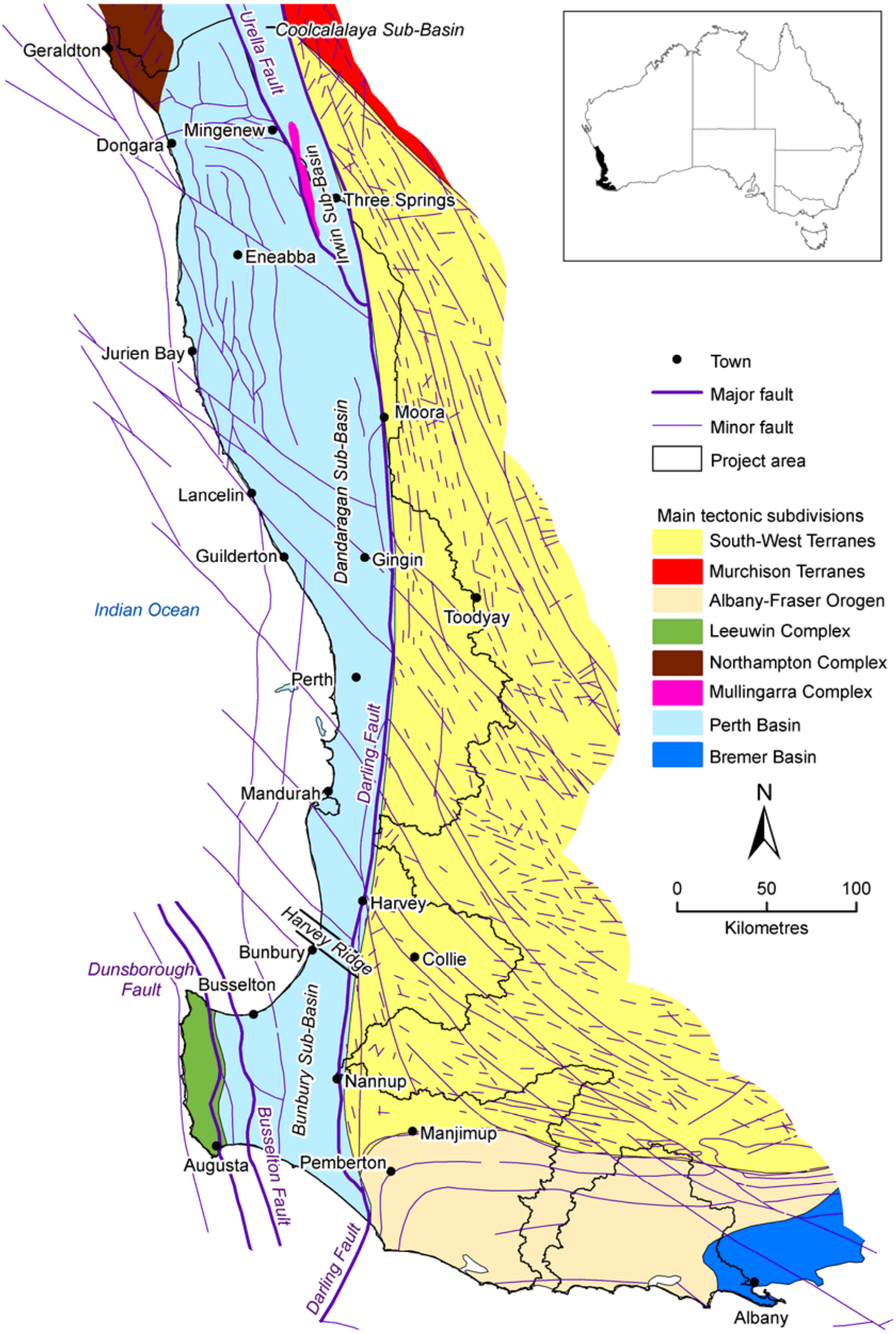


Figure 2-11. Main tectonic subdivisions of the project area

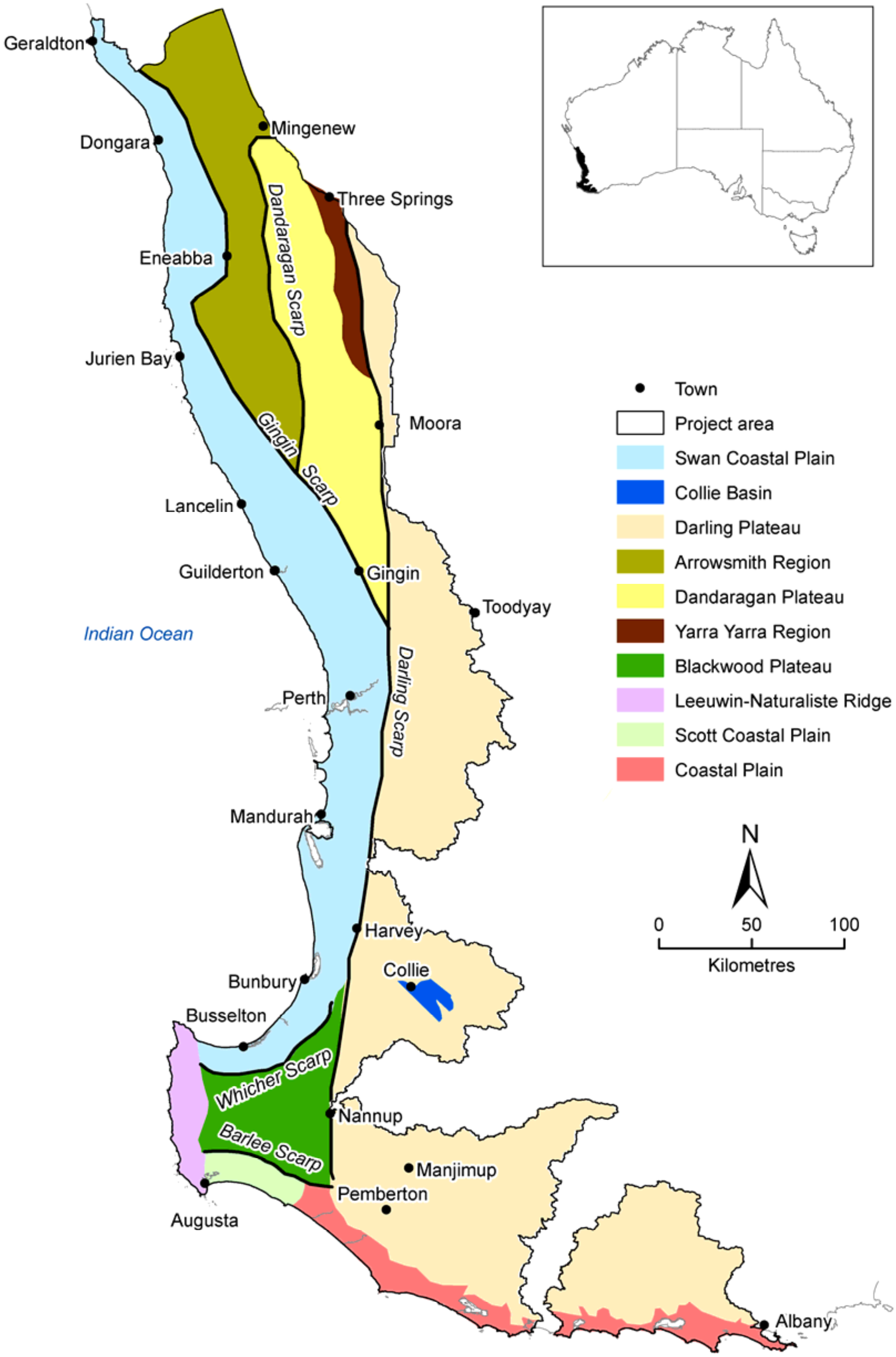


Figure 2-12. Main geomorphologic regions of the project area

2.3.2 Topography

Main features

The main topographic features of SWWA are the coastal plains with elevations below 150 m AHD (often less than 100 m AHD, Figure 2-13) and escarpments which separate the plains from the inland Darling Plateau (Figure 2-12) with an average elevation of about 350 mAHD.

Almost all rivers rise on this plateau before entering the flatter coastal plains and then the ocean, often through coastal estuaries. The western edge of the Darling Plateau is the Darling Scarp which marks the east of the deep sedimentary Perth Basin. The Darling Plateau close to the scarp comprises lateritic uplands with deep valleys along the scarp. Further inland, the main landforms are sandplain remnants, gentle slopes, ancient drainage zones (now occupied by salt lakes) and rock outcrops. In the south-west of the project area the plateau becomes more dissected. Fresh rock is exposed on the slopes of major valleys but extensive areas of lateritic duricrust remain between the valleys.

The Leeuwin-Naturaliste Ridge, like the Darling Plateau, is also underlain by crystalline basement rocks and abuts the Perth Basin. The Collie Basin occurs as a north-westerly trending valley within the Precambrian rocks of the Yilgarn Craton (Darling Plateau (Figure 2-12) with a length of about 27 km and a width of about 13 km (Varma, 2002). The shape of the basin consists of two lobes which are separated by a basement high of granitic rocks and dykes.

Three small plateaux of uplifted sedimentary rocks occur in the north-east of the project area: the Yarra Yarra region, the Dandaragan Plateau and the Arrowsmith region. The Yarra Yarra region is a small plateau separated from surrounding areas by the Darling and Urella faults (Figure 2-12). The Arrowsmith Region is a laterite-capped plateau, dissected by active drainages. The land surface is gently undulating with elevations ranging between 100 and 200 m AHD. The Irwin and Arrowsmith rivers cross the Arrowsmith region and flow towards the west onto the Swan Coastal Plain. The Dandaragan and Gingin scarps resulted from fluvial and marine erosion in the late Tertiary or early Pleistocene. The Dandaragan Plateau contains Quaternary sand and consists of laterite overlying Cretaceous sediments of the Perth Basin (DoW, 2008b). The plateau has an elevation of up to 300 m AHD. It is relatively flat with older alluvial channels infilled with aeolian sediments and dissected by the Arrowsmith River to the south (Irwin, 2007). Many streams rise on the Dandaragan Plateau and flow in a westerly direction onto the Swan Coastal Plain (DoW, 2008b). Elevations of the Blackwood Plateau range from 60 to 200 m AHD while elevations of the Leeuwin-Naturaliste Ridge range from 60 to 150 m AHD.

Uplifted sedimentary rocks also form the Blackwood Plateau in the south-west corner of the project area between the Swan and Scott coastal plains. These areas contain low hills and gently undulating lateritic uplands (Tille, 2006).

There are a number of modest escarpments that separate these smaller plateaux: the Dandaragan Scarp between the Dandaragan Plateau and Arrowsmith region; the erosional Gingin Scarp between these plateaux and the Swan Coastal Plain; and the Whicher and Barlee scarps which separate the Blackwood Plateau from the Swan and Scott coastal plains respectively. The relief of these scarps is relatively mild with, for example, the Barlee Scarp between the Blackwood Plateau and the eastern Scott Coastal Plain being only about 40 m high (Irwin, 2007).

The Swan Coastal Plain occurs below about 100 m AHD between Geraldton and Busselton. Along the plain – almost parallel to the coast – lie the Quindalup, Spearwood and Bassendean dune systems, the Bassendean being the oldest and most eastern. The dunes form gentle hills, varying in elevation from 1 to 60 m AHD. In the Perth region, the colluvial slopes of the foothills of the Darling and Dandaragan plateaux are the most easterly landform of the Swan Coastal Plain. The alluvial Pinjarra Plain follows to the west, consisting of clay, sand and silt originating from the Darling and Dandaragan plateaux. The Bassendean Dune System follows to the west and forms a gently undulating aeolian sandplain with dunes higher to the north of Perth than those to the south (Davidson, 1995). The younger Spearwood Dune System lies to the west of the Bassendean Dunes and consists of slightly calcareous aeolian sand remnant often overlying the Tamala Limestone. The most westerly dune system is the Holocene Quindalup Dune System consisting of wind-blown lime and quartz beach sand (Davidson, 1995). South of Perth, the coastal plain has an average elevation of about 25 m AHD, with a maximum of about 75 m AHD. To the north of Perth, the plain rises gradually from the coast to about 100 m AHD, but is generally more undulating along the coastal strip of the Quindalup and Spearwood dune systems than in the central and eastern areas (Davidson, 1995). The Swan Coastal Plain also includes large microtidal estuarine systems, such as the Swan-Canning Estuary and a number of lakes which are cut off from the sea by barrier dunes. The Swan Coastal Plain is transected by rivers flowing west from the Darling Plateau, and interspersed by wetlands. Some caves and karst features occur in areas associated with the Tamala Limestone (Spearwood Dunes).

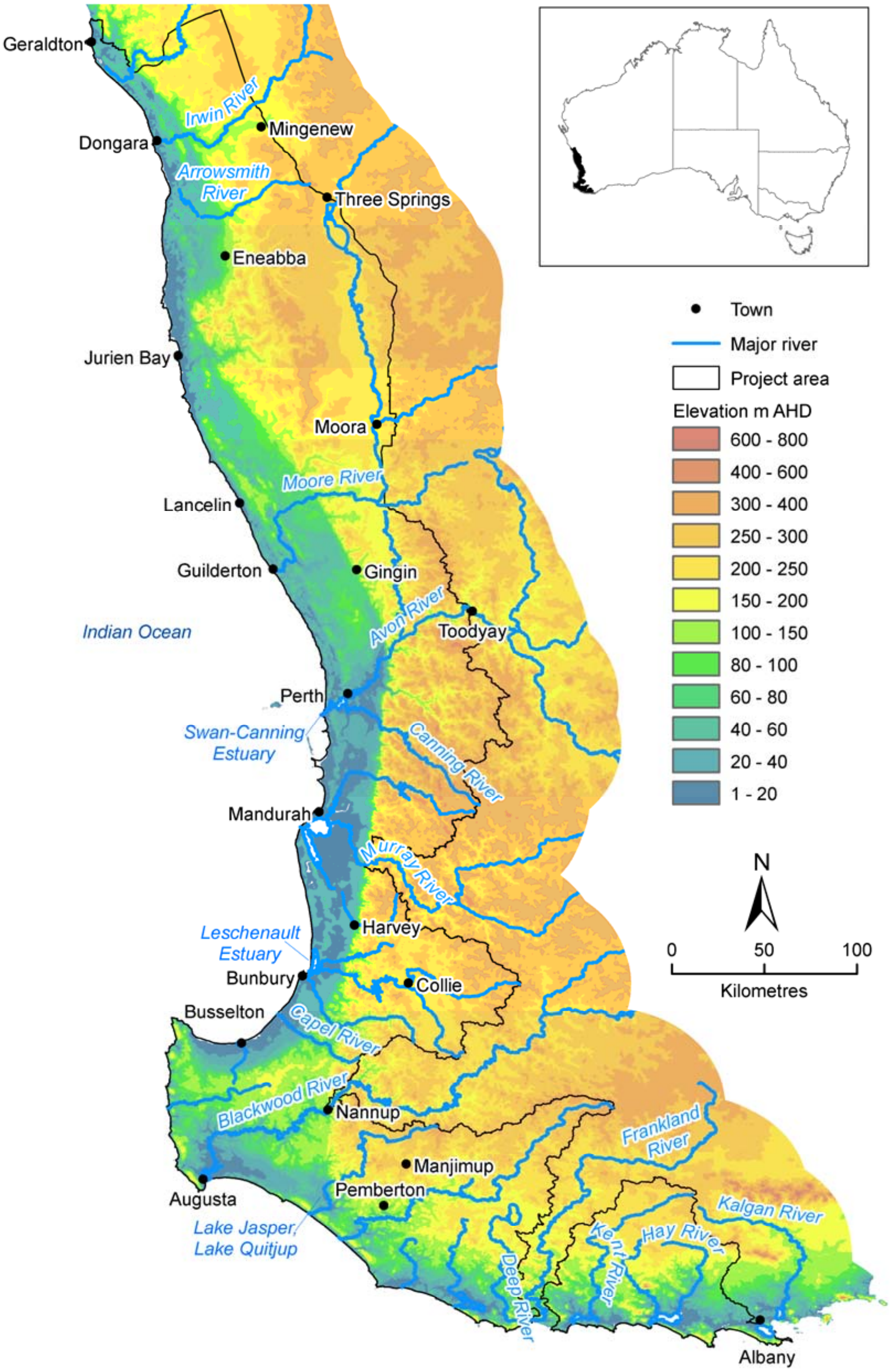


Figure 2-13. Topography of the project area

The Scott Coastal Plain east of Augusta contains a mixture of sandplains, dunefields and alluvial flats. There are several ancient shorelines, often topographically expressed as minor scarps. The Quindalup, Milyeannup, Warren and Donnelly dune and shoreline systems are present on the Scott Coastal Plain and are geomorphologically equivalent to those on the Swan Coastal Plain (Irwin, 2007). These dune systems run parallel to the present shoreline and the Quindalup dunes are still being deposited along the coast. The eastern Scott Coastal Plain is an internally drained area of the Scott Coastal Plain.

Along the south coast of the Albany Area are large dunefields separated by rocky headlands and limestone cliffs (Tille, 2006). A gently undulating plain has formed on the granitic rocks of the southern edge of the Yilgarn Craton and the plain has been dissected by a number of short rivers.

2.4 Rivers and catchments

There are 13 major surface water basins within the project area (Figure 2-13). The largest rivers extend into the inland regions of Western Australia which experience dryland salinity. Saline reaches of the Avon, Murray, Blackwood and Frankland rivers have been excluded from analysis in this project as they are too salty to be used for irrigation, industry or drinking.

Rivers north of Gingin Brook were not included in the project because they contain relatively minor fresh water resources relative to rivers in the south-west of the project area. Some surface water is used from the Moore and Hill rivers but groundwater is the dominant source of water for irrigation, towns and industry north of Gingin Brook.

Under native vegetation the clayey soils that are common east of the Darling Range retain salt deposited with rainfall and as dry fallout when the annual average rainfall is less than about 900 mm, because the native vegetation does not leave enough water to flush salt out of the weathered zone into the river systems. Five catchments within the project area contain marginal quality water due to salinisation, namely the Helena (Swan Coastal), Collie, Warren, Kent and Denmark. In 1976 to 1978 clearing control legislation was introduced under the *Country Areas Water Supply Act 1947* and since 1996 the Water and Rivers Commission (now the Department of Water Western Australia (DoW)) has been responsible for implementing the Salinity Action Plan (Agriculture Western Australia et al., 1996) which aims to achieve potable water by 2015 to 2030 in these five catchments. Afforestation and saline water diversion have been carried out with mixed results in some of these catchments.

2.5 Soil-landscapes

Soil-landscape mapping follows a hierarchy of regions, provinces and zones, which form a part of the Australian Soil Resource Information System (ASRIS) which provides information on soil and land resources in a consistent format across Australia. The following soil-landscape descriptions follow mainly Schoknecht et al. (2004).

Soil-landscape zones in the project area are detailed in Figure 2-14.

The zone of ancient drainage is characterised by ancient broad valleys with drainage lines containing clayey soils and salt lakes or playas. The gradient of the valleys increase in the zone of rejuvenated drainage and the valleys are more incised, the soils are formed from younger parent material and often have sandy topsoil over clayey subsoil (duplex), and there are no playas.

The Geraldton Coastal zone comprises calcareous and siliceous dunes with alluvial plains and sand sheets, as well as low hills of Tamala Limestone. The soils of the Arrowsmith and Dandaragan Plateau zones are predominantly sandy and gravelly, formed from colluvium and weathered rock. The Chapman zone soils were formed from rock weathered in situ from migmatite, granulite and dolerite, and also contain lateritic colluvium weathered from sedimentary rocks. Within the Victoria Plateau zone there is laterite formed over sandstone and granulite parent materials. The Lockier zone comprises alluvial clayey to silty soils in valley plains.

The main soil groups of the Perth Coastal zone are calcareous and siliceous sands. Further to the east of the Perth Coastal zone lies the Bassendean zone in which non-calcareous sands are common as well as podsolised soils with low-lying wet areas (usually clays and loams). The Pinjarra zone, which lies at the foot of the Gingin, Darling and Whicher scarps, contains mainly clayey to sandy alluvial soils with wet areas. In the Donnybrook Sunkland zone on the

Blackwood Plateau, lie in situ weathered sedimentary rocks and alluvium which in the south is developed as a poorly drained sandy alluvial plain. Non-calcareous sands dominate together with podsolised soils in low-lying wet areas in the Scott Coastal zone. Within the Leeuwin zone on the Leeuwin-Naturaliste Ridge, valleys are mainly covered by colluvial soils. The granite on the western margin is overlain by Tamala Limestone and some coastal dunes.

The Eastern and Western Darling Range zones are dissected with broad shallow valleys. Laterite overlies granite and soils are derived from laterite colluvium, granite and gneiss weathered in situ. The Warren-Denmark-Southland zone comprises a series of broad benches extending north from the Southern Ocean to the Blackwood Valley, with mainly deeply weathered granite and gneiss, which is overlain by Tertiary and Quaternary sediments in the south, locally with swampy areas.

The Albany Sandplain zone is a gently undulating plain which is dissected by short rivers. The soils are predominantly sandy duplex soils, often alkaline and sodic, with some sands and gravels.

The coastal plains often contain sandy, dunal material which may contain swamps and peaty soils where the watertable is high or clayey alluvial soils perch water. The uplifted sedimentary areas (Arrowsmith, Dandaragan and Blackwood Plateaux zones) are often gravelly and while they can be sandy (like the coastal plains) they also contain clayey material depending upon the nature of the underlying sediments. East of the Darling Scarp the soils are often gravelly and overlie clays which may be tens of metres thick and have the potential to store salt deposited in rainfall if the drainages are unable to leach this salt back to the ocean.

These soil-landform attributes affect the hydrology by making the eastern parts of the project region more suited to surface water development and the coastal and uplifted sedimentary areas more likely to contain usable groundwater.

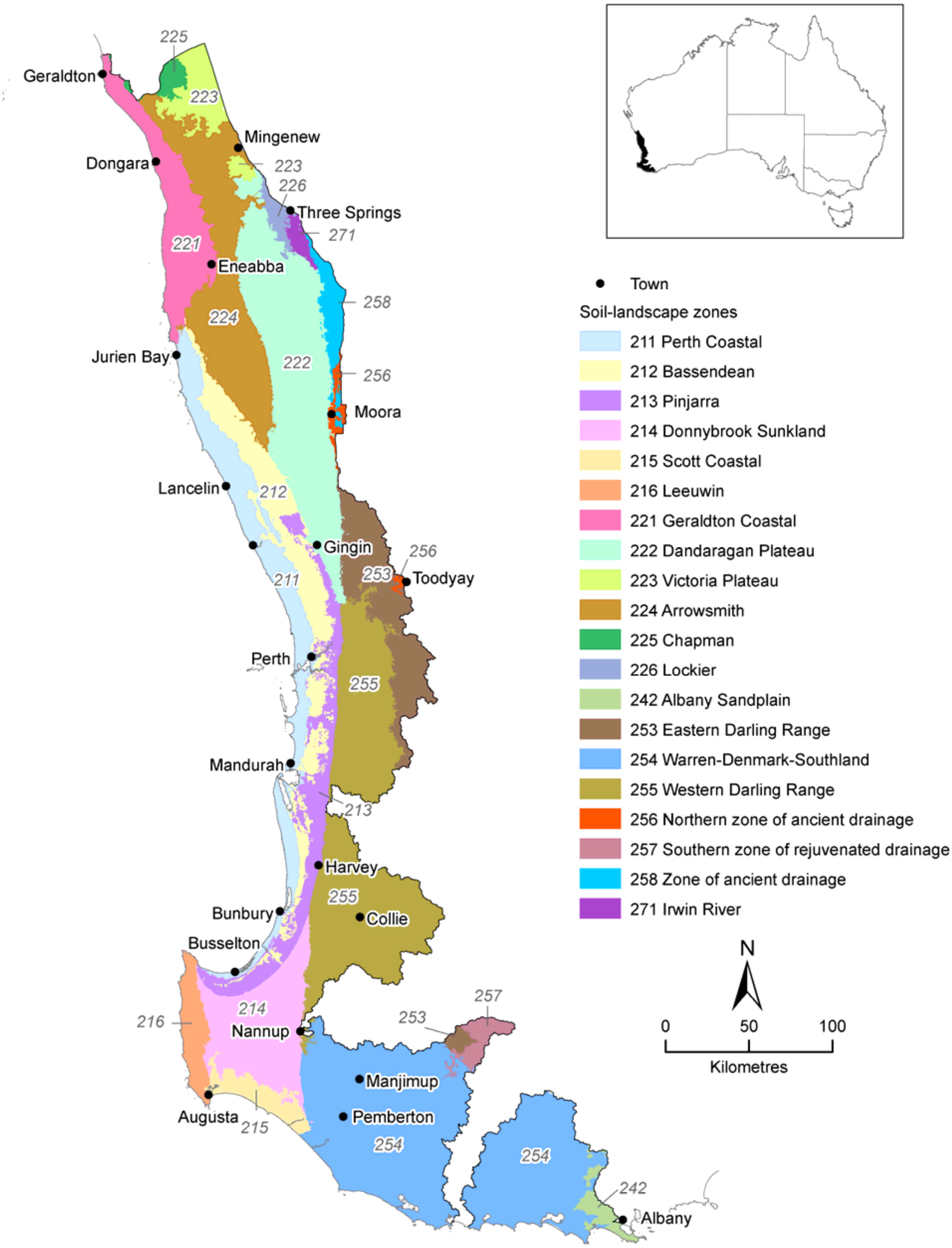


Figure 2-14. Soil-landscape zones of the project area

2.6 Land use and demographics

2.6.1 Land use and effect on hydrology

An overview of major land uses (in the form of land cover types) within the project area is shown in Figure 2-15. This map was developed by classifying multiple year Landsat TM images. The map units were chosen to represent land covers that most affect hydrology, especially groundwater recharge and discharge and streamflow generation. The area associated with the individual land cover types is shown in Table 2-1.

Over 52 percent of the 62,500 km^2 area is covered in native vegetation and a further 40 percent used for dryland agriculture. Commercial plantations cover 3 percent of the area (70 percent hardwood and 30 percent softwood). Areas which remain wet in summer (producing a strong vegetation reflectance) occupy about 1.7 percent of the area, of which about one-third is irrigated land.

Intensive urban and commercial land use occurs in the Perth region and, to a lesser extent, around Bunbury and Busselton. When urban areas are built on sandy soils, roof and road runoff are commonly directed into the unconfined Superficial Aquifer so this land use can enhance both recharge and runoff (stormwater). Under the Landsat TM land cover classification bare soil is included in this classification because it also has a similar reflectance to the urban areas.

Cleared areas used for dryland cropping and grazing are extensive on the Swan Coastal Plain and in the Northern Perth Basin. Recharge is enhanced where the land use is annual crops and pastures with shallow root systems that cannot utilise all of the incoming winter rain. Sandy soils also enhance recharge under this land use.

Some valleys in the Darling Range have been cleared as have the Upper Helena, Collie, Warren, Kent, Denmark and Hay River catchments, which in large part causes their salinity problems. The main areas under native vegetation occur east of the Darling Fault in the Darling Ranges (mainly Jarrah-Marri forest), along the South Coast (mainly Karri and Jarrah forests), north of Perth (mainly Banksia woodlands) and in the coastal parts of the Northern Perth Basin (mainly sandplain heaths).

Pine plantations occur in the Gnangara area north of Perth, near Myalup east of Lake Clifton, on the Blackwood Plateau (also called the Donnybrook Sunklands), and scattered throughout the Jarrah forest in some coastal catchments. *Pinus radiata* (Monterey Pine) is common in higher rainfall zones (>700 mm) while *Pinus pinaster* (Maritime Pine) is more common in the lower rainfall zones. *Eucalyptus globulus* (Tasmanian Blue Gums) are grown in catchments with an annual rainfall greater than 600 mm in the south of the project area between Collie and Albany. These plantations can be useful for reducing salinity problems in the 600 to 900 mm rainfall zone but they can also cause a decline in fresh water yields in higher rainfall zones.

Irrigation

Irrigated agriculture is carried out across the project area supplied by either schemes or self-supply. The main scheme is the South West Irrigation Area (Harvey Water) which supplies the Waroona, Harvey and Collie irrigation districts. A smaller scheme is the Preston Valley Irrigation Scheme, which supplies water from the Glen Mervyn Dam to irrigators along the Preston River Valley. The remainder of irrigation water is self-supplied, mainly by pumping groundwater and by on-stream dams or capturing runoff in off-stream farm dams in the high rainfall areas in the south-west of the project area (DoW, 2003). There is little run-of-the-river pumping carried out in the region.

Irrigated areas are green in summer so are easy to map using satellite imagery but can be confused with areas that are wet due to natural groundwater discharges. At the regional scale Figure 2-15 provides only limited visual information. There are surface water irrigation schemes in the Harvey and Preston areas and self-supplied groundwater irrigation schemes around the Gingin area, in peri-urban parts of Perth, and in south-western coastal areas at Myalup, Jindong, Margaret River and the Scott Costal Plain. Irrigation of horticultural crops using water from farm dams is common in the Whicher area, Manjimup, Pemberton and Donnybrook areas. Areas on the South Coast that are naturally wet in summer are shown in the same classification as irrigated areas because they remain green in summer (Figure 2-15).

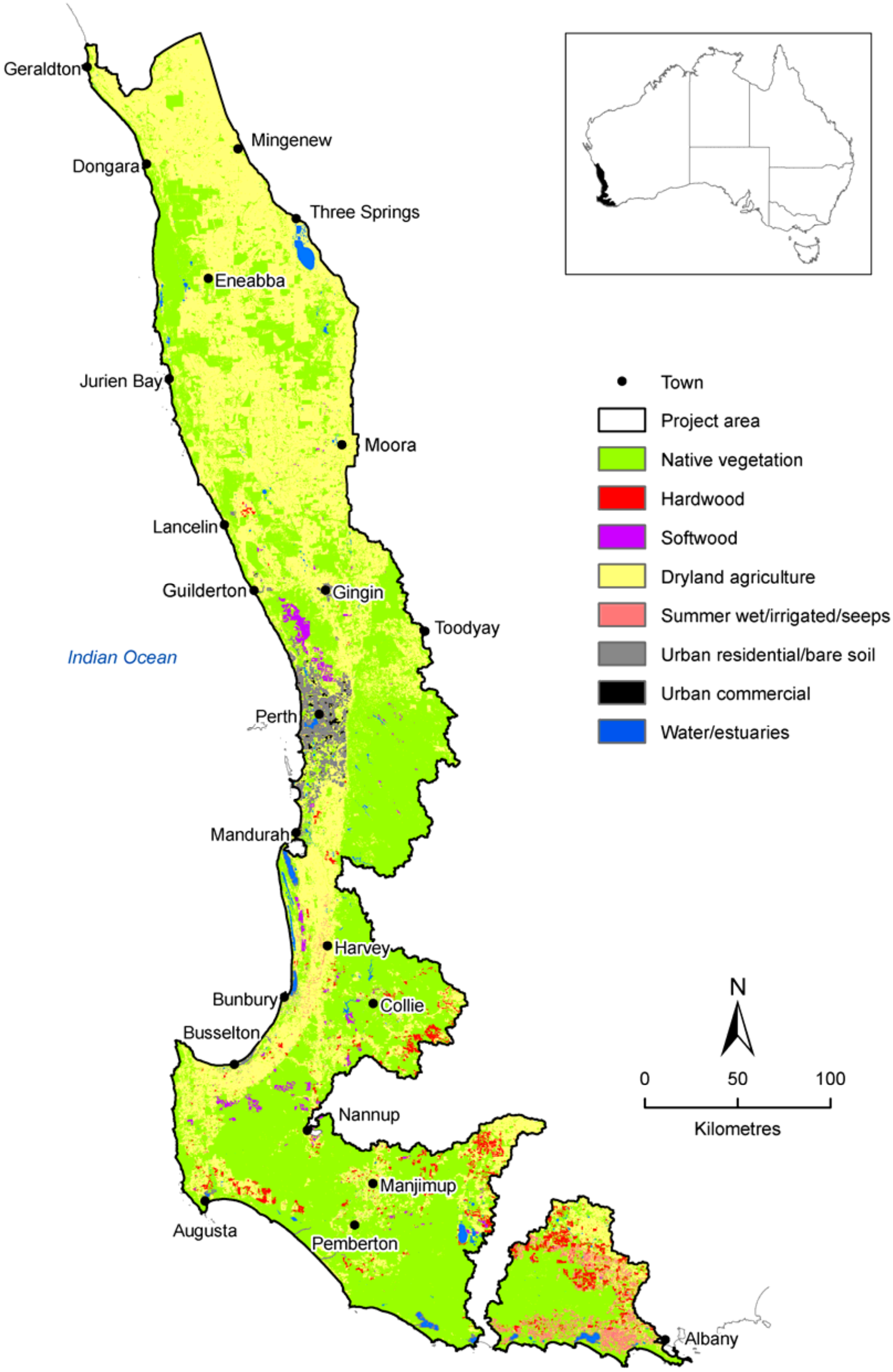


Figure 2-15. Major land cover types in the project area in 2005

Table 2-1. Areas of land cover type in the project area as mapped using satellite imagery for 2005

Land cover type	Area	
	km^2	percent
Native vegetation	32,809	52.5%
Hardwood plantations	1,312	2.1%
Softwood plantations	562	0.9%
Dryland agriculture	24,914	39.9%
Summer wet areas including irrigated areas and seeps	1,050	1.7%
Urban residential including bare soil	975	1.6%
Urban commercial	81	0.1%
Open water including estuaries	810	1.3%
Total	**62,513**	**100.0%**

Table 2-2 lists irrigated areas, water allocations, main irrigation industries and key issues for irrigators according to the State Water Strategy Irrigation Review for Western Australia (DoW, 2005). Water availability is reportedly a concern for irrigators in all areas.

Table 2-3 presents estimates of water usage in each region by type of crop for 2003. Scheme-supplied surface water use on-farm is measured by Dethridge Wheels and flow meters which have been installed for users of >5 ML/year for self-supply GWAs at Gnangara and Myalup and for larger users (>500 ML/year) throughout the project area. There are audits of unmetered irrigated areas to ensure that growers are complying with their licence but these estimates are liable to contain some error.

The irrigation water consumed in the project area is estimated to be about 340,000 ML/year (Table 2-3). Fruit trees and crops use the most water (38 percent), followed by vegetables and pasture which use similar amounts (28 percent). Therefore while irrigated agriculture is a relatively small component of land use in the project area, most of the irrigation that does occur is for high value crops.

The important irrigation areas are Peel-Harvey (29 percent), Preston-Warren-Blackwood (18 percent), Gingin (16 percent) and combined Perth Metro (23.4 percent). Most of these areas have experienced reduced water availabilities in recent years as a result of low rainfall since about 1998.

Table 2-2. Details of irrigation regions in the project area

Irrigation area/ district	Area irrigated	Irrigation supply system	Water allocation	Main irrigation industries	Key issues for irrigators
	ha		ML		
Mid-West					
	721	Self-supply	8,375	Pasture; vegetables; fruit	Water availability
Gingin					
	3,206	Self-supply	84,419	Vegetables; fruit (including olives, grapes)	Water availability
Metro North					
Wanneroo/ Carabooda	5,620	Self-supply	83,693	Vegetable, crops; some perennial horticulture (e.g. avocados)	Water availability; environmental impacts
Metro East					
Hills area		Self-supply		Perennial horticulture (fruit)	Land use conflict
Metro South					
		Self-supply		Viticulture vegetables	Water availability; land use conflict
Peel-Harvey					
Harvey Water (SWIA)	10,426	South West Irrigation Management Cooperative, trading as Harvey Water	180,379	Traditionally dairy pastures; more recent growth of horticulture and viticulture	Wellington Dam salinity; dairy industry-related market drivers contributing to changing land use systems
Myalup		Self-supply		Mostly annual vegetable crops	Water availability
Whicher					
Busselton	5,331	Self-supply	33,864	Viticulture; vegetables	Water availability and quality
Margaret River					
Scott River					
Preston-Warren-Blackwood					
Donnybrook	5,966	Preston Valley	41,958	Perennial horticulture (fruits including grapes); vegetables	Water availability and quality
		Irrigation Scheme			
Manjimup		Self-supply			
Great Southern					
Frankland	3,212	Self-supply	756	Viticulture	Salinity of water; water availability
Mt Barker					
Total	**34,482**		**433,444**		

Source: State Water Strategy Irrigation Review (DoW, 2005).

Table 2-3. Irrigation water use by key commodity groups in the irrigation regions in the project area (DoW, 2005)

Region	Pasture	Vegetables*	Fruit	Other	**Total**	
			ML/y			percent
Mid-West	1,562	1,346	1,499	3,166	**7,573**	2%
Gingin	790	23,380	23,904	6,538	**54,611**	16%
Metro North	939	17,238	8,402	2,721	**29,300**	9%
Metro East	733	568	25,077	2,874	**29,253**	9%
Metro South	2,119	12,360	5,081	1,468	**21,027**	6%
Peel-Harvey	81,161	10,713	4,881	1,578	**98,333**	29%
Whicher	2,974	7,637	11,295	2,022	**23,928**	7%
Preston-Warren-Blackwood	4,638	20,086	35,191	1,450	**61,365**	18%
Great Southern	519	2,274	12,974	717	**16,485**	5%
Total	**95,435**	**95,602**	**128,304**	**22,534**	**341,875**	**100.0%**
Percent	28%	28%	38%	7%	**100%**	

* Including grapes and olives.

2.6.2 Demographics and total water use

Water use

The use of surface and groundwater in Western Australia since 1900, along with a projection of future use, is shown in Figure 2-16. Before 1960, groundwater was a small proportion of total use but by 1985 it was equivalent to surface water in importance. Rapid economic development has resulted in total water use rising dramatically since that time (at about 50 GL/year) with most new growth being in groundwater. This change reflects the full development of many surface water resources, their reduced yields in the historical period (1975 to 2007), concerns about the impacts of dams on the environment, and the recognition of the abundance of groundwater stored in the sedimentary basins in Western Australia.

While Figure 2-17 is for the state of Western Australia, a similar relationship occurs in the project area where most water use takes place (Chapter 6).

The Australian Water Resources Assessment (NWC, 2005) calculated that agriculture used 65 percent of all water used in Australia. In Western Australia the proportion used by agriculture is only about 37 percent (DoW, 2007). This difference probably relates to the low availability of fresh surface water resources in SWWA where all major river systems are too saline for agricultural use or have low yields relative to the Murray Darling Basin. The only rivers suitable for irrigation arise in forested catchments, some of which become saline if cleared. Self supply surface water irrigation is important in the high rainfall south-west but the main irrigation developments in the past 20 years in SWWA have been self-supplied groundwater systems on the Swan Coastal Plain.

The future yield of drinking water supply catchments is uncertain due to reduced inflows to water supply storages; the requirement to provide environmental water and land uses in drinking water supply catchments may impact on water quality (Water Corporation, 2009). Surface water for irrigation is similarly impacted by reduced runoff and environmental concerns and there is also competition for land from forestry, sub-division of land, and land use conflicts. For example smoke from fuel reduction burns or pesticide spray drift may impact on surrounding areas.

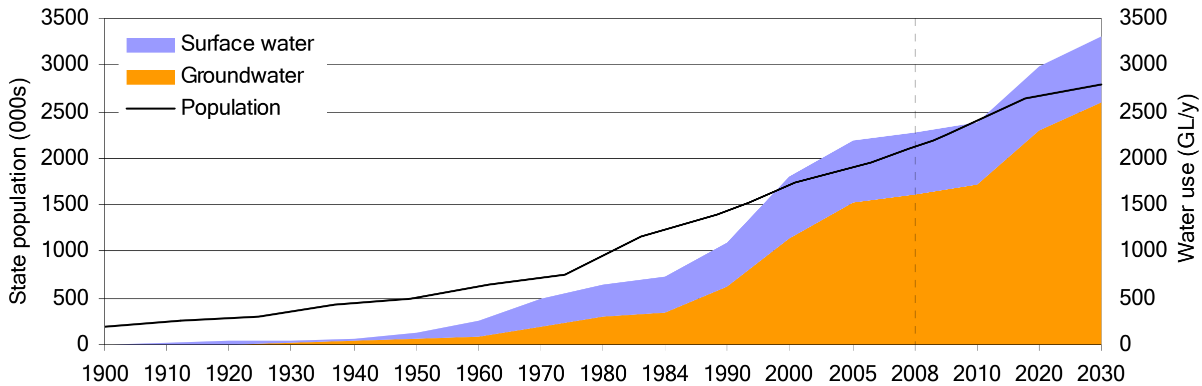


Figure 2-16. Water use in Western Australia since 1900, and demand projections (includes both licensed and unlicensed use)

Population growth and water demand

Western Australia is growing rapidly and is expected to continue to grow in the near future placing further pressure on existing water resources. In the State Water Plan (DoW, 2007) it was estimated that the groundwater sustainable yield for the Perth Basin was 1937 GL/year, the allocation limit 1472 GL/year and the estimated actual use 908 GL/year. The sustainable yield for surface water in SWWA was estimated to be 1610 GL/year, the allocation limit 1054 GL/year and the estimated water use 312 GL/year (DoW, 2007).

The Integrated Water Supply Scheme (IWSS) supplies water to people in Perth (85 percent), the goldfields and the agricultural region (10 percent), and Mandurah and towns in the south-west region (5 percent). Almost 80 percent of drinking water is used by domestic consumers with the remainder being used by commerce and industry.

In the Arrowsmith and Jurien GWAs water (Figure 2-2) is used mainly for town water supply, mineral ore processing and irrigation. Current allocations for the Arrowsmith GWA are about 84 GL/year with an allocation limit of 190 GL/year. For the Jurien GWA, current allocations are about 40 GL/year with an allocation limit of 97 GL/year. Future development in both GWAs will require groundwater for public water supply, for increased mining activity (including petroleum, gas, iron ore and mineral sands) and for larger irrigation requirements.

The groundwater resources of the Gingin GWA (between 40 km and 150 km north of Perth) are either fully allocated or approaching full allocation. In some sub-areas the demand exceeds supply which, if satisfied, could threaten the long-term sustainability of these resources (Water and Rivers Commission, 2002). It is estimated by the Water Corporation that by 2060, Perth will extend further up the north coast from Yanchep to Lancelin and the local water resource in the Gingin GWA may be drawn into the water supply scheme (Water Corporation, 2009).

The Gnangara groundwater system is of vital importance to the continuing social and economic development of the Perth region. The system as a whole is approaching full allocation with some aquifers now considered over-allocated in a number of GWAs (DoW, 2008a). A Gnangara Sustainability Strategy has just been drafted to address land use and management issues that affect recharge and discharge to the Superficial Aquifer (DoW, 2009a).

In the lower SWWA (which includes the area between Harvey, Margaret River, Albany, Boyup Brook and Collie), irrigated agriculture is the largest user of water (50 percent), followed by the mining and industry sectors (22 percent), plantations (17 percent) and the household and commercial sectors (8 percent). Population growth and economic expansion will result in increasing urban residential development, more intensive industrial and mining activity, and changes in agricultural production (such as installation of farm dams and development of plantations). Hence, by 2030, lower SWWA is likely to have seen growth in agricultural water demand by more than 50 percent, increased mining and industry demands by about 33 percent, expansion of town water supplies by about 50 percent, and increased plantation water use by about 15 percent (DoW, 2008c).

More details on the expected growth in water demands can be found in Chapter 6.

2.7 Vegetation

Variation of rainfall, geology, topography, occurrence of water features, soil and soil depth across the project area encourages rich speciation of plants adapted to specific ecological niches. The vegetation form affects the local surface and groundwater hydrology and will itself be affected by climate change and interact with the hydrology in complex ways.

The major native vegetation forms within the project area have been extensively cleared, especially on the coastal plain (Figure 2-17). Native vegetation remains in state forest and nature conservation areas, while only pockets remain on private land.

The major native vegetation forms within the project area are woodlands and shrublands (Figure 2-17). These occur along the west and south coast, and further inland in the northern project area. *Eucalyptus* and/or *Banksia* woodlands occur on the Swan Coastal Plain and on the Darling Plateau across the project area. Forests with tall eucalypt trees occur in the wetter south-western region of the project area. Heath comprises densely canopied, mixed shrublands which are dominated by species which are typical of infertile and/or waterlogged sites.

On the northern Dandaragan Plateau and in the Arrowsmith GWA low scrubs predominate. Many plants use bacteria and fungi associated with their root systems to extract nutrients from the impoverished sand or obtain nitrogen from the air (DEC, 2009).

The dominant vegetation in woodlands on the Swan Coastal Plain is Banksia and Tuart (*Eucalyptus gomphocephala*) on sandy soils, Sheoak on outwash plains, and Paperbark in swampy areas. Younger sandy areas and limestones are dominated by heath and/or Tuart woodlands, while Banksia woodlands and Jarrah (*Eucalyptus marginata)* and Banksia woodlands are found on the older dune systems. In the north-east of Perth, on the Dandaragan Plateau, Mesozoic sediments contain Jarrah woodland. *Banksia* low woodland, Jarrah-Marri (*Eucalyptus calophylla*) woodland, Marri woodland and scrub-heaths also occur on laterite pavement and gravelly sandplains (ANRA, 2009).

On the Darling Plateau and Darling Scarp, Jarrah-Marri forest grows on laterite gravels, while further east Marri-Wandoo woodlands are found on clay soils. Elluvial and alluvial deposits in the south support *Agonis* shrublands (Myrtaceae Family, commonly referred to as Peppermint). In areas of Mesozoic sediments, Jarrah forests and various species-rich shrublands occur. Vegetation comprises Jarrah-Marri forest in the west with Bullich (*Eucalyptus megacarpa*) and Blackbutt (*Eucalyptus patens*) in the valleys, which grades into Wandoo woodlands in the east. There are extensive but localised sand sheets with *Banksia* low woodlands. Heath is found on granite rocks and is a common understorey of forests and woodlands in the north and east. In the Southern Jarrah Forest, vegetation comprises Jarrah-Marri forest in the west grading to Marri and Wandoo woodlands in the east. Extensive areas of sedgelands and swamps in the south are dominated by Paperbarks and Swamp Yate (*Eucalyptus occidentalis)*. The forest and woodland understoreys reflect the moist nature of this area (ANRA, 2009).

In the south-west region of the project area, on the undulating country of the Leeuwin-Naturaliste Ridge, Blackwood Plateau, Darling Plateau and Albany Orogen, loamy soils support Karri forests. Karri (*Eucalyptus diversicolor*) is one of Australia's tallest hardwoods, with heights from 45 to 80 m. The Karri grows in association with Rates Tingle *(Eucalyptus brevistylis*), Red Tingle *(Eucalyptus jacksonii*) and Yellow Tingle *(Eucalyptus guilfoylei*) which are endemic to the region.

Medium height forests of Jarrah and Marri grow on the poorer, lateritic or leached sandy soils of the south-west region of the project area. This region is considered to be one of the most important centres of plant endemism in SWWA.

The largest rivers in the south-west of the project area mostly have their headwaters in salt lakes of the Wheatbelt. Therefore, their riparian vegetation is controlled by the water content and salinity. Paperbarks, Sheoaks, Flooded Gums (*Eucalyptus rudis*) and Sedges (*Juncus, Lepdiosperma*) grow along the banks. The smaller freshwater streams of the south-west are usually lined with *Agonis* species (George, 2002).

2.8 Water dependent environmental assets

Specific hydrogeological and hydrological conditions of SWWA have resulted in the development of unique ecological systems associated with groundwater and surface water.

Important groundwater dependent ecosystems (GDEs) occur in the areas with shallow groundwater in the Swan and Scott coastal plains and in other parts of the project area. As a result multiple wetlands and groundwater dependent terrestrial ecosystems are plentiful within the natural environment in the region. Other GDEs include important stygofauna in limestone caves.

Surface water resources, particularly in the high rainfall region in the south-west of the project area, sustain in-stream ecological systems and riparian zone vegetation. Groundwater contributions to baseflow are important in a number of the streams east and west of the Darling escarpment.

Often both groundwater and surface water contribute to water dependent ecosystems, but the classification of the environmental assets is usually based on the predominant component of the water balance being either groundwater dependent ecosystems (GDEs) or surface water dependent ecosystems (SWDEs). In many cases this definition was a value judgement based on existing hydrological information.

As a result of the geographic isolation of SWWA there is an unusually high degree of endemism in plants and animal species and many water dependent ecosystems are recognised at an international (Section 2.8.1), national (Section 2.8.2) and state (Section 2.8.3) scale. Additional assets of interest as areas of scientific study and knowledge are also discussed.

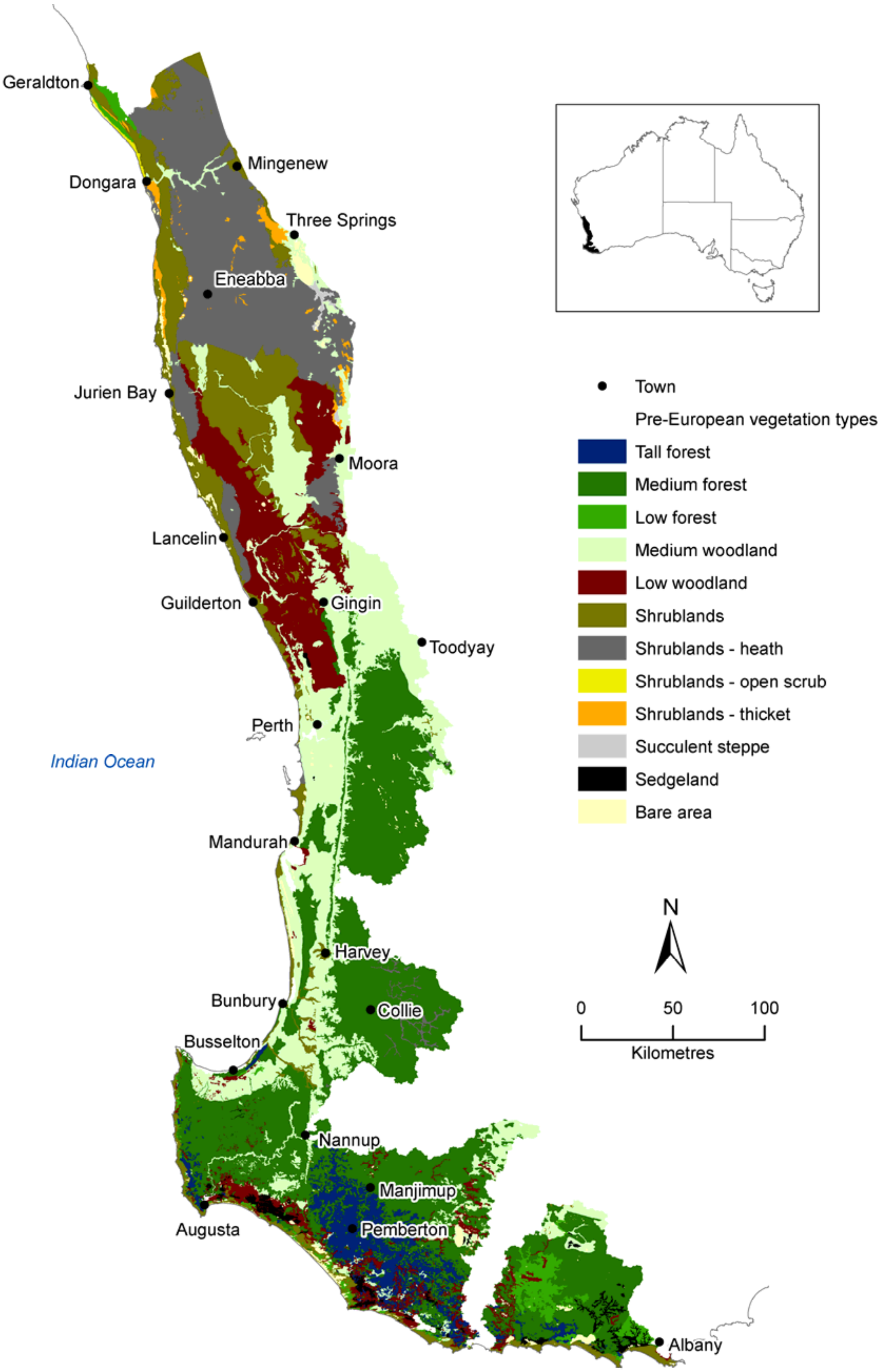


Figure 2-17. Main native vegetation groups in the project area (Beeston et al., 2002)

2.8.1 Internationally important water dependent environmental assets

Many water dependent environmental assets of international importance have been listed under the Ramsar Convention, an international agreement committing signatories to the protection and conservation of significant, representative, rare or unique wetlands or wetlands that are important for conserving biological diversity and their associated resources. Wetlands listed under the Ramsar Convention are protected in Australia under the Australian Government *Environment Protection and Biodiversity Conservation Act* (DEWHA, 1999). Under the convention the term 'wetlands' includes permanent or temporary swamps, marshes, billabongs, lakes, mudflats, fens and bodies of water both natural and artificial (BMT WBM, 2007). Wetlands listed under the Ramsar Convention are chosen for their botanical, zoological, limnological or hydrological significance.

In the project area there are six Ramsar sites: Thomsons Lake, Forrestdale Lake, the Becher Point Wetlands, the Peel-Yalgorup System, the Vasse-Wonnerup System and the Muir-Byenup System (Figure 2-18). The catchments of many Ramsar-listed wetlands have been affected by clearing and other land use changes (Figure 2-18).

The Thomsons and Forrestdale lakes are located about 20 km south of Perth and are the best remaining examples of inland brackish, seasonal lakes with extensive fringing sedgelands typical of the Swan Coastal Plain. The two lakes cover an area of 754 ha and are set within an urban environment. They are surrounded by emergent vegetation (e.g. *Melaleuca*) immediately adjacent to the lakes, while a *Eucalyptus*- and *Banksia*-dominated woodland surrounds the more elevated landscape. In a regional context they constitute a major breeding, migration stop-over and semi-permanent drought refuge area for more than 10,000 waterbirds (Lane, 2003b; Ramsar Convention Secretariat, 2000; BMT WBM, 2007).

The Becher Point Wetlands are situated about 50 km south of Perth and comprise a system of approximately 200 inter-dunal depressions that have become small individual seasonal wetlands. This type of wetland suite is unique in SWWA. The reserve covers an area of 677 ha of which only 105 ha are wetland. The geomorphology, hydrology and vegetation within the wetlands show a continuum of development over time and are one of the youngest wetland systems (Holocene) on the Swan Coastal Plain. The associated sedgelands are listed as a threatened ecological community under the *Environment Protection and Biodiversity Conservation Act* (DEWHA, 1999; Lane, 2003a; Ramsar Convention Secretariat, 2000; BMT WBM, 2007).

The Peel-Yalgorup System is located in the Mandurah and Harvey region, about 80 to 100 km south of Perth, and is a system of shallow estuary and saline, brackish and freshwater lakes covering an area of 26,530 ha. It is situated in the region of the Peel Inlet and Harvey Estuary and includes Lake Mclarty, Lake Mealup and Lake Clifton. The system supports over 20,000 waterbirds including large numbers of migrant shorebirds from the northern hemisphere annually, making it the most important area for waterbirds in SWWA. It is also one of only a few sites in the world with living thrombolites, a type of microbialite that is a primitive life form that superficially resembles stromatolites. The fringing vegetation is dominated by samphire flats moving to rushlands and sedgelands.

The Vasse-Wonnerup System lies in the Busselton region, about 300 km south of Perth, and is an extensive, shallow, nutrient-enriched, wetland system that acts as a basin for four different rivers (Ludlow, Sabina, Abba and Vasse) with widely varying salinities. The system covers 1115 ha with an elevation of between zero and 6 m AHD. Its two principal components, the Vasse and Wonnerup estuaries, are now regarded as lagoons as saltwater intrusion is largely prevented from entering the river mouths by floodgates. The system acts as an important coastal habitat for thousands of resident and migratory waterbirds of various species and supports the largest regular breeding colony of Black Swans *(Cygnus atratus*) in SWWA. The Vasse-Wonnerup System's open water areas are surrounded first by samphire and rushes that turn into *Melaleuca* woodlands or *Eucalyptus* woodlands on higher areas (Lane, 2003d; Ramsar Convention Secretariat, 2000; BMT WBM, 2007).

The qualities that enable the Peel-Yalgorup and Vasse-Wonnerup systems to be Ramsar listed are partly due to their surface and groundwater resources but mainly their marine features which are not the subject of this project.

The Muir-Byenup System is 55 km east-south-east of Manjimup in SWWA. It is a 10,631 ha nature reserve of interconnected lakes and swamps of varied size, salinity and permanence. The open lakes provide habitat and drought refuge for thousands of ducks of various species. The swamps, the largest sedgelands in Western Australia, as well as the shrub-dominated swamps, support three types of vulnerable orchids and a colony of Australasian Bittern (*Botaurus poiciloptilus*) (Lane, 2003c; Ramsar Convention Secretariat, 2000; BMT WBM, 2007).

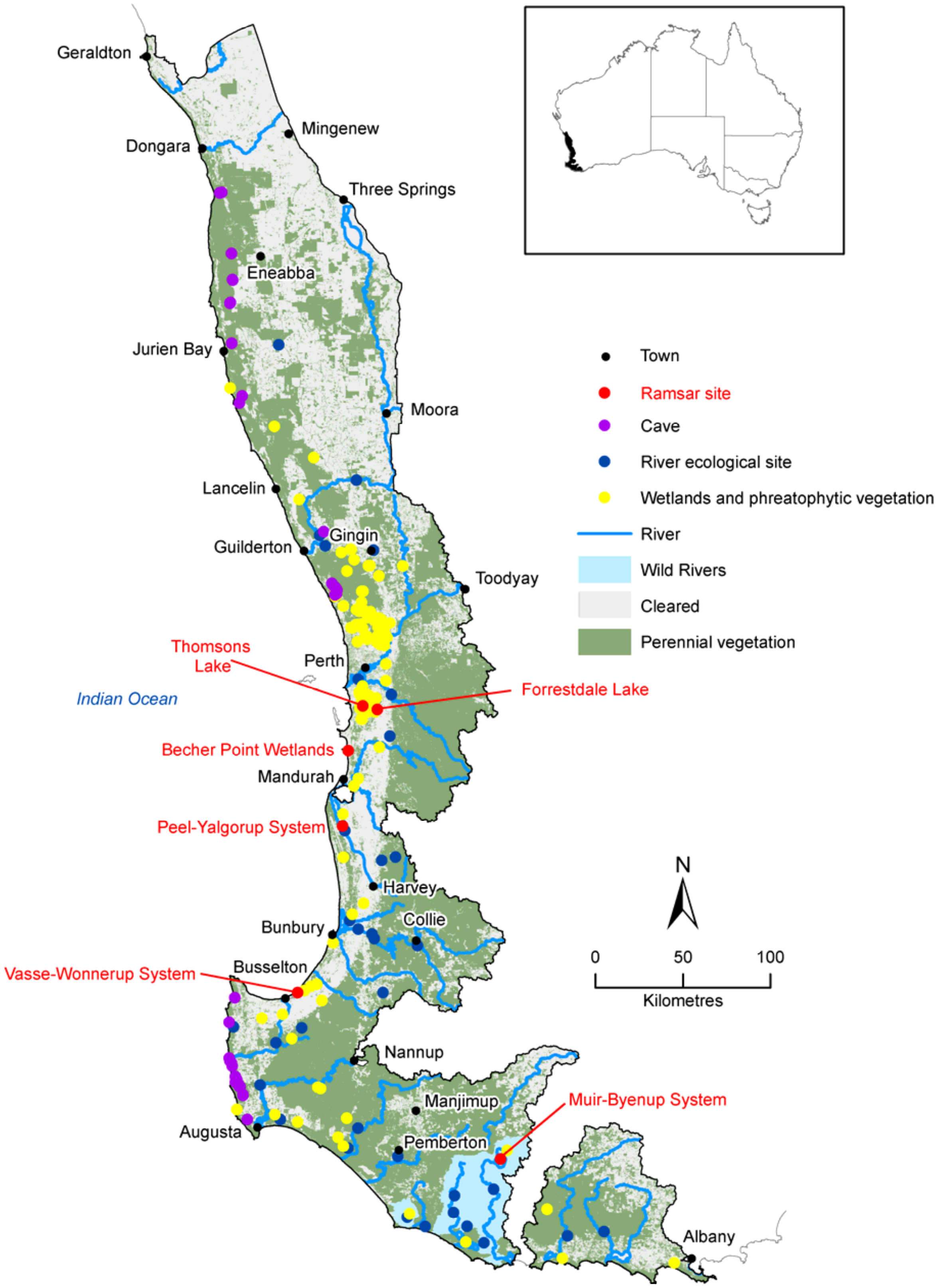


Figure 2-18. Location of Ramsar-listed wetlands, Wetlands of National Significance, wild rivers, and caves and conservation category wetlands in the project area

2.8.2 Nationally important water dependent environmental assets

Wetlands of National Significance

The Directory of Important Wetlands in Australia (DIW) is a joint venture between the Australian Government and states to recognise wetlands that meet criteria of national importance. The directory identifies important wetlands and provides substantial data on their individual attributes including details of the wetlands' hydrological characteristics and associated flora and fauna elements (Environment Australia, 2001). Cultural and social values of wetlands are also listed as well as some ecosystem processes and benefits provided by individual wetlands. The information provided for input to the directory is also used to identify potential Ramsar sites. In Western Australia, 120 wetlands are listed in the total area of 2,583,325 ha (Environment Australia, 2001) of which 36 are in the project area (Figure 2-18).

Wild rivers

In Western Australia a Wild Rivers Project began in 1992 to identify rivers in near-pristine condition and to encourage their protection and management (Stein et al., 1998). The Project identified categories of river condition and highlighted rivers of special conservation value or rivers with very little human modification from their natural state. The most important categories for classification of a wild river are rarity, habitat, water quality and scientific values. Wild rivers are unregulated and exist in catchments where biological and hydrological processes are continuing without significant alteration from the impacts of modern human activities. They occur over a variety of landscapes and can be permanent, seasonal or dry (Williams et al., 1999).

These identified catchments are considered of very high environmental value because their undisturbed state has enabled the rivers associated with them to retain very high water quality levels and thus maintain biodiversity values in the region. The identified wild rivers also act as a benchmark for catchment and river condition status under unaltered conditions against which altered catchments can be compared. The project categorised catchments into two priority-type rivers (P1 and P2). Both P1 and P2 classified rivers are managed in the same way as the differences in the two categories are nominal (DoW, 2009b).

Within the project area there is one P1 river: the Forth River; and five P2 rivers: Doggerup Creek**,** Blackwater Creek**,** Shannon River, Deep River and Inlet River (Figure 2-18).

2.8.3 State significant water dependent environmental assets

Caves

Caves in SWWA often contain unique ecological systems that depend on a stable groundwater environment for survival (SKM, 2001, Humphreys, 2006). They represent key cave ecosystems and habitats that support unique and rare species. There are 26 caves within the project area that have been assessed for environmental impact (Figure 2-18). These caves are predominantly clustered in the north within the Yanchep National Park or in the south in the Busselton-Capel region. Caves and their associated flora and fauna are classed as groundwater dependent ecosystems and as such all caves are reported on in Chapter 5.

Conservation category wetlands

In Western Australia there are certain wetlands defined as environmentally sensitive areas and managed by the Department of Environment and Conservation (DEC) (Figure 2-18). DEC have categorised wetlands in Western Australia into three categories which, in order of increasing disturbance and loss of nature conservation values, are: conservation, resource enhancement and multiple use. Wetlands classed as being in the conservation category are considered in Chapter 5.

Wetlands identified by DEC as being of high environmental value are included in the following DEC datasets:

- conservation category wetlands identified in DEC geomorphic wetlands datasets
- wetlands mapped in Pen (1997)
- wetlands mapped in Semeniuk and Semeniuk (1997)

- wetlands listed in the Western Australian government's *Environmental Protection (Swan Coastal Plain Lakes) Policy 1992 (*EPA, 1992).

2.8.4 Other water dependent environmental assets

Other sites that have been included for an assessment of the impacts of climate change and discussed in Chapters 4 and 5 are:

- sites with ecological water requirement studies completed
- sites with environmental water provisions in place
- various other sites nominated as having special interest or high conservation value.

2.9 Water yield modelling and results

Companion reports (CSIRO, 2009a, b) give details of the surface and groundwater modelling that estimate streamflow and groundwater yields used in this report. An overview of the methods used and results is presented here.

2.9.1 Surface water yield modelling

Six rainfall-runoff models were tested for their ability to reproduce daily streamflow against the available record within the historical period (1975-2007). The individual models are relatively simple bucket models, but the modelling results had high model efficiencies. The results from two of the models demonstrated the best agreement with measured streamflow and the mean of the daily runoff generated by these two gave the best reproduction of observed data of all other combinations or single models tested. This 'adopted model' was therefore used for all analysis (CSIRO, 2009b; Chapter 5).

The models were implemented on a spatial grid with cells of 0.05 x 0.05 degrees of longitude and latitude, equivalent approximately to 5 x 5 km cells. Each cell received its own set of rainfall and APET data in accordance with relevant climate scenarios. Model parameters were determined for each cell within a designated catchment on the basis either of calibration, if streamflow data was available, or on the basis of hydrologic similarity (CSIRO, 2009b; SKM, 2008).

The scenario climate data were applied to the models across the project domain and runoff produced for each cell was accumulated within a catchment to each Streamflow Reporting Node (SRN). These SRNs are catchment outlets, reservoirs, terminal lakes, streamflow recording gauges or environmental water requirement points.

The model outputs were daily flows on a cell-by-cell basis and at each SRN which were then analysed for flow statistics of interest, particularly flow frequency distribution. These model outputs were analysed further in Chapters 4 and 7 of this report.

The surface water results were compiled for three regions, a northern region (Gingin to Murray basins), central region (Harvey to Preston basins), and southern region (Busselton Coast to Denmark basins) (Figure 2-1).

The main results are that there is estimated to be a significant decline in streamflows under all future climates relative to the historical climate. These results are summarised in Table 2-4. Figure 2-19 shows the changes in rainfall and runoff, , for scenarios B and C relative to Scenario A across the surface water modelled area.

Across the project area mean annual rainfall under scenarios Cwet, Cmid and Cdry are projected to decline by 2, 8 and 14 percent, to 819, 769 and 717 mm respectively, relative to the mean annual rainfall of 837 mm under Scenario A. Under Scenario Cwet, the northern and central regions have slightly more rain than Scenario B, but this is not the case in the southern region. The southern region has the greatest proportional decline in rainfall (3 percent) under Scenario Cwet and the northern region has the greatest proportional decline in rainfall under scenarios Cmid and Cdry of 10 and 16 percent respectively.

Table 2-4. Average annual rainfall, runoff, runoff coefficients, and streamflow volumes under Scenario A, and change in rainfall, runoff, runoff coefficients and streamflow volumes for each surface water region in the project area and the area as a whole under scenarios B, Cwet, Cmid and Cdry

Scenario	Mean annual rainfall		Mean annual runoff		Mean annual rainfall minus runoff		Runoff coefficient	Streamflow volume	
	mm	change from Scenario A	mm	change from Scenario A	mm	change from Scenario A	percent	GL	change from Scenario A
Surface water modelling area*									
A	837		98		740		12%	3411	
B	818	-2%	91	-7%	728	-2%	11%	3172	-239
Cwet	819	-2%	88	-10%	731	-1%	11%	3068	-343
Cmid	769	-8%	74	-25%	695	-6%	10%	2575	-837
Cdry	717	-14%	57	-42%	660	-11%	8%	1986	-1426
Northern (Gingin to Murray) region									
A	766		46		720		6%	457	
B	738	-4%	40	-13%	698	-3%	5%	396	-62
Cwet	754	-1%	43	-8%	711	-1%	6%	422	-36
Cmid	692	-10%	33	-30%	659	-8%	5%	320	-137
Cdry	643	-16%	22	-53%	621	-14%	3%	217	-241
Central (Harvey to Preston) region									
A	818		121		697		15%	742	
B	783	-4%	108	-11%	675	-3%	14%	663	-79
Cwet	803	-2%	112	-7%	691	-1%	14%	689	-53
Cmid	742	-9%	93	-23%	649	-7%	12%	569	-174
Cdry	694	-15%	72	-40%	622	-11%	10%	443	-299
Southern (Busselton Coast to Denmark) region									
A	881		117		764		13%	2212	
B	871	-1%	111	-4%	760	-1%	13%	2113	-99
Cwet	858	-3%	103	-12%	755	-1%	12%	1957	-255
Cmid	818	-7%	89	-24%	729	-5%	11%	1686	-526
Cdry	763	-13%	70	-40%	693	-9%	9%	1326	-886

* Calculated as area weighted mean of the three regions.

Under Scenario Cdry, the reductions in mean annual rainfall are about the same quantum across the three regions, of about 120 mm, but these result in significant differences in runoff across the area, with a 53 percent decline in the northern region, and 40 percent declines in the other two regions. However, although the percentage change in runoff is lower for the central and southern regions, the volumetric change is substantially greater than the northern region, with a 49 mm and 47 mm decline in runoff respectively.

The area has a strongly winter dominant rainfall with about 80 percent of annual rainfall falling in the six months May to October. The seasonality of rainfall under Scenario B is different from Scenario A, with less rainfall occurring early in the wet season and a shift to later, with substantially higher rainfall in August. There is no change in the seasonality of rainfall under scenarios Cwet, Cmid and Cdry as they are generated by scaling Scenario A and therefore follow the same pattern.

Rainfall-runoff modelling with future climate projections from global climate models indicates that runoff is likely to decline in future (Figure 2-19). Under the median future climate (Scenario Cmid), mean annual rainfall across the surface water modelling area decreases by 8 percent and mean annual runoff decreases by 25 percent relative to the historical climate. While all future climate scenarios are drier than the historical climate, there is a large range. Projected declines in mean annual runoff range from 7 percent under the wet extreme future climate (Scenario Cwet) in the central (Harvey to Preston) region to 53 percent under the dry extreme future climate (Scenario Cdry) in the northern (Gingin to Murray) region.

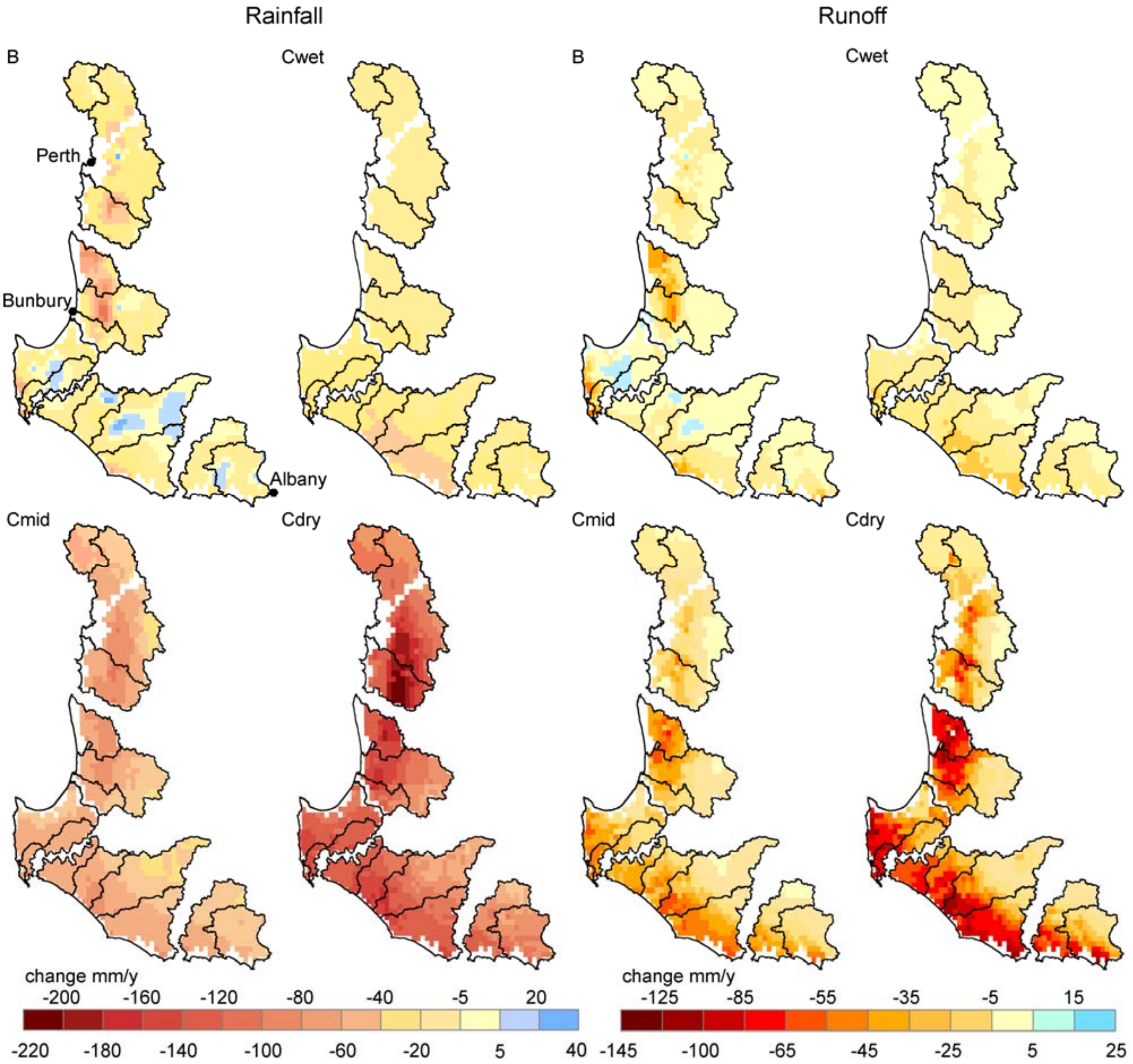


Figure 2-19. Spatial distribution of difference in mean annual rainfall and runoff across the surface water modelling area under scenarios B and C relative to Scenario A

Under a continuation of the historical (1975 to 2007) climate (Scenario A), rainfall is about 8 percent higher and potential evapotranspiration (APET) about 8 percent lower (Figure 2-19) in the southern (Busselton Coast to Denmark) region than in the central region but runoff is slightly greater in the latter. This difference could be because the central region has more intense rainfall or less dense vegetation, though there may be many other influences. More research is required to understand the drivers of these regional differences and to determine whether these relationships will change under a future climate.

The hotter, drier northern region has a runoff coefficient less than half that of the other two regions. This difference is probably mainly due to climate, although mining and subsequent land rehabilitation in some of these catchments may have also had an influence (Croton et al., 2005; Croton and Reed, 2007). Relative to Scenario A, all three regions have lower rainfall and runoff under Scenario B although these differences are small in the southern region. Under the future climate scenarios the greatest decline in rainfall and runoff are in high rainfall areas around the Darling Scarp, which include the main water supply reservoirs, and the rivers in the southern region. Although the decline in runoff under Scenario B relative to Scenario A is not as severe in the southern basins as further north, under Scenario Cmid the decline in runoff is of a similar magnitude to that further north.

The percentage decline in mean annual runoff under scenarios B and Cmid relative to Scenario A is shown in Figure 2-20 for all basins in the project area. Dam inflows have declined substantially over the last 11 years relative to the previous 22 years, and this is also reflected in the decline in runoff under Scenario B relative to Scenario A (Water Corporation, 2009). The focus of much streamflow analysis in the recent past has been in the major water supply catchments in the northern and central regions of this project, namely the Swan Coastal, Murray, Harvey and Collie basins. Figure 2-20 shows the decline in runoff under Scenario B relative to Scenario A, and also shows that although the decline under Scenario B relative to Scenario A is not as severe for the southern basins (Busselton Coast to Denmark), under Scenario Cmid the percentage decline in runoff relative to Scenario A for the more southern catchments is of similar order to those further north. This means that although the impact of the recent climate is relatively minor in the southern catchments, under the future climate scenarios this impact increases and is similar to that in the northern and central regions.

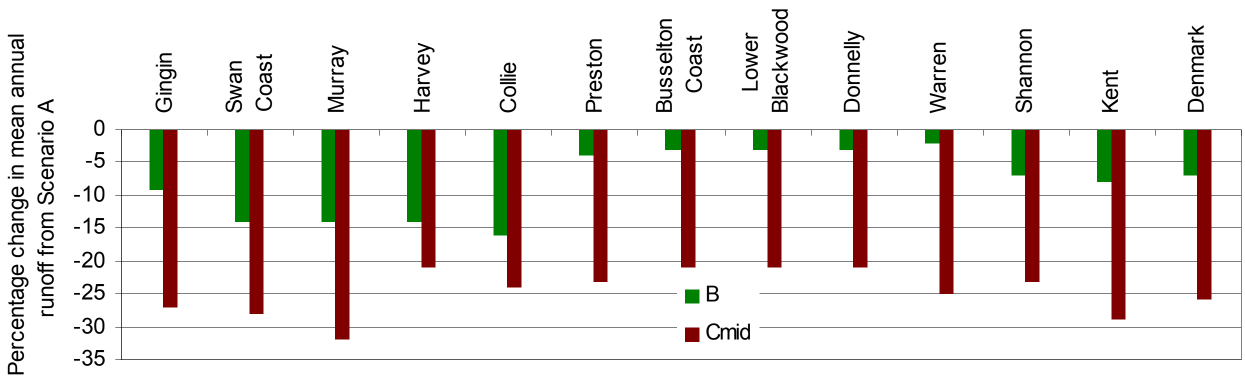


Figure 2-20. Percentage change in mean annual runoff under scenarios B and Cmid relative to Scenario A for all basins in the project area

The results of the surface water modelling translated into future possible yields are described in Chapters 4 and 7.

2.9.2 Groundwater yield modelling

The effect of climate and development scenarios on groundwater levels and the overall water balance of aquifers was investigated using groundwater models coupled with Vertical Fluxes Models (VFMs) where they were available (CSIRO, 2009a). Daily rainfall and potential evapotranspiration were used as inputs into the VFM and groundwater models. The climate scenario data used in the scenario modelling are described in Charles et al. (2010). A brief summary is given here.

The historical climate scenario (Scenario A) is the baseline against which other scenarios were compared. It is based on observed climate data from 1975 to 2007. The project area was divided into 15 climate zones based on the Thornthwaite moisture index, annual rainfall and potential evapotranspiration (APET) gradients. For each climate zone a dominant soil profile and representative groundwater depth was selected and used in the WAVES model to estimate annual recharge from 1975 to 2007. The groundwater models were run from 2008 to 2030, a span of 23 years, whereas there are 33 years of climate data from 1975 to 2007 that could be used. Three 23-year sequences were derived from the available climate series for scenarios Awet, Amid and Adry representing the periods for the 10th, 50th and 90th percentile of estimated recharge. The differences in average recharge between these scenarios were insignificant and therefore the VFM-coupled groundwater model used the median recharge for Scenario A.

The recent climate scenario (Scenario B) is used to assess future water availability should the climate in the future prove to be similar to that of the recent past. Climate data for the 1997 to 2007 period are repeated three times to produce a 33-year daily climate sequence.

The future climate scenarios (Scenario C) were used to assess a range of possible climate conditions for projected climate change by 2030. The climate sequences for scenarios Cwet, Cmid and Cdry were derived from historical climate modified by GCM predictions of the annual patterns and statistics for the year 2030 under different future global warming trends. The future climate variants come from scaling the 1975 to 2007 climate data to represent ~2030 climate, based on analyses of 15 global climate models (GCMs; as listed in Charles et al., 2010) and three global warming scenarios (high, medium and low global warming of 1.3, 1.0 and 0.7°C respectively).

Representative climate stations in each of the 17 climate zones were selected and their data scaled for the future climate scenarios Cwet, Cmid and Cdry. A VFM was used to estimate recharge rates under major soil types and bare soil and scaled climate data from the representative climate stations. The estimated annual recharge rates were ranked to select the GCMs which represent 10th, 50th and 90th percentile annual recharge for the Cwet, Cmid and Cdry scenarios. Based on ranking of annual recharge the most appropriate GCM was selected.

2.9.3 Groundwater model descriptions

The Perth Regional Aquifer Modelling System (PRAMS) model was used in the Central Perth Basin which covered an area of about 10,000 km^2 between Mandurah in the south and Moora in the north. PRAMS is a finite difference MODFLOW-based model (McDonald and Harbaugh, 1996) which has been coupled with a VFM. It has a uniform grid of 500 by 500 m (25 ha cells). This model has undergone significant improvements over time. PRAMS version 3.2 had been calibrated and validated to 2008 and was used for scenario modelling in this project. All scenarios assumed that the pine plantations on the Gnangara Mound would be removed by 2028 and urban areas would expand. It was also assumed that abstraction for public water supplies will be reduced from 158 to 135 GL/year. All other land cover and groundwater abstraction were kept unchanged between 2008 and 2030. The annual groundwater abstraction from the Superficial Aquifer was increased by 133 GL in the development scenario, Scenario D.

The Peel-Harvey Regional Aquifer Modelling System (PHRAMS) model in the Peel-Harvey Area covers an area of about 4095 km^2 between Peel Inlet and Bunbury. It was developed as part of this project and constructed using Visual MODFLOW Version 2009.1 Pro and run with MODFLOW-SURFACT Version 3.0. PHRAMS was calibrated under both steady-state and transient conditions. The horizontal finite-difference grid is uniform with cell dimensions of 500 m x 500 m (0.25 km^2). The transient calibration of the model was from 1985 to 2002 and the calibration validation from 2003 to 2008. The groundwater abstractions and land cover were kept at 2008 levels in all scenarios except Scenario D where the annual groundwater abstraction was increased from 29 GL under scenarios A, B, Cwet, Cmid and Cdry to 81 GL.

The South West Aquifer Modelling System (SWAMS) model in the in the Southern Perth Basin covers three main aquifers (Superficial, Leederville and Yarragadee) of this region. SWAMS consists of a MODFLOW 2000 saturated flow model, pre- and post-processors and a GIS database. The model covers an area of about 8500 km^2, of which 6000 km^2 is onshore. SWAMS was developed to test the impact of groundwater abstraction from the South West Yarragadee Aquifer for public water supply (PWS). Significant upgrades were made to SWAMS v2 model as a part of this project. SWAMS model v2.1 was coupled with a VFM making it similar to the PRAMS model. It was calibrated for the period 1990 to 2000, and validated from 2000 to 2008 after updating the groundwater abstraction and monitoring databases. Water level data from investigation wells that were drilled on the Blackwood Plateau in 2002/03 were available for this project which together with revised recharge values obtained from the VFM model resulted in the SWAMS v2.1 having a similar calibration to the earlier version (v2). The additional recharge from overland flow in the eastern Scott Coastal Plain estimated by the Eastern Scott Coastal Plain model (Aquaterra, 2006) was incorporated into the SWAMS model. Annual groundwater abstraction of around 73 GL in 2007 was kept constant during the predictive period in all scenarios except Scenario D for which the current allocation limit of 156 GL/year was used. The land cover in 2008 remained unchanged over time.

The Collie Basin groundwater model of the Collie basin consisting of sedimentary deposits within the Yilgarn Craton is based on an existing GMS–MODFLOW model of Collie developed by DoW (Zhang et al., 2007). The model grid, river cells, measured bore abstractions and all physical dimensions and properties of the aquifers were assembled and reproduced in a groundwater model similar to PRAMS. It is a variable finite difference grid model with the grid size varying from 50 x 100 m to 400 x 400 m with an active area of 535 km^2. The new model developed for this project employed a vertical flux model (VFM) that used the WAVES model to estimate recharge based on the land cover, soil properties, climate and depth to watertable. After its coupling with VFM this model was calibrated and validated to enable its use for scenario modelling. The land cover and annual groundwater abstraction of around 18 GL were kept unchanged between 2008 and 2030 in all scenarios except D where the annual groundwater abstraction was increased to 74 GL.

These models were used to predict the impacts of current and future climates and land development on groundwater levels in the Superficial and confined aquifer systems. The ecological functions of GDEs are mainly defined by groundwater levels in the Superficial Aquifer although some wetlands are perched. Groundwater levels in the unconfined aquifer depend mainly on rainfall inputs, topography, the hydraulic properties of the aquifer and distance from a discharge point. The highest elevations of the watertable are mainly distant from a discharge point and consist of groundwater mounds with radial flow away from these points. Wetlands which frequently occur in inter-dunal swales are often an expression of the watertable. Local factors such as drainage, pumping and land uses may affect groundwater recharge or discharge subsequently influencing groundwater levels and therefore the GDEs. A summary of the future groundwater levels under various climate and land development scenarios is given below. Details of the groundwater models and results are contained in CSIRO (2009a).

2.9.4 Groundwater results

Groundwater levels in the unconfined Superficial Aquifer are sensitive to climate, topography, hydraulic properties of soils and the aquifer, groundwater abstraction, land use, depth to watertable and distance from a discharge point.

Results from the PRAMS, PHRAMS and SWAMS groundwater models that cover the Central Perth Basin, Peel-Harvey Area and the Southern Perth Basin were combined to provide data on the response of over the southern half of the Perth Basin to climate and development changes (Figure 2-21).

Under most scenarios, groundwater levels are expected to be higher in the north-east of the region (under the Dandaragan Plateau) and lower in the south (under the Blackwood Plateau). Another regional pattern that is evident from Figure 2-21 is the relative resilience of the Swan and Scott coastal plain aquifers to climate and abstraction. Almost all of these coastal plains have groundwater level changes under all scenarios within 3 m of 2008 water levels – with some areas within 0.5 m even under scenarios Cmid and Cdry and abstraction at full allocation limits. The unconfined aquifer under the coastal plains is usually shallow and the sandy dunal soils are easily recharged over winter. Excess water is lost through artificial and natural drainages and evapotranspiration from groundwater dependent ecosystems which limits large rises and falls.

There is a continuum of climate impacts on the Swan Coastal Plain with expected rises in the south, stable or slightly falling levels under scenarios Cdry and D in the Peel-Harvey Area, and slightly greater falls in the north. This reflects the rainfall gradient in many respects.

The coastal plain areas that may experience a decline greater than 3 m are the Gnangara Mound north of Perth, a small area north of Waroona in the Peel-Harvey Area and the Scott Coastal Plain under Scenario Cdry. Gnangara has an unusually deep and thick aquifer which is mainly covered by native vegetation and pines which reduce recharge rates. Being further from discharge areas the Mound has been in decline since the late 1960s and this is expected to continue even under Scenario B. The replacement of the pines with higher recharge parklands is expected to result in rising levels under parts of the Mound under all scenarios except Scenario Cdry. The Gnangara area also has the highest rates of abstraction anywhere in the Perth Basin.

Due to the shallow watertables over large parts of the Peel-Harvey Area, any decrease or increase in recharge under wet or dry climate scenarios is partially compensated by decreases or increases in evapotranspiration and discharge to drains, rivers and the ocean. As a result the average change in the area's watertable under the climate scenarios by 2030 ranges by only 0 and 1 m with levels predicted to either slightly decline or remain stable over time (Figure 2-21). The shallowness of the watertable under much of the Peel-Harvey Area means that there are very large areas of potential wetlands that may be affected by changes in levels. Many of these areas lack vegetation and are therefore not of high conservation value. The inflows into coastal lakes reduce under scenarios Cmid and Cdry. Although the average watertable declines are expected to be modest, when combined with a reduction in groundwater inflows into coastal lakes, implications for the GDEs can be significant.

The Scott Coastal Plain is expected to experience lower groundwater levels under scenarios Cdry and D and have rising groundwater levels under scenarios A, B and Cwet. Recharge in this area is partly due to overland flow and winter ponding and therefore estimates made using a regional groundwater model may not be robust. An area in the west of the Scott Coastal Plain and the Vasse Shelf is expected to have rising levels under all scenarios except Scenario Cdry. This area has high rainfall and sandy soils, and parts are cleared of native vegetation which facilitates recharge. Areas under native vegetation in the eastern Scott Coastal Plain are estimated to have falling groundwater levels under Scenario Cdry.

The results of the groundwater modelling summarised above was translated into possible future yields as described in Chapter 7.

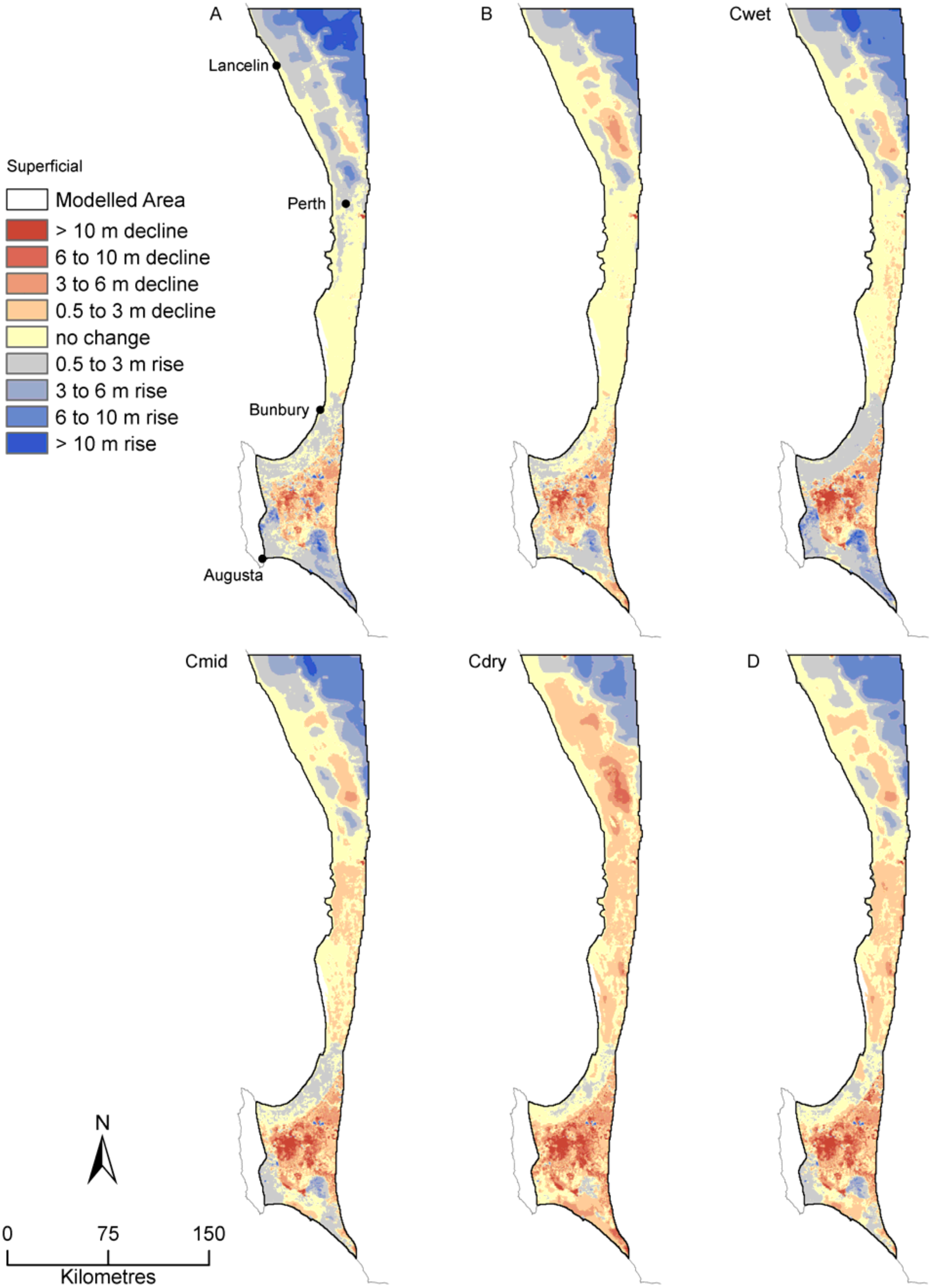


Figure 2-21. Change in groundwater levels between 2008 and 2030 in the southern half of the Perth Basin

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3 Water management regime

3.1 Key findings

- Licences are required to take water from proclaimed water resources in the project area. Only a few surface water catchments and small areas of the Perth Basin groundwater resources remain unproclaimed.
- Regional water plans are being progressively developed to set the strategic context for water plans and policies.
- Allocation limits have been set for most proclaimed surface water catchments and groundwater areas through water allocation plans. These set a cap on the amount of water that can be licensed for extraction. Allocation plans account for exempt and unlicensed use.
- While relatively few groundwater management areas are over-allocated, a number of sub-areas have aquifers that are over-allocated, mainly as a result of downward revisions of allocation limits because of managing for climate change. At the groundwater area level, 7 out of 24 were over-allocated in October 2009.
- Recent allocation plans have taken climate change into account. However they have not used future climate projections.

3.2 Legislation

The South-West Western Australia Sustainable Yields Project is completely within the state of Western Australia and therefore there is only one jurisdiction that governs water management. The main Act of Parliament that governs water resource management is the *Rights in Water and Irrigation Act 1914* which is administered by the Department of Water Western Australia (DoW).

Water services provision and water resource management were separated as a result of the Council of Australia Governments' water reforms in 1994, with this separation starting in January 1996.

The Water Corporation provides most of the potable water and sewerage services in Western Australia. There are two additional potable water service providers in the project area: the Bunbury Water Board (trading as Aqwest) which provides drinking water services to Bunbury, and the Busselton Water Board which provides similar services to Busselton. There are also two licensed irrigation water service cooperatives: Harvey Water, which provides irrigation water to the Waroona, Harvey and Collie irrigation districts, and the Preston Valley Irrigation Authority, which provides irrigation water to the Preston Valley Irrigation District. Drainage services are provided by the Water Corporation and local government.

The *Rights in Water and Irrigation Act 1914* includes provision for water planning and management. The Act vests all natural surface water and groundwater in Western Australia in the Crown. Water users in proclaimed areas must hold a licence to take and use water resources. In addition, all artesian water abstraction anywhere in the state must be licensed.

Surface water catchments and rivers have been proclaimed in many parts of the project area but there are still areas where a licence is not required, including outside of streambeds in catchments such as Margaret River (Figure 3-1). There are some proclaimed surface water catchments outside the project area but their yields and licensed diversions are small in comparison with catchments inside the project area and therefore they were not analysed.

As a result of historical demand for groundwater, all groundwater resources within the Perth Basin have been proclaimed, other than two small areas adjacent to the Darling Scarp near Harvey and Nannup (Figure 3-2).

In the project area stock and domestic water users, and small riparian users, are allowed to take limited quantities of water without a licence. This water use is very important to farms in rural and peri-urban areas and to an estimated 176,000 homes with domestic garden bores in the Perth-Peel region. These low volume water users make up less than 10 percent of total water use in many areas but cumulatively amount to a substantial abstraction in urban areas.

However it is only in unusual management circumstances that there is a need to license every small user because of the small benefits relative to the expense. The Albany wellfield area is one such case in the project area.

The *Rights in Water and Irrigation Act 1914* requires that water be set aside to sustain the environment. The water provision for the environment is set aside before water for consumptive use is estimated and allocated. In some circumstances water is reserved for future public water supply or allocated to major developments (often mining) in accord with State Agreement Acts. The water that is set aside still requires a license to be used.

The state, through the DoW, is required to develop plans for the orderly management and allocation of water to users. This can be through regional water plans and water allocation plans.

It is possible to trade water entitlements with all trades requiring approval from DoW. Water users who obtain their supplies from surface water irrigation schemes do not hold licences. They obtain their rights from contracts or membership in irrigation cooperatives which holds the license. Trading in these ‘commercial’ rights is common. Both surface water and groundwater licence transfers from one property owner to another as part of the sale of an irrigation enterprise is also common. There has also been trading of significant entitlements from irrigation to public water supplies between Harvey Water and the Water Corporation. This trading has taken place with Harvey Water on behalf of its cooperative members with the traded water being saved by piping open channels which were leaking water into the groundwater system.

Trading is not common in groundwater systems although some has occurred in the project area. Where trading of groundwater entitlements takes place between licence holders, an assessment is usually made of the impact of the trade on groundwater dependent ecosystems (GDEs) in the areas involved.

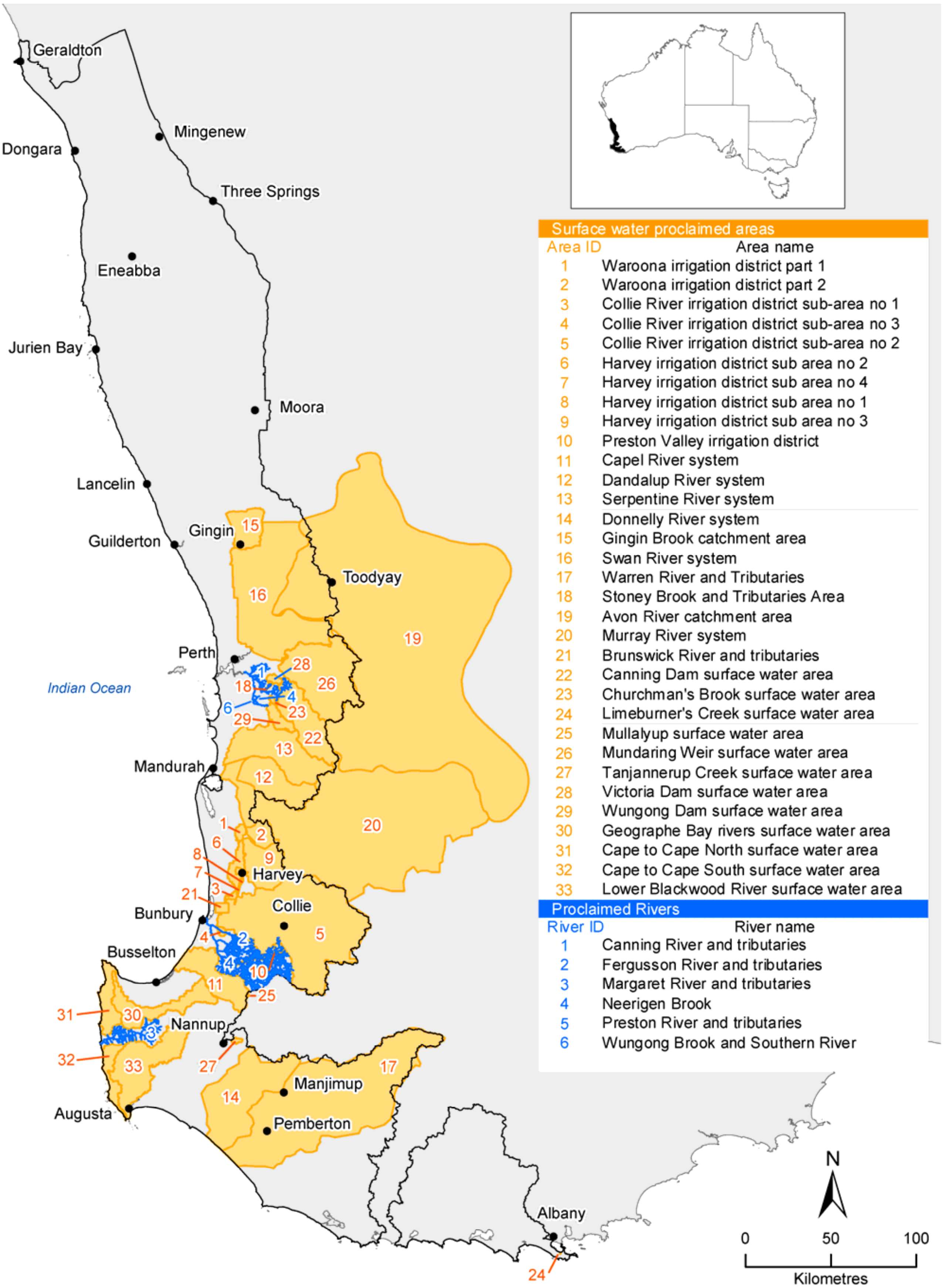
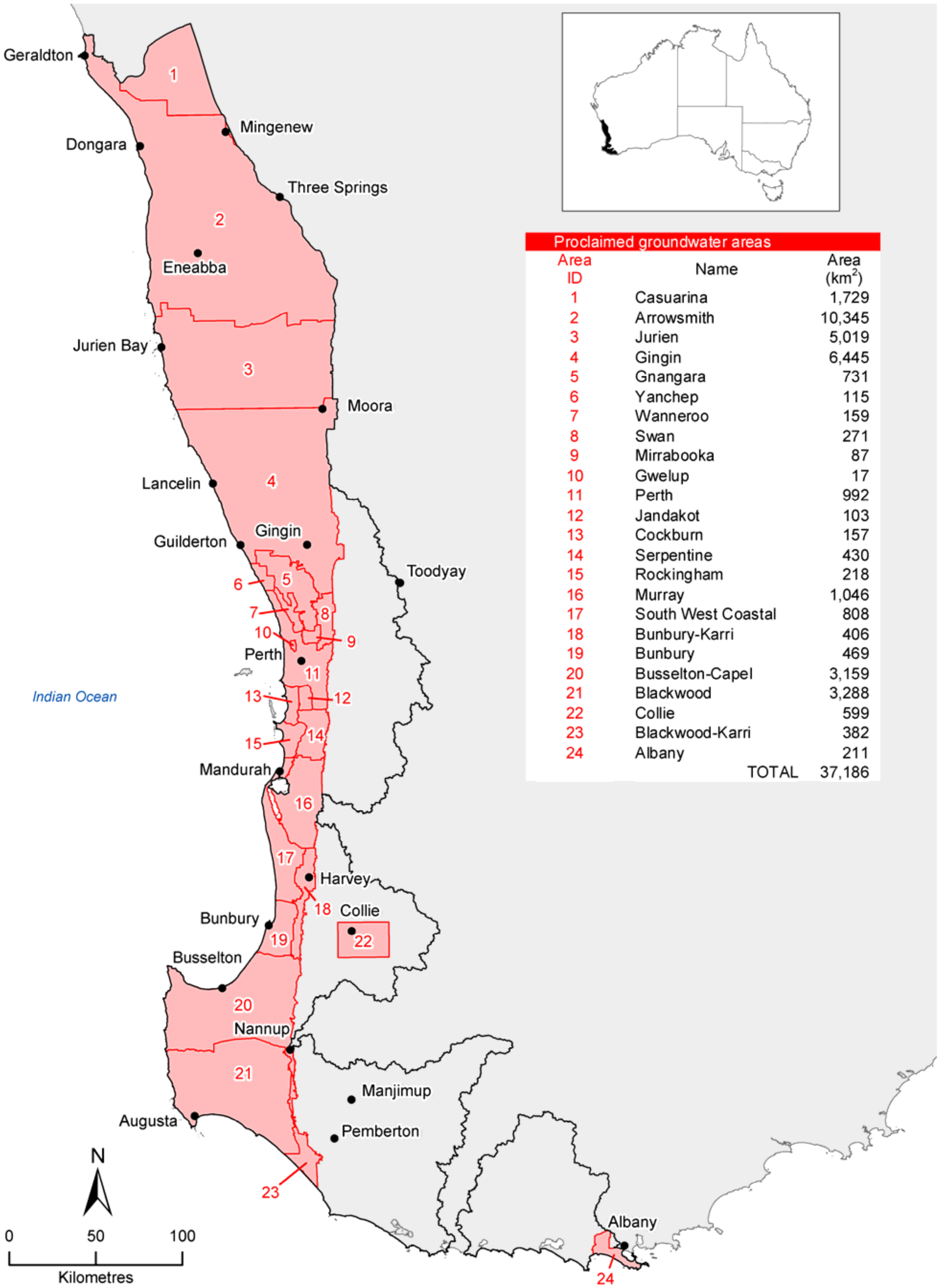


Figure 3-1. Location of proclaimed surface water catchments and rivers in the project area



Proclaimed groundwater areas

Area ID	Name	Area (km^2)
1	Casuarina	1,729
2	Arrowsmith	10,345
3	Jurien	5,019
4	Gingin	6,445
5	Gnangara	731
6	Yanchep	115
7	Wanneroo	159
8	Swan	271
9	Mirrabooka	87
10	Gwelup	17
11	Perth	992
12	Jandakot	103
13	Cockburn	157
14	Serpentine	430
15	Rockingham	218
16	Murray	1,046
17	South West Coastal	808
18	Bunbury-Karri	406
19	Bunbury	469
20	Busselton-Capel	3,159
21	Blackwood	3,288
22	Collie	599
23	Blackwood-Karri	382
24	Albany	211
	TOTAL	37,186

Figure 3-2. Location of proclaimed groundwater areas in the project area. Areas 18 and 23 are still to be proclaimed

3.3 Planning and management processes

There are three levels of planning adopted for water in Western Australia: a state water plan, regional water plans and water management plans (Figure 3-3). The main plans that are relevant for this project are water allocation plans.

Strategic water issue plans cover important strategic areas such as the Gnangara Sustainability Strategy which addresses land and water planning issues on the Gnangara Mound. This strategy is due to be finalised in late 2009 (DoW, 2009). Water user and community plans include Water Corporation's Water Forever Plan which covers water services for Perth and surrounding regions to 2050 (Water Corporation, 2009).

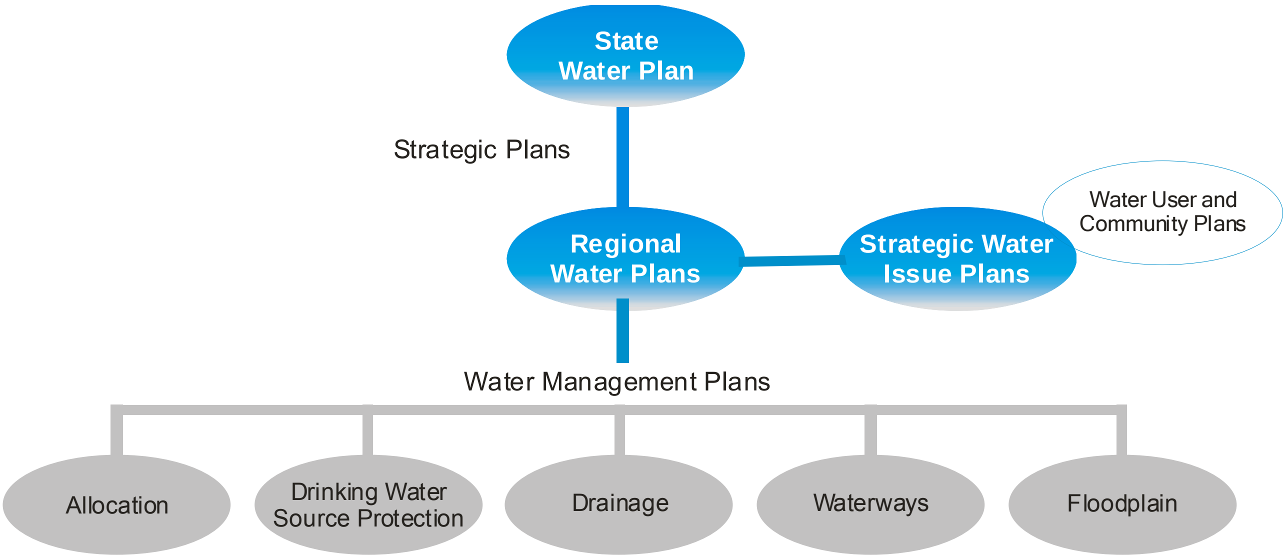


Figure 3-3. The Western Australian water planning framework (DoW, 2008b)

Regional water plans define the regional context for surface water and groundwater resources, their uses and likely demands. In addition, the health of waterways is also assessed. In comparison with water allocation plans, which relate to either surface water or groundwater resources, regional water plans consider longer term and broader issues, such as climate change and the impact of plantations and farm dams on future water yields as well as inter-regional transfers of water where these are relevant (especially in the Perth-Peel region). The regional water plans set broad planning and policy guidelines for consideration when making allocation decisions and therefore could be influenced by this project's results in the future.

Water allocation plans contain allocation principles that determine how much water will be retained for the environment (either as a volume or a water regime) after environmental, social and economic issues have been taken into account and how much water can be allocated for consumptive uses. In addition, the plans set the rules and guidelines to be followed by each person or organisation applying for and issued with a licence to take water. Most plans set volumetric allocation limits for individual water resources that limit the amount of water that can be licensed for use.

The Gnangara Sustainability Strategy (DoW, 2009) involves additional groundwater modelling of past (1950 to 1975; 1976 to 2006; 1997 to 2006) and a possible future climate (1980 to 1999 climate less 11 percent rainfall). These scenarios are very similar to Scenarios A (1975 to 2007), B (1997 to 2007) and C (2030 future climate) used in this project with the exception that this project used outputs from 15 global climate models and three global warming scenarios in its estimates of future climate. The future climate modelled in the Gnangara study used synthetic climate sequences where the same monthly data are repeated for each year between 2008 and 2030. The Gnangara study also simulated more detailed options for changes in land and water use than has been undertaken in this project.

The Water Corporation released a draft Water Forever Plan in February 2009 which outlined the corporation's strategy to secure public water and wastewater service delivery for Perth and surrounding areas until 2050 (Water Corporation, 2009). For water source planning purposes the corporation assumed that by 2030 rainfall would reduce by 20 percent compared with a 1980 to 1999 baseline and by 40 percent compared with the baseline by 2060. Under these assumptions, runoff into metropolitan dams was estimated to reduce from 232 GL/year in the baseline period to 75 GL/year in 2030 and to 25 GL/year in 2060.

Details about specific regional and management plans are provided in Sections 3.4 and 3.5 respectively.

3.4 Regional water plans

There are four regional water plans that will eventually cover the project area: South West, Perth-Peel, Mid-West Gascoyne and Great Southern. The regional plans are shown with regard to existing surface water allocation plans in Figure 3-4 and with regard to groundwater allocation plans in Figure 3-5.

3.4.1 South West Regional Water Plan

Prior to developing the South West Regional Water Plan, DoW developed a number of background reports, including an overview of water policies (DoW, 2007d). At that time, the report indicated that surface water licences (including reservations) exceeded groundwater licences by 297 to 199 GL/year respectively. Actual water use may vary from these allocations so they are indicative only. Interestingly, 4.8 percent of surface water licences issued in excess of 500 ML/year accounted for over 85 percent of surface water allocations, and 1.8 percent of groundwater licences in excess of 500 ML/year accounted for over 78 percent of groundwater allocations. Small users (<5 ML/year) accounted for less than 5 and 2 percent of total allocations for surface water and groundwater respectively. Stock and domestic users (usually <1.5 ML/year) do not require a water licence in proclaimed areas and are thought to be numerous but account for only a small proportion of total water use.

The South West Regional Water Plan, and a supporting detail report, was released for public comment in June 2008 (DoW, 2008a; b). The plan's purpose was to:

- assess the current state of water resource management in the South West region
- identify regional trends and factors that influence water management in the coming years
- assess current and future water availability and demand at a regional scale
- engage with the community on regional water management priorities
- communicate state government priorities for water resource management
- set a vision for water policy, planning and management in the region
- determine priority actions to support water policy and plan implementation and improved water resource management in the South West region.

This project has similar aims to the third dot point, the assessment of current and future water availability and demand at a regional scale.

Of 20 priority issues identified at a South West Regional Forum, quantifying the impact of climate change on water was ranked second (behind recycling and reuse). Scientific support for sustainable yields and allocation limits was third, impacts of plantations was fifth, future availability of surface water was ninth, and future availability of groundwater was tenth (DoW, 2008d). All of these issues are addressed in this project.

Management principles developed for the South West region included:

- the inclusion of potential effects of climate change and associated uncertainties in all water allocation plans
- the availability of naturally occurring water resources recognised as a potentially limiting factor in land use planning and economic development, and given appropriate and early consideration in planning processes.

The South West Regional Water Plan identified climate change as having the potential to dramatically decrease water availability, reduce water quality, decrease groundwater levels and increase the demand for water. The plan considered a likely scenario to be a median winter rainfall decline in the South West region of 2 to 20 percent by 2030 relative to the standard 1960 to 1990 climate period used by the Bureau of Meteorology. This could result in a 5 to 40 percent decrease in runoff relative to 1990 based on a two- to three-fold decrease in runoff relative to rainfall reductions.

The 1960 to 1990 standard climate period straddles the recorded climate changes in 1975 in south-west Western Australia (SWWA) and is therefore not ideal for planning purposes.

The plan adopted the post-1975 period as the primary period of record applying to water planning and modelling with the following adjustments:

- 2005 to 2010 – adopt the 1975 to 2003 period of rainfall with risk factors stated
- 2010 to 2020 – decrease the standard period average winter rainfall by 5 to 8 percent
- 2020 to 2030 – decrease the standard period average winter rainfall by 8 to 11 percent.

Surface water flows have declined as a result of drier years (especially 2001, 2002 and 2004) and growth in both the number and storage capacity of on-stream dams, especially in the Busselton Coast River Basin and the Warren River Basin (DoW, 2008d).

Groundwater levels in the unconfined and confined aquifers have declined in many areas as a result of lower rainfalls with steeper declines in areas of heavy abstraction (DoW, 2008d). The declines detailed in the plan, however, are generally much less than those reported for the Perth-Peel region.

Two emerging issues were reported in the South West Regional Water Plan: water interception by trees and acid sulphate soils.

- In the ‘low’ rainfall zone (<900 mm/year), trees help reduce stream salinity by keeping groundwater levels low and help prevent saline groundwater from discharging into streamlines. Therefore, plantations provide environmental benefits in the upper Collie and Warren catchments. In ‘high’ rainfall zones (>1100 mm/year), plantation forestry reduce inflows of fresh water into streamflows and therefore reduce water yields. The intermediate rainfall zone (900 to 1100 mm/year) is a zone of transition. Lower rainfalls have resulted in reduced runoff in these zones and therefore the risk of salinity is now much lower but the yield of these catchment areas is also lower.
- There is currently no legal regulation of water interception by commercial plantations and other land use changes in Western Australia. The two main types of tree plantations in the South West region are softwoods such as *Pinus radiata* which are grown in 25- to 35-year rotations and Tasmanian Blue Gums (*Eucalyptus globulus*) which are grown in 8- to 10-year rotations with a likelihood of other one or two coppice rotations. The total area reported in the South West region by the Forest Industry Federation of Western Australia was 55,000 ha in 2007 (DoW, 2008d). As about 50,000 ha of the plantation area was established before the mid-1990s the effect of these trees has been included in the runoff monitoring record and calibration of surface water models used in this project and other studies. DoW (2008b) estimated the impact of the 55,000 ha of plantations was a reduction in runoff of about 80 GL/year or 17 percent of total surface water use in the region. Plantations compete with other water users in the western Scott Coastal Plain, Nannup and near Bridgetown but provide salinity mitigation benefits in the Collie, middle Blackwood and Warren catchments (DoW, 2008b).
- Acid sulphate soils are found on low lying parts of the Swan and Scott Coastal Plains in the South West region (DoW, 2008d). Lower groundwater levels caused by a drier climate, water abstraction or soil disturbance can initiate acid formation if these soils are exposed to the air. Maps of acid sulphate soil risk for the Swan Coastal Plain and for Albany–Torbay have been developed by DEC (2007). The risk of acid sulphate soils has been recognised relatively recently and is often unquantified. As a result, minimum groundwater levels to help ensure the soils do not dry out are yet to be included in groundwater allocation plans.

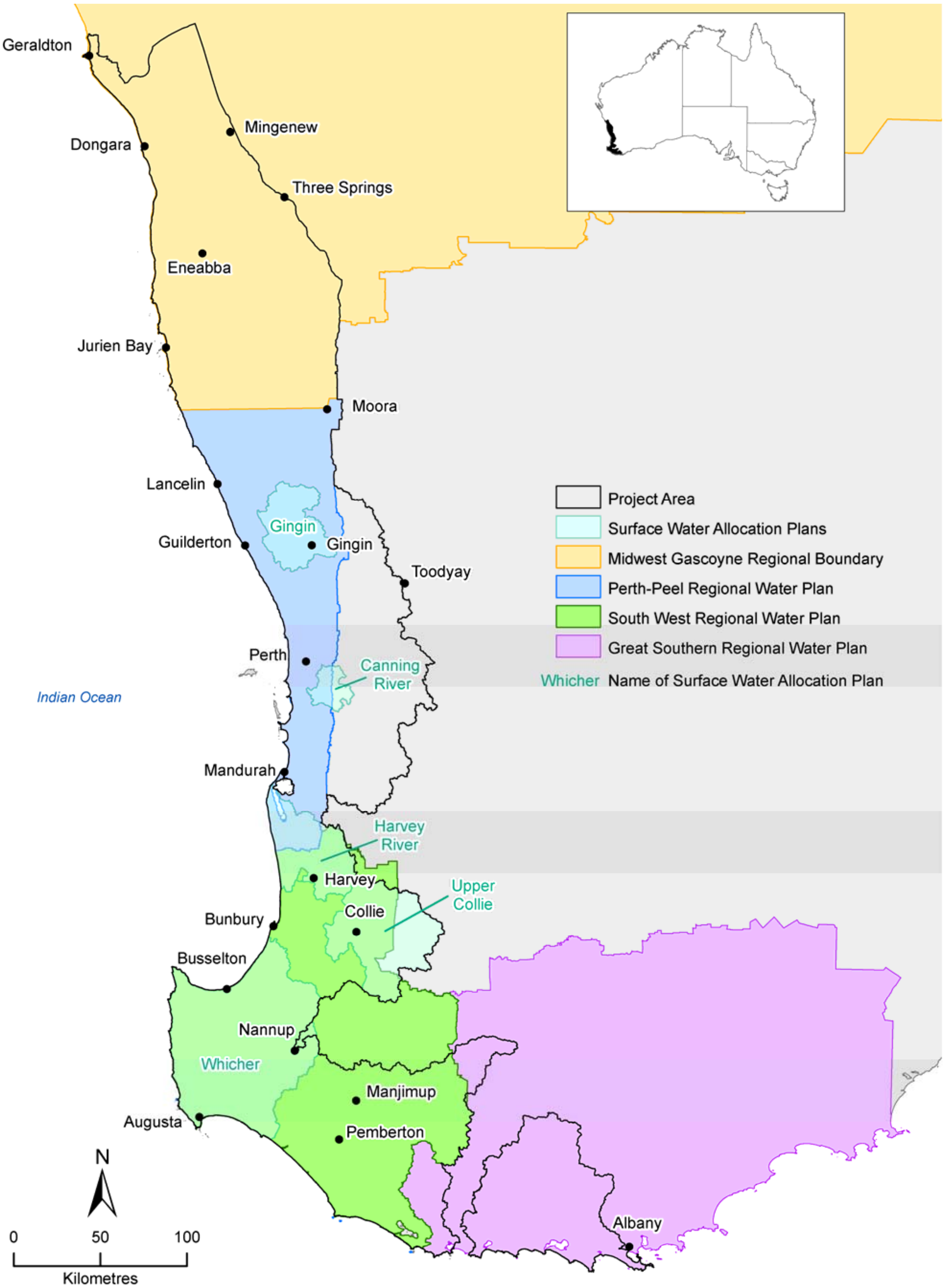


Figure 3-4. Location of regional water plans and surface water allocation plans in the project area

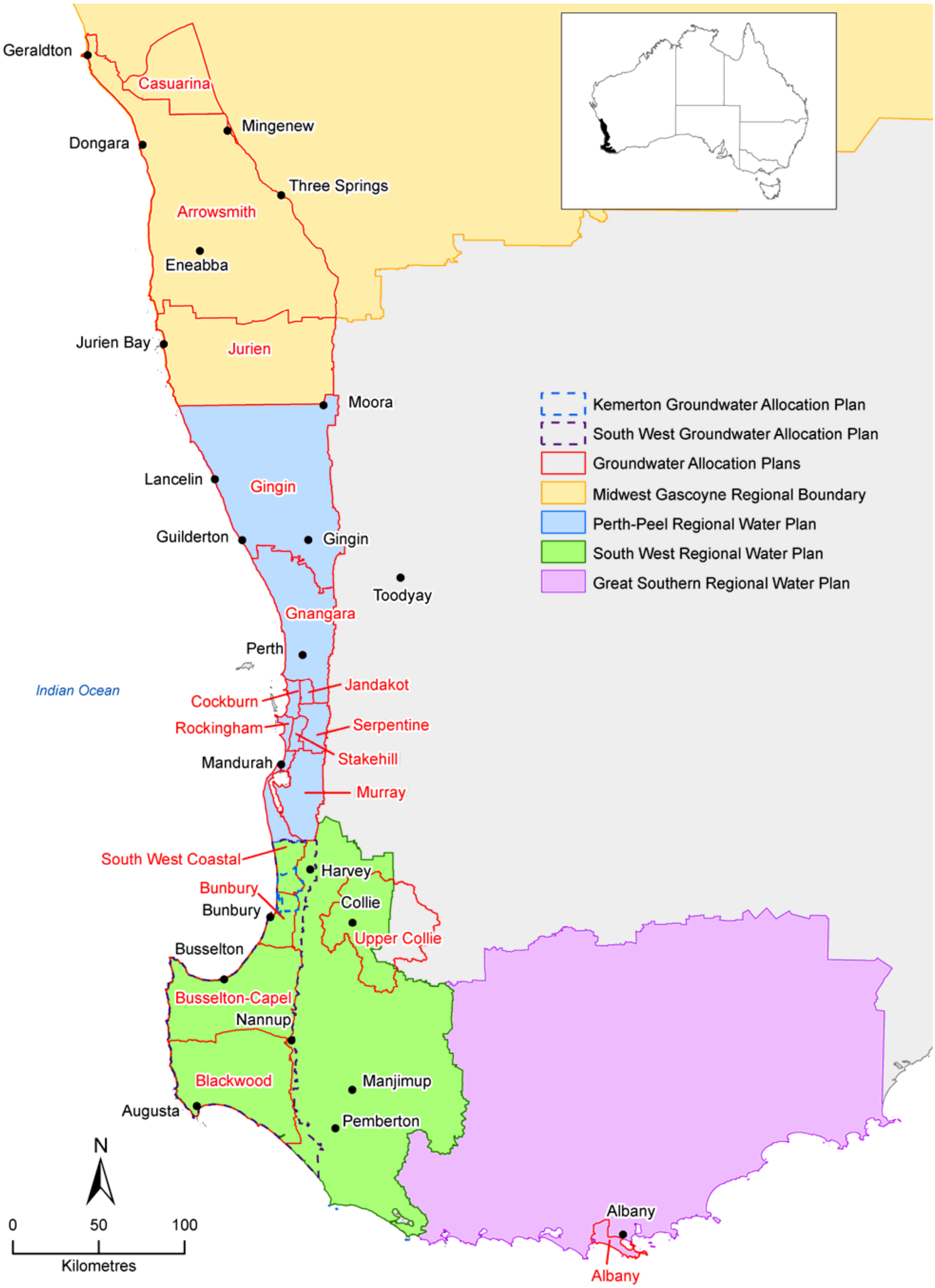


Figure 3-5. Location of regional water plans and groundwater allocation plans in the project area. The Upper Collie plan also includes surface water resources

An assessment of the degree of available surface waters was made in the South West Regional Water Plan (DoW, 2008c). Medium (30 to 70 percent of available water in use) and high (>70 percent in use) was estimated for the northern areas of Harvey, Collie, Preston and Capel. A mixture of low (<30 percent), medium and high water use was estimated for the southern areas of Busselton Coast, Lower Blackwood, Middle Blackwood, Donnelly, Warren and Shannon (Figure 12, DoW, 2008b).

The South West Regional Water Plan estimated that about 820 GL/year was available for use in the region, comprising 600 GL/year of surface water and 220 GL/year of groundwater. Assuming reduced rainfall by 2030 (see above), the available water was estimated to reduce to 610 GL/year, or a 26 percent reduction. This amount would be sufficient to meet estimated future demands if there were 20 percent efficiency gains and a moderate growth rate but would not be sufficient if higher growth and/or efficiency gains were not attained (DoW, 2008).

The method used to estimate water demand by DoW did not put restrictions on expansion due to a lack of available water for irrigation and other industries so these demand estimates are upper estimates. The method used in this project has enabled more detailed estimates of the effects of climate change on available water and placed restrictions on water demand growth where water becomes limiting between 2008 and 2030 (Chapter 7). The South West Regional Water Plan estimated that demand may exceed available water in the Preston subregion which covers the area between Harvey, Bunbury, Donnybrook and Collie by about 2020 while some available water would remain unused in both the Vasse and Blackwood demand regions in 2030. Demand in the Preston subregion was expected to derive from irrigated agriculture (Harvey Water), mining and industrial use in the Collie and Harvey shires, and town water supplies, especially in the Greater Bunbury area. The plan identified a need for further work to refine the demand and water availability estimates for this subregion especially (DoW 2008a).

3.4.2 Perth-Peel Regional Water Plan

The Perth-Peel Regional Water Plan will provide strategic direction for water management to 2030 in Western Australia's most water-challenged region. A draft plan is due for completion in mid to late 2009 and discussion papers have been developed (Beckwith Environmental Planning, 2009a, b). These comments relate to these draft documents and they may not be reflected in the final plan.

The Perth-Peel region has been divided into three sub-regions – Gingin, Perth and Peel – and approximates the water demand regions of Moore (southern part), Perth and Peel (Figure 2-3).

By 2030 the plan aims to ensure that all water dependent ecosystems are supported, waterways are healthier than in 2008, all resources are used within their sustainable limits, water use is efficient, alternative water sources are used where appropriate, planning occurs in an orderly fashion, water is recognised as a key driver for regional and urban planning, and the public has the information required to partner with government in planning.

Three possible future average rainfall regimes were considered relative to a 1980 to 1999 baseline: a 'wet' scenario (zero percent change in the baseline rainfall), 'median' (-8 percent), and 'dry' (-15 percent) to which +/– 10 percent in natural variability were added (Beckwith Environmental Planning, 2009a, b). This plan uses the same baseline as the Water Corporation's Water Forever Plan (Water Corporation, 2009) but has adopted a lower estimated rainfall reduction (8 and 15 percent versus 20 percent in the Water Forever Plan). However when natural variability is taken into account, the Water Forever Plan's 20 percent rainfall reduction is within the regional water plan's rainfall reduction range of 18 to -25 percent for the 'median' and 'dry' average rainfall scenarios in combination with dry sequence natural variability.

The Perth-Peel Regional Water Plan considers potable scheme water supplies and self-supplied water (often non-potable) separately, unlike the South West Regional Water Plan which considered all water resources together. Groundwater abstraction in the Perth-Peel region is estimated to fall from 830 GL/year currently to 700 and 580 GL/year under the median and dry scenarios (Beckwith Environmental Planning, 2009a, b). The surface water yield for the potable Integrated Water Supply Scheme (IWSS) is estimated to reduce from 105 GL/year (average since 2001) to 95 GL/year under the dry scenario. This compares with an estimate of 75 GL/year for the Water Forever Plan.

Under the various planning assumptions, the supply–demand balance for the IWSS in 2030 was estimated to range between a surplus of 45 GL/year to a deficit of 85 GL/year. Private demand would need to reduce by about 35 percent to meet availability in 2030 under the dry climate scenario (Beckwith Environmental Planning, 2009 a, b).

3.4.3 Mid-West Gascoyne Regional Water Plan

This plan will cover the coastal plain area north-west of Moora and extends north of the project area and is due to be completed in 2009/10.

3.4.4 Great Southern Regional Water Plan

This plan will cover the area between Walpole on the South Coast and extends north-east of the project area and is due to be completed in 2009/10.

3.5 Water allocation plans

There are many proclaimed surface water catchments in the project area which are covered by water allocation plans developed between 1989 and 2008, or have plans under development, as shown in Figure 3-4. There are also 22 proclaimed groundwater areas (GWAs) in the project area. All except Casuarina are covered by water allocation plans as shown in Figure 3-5. Recent water allocation plans have been for larger areas than was the case in the 1980s and 1990s and in some cases both surface water and groundwater resources are covered in the same plan (e.g. Upper Collie).

3.5.1 Harvey River Surface Water Allocation Plan

A Harvey Basin Surface Water Allocation Plan was released in 1998 (WRC, 1998). Surface water yields were based on analyses of rainfall and runoff for the 1948 to 1995 period although some estimates were also done for the 1975 to 1995 period due to concerns about reduced runoffs because of climate variability and change. The availability of this plan enabled new resources at Stirling and Wokalup to be quickly developed for public water supplies after very poor runoff into the Perth Metropolitan dams in 2001. This plan was completed in a period when climate change was first being taken as a serious factor in affecting water supplies.

3.5.2 Whicher Area Surface Water Allocation Plan

This plan covers the Capel River, Busselton Coast and Lower Blackwood surface water management areas (SWMAs) and receives stakeholder input from one of only two Water Resource Management Committees in Western Australia (DoW, 2008e). The plan sets allocation limits for all surface water management sub-areas in proclaimed and unproclaimed areas. Historical water use will be recognised and water licences issued to provide security in newly proclaimed areas (September 2007) in the Cape to Cape North, Cape to Cape South, Geographe Bay Rivers and Lower Blackwood surface water areas. Before this, only surface water resources in the Capel River, Margaret River and Tanjannerup Creek catchments had been proclaimed.

Volumetric allocation limits were set for each sub-area within the three SWMAs (DoW, 2008e). Water entitlements will be granted in proclaimed areas up to each limit subject to licensing application and assessment processes. In June 2008 of 52 sub-areas, 12 were fully allocated, 2 had limited available water and the remaining 38 had water available provided conditions were able to be met. Interactions with groundwater resources are considered in the plan.

3.5.3 South West Groundwater Areas Water Allocation Plan

The plan covers the South West Coastal, Bunbury, Busselton-Capel and Blackwood GWAs (DoW, 2008b). The latter two areas are covered by the South West Aquifer Modelling System (SWAMS) which is a groundwater model suitable to assess the impacts of climate change and abstraction on groundwater levels in all aquifers in these areas. The model estimated about 655 GL/year of gross recharge to the groundwater system for the period 1990 to 2003. To account for climate change between 2003 and 2030 about 620 GL/year of recharge was assumed.

As at February 2008 the Bunbury area had 25 percent of the allocation limit available for licensing in the Superficial Aquifer, 10 percent in the Leederville, less than 1 percent in the Yarragadee and 75 percent from the Cattamarra Coal Measures. The Busselton-Capel area had 20 percent of the allocation limit available in the Superficial Aquifer, 20 percent in the Leederville and less than 4 percent in the Yarragadee Aquifer. The Blackwood area had 85 percent of the allocation limit available in the Superficial Aquifer, 1 percent in the Leederville, 25 percent in the Yarragadee and less than 1 percent from the Lesueur Sandstone Aquifer. The South West Coastal area had 50 percent of the allocation limit available in the Superficial Aquifer, less than 1 percent in the Leederville and 100 percent from the Cattamarra Coal Measures.

While GWAs had available water, five of 45 sub-areas were designated as being over-allocated in the plan. The plan is expected to be revised and developed into a statutory plan once new water legislation is enacted. This area is covered by the South West Regional Water Plan.

3.5.4 Gnangara Groundwater Area Allocation Plan

A draft water allocation plan was issued in March 2008 for the Gnangara GWA located north of the Swan Estuary, east of Ellen Brook and south of Moore River – Gingin Brook (DoW, 2008a). About 60 percent of licensed allocation is from the Superficial Aquifer, 19 percent from the Leederville, 16 percent from the Yarragadee and 5 percent from the Mirrabooka Aquifer.

In the Superficial Aquifer there are 51 sub-areas, 27 of which had licensed allocations in excess of the allocation limit as at February 2008. A further 58 GL/year was estimated to be abstracted by unlicensed private bores in the management area. These are used for domestic garden watering and are not commercial. There are eight sub-areas in the Leederville Aquifer, seven of which had licensed allocations in excess of the allocation limit. Of the seven sub-areas in the Yarragadee Aquifer with allocation limits, five have licensed allocations in excess of the limit. These numbers indicate the degree of importance and stress that has been placed on the Gnangara Groundwater System aquifers as a result of rapid growth and climate change. In addition, land use decisions such as the location of dense pine plantations over aquifer recharge areas has exacerbated the fall in groundwater levels and confined aquifer pressures in some areas. The plan is expected to be revised and developed into a statutory plan once new water legislation is enacted. This area is covered by the Perth-Peel Regional Water Plan.

The Gnangara Sustainability Strategy has been developed to address the land use and management issues so that recharge and discharge are more in balance (DoW, 2008b).

3.5.5 Upper Collie Water Allocation Plan

This allocation plan covers both surface water and groundwater resources, a reflection of the important interactions that occur between these two resource types within this basin. Although there were only 32 licences to take surface water, all resources were identified as approaching full allocation with the exception of some marginal to brackish surface water (DoW, 2007e). The surface waters covered by the plan include the Collie, Harris and Bingham rivers and the groundwater is contained in the Collie Coal Basin.

Dewatering for coal mining is a reason why most aquifers are heavily over-allocated compared with their long-term recharge rates. Some of this water is used for electricity generation in coal-fired power stations. The main determinant of the allocation limits is the need to support riverine pools. However the longer sulphide material is exposed in the open cut mines, the greater the acidity of the groundwater when groundwater levels recover.

Provision was made in the plan for an update to be triggered if rainfall were to reduce by more than 15 percent compared with the periods used in its compilation, namely 1975 to 2003.

The plan is expected to be revised and developed into a statutory plan once new water legislation is enacted. This area is covered by the South West Regional Water Plan.

3.5.6 Gingin Groundwater Area Allocation Plan

An interim sub-regional allocation strategy was developed for the Gingin GWA in October 2002 (WRC, 2002b) to update a 1993 management plan. At the time the groundwater resources were either fully allocated or approaching full allocation as a result of rapid development of horticulture in the area.

In the strategy an allocation limit was defined as the lower limit of the uncertainty in the sustainable yield of an aquifer. Allocation limits in the area were calculated from estimates of annual rainfall, the recharge area and a percentage of rainfall that was likely to become recharge based on land use.

A major effect of the plan was to increase the allocation limit for Sub-area 4 for the Leederville Parmelia aquifers from 6.3 to 11 GL/year. About 72.5 GL/year was reserved for future public water supplies. Climate change was not taken into account in setting the allocation limits.

3.5.7 Jurien Groundwater Area Allocation Plan

When this plan was developed in 2002 adjustments to allocation limits to account for climate change were deemed unnecessary but there was a statement about the possibility of limits being adjusted in future (WRC, 2002b). A review of recharge into the Leederville-Parmelia Aquifer in the Dinner Hill sub-area found that recharge estimates had been too high previously. Coastal recharge was also reduced because of upward gradients in the aquifers. About 20.3 GL/year was reserved for future public water supplies.

3.5.8 Arrowsmith Groundwater Area Allocation Plan

An interim sub-regional allocation strategy was developed for the Arrowsmith GWA in January 2002 (WRC, 2002a). Allocation limits were reduced for the Yarragadee Aquifer in the Allanooka sub-area and in coastal areas with upward gradients. The Casuarina sub-area north of Arrowsmith was proposed as a result of this plan. It was considered that climate change may pose a future risk to water supplies but it was not taken into account in setting allocation limits in this plan.

3.5.9 Kemerton Groundwater Sub-areas Allocation Plan

This plan covers the area around Kemerton Industrial Park (KIP) north-north-east of Bunbury. Four sub-areas were defined for the Superficial Aquifer: Australind and KIP South (in the Bunbury GWA), and KIP North, Myalup and Wellesley in the South West Coastal GWA (DoW, 2007b). Two sub-areas were defined for confined aquifers: Kemerton South and Kemerton North. In late 2007 there was water available in almost all sub-areas. Allocation limits were estimated for several sub-areas using estimates of recharge using rainfall records between 1970 and 1999. It was recognised that allocation limits may need to be changed to reflect future climate conditions.

3.5.10 Cockburn Groundwater Area Allocation Plan

This 2002 revision of a 1993 plan found that declining groundwater levels were common in the area and availability for additional abstraction of groundwater was limited (DoW, 2007a). No further allocations were recommended from the Leederville and Yarragadee aquifers because of falling piezometric heads. Climate change was not considered in any estimates of water availability in the report.

3.5.11 Rockingham Groundwater Area Allocation Plan

This plan indicated that licensed abstraction had reached the sustainable level of allocation in the Leederville Aquifer and water was available in the Superficial - Rockingham Sand Aquifer from only two sub-areas (DoW, 2007c). Water levels in eight wetlands have declined in recent years to below their staff gauge in most cases making an estimate of trends difficult. Tree deaths were reported to be more concentrated in areas of groundwater abstraction. Climate change was considered when setting allocation limits for groundwater sub-areas by using only rainfalls from 1975 to 2003 in PRAMS groundwater modelling. Wetlands, GDEs, saltwater intrusion and acid sulphate soils were all considered under environmental protection.

3.6 Contemporary water planning and management

3.6.1 Water allocation planning

Allocation plans are developed by the DoW and outline how groundwater and surface water is allocated and managed. Allocation planning involves deciding what water can be taken for consumptive use while leaving an adequate water regime in the environment to meet in situ ecological, and recreational or cultural needs. The aim of the planning is to manage water use within the renewable capacity of the resource over an appropriate time frame. Through defining objectives for the water resource and for management, allocation plans set the direction for water resource management in an area. This may vary for different areas.

Under current legislation in Western Australia, the licence is the key regulatory instrument. Each licence defines an annual right to take water (an individual annual entitlement or allocation) and sets conditions that apply to the allocation. Allocation plans set the DoW's approach to managing allocations on a geographical or collective scale, and set the framework for the licensing of individual allocations in the plan area.

The focus of the planning process is the management decisions on the volume or regime (location, rate, timing) of water to be allocated for consumptive use. The management decision is risk based and depends on a number of factors; mainly confidence in the information supporting the sustainable level of extraction, and the capacity to monitor and manage the consequences of this level of extraction. Where the level of confidence in supporting information is high and the capacity to manage consequences is also high, a higher allocation is possible. Where the level of confidence in supporting information is low a more conservative allocation limit is set.

Prioritising allocation planning

The DoW is aiming to have up-to-date allocation plans for all proclaimed areas in Western Australia. Planning priorities depend upon the pressure on the resource and on other obligations. The diminishing gap between supply and demand in a drying climate and the consequent need for a higher level of management is the main driver for developing a water management plan. Policy priorities, government obligations, stakeholder commitments, and rapid changes in demand or climate projections also influence planning priorities.

Types of allocation plans

Plans are generally of two types. Where quickly updating management settings is the priority, existing information, including changes to recharge and runoff is used to reset allocation limits. These risk based limits combined with plan-specific management rules provide a broad level of resource protection and higher security for water users. Where water use is relatively low or isolated, regular updates to allocation limits and management through individual water licences is the main method used.

A higher level of precision is needed where water use is near the renewable limits of the resource. Specific, newly commissioned information is used to decide a water regime to meet in situ needs, while optimising water available for consumptive use. This needs a higher level of management and monitoring. Management may include extraction rules that vary with location or timing, recovery mechanisms if allocation limits are reduced below the current take, and an emphasis on efficiency, trading, fit for purpose use and alternative sources. After new water legislation is introduced it is envisaged that other mechanisms will be used to effect management of water resources. A high level of management needs to be complemented by effective monitoring. Monitoring against impact thresholds, with management responses to prevent impact beyond the resource objective is essential to optimise water available for consumptive use.

3.6.2 The planning and management approach

To set the level of extraction (or allocation limit) planners draw on information about the water resource and information about water use. Where information is limited, planning makes use of the best available information rather than delaying management decisions.

Hydrological work informs how much water can be taken, relative to current take, without compromising the renewability of the resource. Maintaining the renewability or productive base of the water resource in turn means maintaining the ecology of the system, whether for biodiversity outcomes or to maintain ecosystem services. Ecological work may be used to refine the sustainable yield, within a confidence interval and relative to a timeframe or a benchmark. In some cases, sophisticated modelling of various abstraction scenarios against resource constraints is used to support decisions. In others, it is a series of risk based steps from hydrology through to the allocation decision.

The allocation decision also depends on the level of risk. There is a management step to the decision making that takes into account the level of uncertainty associated with the sustainable yield, and the consequences of exceeding this.

Setting up the management approach through specifying licensing policies and monitoring requirements underpins the implementation of water allocation plans. Licensing policy includes establishing conditions to apply to licences in the plan area and enables the impact of individual extractions to be effectively managed. Monitoring of use, and the response of the resource to that use, is required to adapt and respond effectively to change (including climate change) over time.

3.7 Discussion

Pressure on resources has required the progressive investigation, proclamation, licensing and planning of surface water and groundwater resources in south-west Western Australia (SWWA). Volumetric allocation limits were initially set conservatively with an opportunity to assess the resources' response to abstraction before more accurate limits were set in subsequent plans on the assumption that each revision would take the limits closer to the long-term sustainable yield. Climate change, and to a lesser degree farm dams and plantations, has reduced the sustainable yield of all resources so adopting a conservative approach to allocation has probably avoided major over-allocation problems in SWWA. In addition, water that has been licensed but never used, or is no longer required, may be reclaimed when a licence come up for renewal to reduce the possibility of over-allocation.

Where necessary, allocation limits are reduced through current plans – essentially capping the allocation. Recovery is initiated through the licence renewal process. The limits may also be adjusted through seasonal allocation announcements.

Early water allocation plans were for individual management areas and for either surface water or groundwater. More recent plans have combined geographical management areas, often consider surface water and groundwater together and increasingly account for climate change. These plans will progressively be included under non-statutory regional water plans that provide a broader and longer term context for allocation decisions. Each regional and allocation plan includes more aspects than the previous one so there is an evolutionary nature to them. All plans need to take account of the National Water Initiative and the requirement that, in some areas, volumetric licences will be eventually replaced by shares in a defined consumptive pool.

Climate change provisions in the plans are either non-quantitative or based on assumptions about rainfall, runoff and/or recharge reductions compared to a baseline period or time. Currently the baselines and estimated reductions are not always consistent between plans and with studies such as the Gnangara Sustainability Strategy and Water Forever Plan (Water Corporation, 2009). It is hoped that this project may provide a more rigorous basis for making provision for climate change and development impacts on future water yields in regional water plans.

The main limitation to water abstraction in the water allocation plans is the environment which depends on water regimes for their existence. If the climate in SWWA continues to get warmer and drier as predicted by the Indian Ocean Climate Initiative studies (Bates et al., 2008) then these environmental values may be lost or certainly changed as is currently occurring on Gnangara Mound. Constraints to abstraction may therefore become acid sulphate soil formation, saltwater intrusion and/or the cost of diverting or abstracting water from rivers and aquifers. These changes, in addition to the transition from volumetric to capacity share amounts of the resource and make it particularly difficult to estimate how allocation limits as defined in water plans may change between 2008 and 2030. The limits are based on Environmental

Water Provisions which take account of social, economic, cultural and environmental values and are therefore not able to be estimated by calculations of future water yields and environmental impacts themselves.

The hydrological estimates could be very useful, however, in setting priorities for management intervention by anticipating gaps between future levels of resource allocation relative to yields and management response. Chapter 7 develops and applies a framework for comparing the gap between future water yields and likely demands under scenarios A, B and C.

3.8 References

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4 Surface water dependent ecosystems

This chapter extends the results of the surface water modelling (CSIRO, 2009), which is summarised in Section 2.9.1, to a broad regional assessment of the impact of climate on environmentally significant flow characteristics as identified by previous research in the region. The conclusions are valid within the limitation of the surface water models and within boundaries of their assumptions, limitations and uncertainties. These limitations are described in Sections 4.6 and 4.7. In addition the chapter describes how the environmental flow needs are being considered by the Department of Water Western Australia (DoW) when developing limits for small self-supply diversions across the region.

4.1 Key findings

- About 83 percent of surface water resources are generated during the winterfill period from 15 June to 15 October.
- Relative to the historical climate (Scenario A), winter runoff across the project area may decrease by between 5 and 20 percent under Scenario Cwet, by 20 to 30 percent under Scenario Cmid, and by 40 to 50 percent under Scenario Cdry.
- The future climate is likely to affect runoff between 15 October and 15 June when river flows are particularly important for in-river ecosystems. The reduction in runoff during this summer period is 4 to 7 percent greater than during winter.
- The greatest effect of future climate on runoff occurs in the upper parts of the Kent and Denmark basins and in the Gingin basin. For instance, the reduction in runoff under Scenario Cmid is 40 to 65 percent relative to Scenario A, while it is between 20 and 30 percent in other rivers.
- Using the regional method for estimating limits on small-scale diversions by self-supply users (sustainable diversion limits), it was determined that the amount of water to be maintained for the environment is about 85 percent of runoff over the winterfill period.
- Under Scenario C perennial rivers remain perennial but with smaller flows.
- In nine reaches of six rivers, the Department of Water Western Australia (DoW) has defined the daily river flow rates which are significant for specified ecological river functions. The frequencies that these flow thresholds are met reduce under scenarios Cmid and Cdry.
- The frequency and duration of high flow events may be most affected under scenarios Cmid and Cdry. Those elements of river ecosystems which are influenced by high flow may be most affected by climate change.

4.2 Ecological water requirements and environmental water provisions for surface water systems

4.2.1 Classification of surface water dependent ecosystems

Surface water dependent ecosystems are ecosystems that rely predominantly on rainfall and surface water flows to maintain all or important components of their ecological function, composition or structure.

Although there are many types of surface water dependent ecosystems in Western Australia, they can be loosely grouped into two categories:

- near stream terrestrial ecosystems (including vegetation and faunal communities)
- aquatic ecosystems (river and wetland).

Each category can be further sub-divided into the individual ecosystem components that are dependent on surface water; for example aquatic macroinvertebrates, fish and amphibians in wetlands and rivers or the bird, mammal and reptile communities dependent on terrestrial habitats that depend on surface water.

4.2.2 Surface water ecological water requirements

Under the environmental water provisions (EWPs) policy for Western Australia 2000 (WRC, 2000), ecological water requirements (EWRs) are based on the best available scientific information (literature reviews, expert panel opinions and – where possible – direct investigations in the field) as well as on local knowledge (Gardner and Chung, 2005). An ecological water requirement is known as the water regime required for maintenance of the ecological values of a river, and is a consideration in the determination of environmental water provisions.

The stresses on aquatic ecosystems caused by changes in the flow regimes of rivers (magnitude, frequency and duration of events) as a result of climate change can be assessed using key ecological flow thresholds. As illustration Figure 4-1 shows the example of ecologically significant flow rates in a river (Cottingham et al., 2003, Donohue et al., 2009d). Changes in the frequency and duration of these flows can potentially affect the availability and quality of habitat (such as pools and riffles) and process such as fish lifecycle requirements, nutrient cycling sources and channel morphology. The individual ecosystem components of a surface water dependent ecosystem and their dependency on a surface water regime are described in the following sections.

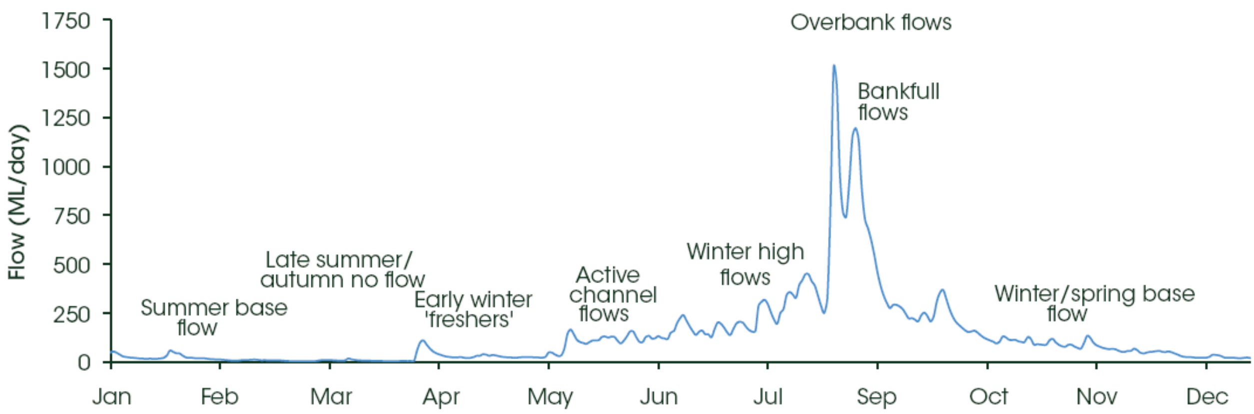

Figure 4-1. Representative hydrograph with different flow components labelled (after Cottingham et al. (2003) as adopted by Donohue et al. (2009d))

Investigations into EWRs are used to estimate the ecologically sustainable yields of water resources and to help set limits on consumptive allocations that ensure the maintenance of the existing ecosystems; maintenance of the ecological values that have evolved as a result of water resource development, or restoration of lost ecological values in ecosystems. EWR studies consider rivers' biodiversity, food-web interdependencies, ecosystem processes and the water-dependent ecological processes that support these food webs (Donohue et al., 2009d). As a result the established EWRs are consistent with the natural water regime and the understanding that the observed ecological status of a river is a direct result of the ecosystem evolution in response to the natural flow regimes that exist within the river (Poff et al., 1997; Donohue et al., 2009d). The defined series of ecological flow thresholds or events that perform specific ecological functions are used to construct an environmental flow that will maintain these functions.

4.2.3 Surface water environmental water provisions

EWPs are usually built on understanding water regimes that need to be met both temporally and spatially (DEWHA, 2008). In Western Australia EWPs are usually established at sub-regional and local water management levels. The

Environmental Water Provisions Policy for Western Australia (WRC, 2000) outlines a framework by which water is retained for protecting a number of values while meeting multiple benefits.

An EWP can be based on EWRs as a consideration in the decision-making process. However it also accounts for social, economic and cultural values associated with the water resource (WRC, 2000; Eamus and Froend, 2006). It is desirable that an EWP equals the EWR (Eamus and Froend, 2006). Under the state policy, the key ecological values of the ecosystem must be retained (WRC, 2000).

4.3 Surface water management approach in Western Australia

The sustainable yield of a water resource is the amount of water that can be reliably harvested each year while enough water remains to meet environmental needs. This section outlines the methods used in Western Australia to estimate environmental flow requirements and the amount of water that can be diverted from a river for water supply purposes. Two methods, currently used and being evaluated by the DoW, are:

- in situ investigations of the river ecological functions and their dependency on the river flow regime to establish EWRs for selected river reaches (Donohue, 2009a, b; Donohue et al., 2009a, b, c, d) in excess of which surface water can be harvested with low risks to surface water dependent ecosystems
- assessment of sustainable diversion limits (SDLs) (Jordan et al., 2009; Lang, 2008), as estimates of acceptable limits on the direct pumping of water from streams during winter flow periods, assuming no addition of on-stream storage is provided. The approach is relevant to areas where diversions are a small portion of the average flow and distributed throughout the catchment, and more comprehensive studies are unwarranted. It is based on assessing ecologically acceptable minimum flows and maximum daily diversion rates during the winter flow period. The approach has only been used by DoW to define initial allocation limits in low use sub-areas of the Whicher Surface Water Management Area (DoW, 2008); located in the Vasse demand region (Figure 2-3).

These methods are described below.

4.3.1 In situ investigations of flow regions for ecological water requirements

DoW is currently undertaking an investigation into EWRs in the project area, mainly in the south-west between the Busselton Coast and the lower Blackwood groundwater areas (Table 4-1). The approach is based on establishing flow thresholds that achieve the following ecological functions: water depths and velocities that maintain pool water quality, fish migration, inundation of fish breeding habitat, and flows needed to scour the channel of sediment and maintain a diversity of habitat (Table 4-1) (Donohue et al., 2009d).

High winter flow is particularly important for riparian vegetation, fish migration and carbon sources in the river environment. During this flow period riparian vegetation on river banks and benches are inundated. This prevents incursion of riparian vegetation and also supplies organic matter to the river. Detritus and leaf litter can be deposited directly into the channel during inundation, which are redistributed during high flows along the river channel and may be deposited in river pools for use by the ecosystem during summer.

High flows also affects the river channel morphology by reducing sedimentation, maintaining channel structure and scouring river pools. High flows can also scour solid surfaces, thus reducing algal build-up. High flows can facilitate upstream migrations by inundating or removing barriers to migration. Reductions in the frequency and duration of high flow events will result in less frequent scouring of pools, change channel morphology and may allow vegetation to encroach into the river channel. However, these changes are not expected to greatly alter river ecological processes, although changes in the frequency of occurrence of some processes may be expected.

Winter low flow levels are important for fish and macroinvertebrates communities. Trailing vegetation inundated by 10 cm of water provides a spawning habitat for fish, and water depths of more than 10 cm throughout the reach allows upstream fish migration. The habitat of macroinvertebrates is dependent on riffles inundated to a depth of at least 5 cm over the entire channel width. Therefore reductions in winter baseflow may affect both fish migration regimes and macroinvertebrates habitats.

Surface water dependent ecosystems are particularly sensitive to variations in summer low flows (summer baseflow). Summer baseflow can maintain the depth and quality of pools and provide summer refuges for fauna such as fish, crayfish and other invertebrates, and habitat for tortoises and frogs (Penn, 1999). Pools with a minimum water depth of less than one metre are unlikely to support water rats. Riffles inundated to a depth of at least 5 cm over 50 percent of the stream width provide habitat for macroinvertebrates during summer months.

Reductions in summer inflow to these pools results in increased water temperature and decreased dissolved oxygen levels. The loss of connectivity between pools can also affect downstream movement of nutrients such as carbon.

EWR analyses can be presented as flow duration curves with reference to the significance of specified flow rates for various ecological functions of the river (Table 4-1).

In order to define ecologically significant river flow thresholds, a site-specific investigation is required within an individual river reach, and as such the established EWRs are ‘reach-specific’. The flow thresholds may vary between reaches within the same river (Table 4-1). Determining an EWR regime by this method is resource intensive. However regionalisation of the individual results from a number of river reaches across the south-west region is being investigated by DoW. The method characterises a river’s ecological function in terms of its daily flow regime. Given satisfactory regionalisation, EWR regimes can be estimated from daily flows in unregulated rivers. The surface water available for diversion is the amount in excess of this EWR regime. The method has the limitation of producing a daily variable diversion regime, albeit ecologically acceptable. Another limitation is that it requires real time measurements of river discharge to estimate the diversion limit on any given day.

Though the described above approach was used to define the thresholds for specific and environmental significant flow rates, there is a need to develop a framework for assessing ecological risks associated with changes in the frequency of exceedance for flow rates. This framework currently does not exist, but it is known that ecological communities are more sensitive to changes in low flows rather than high flow rates.

Table 4-1. River flows with specified ecological significance for nine river reaches

	Lefroy	Brunswick		Margaret		Cowaramup	Chapman	Wilyabrup	
Streamflow reporting node	60702	612032	61204	610001	61016	61006	609022	610006	61015
Catchment area (km^2)	92.1	509.4	235.9	443.0	359.3	21.5	180.0	82.3	43.6
Ecologically significant flows									
	ML/d								
Maintain pool habitat in summer	1						1	1	1
Minimum flow to maintain pool quality	6	2	2			2	6		9
Summer habitat for invertebrates	16	5	15	2	2	1	6		2
Upstream migration of small native fish	10	10	4	7	73	5	6	6	24
Winter habitat for invertebrates	60	10	120	7	6	4	9		61
Upstream migration of large native fish		22	28				38		
Inundate trailing vegetation	120						9	35	67
Inundate active channel	120	900	170	112	128	30	185	172	93
Inundate low elevation benches	320	31	177		45	4	9		30
Riparian vegetation							9		
Inundate medium elevation benches		350				10	100		
Inundate high elevation benches	1080	1400	530	270	340				
Inundate floodplain		1970	2200	960	778	280	460	968	363

Sources: Donohue, 2009a, b; Donohue et al., 2009a, b, c, d.

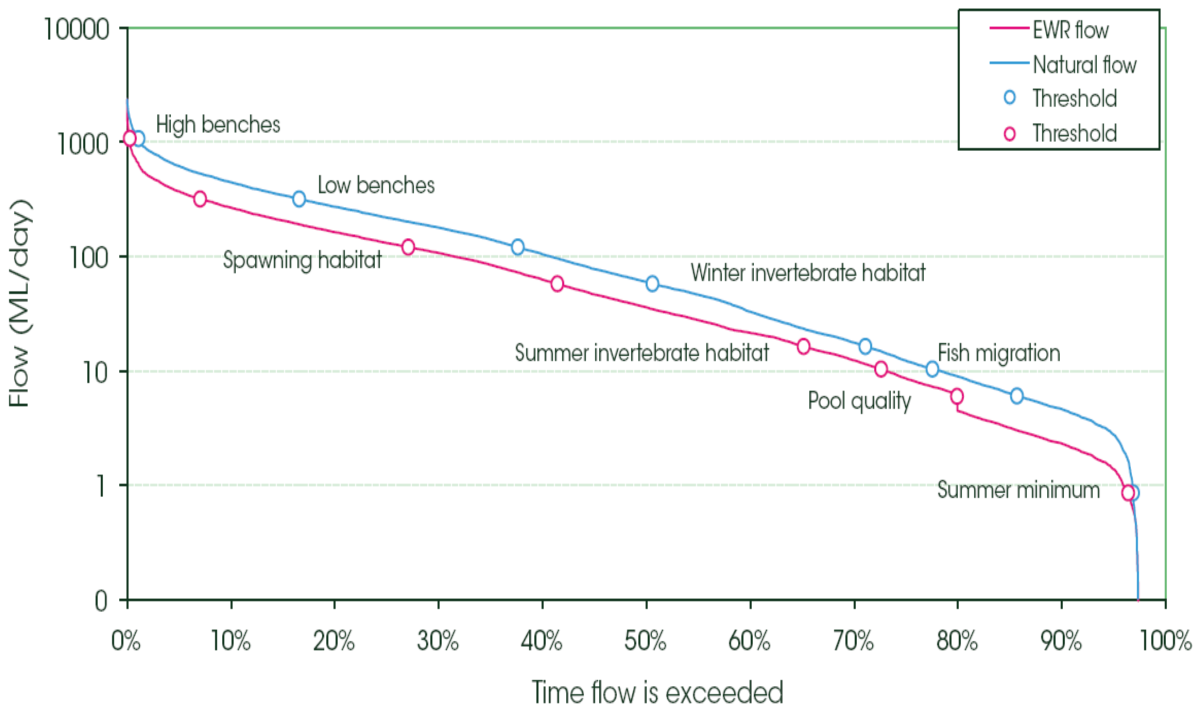

Figure 4-2. Daily flow duration curve for Lefroy Brook, observed flow versus modelled ecological water requirement flow (from Donohue et al., 2009d)

4.3.2 Sustainable diversion limits

The sustainable diversion limit method is used by the DoW as a means of providing initial estimates of surface water diversion limits in self supply areas where results from site specific studies are unavailable, and current water use is low. The approach was developed to provide initial allocation limits where allocation plans were not available and where planning and management is at an early stage (Jordan et al., 2009). It can be applied across a region if flows can be estimated at the outlet of all the small catchments within the region. However, they have only been used by DoW to define initial allocation limits in low use sub-areas of the Whicher Surface Water Management Area (DoW, 2008).

The method is based on calculating acceptable limits on the direct pumping of water from streams during winter flow periods based on ecological considerations, assuming no additional in-stream storage is established. The ecological assessment involves estimating a minimum flow to be retained, a maximum daily diversion rate during the winter flow period, and a winterfill period that excludes initial winter flows as described below. The diversion limits are usually expressed as an annual diversion limit for each small catchment.

The application of the methodology across south-west Western Australia (SWWA) was guided by DoW hydrologists with support of a consultant technical team from SKM, who developed the original methodology. In addition DoW and consultant ecologists advised on the selection of the minimum threshold, maximum diversion rates flows and winter fill period. The approach was initially applied at unregulated gauging stations throughout the south-west and regionalised to ungauged areas. The regional equations correlated flow parameters, with hydro-climatic and physiographic characteristics of the gauged catchments (Lang, 2008).

Three rules were used as a basis for SDL estimation taking into account the frequency and duration of spells above a range of thresholds, the magnitude and sequencing of selected flows, and the magnitude of frequent floods, all significant in terms of ecological sensitive flow rates. The rules are:

1. Winterfill period for extraction

This was the first consideration when setting the SDL rules and details the time period when extractions are allowed to occur. This is because the transition between a 'dry' and a 'wet' phase of a stream is considered to be of particular importance to the ecological systems within the river. The dry periods of a stream typically have lower flows and poorer water quality, placing considerable natural stress upon the river biota. If extractions were to occur during this period the additional stress could be beyond the capacity of the ecosystem. The first flows of the 'wet' period act as environmental cues for biota to perform various stages of their lifecycle, such as fish movement for breeding (Humphreys, 1989). In ephemeral streams these movements trigger invertebrate hatching and production (Boulton and Lake, 1992; Lang, 2008). The reverse movement from 'wet' to 'dry' is considered to be of equal ecological importance (Lang, 2008). Thus is it seen as being essential for ecosystem health to maintain the first and final high flows of the wetting and drying periods of the streams in SWWA. The project team chose the period from 15 June to 15 October inclusive as being a period within the wetter months that still allows the normal wetting and drying phases to occur.

2. Minimum flow threshold

The minimum flow threshold (MFT) is quantified as the maximum of 0.3 times the mean daily flow and the 95th exceedance percentile of the median winterfill period daily flow (i.e. diversions should cease once stream flows are less than either 0.3 of the mean daily flow or the 95th percentile of the median winterfill period for daily flow) (Lang, 2008). The objective of this rule is to maintain the mean daily natural flow and thus avoid extending the time the stream spends at zero or low flows. The effective consequence of the rule creates a target which the stream flow should not fall below. If it does, water will not be available for harvesting on every day of the winter fill period (Lang, 2008).

3. Maximum extraction rate

The maximum extraction rate (MER) is defined as the 25th exceedance percentile of the difference between the daily flow and the MFT for those days in the winterfill period when the MFT is exceeded (Lang, 2008). It means that the MER should be set so that a maximum of 25 percent of days that are above the MFT will flatline at the MFT amount under impacted conditions. Without this check the hydrograph would flatline at the MFT amount for long periods of time removing the high flow component and in turn reduce the interannual variability of flows. The MER limits the days spent at an artificial MFT and therefore limits the maximum extraction volume removed from the catchment in any one day. The MER is in effect a maximum extraction rate for an individual catchment for any single day within the winterfill period (Lang, 2008).

The SDL represents a maximum volume of water at 80 percent reliability (volumetric cap) that may be diverted in any single year without subjecting the environment to unacceptable levels of risk of damage occurring as a result (Lang, 2008). Once the extraction SDL has been reached by an individual diverter then they are no longer allowed to extract water from the resource.

SDLs vary from catchment to catchment but there was found to be a strong correlation between SDL and mean rainfall for the winterfill period; streams that received groundwater discharges were found to have a higher diversion potential than ephemeral streams receiving no groundwater and that only produce runoff in direct response to rainfall (Lang, 2008). In SWWA this approach allows more that 80 percent of the mean winterfill period flow to remain for the environment. If the above rules are applied when water diversion takes place then the hydrographs of the impacted streams remain within the bounds of the natural variability of the site (Lang, 2008).

This project used SDLs estimates and their associated assumptions to provide a consistent measure of the possible impacts of future climate scenarios on surface water environments across the region. However, they are not allocation limits endorsed by the DoW.

4.4 Indicators of changes and impacts on surface water ecosystems

The surface water dependent ecosystem indicators which were adopted to assess the effect of future climate on ecologically significant river flow rates and volumes were selected based on the available information on surface water regime characteristics and the significance of ecological river functions. The analyses varied for rivers where an EWR had been estimated and for rivers where data for sustainable diversion limits were available. More detailed ecological information would be required to undertake an ecological risk assessment which may be related to the impact of future climate on river hydrological regime.

For rivers where an environmental flow requirement was available (Table 4-1) the following data were additionally derived from the results of the surface water modelling:

- flow duration curves for future climate scenarios
- changes in the flow frequencies with the specified daily flow rates defined in Table 4-1 for future climate scenarios
- relevant change in the flow frequencies when compared with the flow frequencies under Scenario A.

Overall 33 sites were selected (Figure 4-3; Table 4-2) with the aims of:

- demonstrating the climate impacts on runoff during both the winterfill period and the rest of the year
- identifying the variation in sustainable diversion limits under future climate scenarios
- evaluating variations in environmental flow such as runoff into wetlands or in wild rivers at selected sites.

Sites were selected to cover the extent of surface water modelling in the project area, environmentally sensitive areas and rivers which contributed to environmental assets outside the modelled area (Figure 4-3).

The runoff from the catchment upstream from the evaluation sites was estimated based on the surface water modelling results over 33 years under each climate scenario. The results under scenarios B, Cwet, Cmid and Cdry were compared with Scenario A for the reporting period. The considered parameters included:

- median total runoff during the winterfill period between 15 June and 15 October, the time when most water resources are generated
- median total runoff between 15 October and 15 June (or ‘rest of the year’) which includes summer baseflow and early winter freshes and as such is considered to have high ecological value.

The non-extractable volumes (as a difference between median winterfill streamflow and SDL volumes) under Scenario A were calculated to provide a measure of environmental water at each evaluation site. The SDL values for other climate scenarios were obtained by applying the ’rules’ described in Section 4.3.1, assigning the same values of MFT, as minimum flow threshold, and MER, as maximum extraction rate, which were obtained under Scenario A, but using the surface runoff data from modelling under climate scenarios B, Cwet, Cmid and Cdry. Variations of the estimated SDLs under each climate scenario were established using this method, assuming they change proportionally to changes in runoff for each climate scenarios.

In addition, the impact of climate scenarios on the duration of the ’no-flow’ period was estimated in terms of annual average days with runoff less than 0.01 mm on a cell-by-cell basis across the project area.

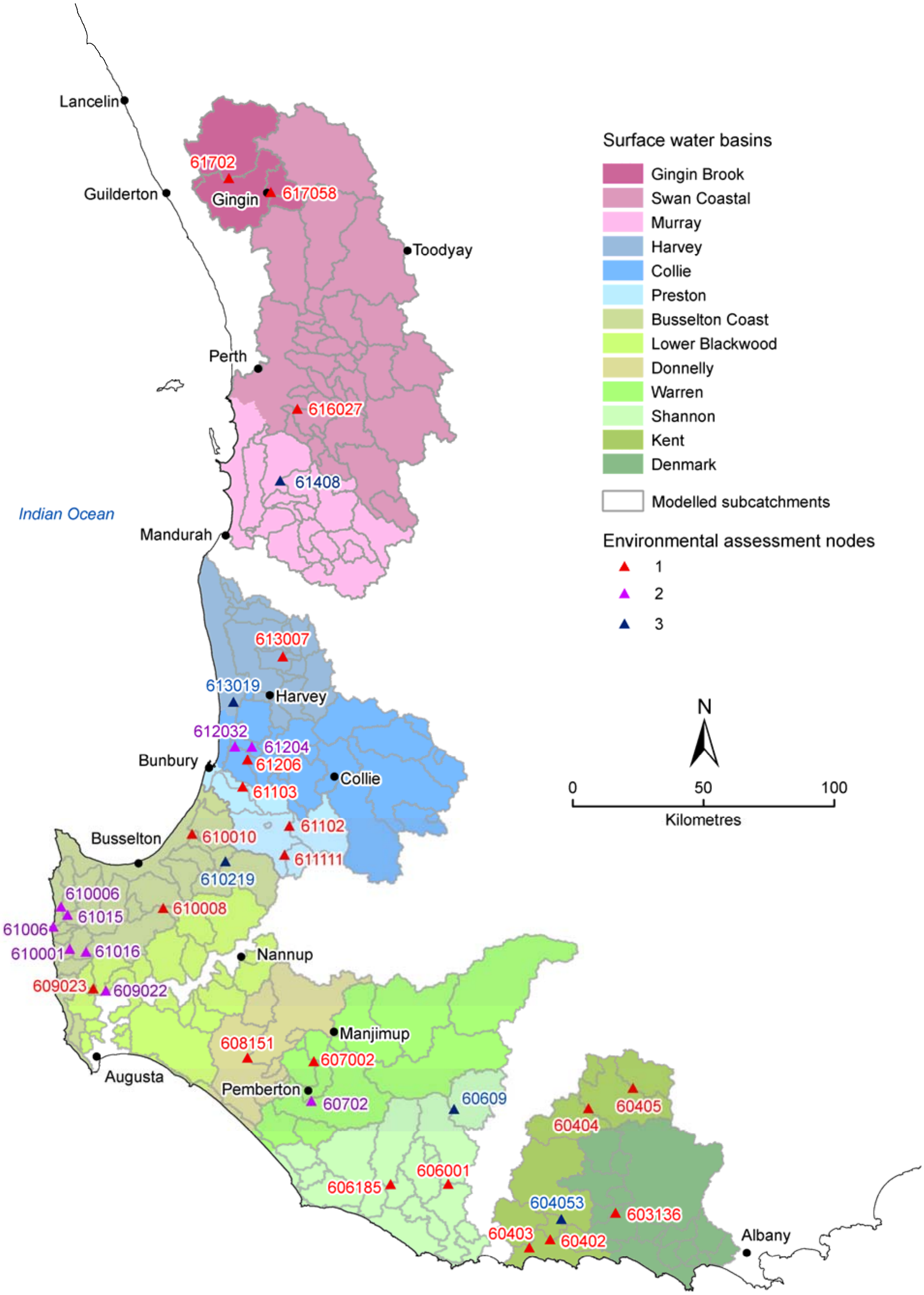

Figure 4-3. Location of surface water dependent ecosystem evaluation points: 1 – sites where sustainable diversion limit data were available; 2 – sites where sustainable diversion limit and ecological water requirement data were available; 3 – site of special interest where sustainable diversion limit and ecological water requirement data were not available

Table 4-2. Details of sites chosen for surface water dependent ecosystem analysis

DoW gauging station number	Additional modelled location	River catchment	Region	Catchment area
				km^2
617058		Gingin Brook	Gingin to Murray	105.8
	61702	Gingin Brook North	Gingin to Murray	710.6
616027		Canning River	Gingin to Murray	149.0
	61408	Serpentine River	Gingin to Murray	160.1
613019		Harvey	Harvey to Preston	272.3
613007		Bancell Brook	Harvey to Preston	13.6
612032		Brunswick River	Harvey to Preston	509.4
	61204	Brunswick River	Harvey to Preston	235.9
	61206	Collie River	Harvey to Preston	146.7
611111		Thomson Brook	Harvey to Preston	102.1
	61103	Ferguson River	Harvey to Preston	114.5
	61102	Preston River	Harvey to Preston	311.6
610010		Capel River	Harvey to Preston	394.7
610008		Margret River North	Busselton Coast to Denmark	15.5
	61016	Margaret River	Busselton Coast to Denmark	359.3
610001		Margaret River	Busselton Coast to Denmark	443.0
	61006	Cowaramup	Busselton Coast to Denmark	29.8
	61015	Wilyabrup Brook	Busselton Coast to Denmark	43.6
610006		Wilyabrup Brook	Busselton Coast to Denmark	82.3
609023		Chapman Brook	Busselton Coast to Denmark	45.2
609022		Chapman Brook	Busselton Coast to Denmark	180.0
608151		Donnelly River	Busselton Coast to Denmark	782.1
607002		Lefroy Brook	Busselton Coast to Denmark	92.1
	60702	Warren River	Busselton Coast to Denmark	345.9
606185		Shannon River	Busselton Coast to Denmark	407.6
606001		Deep River	Busselton Coast to Denmark	467.8
	60609	Lake Muir	Busselton Coast to Denmark	311.8
604053		Kent River	Busselton Coast to Denmark	1806.0
	60405	Kent River	Busselton Coast to Denmark	247.8
	60404	Kent River	Busselton Coast to Denmark	736.4
	60403	Kent River	Busselton Coast to Denmark	250.2
	60402	Kent River	Busselton Coast to Denmark	1868.3
603136		Denmark River	Busselton Coast to Denmark	502.4

4.5 Climate impacts on ecologically significant surface water flow regime

4.5.1 Ecological water requirement site and climate effect on river ecological thresholds

As mentioned above, daily flow thresholds in several rivers have been identified as being ecologically significant. Climate change effects on the frequency of exceedance of river flow thresholds (Appendix D) were illustrated by the following information:

- flow duration curves for all climate scenarios with the identified flow thresholds
- frequency of flow threshold occurrence under scenarios A, B, Cwet, Cmid and Cdry
- absolute changes in the frequency of daily flow threshold under scenarios A, B, Cwet, Cmid and Cdry relative to the frequency under Scenario A

- relative changes in the frequency of flow threshold under scenarios B, Cwet, Cmid and Cdry relative to the frequency under Scenario A.

Although the reduction in exceedance frequencies of the ecologically significant flow rates under future climate scenarios appears to be broadly uniform for the considered rivers, some variations were observed.

The effect of future climate on flow duration and the frequency of daily flow thresholds exceedance in the upper reaches of the Brunswick River (235.9 km^2) is illustrated in Figure 4-4, Figure 4-5 and Figure 4-6. For all climate scenarios the greater effect is related to the flow frequencies required for summer habitat for invertebrates (15 ML/day) and the upstream migration of large native fish (28 ML/day). The effect of the future climate on other identified thresholds is similar: 1 to 2 percent under Scenario Cwet and Scenario B, 4 to 5 percent under Scenario Cmid and 8 to 9 percent under Scenario Cdry. Frequencies of river flow which allow the minimum flow to maintain pool quality (1 ML/day) and to inundate floodplain (2200 ML/day) are not affected by the climate scenarios according to the surface water modelling results.

When the effect of the climate on ecological flow thresholds is considered for two reaches of Brunswick River, it appears that the climate impact on frequency of ecological flow threshold appears to be greatest in the upper river reach (Appendix D).

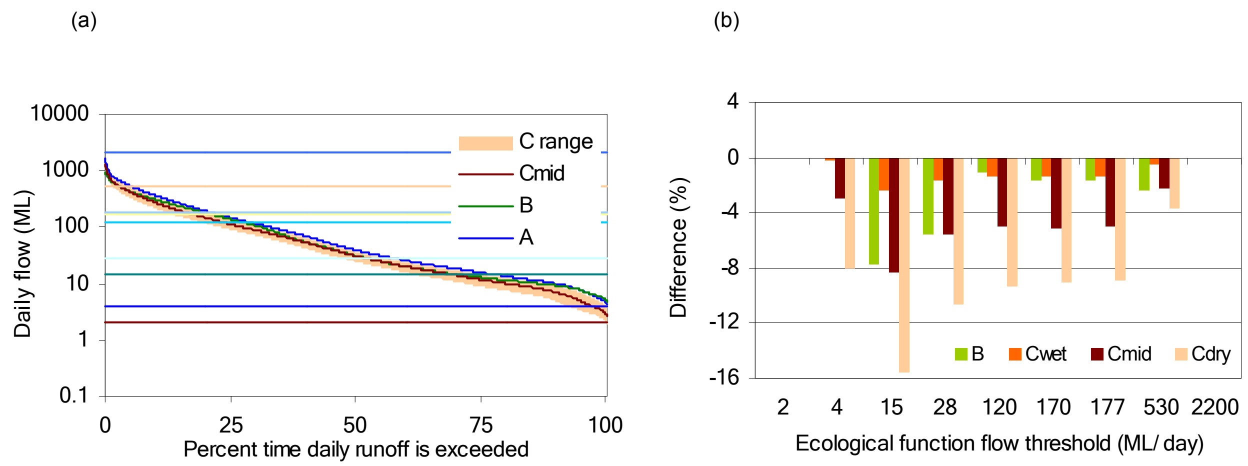

Figure 4-4. Flow duration curves under scenarios A, B and C, the ecological flow thresholds for Brunswick River (SRN 61204 in Table 4-1) and the change in the identified flow frequency under scenarios B, Cwet, Cmid and Cdry relative to scenario A

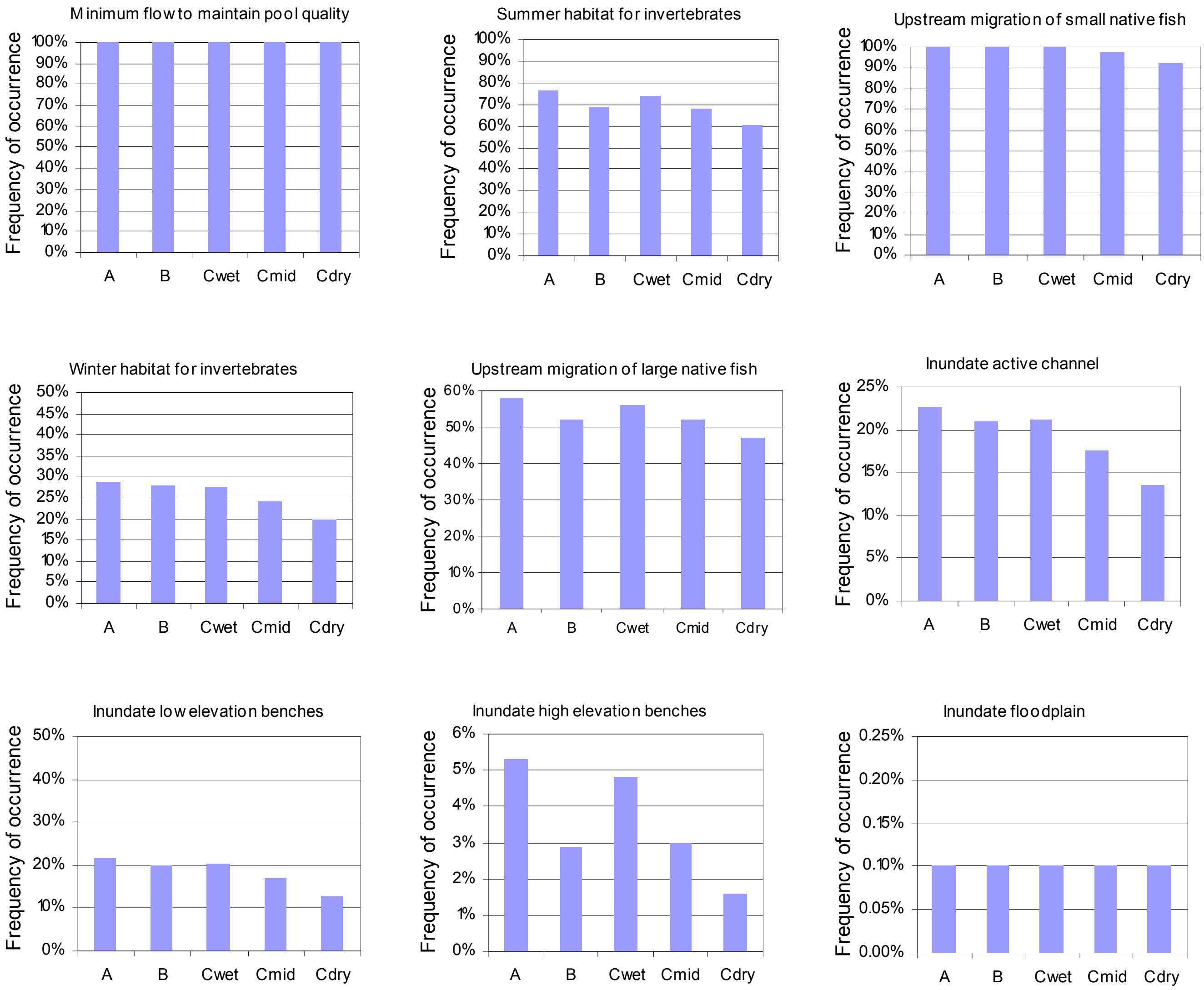

Figure 4-5. The variation in frequency of the flow, associated with the identified ecological functions for the Brunswick River (streamflow reporting node 61204 in Table 4-1) under scenarios A, B, Cwet, Cmid and Cdry

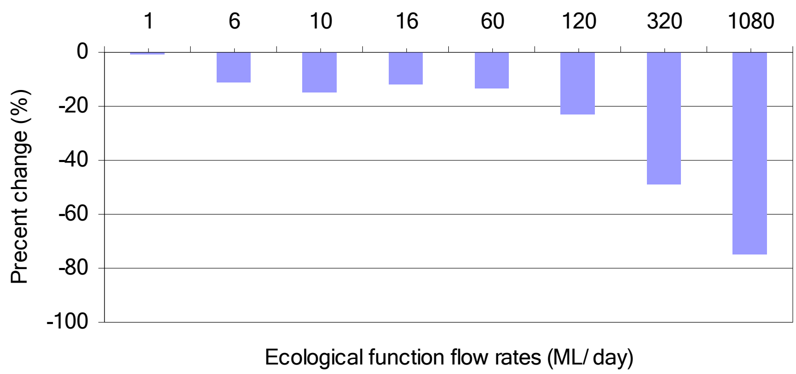

Figure 4-6. The relative difference between flow frequency under scenarios A and Cdry for the Brunswick River (streamflow reporting node 61204 in Table 4-1)

The results of analyses related to other rivers are given in Appendix D and briefly summarised below:

- Lefroy Brook: the climate impact on exceedance frequencies of ecological flow thresholds appears to be greater during low flow periods when stream flow is required to maintain both summer pool quality (6 ML/day) and the upstream migration of small native fish (10 ML/day). Low flows may increasingly restrict fish access to breeding habitats with implications for recruitment to populations or shortening the breeding period or opportunity. Otherwise the climate has a similar effect on river flow frequencies: 1 to 2 percent under Scenario B, 1 to 3 percent under Scenario Cwet, 4 to 7 percent under Scenario Cmid, and 6 to 12 percent under Scenario Cdry.
- Cowaramup River: the effect of all climate scenarios is greatest during the period required to maintain pool habitats in summer, which has been identified as being 1 ML/day. This may result in increased water temperatures and lower dissolved oxygen levels in summer pools.
- Wilyabrup River: The changes in exceedance frequencies of thresholds under each climate scenario are similar across all identified flow thresholds: 1 to 2 percent under Scenario B, 1 percent under Scenario Cwet, 3 to 4 percent under Scenario Cmid and 8 to 10 percent under Scenario Cdry. These changes are similar for both river reaches included in the EWR analysis.
- Margaret River: the impact of all climate scenarios on exceedance frequencies of thresholds associated with specified ecological functions appear to be similar for both reaches for all climate scenarios: 1 to 2 percent under Scenario B, 2 to 3 percent under Scenario Cwet, 4 to 8 percent under Scenario Cmid, and 10 to 12 percent under Scenario Cdry.
- Chapman River: the future climate impacts on the flow frequencies that are significant for ecological functions are similar for both reaches for all climate scenarios: 1 to 2 percent under Scenario B, 2 percent under Scenario Cwet, 4 to 6 percent under Scenario Cmid and 7 to 10 percent under Scenario Cdry.

The responses of these rivers are all within 2 or 3 percent of each other with the impact under Scenario Cdry (8 to 12 percent) being up to twice that under Scenario Cmid (4 to 8 percent). Under scenarios B and Cwet the changes in frequency are less than 3 percent. The significance of this difference is greater for low frequency-significant ecological function flows (Figure 4-6). However as was mentioned above the ecological river functions are more sensitive to variation in summer low flow, when frequency of exceedance of thresholds appears to be less affected by future climate.

4.5.2 Variation in median runoff during the winterfill period and the rest of the year

The 122-day winterfill period between 15 June and 15 October generates about 83 percent of annual runoff throughout the project area despite this period constituting only a quarter of the year (Figure 4-7).

The winterfill runoff decreases by 5 to 20 percent under both scenarios B and Cwet relative to that under Scenario A. In some rivers some increase in winter runoff under Scenario B was estimated. These are the upper Margaret River (SRN 610008) with a projected 21 percent increase, and Thomson Brook (SRN 611111) with a projected 13 percent increase. Under Scenario Cmid the rivers' winterfill runoff reduces relative to Scenario A by 20 to 30 percent. Under all future climate scenarios the greatest impact on winter runoff is in the Denmark and upper Kent catchments in the south and Gingin Brook in the north. Under Scenario Cdry, runoff is reduced by about 40 to 50 percent relative to Scenario A and by nearly 80 percent in the upper Kent catchment.

The changes in median runoff during the period outside of the winterfill period are similar under all climate scenarios. Although the majority of the changes fall within a similar range of runoff reduction, on average summer runoff reductions are 4 to 7 percent greater. These results are summarised in Table 4-3 and Figure 4-8.

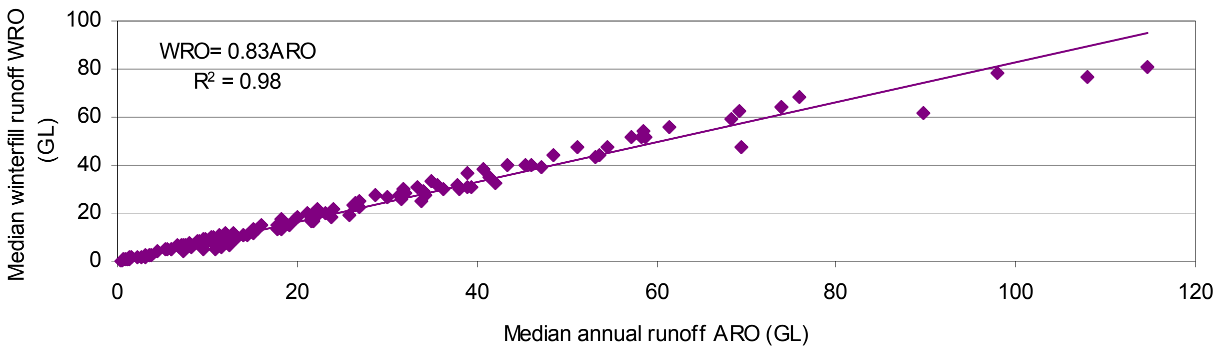

Figure 4-7. Relationship between runoff during the winterfill period and median total annual runoff over 33 years under all climate scenarios

Table 4-3. Variation in median runoff during the winterfill period and the rest of the year under scenarios B and C relative to Scenario A

Changes relative to that under Scenario A	Number of rivers within the identified changes range (out of total 33)	
	Winterfill	Rest of year
Scenario B		
5 to 20% reduction	15	16
>20% reduction	15	10
Increase	2	2
Scenario Cwet		
5 to 20% reduction	30	23
>20% reduction	3	9
Increase		1
Scenario Cmid		
20 to 30% reduction	20	20
>30% reduction	9	12
<20% reduction	4	1
Scenario Cdry		
40 to 50% reduction	19	13
>50% reduction	5	10
<40% reduction	9	10

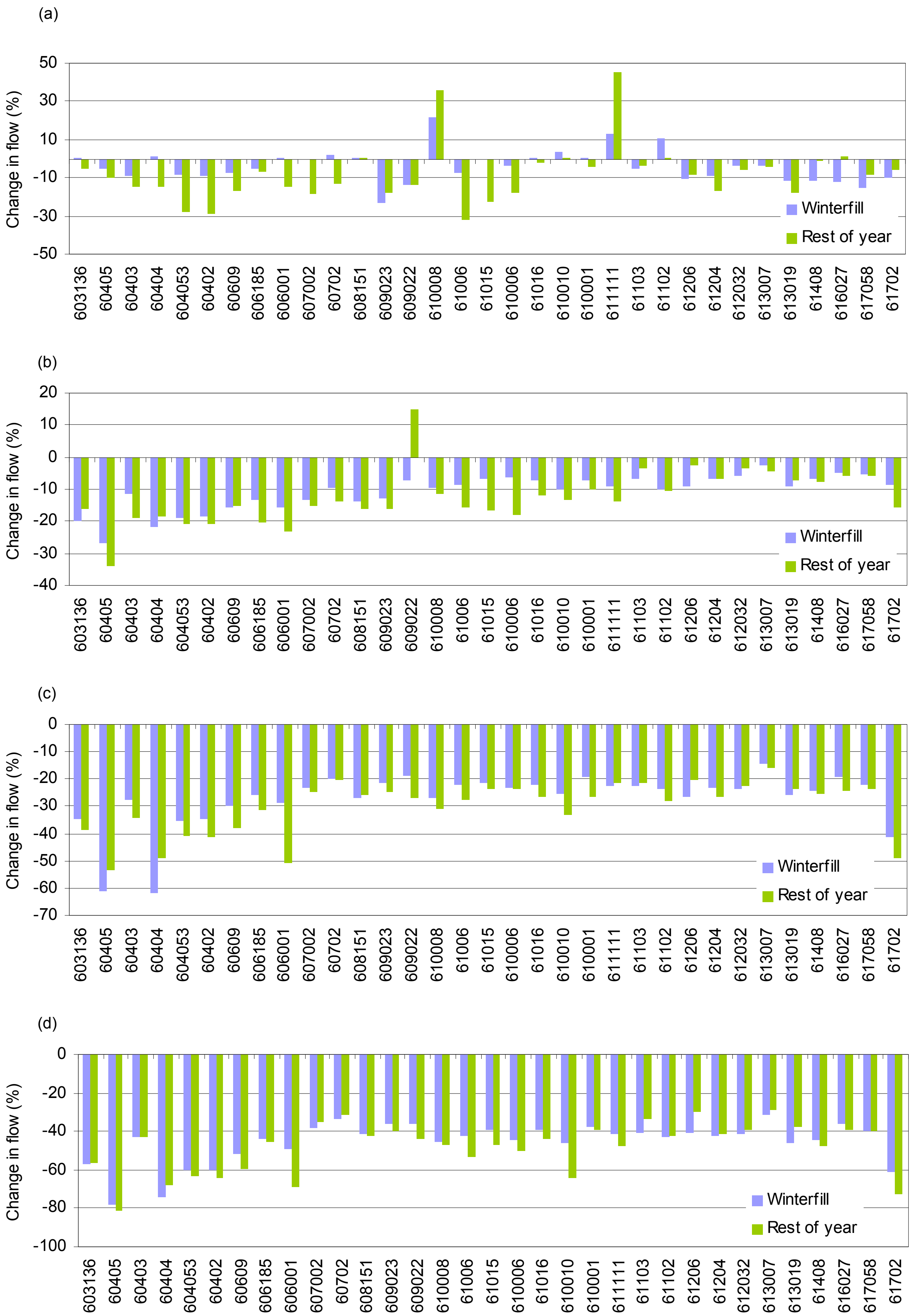

Figure 4-8. Change in median runoff during the winterfill period and the rest of the year for the 33 surface water dependent ecosystem evaluation sites under scenarios (a) B, (b) Cwet, (c) Cmid and (d) Cdry relative to Scenario A

4.5.3 Comparison with sustainable diversion limits

The potentially extractable river yields, estimated using the SDL approach, allows over 85 percent of total annual streamflow to be maintained in the environment. Consequently the SDL volumes under all climate scenarios and all selected rivers were compared to the median winterfill streamflow. As shown in Figure 4-9 volumes of potentially extractable river yields compose approximately 15 percent of the median winterfill runoff under all climate scenarios.

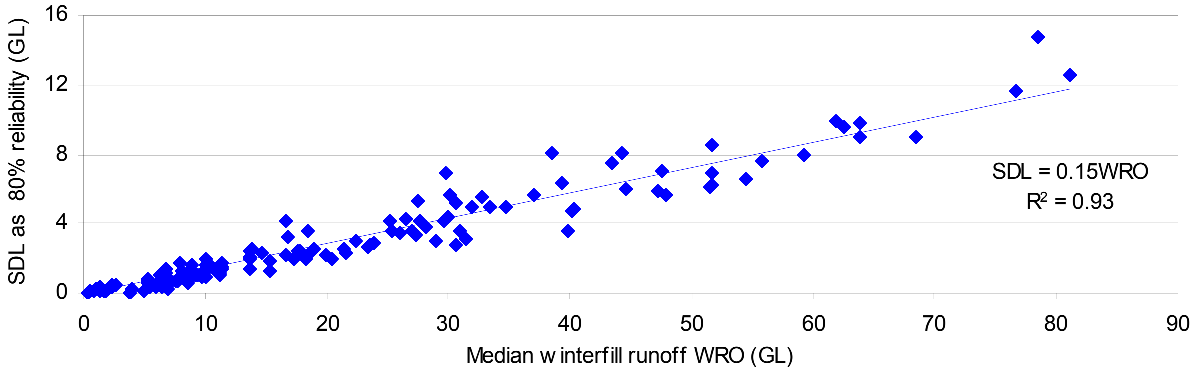

Figure 4-9. Relationship between sustainable diversion limits and median runoff during the winterfill period over 33 years under all climate scenarios

4.5.4 'No flow' days

Summer flow has a particularly significant ecological value and changes may affect ecological functions of the rivers (Section 4.3.1). One of the important characteristics associated with the summer flows is the duration over which rivers effectively cease to flow. Particularly dramatic impacts on in-river ecosystems may occur if perennial rivers become intermittent. However the surface water modelling described in CSIRO (2009) suggested that perennial rivers remained perennial under all future climate scenarios. Some model estimates over-predicted runoff towards the end of the calibration period which could be due to a change in rainfall-runoff mechanism such as a loss of contact between the regional groundwater system and the river invert. The assumption of continued perenniality may therefore be invalid if this were to occur.

Cell based analysis of runoff results shows that under Scenario A in some regions runoff does not occur for most of the year (Figure 4-10). This is particularly evident in the eastern part of Darling Scarp within the Swan Coastal and Murray basins. On the other hand the area where runoff is continuous throughout the year is in the western part of the Harvey and Collie basins, catchments in the lower Donnelly and Denmark basins and western catchments of the Shannon basin. In addition to groundwater discharge supporting continuous baseflow, some catchments in the Harvey basin on the Swan Coastal Plain receive irrigation returns artificially maintaining summer flows.

A comparison with results under the other climate scenarios indicates that under Scenario B there is a reduction in the number of 'no-flow' days or in other words there is an increase in the river flow duration period on an annual basis. This trend was identified for the Harris catchment in Collie Basin, some parts of Lower Blackwood basin and Margaret River catchment, the Upper Donnelly and Warren Basins and near Mount Lindsey station in the Denmark Basin. An increase in summer runoff in Margaret River was also identified for Scenario B.

A particularly significant reduction in flow duration (average annual days with 'no-flow' greater than 90 days) under Scenario Cdry was identified in the Denmark Basin, middle Kent and Warren Basins, middle Preston and Murray Basins as well as along the hill catchments of the Swan Coastal Basin.

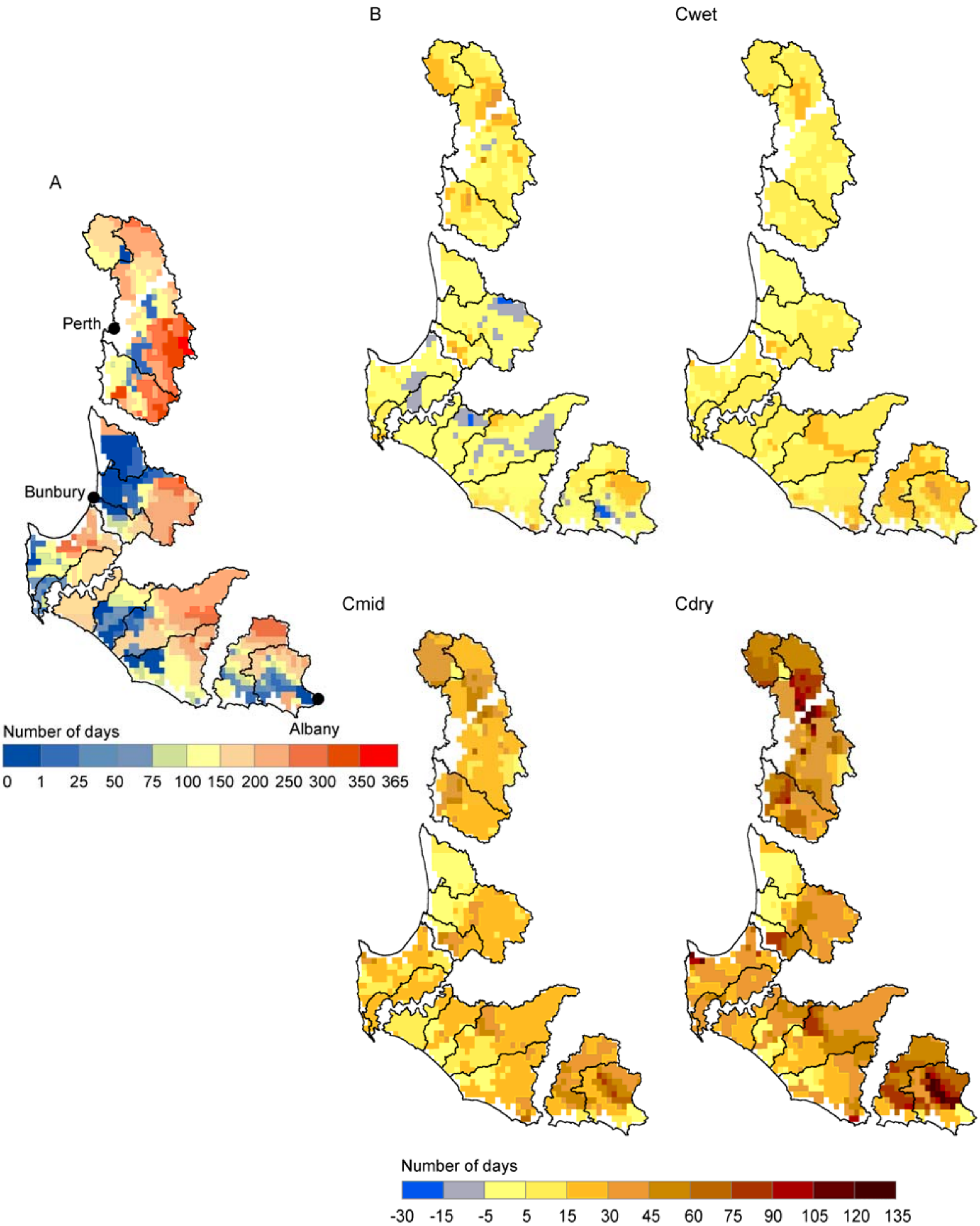

Figure 4-10. Average annual number of ‘no-flow days’ (as days with runoff less than 0.01 mm/day) across the surface water modelling area under Scenario A and the change in the number of ‘no-flow days’ under scenarios B, Cwet, Cmid and Cdry

4.5.5 Other sites

Three sites were selected to identify variations in runoff regime under climate scenarios for the purpose of assessing the impacts on:

- runoff into Lake Muir, as surface water dependent system listed as a RAMSAR site (see Chapter 2.8.1)
- runoff in the catchment downstream from the Serpentine Reservoir as an example of the climate change effect on summer and winter river flow within the area which has already been affected by water harvesting
- flows in the Harvey Diversion Drain.

The results are summarised in Table 4-4. For Lake Muir under scenario Cdry, median runoff during the winterfill period may decrease more than 50 percent and by almost 60 percent during the rest of the year. Flows downstream of the Serpentine Reservoir will be significantly affected under scenarios Cmid and Cdry throughout the year. The results also indicate that under scenario B the climate change has a particularly significant effect on runoff in winter than in summer.

The Harvey Diversion Drain receives significant groundwater inflow from aquifers on the Swan Coastal Plain and any estimates of reductions shown in Table 4-4 would need to take account of estimates of future groundwater levels near the drain. Under scenarios Cmid and Cdry, winter flows are expected to decline more than during the rest of the year under Scenario A. In this case the effect of climate change on summer runoff under Scenario B is greater on winter runoff.

Table 4-4. Median runoff changes for Lake Muir, Serpentine River and the Harvey Diversion Drain under scenarios B and C relative to Scenario A

	Median runoff changes during the winterfill period				Median runoff changes during the rest of a year			
	B	Cwet	Cmid	Cdry	B	Cwet	Cmid	Cdry
	percent change from Scenario A							
Lake Muir	-7.5%	-15.7%	-29.6%	-51.9%	-16.8%	-15.1%	-37.8%	-59.3%
Serpentine River	-11.7%	-6.9%	-24.4%	-44.2%	-1.1%	-7.6%	-25.6%	-47.8%
Harvey Diversion Drain	-11.2%	-8.8%	-26.1%	-46.4%	-17.6%	-7.0%	-23.6%	-37.2%

4.6 Confidence, variability and uncertainty

The main sources of uncertainty in the results of the undertaken analysis were mainly related to the modelled estimates of runoff under the future climate scenarios. These uncertainties in turn are derived from uncertainties in the climate inputs, in the runoff estimates that used these inputs and uncertainties in ecological functions and their dependence on river flow regimes.

4.6.1 Climate modelling

The method used to generate the Scenario C series did not allow for change in the seasonality of rainfall or the number of rain days relative to Scenario A because they were derived by scaling Scenario A data. Scenario B has different seasonality and rain days from Scenario A and these were most pronounced in the northern and central catchments.

Uncertainty in the modelling projections also arises from the lack of sub-daily intensity data in the synthetic climate sequences, which were not required because the rainfall-runoff models were all daily response models. Studies have found that there has been a significant change in rainfall intensity in the project area and, although not proved as a major cause, this has been correlated with declines in runoff coefficients in streams in the area. Uncertainty in the projections also arises from the original dataset derived from the SILO DataDrill data series.

4.6.2 Surface water modelling

A limitation of the rainfall-runoff models used may be that they do not capture the decline in groundwater levels observed in the forested catchments in the project area. This decline is believed to be due to the lower rainfall received during the last 33 years, particularly relative to the 1950s and early 1960s which were particularly wet. To address this perceived shortfall the LUCICAT catchment model (Bari and Smettem, 2006) was assessed in several catchments but it failed to improve the estimates in runoff over those of the simpler models IHACRES and Sacramento.

It is also possible that the range of future climate scenarios may be outside the bounds of reliable model performance based on the calibrations attained. The models were calibrated on streamflow data through the historical period (1975 to 2007) forced with historical rainfall and areal potential evapotranspiration (APET) data. These climate variables may in future have values outside the historical range. If rainfall-runoff relationships change under these future climates the estimates of future streamflows may be unreliable. The models also do not take account of how vegetation may change under a hotter, drier climate, nor with higher atmospheric CO_2 levels, all of which may change the plant water use characteristics and therefore the evapotranspiration and water balance of catchments.

More details on modelling uncertainties are given in CSIRO (2009) and Silberstein et al. (2010).

4.6.3 Uncertainty in ecological functions and their dependency on river flow

Although the greatest uncertainty is probably related to climate change estimates, there is also significant uncertainty in the ecological function analyses. The river thresholds for ecological functions have been chosen by DoW and SKM experts, but may not capture all of the significant components. The uncertainty may also arise from the fact that different river reaches have different sets of ecological functions, and applying findings across whole river systems or into neighbouring systems may be invalid. The ecological risk assessment related to the changes in frequency of thresholds for ecological functions also requires further development.

The ’rules’ for the SDL are but one approach and may well be challenged in the future as knowledge improves.

4.7 Discussion

The reported results on the possible climate impact on surface water dependent ecosystems are based on the results of climate and surface water modelling and therefore they inherit the assumptions, limitation and uncertainty of these methods. Within these constraints the analysis indicates that the frequency of flow exceeding the major ecological thresholds change by less than 2 percent under Scenario Cwet, less than 7 percent under Scenario Cmid and less than 12 percent under Scenario Cdry relative to Scenario A. The changes across the flow frequencies in the individual rivers appear to be similar for an individual scenario, which is likely to be a result of the deployed climate data sequences. The rainfall data were uniformly scaled down for Scenario C, resulting in nearly uniform reduction runoff frequency, as shown on the flow duration curves.

Climate and flow models suggest that the frequency of flow exceeding the major ecological thresholds for high flow events are most affected under scenarios Cmid and Cdry. This suggests that elements of river ecosystems influenced by high flow are likely to be most affected by climate change. These elements include channel scouring, channel morphology (e.g. silt removal) and the inundation of floodplain wetlands. Such changes in flow regime under Scenario C are an end result of the uniform scaling down of the daily rainfall intensity. Validity of such an approach is discussed in this project’s companion report on climate (Charles et al., 2010) and is also illustrated by Figure C-3 in Appendix C, indicating the reduction in rainfall intensity in the project area under the recent climate shift in Western Australia. This may also be confirmed by comparing the effect of historical climate (A) and the recent climate (B) on rivers flow regime, which also suggest that the greatest changes in the flow exceedance frequencies are related to the high flow and low frequency events for the majority of the considered rivers (except for Margaret River, see Appendix D).

Surface water dependent ecosystems are more sensitive to alterations in the summer flow rates, which show the least relative changes in the frequency of flow exceeding the major ecological thresholds under future climate scenarios. While the modelling method that was used ensures consistency between different scenarios and regionally in their relative fluxes magnitudes, the accuracy of the individual results (particularly during baseflow) has not been analysed in detail. The conclusion related to low flow frequency and their changes under the future climate would require further validation.

Across the project area the runoff during the winter months decreases relative to Scenario A by between 5 and 20 percent under Scenario Cwet, by 20 to 30 percent under Scenario Cmid, and by 40 to 50 percent under Scenario Cdry. Under Scenario B, runoff in most rivers remains unchanged or even increases.

The upper catchments of the southern rivers (Kent and Denmark) and the most northern river (Gingin) are particularly sensitive to climate variability. Here the runoff reductions during the winterfill period and the rest of the year are 50 to 60 percent greater than in other rivers under the future climate.

Within the modelling assumptions, the climate does not result in river flow cessation in current perennial rivers.

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5 Groundwater dependent ecosystems

This chapter is based on the results of the groundwater modelling and groundwater hydrograph analysis, reported in the companion groundwater report (CSIRO, 2009) and summarised in Section 2.9.2. This chapter extends those results to a broad regional assessment of ecological risks to groundwater dependent ecosystems (GDEs). As described in Section 5.9, this assessment has inherited assumptions, uncertainty and limitations from the analysis of future climate impact on regional groundwater resources. The outcome of these analyses is considered a first approximation to the risk posed to GDEs from future climate and development. The aim is to highlight potentially impacted areas. No individual GDEs were considered.

5.1 Key findings

- Groundwater dependent ecosystems (GDEs) are diverse, uniquely adapted features of the Western Australian landscape which require careful water management practices for their retention and a continuation of the ecological services which they provide.
- This analysis focuses on wetlands and three types of phreatophytic vegetation with depths to watertable of zero to 3 m, 3 to 6 m, and 6 to 10 m. Currently the modelled area of the Central Perth Basin, Peel-Harvey Area and Southern Perth Basin, where wetlands can potentially occur, cover over 3540 km^2 of the area. The outcomes provide a quantitative indication of the potential pressures to ecosystems from climate and groundwater consumptive use in a regional scale. No individual GDEs were considered.
- In the Central and Southern Perth basins high and severe ecological risks may occur over 17 to 19 percent of areas where wetlands can potentially occur under Scenario Cdry. The main risks in the Central Perth Basin are on the Gnangara Mound and Darling Scarp while in the Southern Perth Basin they are on the Scott Coastal Plain.
- In the Peel-Harvey Area a potentially high impact on GDEs is expected under Scenario D, indicating this area is sensitive to abstraction. The affected areas are the coastal lakes and Harvey.
- GDEs associated with caves may be highest for those more distant from discharge areas.
- Groundwater levels are expected to rise in the northern part of the Perth Central Basin and an increase in areas with GDEs may occur, especially for phreatophytic vegetation with a depth to watertable between 6 and 10 m.
- The analysis could be applied to acid sulfate soil risks which are associated with the areas with a shallow watertable.

5.2 Groundwater dependent ecosystems

A GDE is an ecosystem that requires the presence or input of groundwater to maintain some or all of its ecological function, composition or structure (Eamus and Froend, 2006; Murray et al., 2006). They include wetlands, vegetation complexes, river base flow systems and caves. GDEs can have various levels of dependency on groundwater from completely dependent to occasional supplementary utilisation, which in turn affect the ecosystem response to possible changes in the groundwater regime.

A review by Hatton and Evans (1998) led to relatively recent acceptance of GDEs as a distinct class within ecosystems. Although GDEs only cover a comparatively small proportion of land surface area they provide specific ecosystem functions supporting unique and important biological diversity at both local and regional scales (Boulton and Hancock, 2006; Humphreys, 2006; Thurgate et al., 2001; Murray et al., 2006; DEH, 2008). Other than environmental benefits GDEs provide significant social, economic and spiritual values (Murray et al., 2006). A summary of GDE classifications is given below so that the best method of identifying and estimating impacts at a regional scale can be assessed.

5.2.1 Classification of groundwater dependent ecosystems

Hatton and Evans (1998) identified four classes of GDEs: terrestrial vegetation, river base flow systems, aquifer and cave systems, and wetlands. This classification has been expanded to include two new GDE classes: terrestrial fauna, and estuarine or near-shore marine systems (SKM, 2001).

Terrestrial (phreatophytic) vegetation

Terrestrial vegetation, which relies on the presence of groundwater for at least part of its lifecycle, is also known as phreatophytic vegetation. Some vegetation species require constant access to groundwater while others may only require seasonal access to groundwater such as during summer when surface water resources are unavailable (SKM, 2001). However, Hatton and Evans (1998) reported that there was generally a poor understanding of the degree of terrestrial vegetation's dependence on groundwater. However according to Froend and Loomes, 2004, it is unlikely that terrestial revegetation in an area with a depth to watertable more than 10 m can be significantly dependent on groundwater resources.

This class of GDE is particularly sensitive to changes in groundwater level; both declining and rising levels can have catastrophic consequences. An increasing depth to watertable can result in the loss of a plant's ability to reach the groundwater. A rise in groundwater levels can cause waterlogging, anoxia or dryland salinity if the groundwater contains sufficient salts or the site is poorly drained. Waterlogging combined with the effects of high solute (salt) concentration has already led to the elimination of many plant communities in Western Australia (SKM, 2001). In addition to groundwater levels, groundwater quality deterioration in the vicinity of GDEs may also affect ecosystem functionality (SKM, 2001).

Subsequently in this report, groundwater dependent terrestrial vegetation will be referred to as phreatophytic vegetation to distinguish this type of vegetation from the terrestrial vegetation which is not dependent on groundwater water.

River base flow systems

A river base flow system (RBFS) is defined as the aquatic or riparian ecosystem in or immediately adjacent to a stream or river that is fully dependent on groundwater discharging to the river (Hatton and Evans, 1998; SKM, 2001; Murray et al., 2003). The base flow rates and volumes depend on the local hydrogeological conditions (e.g. aquifer transmissivity, hydraulic gradients), the position of the watertable in relation to the surface water network as well as the river bank and floodplain's storage capacity (Boulton and Hancock, 2006; Newson, 1994). Groundwater input can be particularly important in drier seasons or in areas with a low annual rainfall. It can also be critical for ecosystem survival in periods of severe drought (Hatton and Evans, 1998; Murray et al., 2003; Boulton and Hancock, 2006, Lake, 2003).

There are four RBFS sub-classes identified: instream habitats, discrete spring habitats, riparian vegetation and the hyporheic zone. In the hyporheic zone surface–groundwater interaction forms a unique habitat for some invertebrate species (Boulton and Hancock, 2006). Within discharge areas, the groundwater can promote primary production and influence sediment microbial activity.

Groundwater input can also affect the duration of streamflow or water levels in a stream. These in turn determine the nature of the stream habitat and the individual species inhabiting the instream ecosystem (Boulton and Hancock, 2006).

The extent of GDEs in the vicinity of a river varies depending on the local landscape and surface–groundwater interaction processes. For typical conditions in south-west Western Australia (SWWA), a 300 m zone along major rivers and floodplains is currently considered by the Department of Water Western Australia (DoW) as being an adequate development buffer zone around an RBFS to include any associated groundwater dependent riparian vegetation.

Aquifer and cave systems

Since many subterranean waters include some forms of aquatic species they may also be classified as GDEs (Jasinska and Knott, 1991; Murray et al., 2003). Little is known about these ecosystems in comparison to the other GDE classes (Hatton and Evans, 1998, DEH, 2008).

An aquifer can support diverse and unique range-obligate groundwater dependent fauna known as stygofauna (Murray et al., 2003; SKM, 2001). These are usually dominated by invertebrates, largely crustaceans but also including insects, worms, gastropods, mites and fish species, which can be found as far as 600 m below the ground surface (Longley, 1992; Humphreys, 2006). Karst ecosystems in the Cape Range of Western Australia have been named as one of the most diverse of their kind in the world and as such are considered internationally significant (Spate and Thurgate, 1998). The unique attributes that exist within an aquifer ecosystem – such as the absence of light for photosynthesis, long-term stability, limited energy and oxygen availability – have resulted in the evolution of a highly specialised group of short-range endemic species (SKM, 2001, Humphreys, 2006). The limitations to species survival as a result of this specialisation to their unique habitat can be seen in the calcrete aquifers of central Western Australia where a 1 to 2 m reduction in groundwater level was predicted to possibly result in the extinction of the whole suite of species contained within that GDE (Humphreys, 1999). Aquifer and cave ecosystems are also highly vulnerable to changes in groundwater quality, an issue that presents many problems to biodiversity conservation as a whole (Humphreys, 2006).

Wetlands

Groundwater dependent wetlands are possibly the most extensive and diverse class of GDEs in Western Australia. They depend on groundwater influx for all or part of the year and are at least seasonally waterlogged or flooded (Murray et al., 2003; Hatton and Evans, 1998, SKM, 2001). The wetlands and damplands of the Swan Coastal Plain are one example of a diverse suite of groundwater dependent wetlands (Eamus et al., 2006b). These wetlands have been shown to respond rapidly to falling groundwater levels with a loss of wetland species diversity and a reduction in the wetland's spatial area (SKM, 2001). The interaction between adjacent groundwater dependent wetlands, terrestrial vegetation and/or an RBFS can be extremely complex and it may be impossible to quantify all the interactive system processes and their interdependencies (SKM, 2001).

Terrestrial fauna

This type of GDE includes the terrestrial fauna species that inhabit ecosystems supported by groundwater, thereby making the terrestrial fauna also groundwater dependent. However, their dependence on groundwater is most commonly related to water availability for drinking rather than water for habitat provision. Groundwater is especially valuable to larger mammals and birds in arid areas of Australia (SKM, 2001).

Estuarine or near-shore marine systems

These types of ecosystems are the marine equivalent of the terrestrial ecosystems described above and include species from coastal mangroves and salt marshes, coastal lakes, seagrass beds, and marine animals (crocodiles, fish and macro-invertebrates). Here groundwater contributions may be in the form of direct groundwater discharge to the ocean from an aquifer or as the groundwater contribution to a river's baseflow entering the ocean at a river mouth (Hatton and Evans, 1998; SKM, 2001). The groundwater flux has a strong influence on these ecosystems, controlling nutrient concentrations, salinity levels, flow volumes and water levels.

5.2.2 Attributes of a groundwater regime important to a groundwater dependent ecosystem

Eamus et al. (2006a) defined a number of groundwater regime attributes that govern the type of impacts on GDEs when groundwater resources change:

- The depth to watertable combined with the capillary zone (tension saturated) and the rooting depth of the surface vegetation is often the most important groundwater attribute for a GDE (SKM, 2001). Froend and Zencich (2001) show that vegetation dependency on groundwater reduces when the depth to watertable increases and consequently vegetation in such areas is more tolerant to a decline in groundwater levels.
- The subsurface flow rate of the groundwater may impact on the rate of water replenishment to a site where groundwater is being utilised (SKM, 2001, Eamus et al., 2006a). It is also a critical attribute for aquifer and cave GDEs as it heavily influences the influx of fresh organic matter for nutrient cycling (Australian Water Resources Assessment [Natural Heritage Trust, 2000]). Hydraulic head or pressure is one of the governing factors defining groundwater fluxes and therefore it may influence groundwater discharge rates to wetlands and rivers (SKM, 2001). This is particularly important in confined aquifer systems and their contribution to springs discharge.

- The locations of both the groundwater discharge and recharge areas are very important for GDEs relying on the surface provision of groundwater for survival such as a wetland or RBFS (Eamus et al., 2006a, Froend and Zencich, 2001).
- The seasonal groundwater level variation is the most important groundwater attribute for a GDE that relies on both the surface expression of groundwater and surface flows of water (Eamus et al., 2006a). The groundwater maximum and minimum depth to watertable and the timing and duration of water level peaks and troughs are of particular importance.
- The long-term trends in groundwater level are also important. Generally the faster the rate of groundwater level change the less time the ecosystem has to adapt to these changes and the greater is the impact on an ecosystem. For example, Froend and Loomes (2004) found that a wetland system has a severe risk of impact if a groundwater decline of 0.75 m/year occurs but only a low risk of impacts if the rate of decline is about 0.25 m/year.
- The quality of the groundwater is a critical issue for all ecosystems utilising groundwater (Eamus et al., 2006a, Danielopol et al., 2003). Since water quality issues fall outside of this project scope, they are not considered further in this report.

These attributes may vary in relevance and the level of the impact for different GDE types.

A change in these attributes may lead to deterioration of a GDE depending on the exact nature of the interaction between the groundwater and the ecosystem (Murray et al., 2006; Eamus et al., 2006a; DEWHA, 2008). Assessing the level and range of change acceptable within an ecosystem is difficult and time consuming, and requires a high level of local ecosystem knowledge as well as a firm understanding of the groundwater regime and its effect on GDE functions (Eamus et al., 2006a).

Groundwater resources have economic, social, cultural and environmental values, and there may need to be a trade-off between environmental, social and economic drivers when considering acceptable levels of stress to an ecosystem. As detailed in DEWHA (2008) the trade-offs need to be determined in consultation with all stakeholders and on a site-specific basis. Implicit within the concept of groundwater harvesting is the recognition that abstraction will result in some form of groundwater storage depletion. However, the definition of a sustainable groundwater yield in itself constrains the abstraction above a level of acceptable depletion in order to maintain the resource's 'intergenerational equity'. The environmental, social and economic constraints on the level of abstraction are defined in the National Principles for Provision of Water for Ecosystems - A Definition and Approach to Sustainable Groundwater Yield (DEWHA, 2008).

5.3 Groundwater management principles in Western Australia

In Western Australia, groundwater resource planning and management is undertaken by DoW as discussed in Chapter 3 of this report. As in the case of surface water management, water planning implements the Environmental Water Provisions Policy for Western Australia (WRC, 2000) and the defined ecological water requirement (EWR), and similar principles are applied as discussed in Chapter 4.

Development of an ecological water requirement (EWR) as defined by DoW is based on four factors (WRC, 2000):

- the degree of dependency the GDE has upon the groundwater resource
- the specific water requirements of the GDE and how these requirements are met by the groundwater resource
- the potential impacts of changes to the groundwater on the ecological processes in the GDE
- the minimum groundwater input required by the GDE with a minimum level of risk.

However there are still many knowledge gaps and uncertainties in determination of ecological water requirements (EWRs) for GDEs and there is a need to advance currently limited studies in Western Australia on the links between a change in groundwater attribute and the impact on a GDE.

In Western Australia specific limits for ecological water requirements (EWRs) and environmental water provisions (EWPs) are usually established at sub-regional and local water management plan level. Some common examples of ecological water requirements (EWRs) are minimum desirable (or absolute) water levels for wetlands for specific periods of time, minimum groundwater levels and specific water quality parameters. Desirable levels reflect lower levels of risk of environmental damage than absolute levels.

In Western Australia this cautious allocation policy has resulted in most environmental water provisions (EWPs) being set that meet the ecological water requirements (EWRs) for the GDE. Allocation limits have also been initially set conservatively low and increased once the resource's response to development is better known. This conservative management style has been credited with the relatively small number of over-allocated systems despite significant climate change (WRC, 2000; McFarlane, 2005). The further improvement of water resource allocation requires a greater scientific knowledge of both the GDE and its ecological water requirements (EWRs) (WRC, 2000).

5.3.1 Sustainable groundwater yield

A sustainable groundwater yield is 'the groundwater extraction regime that allows an acceptable level of stress or change to occur from groundwater abstraction while protecting the associated economic, social and environmental values of any systems dependent on that groundwater' (DEWHA, 2008). A sustainable groundwater yield and its associated extraction regime are always set for a given planning time frame or planning period, usually on an annual basis (DEWHA, 2008). There are different forms of the limits related to a groundwater extraction regime, which may include a combination of volumetric quantity limits, specified withdrawal regimes based on cumulative accounting, water quality trigger limits, water level parameters and specific rates of extraction over given time periods (DEWHA, 2008). These limits can be probabilistic and/or conditional in nature. One commonly prescribed extraction regime is a maximum extraction volume over one year – in specific circumstances, this volume can vary from year to year in response to unusual rainfall patterns.

In Western Australia the method adopted in the National Land and Water Resources Audit is used by DoW to assess the degree of resource use relative to the sustainable groundwater yield. The level of use as a proportion of the sustainable yield defines the level at which the groundwater resource unit should be managed. The levels are based on a relative scale of management from one (low level of management) to four (high level of management), corresponding to each of the four categories of use. These levels are detailed in Chapter 3 and Appendix D.

5.4 Indicators of ecological risk adopted in the project

As described in Section 5.2, the groundwater regime in the vicinity of GDEs significantly influences their ecological functions. The level of dependency on the local groundwater regime has not been equally established for all GDEs listed in Appendix D and shown in Figure 2-18, and therefore only regional assessments were undertaken to identify an ecological risk caused by variation in the groundwater regime. The analyses were carried out where the results of groundwater modelling under climate scenarios were available and GDEs had been identified. These included the Central Perth Basin (PRAMS model), the Peel-Harvey Area (PHRAMS model) and the Southern Perth Basin (SWAMS model).

In addition vertical flux model (VFM) results and statistical hydrograph analysis in selected bores were used to assess the effect of climate on GDEs where groundwater models were not available (Northern Perth Basin and the Albany Area). The Collie Basin contains some GDEs but the Collie Basin model was not considered sufficiently accurate to assess the impact of climate on GDEs given the large abstractions resulting from mine dewatering and groundwater use.

5.4.1 Application of groundwater model results to ecological risk assessment

DoW has adopted an approach developed by Froend and Loomes, 2004 to assess ecological risks. The approach was based on analyses of both the magnitude of the groundwater level reduction and the rate of this reduction. The thresholds for groundwater level reductions and their rates vary for different GDE types and risk levels (Figure 5-1). In this approach the type of GDE is based on the depth to watertable. Only wetlands and phreatophytic vegetation located over shallow watertables with the depth to watertable less than 10 m were included in this analysis. It was assumed that GDE classes potentially occur in those areas with the specified depths under current (2007) conditions.

The GDE's risk was assessed from minimum annual groundwater levels for the threshold values shown in Figure 5-1.

This approach was used to evaluate the environmental risk of the groundwater level falls in the Superficial Aquifer in response to climate and development changes as determined by groundwater modelling (CSIRO, 2009).

The regional ecological risk assessment was based on the following considerations:

- Areas with zero to 3 m, 3 to 6 m, 6 to 10 m and greater than 10 m maximum depths to watertable were assessed from the relevant groundwater model for current conditions (2007). Since it was found that the minimum annual groundwater levels occurred at different times of the year across the modelled domains, the minimum annual depth to watertable at 12 stress periods (monthly) used for groundwater models was estimated for each cell in a model domain.
- These data were compared with the groundwater level in the Superficial Aquifer at the end of 2030 under scenarios A, B, Cwet, Cmid, Cdry and D as defined in Chapter 1.
- The comparison between 2007 and 2030 was based on variations in the areas (ΔA) specified in for each GDE type for 2007 and 2030, the absolute changes in the minimum groundwater levels over the simulation period (ΔH), and the rate of the groundwater level drawdown $\Delta H/t$, where t is the simulation period of 23 years.

Simultaneous analysis of these parameters allowed mapping of the ecological risk areas where wetlands and various phreatophytic vegetation types may potentially occur.

It is acknowledged that the adopted methodology was developed (Froend and Loomes, 2004) for the Gnangara area, and may have limitations when it is applied at a regional scale. Also the variation in the depth to watertable, significant in terms of ecological risk assessment, may be challenged by the model accuracy in some areas. Considering these limitations, the approach was used only as an approximation to the risk posed to GDEs from future climate change and current abstraction in a regional scale, highlighting the areas where the potential risk is likely to occur.

Furthermore, identified risks may not indicate a full extinction of environmental assets. GDEs can also undergo ecological community change as a result of changes in water availability, as was shown for some wetlands and phreatophytic vegetation, dependent on shallow groundwater, in the Gnangara area (Froend and Loomes, 2004).

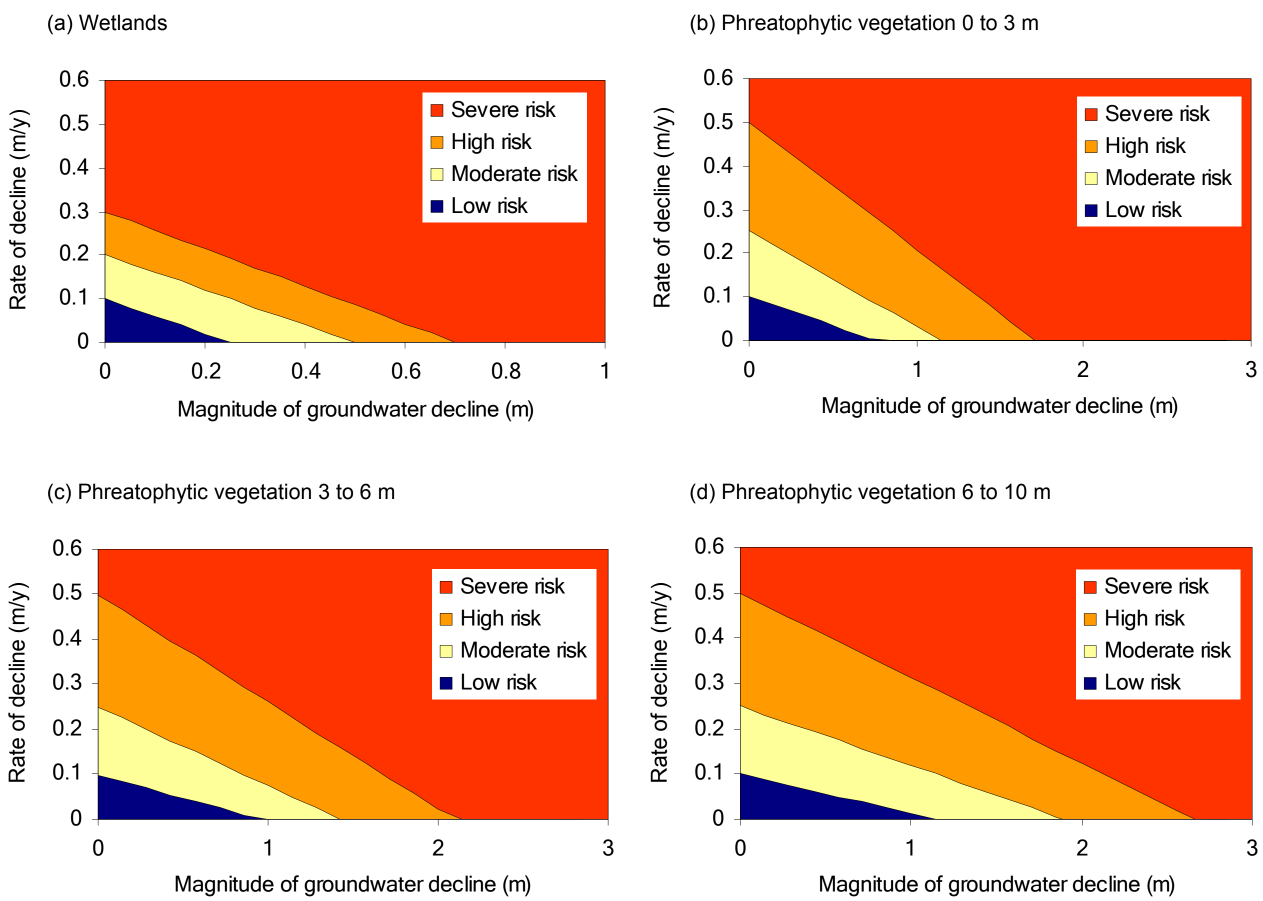

Figure 5-1. Risk of impact for each type of groundwater dependent ecosystem: (a) wetlands, and phreatophytic vegetation with depths to watertable of (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m (Froend and Loomes, 2004)

Table 5-1. The parameters which were used for ecological risk area mapping (adopted from Froend and Loomes, 2004)

Risk mapping criteria	Wetlands			Phreatophytic vegetation with zero to 3 m depth to watertable			Phreatophytic vegetation with 3 to 6 m depth to watertable			Phreatophytic vegetation with 6 to 10 m depth to watertable		
	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
$\Delta H \leq$ (m)	0.25	0.5	0.7	0.75	1.25	1.75	1	1.5	2.25	1.25	2	2.75
$\Delta H/t \leq$ (m/y)	0.1	0.2	0.3	0.1	0.25	0.5	0.1	0.25	0.5	0.1	0.25	0.5
$(\Delta H/t - a\Delta H) \leq b$ *												
a	-0.4	-0.4	-0.43	-0.13	-0.2	-0.29	-0.1	-0.17	-0.22	-0.08	-0.13	-0.18
b	0.1	0.2	0.3	0.1	0.25	0.5	0.1	0.25	0.5	0.1	0.25	0.5

*Defined by the linear equation of the relationship between $\Delta H/t$ and ΔH as shown on Figures 5-1 a to d.

In addition to the spatial analysis, a number of bore hydrographs in the vicinity of the selected GDEs were derived from the groundwater models to illustrate site-specific variations in groundwater levels as a result of the climate and development scenarios. These sites were related to caves within the Central Perth Basin, where the groundwater modelling results were available. The most significant caves in the region are shown in Figure 2-18.

As mentioned above, in the calcrete aquifers a 1 to 2 m change in the groundwater level could result in the extinction of a suite of species contained within these GDEs (Humphreys, 1999). The risk of climate impact on cave ecological systems was therefore defined in terms of the groundwater level reduction in the vicinity of the caves:

- low risk – the groundwater level variation is within inter-annual changes
- moderate risk – groundwater level reduces <1 m
- high risk – groundwater level reduces >1 m.

The main results are described in the following sections, while detailed outcomes are given in the technical report on water yields and demands in the south-west of Western Australia (McFarlane et al., 2010). The results are summarised for scenario Cmid which is considered to be most probable future climate and also for the driest future scenario (Cdry) and development scenario (D), which assumes a Cmid climate scenario and groundwater abstraction at the Allocation Limit for each groundwater sub-area and aquifer. The results of other scenarios, though discussed in the text, are illustrated in Appendix E.

5.5 Risks to groundwater dependent ecosystems in the Central Perth Basin

5.5.1 Wetlands and phreatophytic (terrestrial) vegetation

There are a number of significant water dependent ecosystems in the Central Perth Basin and many of them partly or fully rely on groundwater 14 include three RAMSAR site: Thomson and Forrestdale Lakes and the Becher Point Wetlands. Although the effect of climate and development on individual GDEs was not considered, the areas where the different types of GDEs may occur are show in Figure 5-2 based on the depth to watertable in 2007. These include three zones: phreatophytic vegetation and wetlands with a depth to watertable of zero to 3 m, phreatophytic vegetation with a depth to watertable of 3 to 6 m and phreatophytic vegetation with a depth to watertable of 6 to 10 m. The potential ecological risk for GDEs in these areas varied for climate and development scenarios, as summarised below.

The potential variation in the area of the four GDE types under Scenario Cmid is shown in Figure 5-2 and summarised in Table 5-2. A loss of 36 km^2 of the area where wetlands may potentially occur (zero to 3 m depth to watertable) is estimated under this scenario with most of the losses being in eastern parts of the Swan Coastal Plain. There will also be a loss of about 170 km^2 in areas with a depth to watertable of 3 to 6 m and 275 km^2 of areas with 6 to 10 m depth to watertable. However due to groundwater level rise in some areas (such as in the north of the Central Perth region) there is likely to be an increase in the area where GDEs may potential occur, e.g. 117 km^2 for area with depth to watertable less than 3 m. Losses in one depth category are also gains in the one below so many of these changes reflect the gradual changes in groundwater levels and may potentially indicate evolutionary changes in ecological functions of GDEs over the 23 year period. A high level of ecological risk may occur for individual GDEs in areas where there is no risk shown at a regional level. The relationship developed by Froend and Loomes, 2004 (2004) was used for ecological risk mapping for each GDE type (Figure 5-3 and Table 5-3). Only 3 percent of areas, where wetlands may potentially occur, have a high to severe ecological risk based on the rate and absolute decline in the watertable. Almost all of these are on the Swan Coastal Plain north of the Swan River. High and severe risks are not likely to occur for GDEs as phreatophytic vegetation with a depth to watertable of zero to 3 m, 2 percent of GDEs with a depth to watertable of 3 to 6 m and for 8 percent of GDEs with a depth to watertable of 6 to 10 m. The wetlands that occur south of the Swan River have a much lower ecological risk, possibly because their supporting aquifer is shallow, has a low hydraulic gradient and therefore recharge is sufficient even under climates with less rainfall.

Table 5-2. Changes in the areas associated with groundwater dependent ecosystems in the Central Perth Basin under Scenario Cmid

	Phreatophytic vegetation in the area with the specified depth to watertable		
	zero to 3 m	3 to 6 m	6 to 10 m
Area in 2007 (km^2)	1216	1251	1058
Area in 2030 (km^2)	1298	1324	1169
Reduction in area between 2007 and 2030 (km^2)	36	170	275
Increase in area between 2007 and 2030 (km^2)	117	243	386
Area unchanged between 2007 and 2030 (km^2) and total area in 2007	1181 (97%)	1081 (86%)	784 (74%)

Table 5-3. Percentage of total area with groundwater dependent ecosystems in the specified risk category in the Central Perth Basin under Scenario Cmid

Risk category	Wetlands		Phreatophytic vegetation in the area with the specified depth to watertable					
			zero to 3 m		3 to 6 m		6 to 10 m	
	Total area (%)	Total area	Total area (%)	Total area	Total area (%)	Total area	Total area (%)	Total area
Severe	2%		0%		0%		3%	
High	1%		0%		2%		5%	
Moderate	4%		2%		3%		7%	
Low	22%		26%		28%		26%	
No risk	72%		72%		66%		60%	
Total area (km^2)		1216		1216		1252		1058

The GDE risks under Scenario Cmid dominate by ‘low’ risk category with the exception of areas near the Gnangara Mound. Similar effects were associated with Scenario B (Appendix D).

Under Scenario Cdry the ecological risk increases and the areas where GDEs may be under severe and high risk increase to 19 percent, 10 percent, 21 percent and 38 percent for areas where wetlands, phreatophytic vegetation with a depth to watertable of zero to 3 m, 3 to 6 m and 6 to 10 m respectively (Figure 5-4). As for results under Scenario Cmid, most affected areas are on the Swan Coastal Plain north of the Swan River.

The effect of groundwater abstraction on GDEs ecological risk was defined by comparing risk levels under scenarios Cmid and D. The estimated GDEs risks rises for all GDE classes (Figure 5-6) and the area with identified risk categories increase by 54-60 precent. The risk is likely to remain low with between 29 and 46 percent of all areas falling under the low risk category and 5 to 13 percent of areas with a moderate ecological risk. The rise in the risk level resulting from increased groundwater abstraction is mainly in the south and the north-west where water is still available for abstraction. The changes in the risk categories are most noticeable for wetlands.

Under scenarios A and Cwet the area with identified ecological risks is limited for all GDE classes (see Appendix D). Overall less than 10 percent of the area where a GDE may occur is at risk with a predominantly low risk category. A similar impact was estimated under Scenario Cwet (Appendix D).

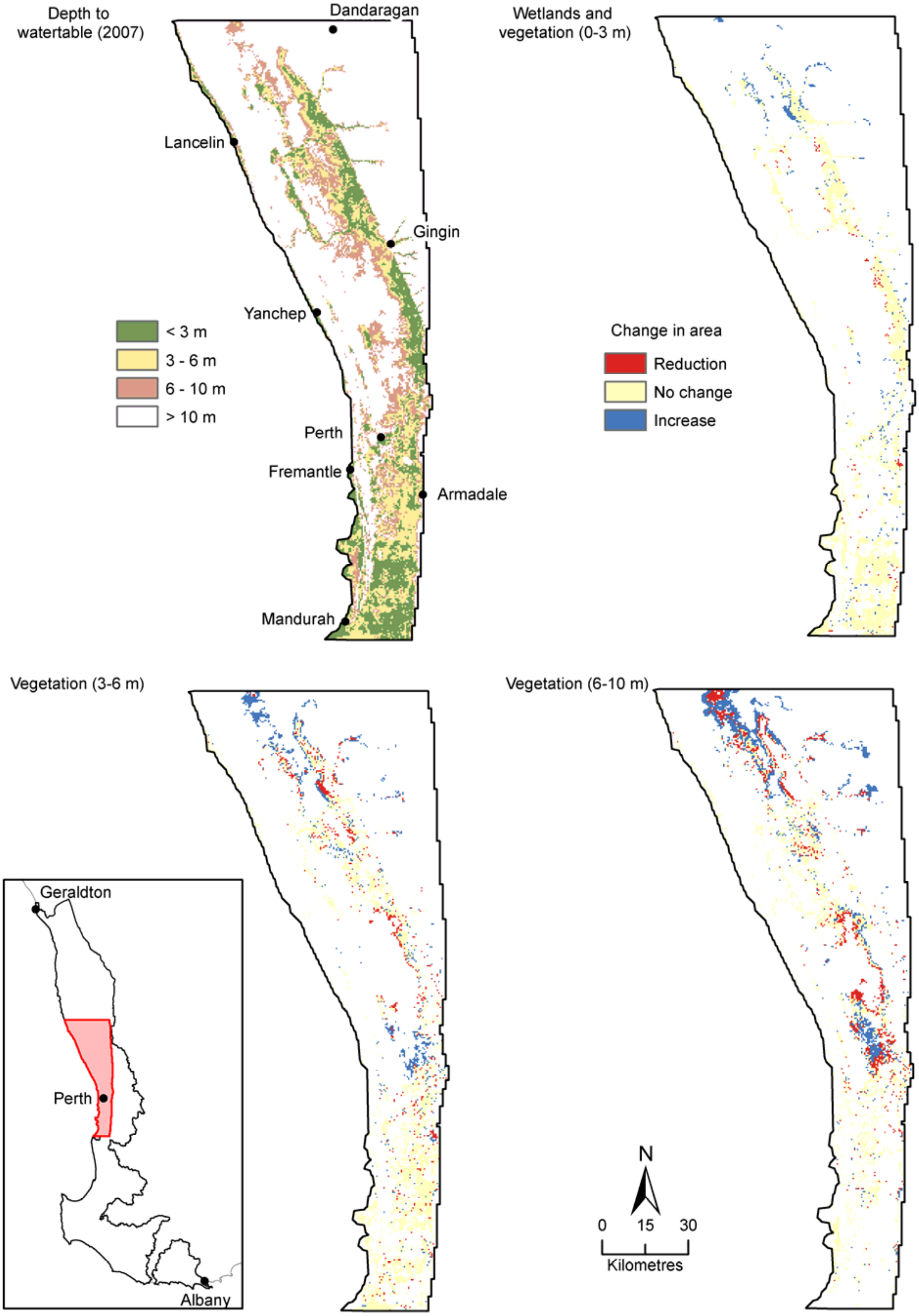

Figure 5-2. Depth to watertable (2007) and change in area associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario Cmid

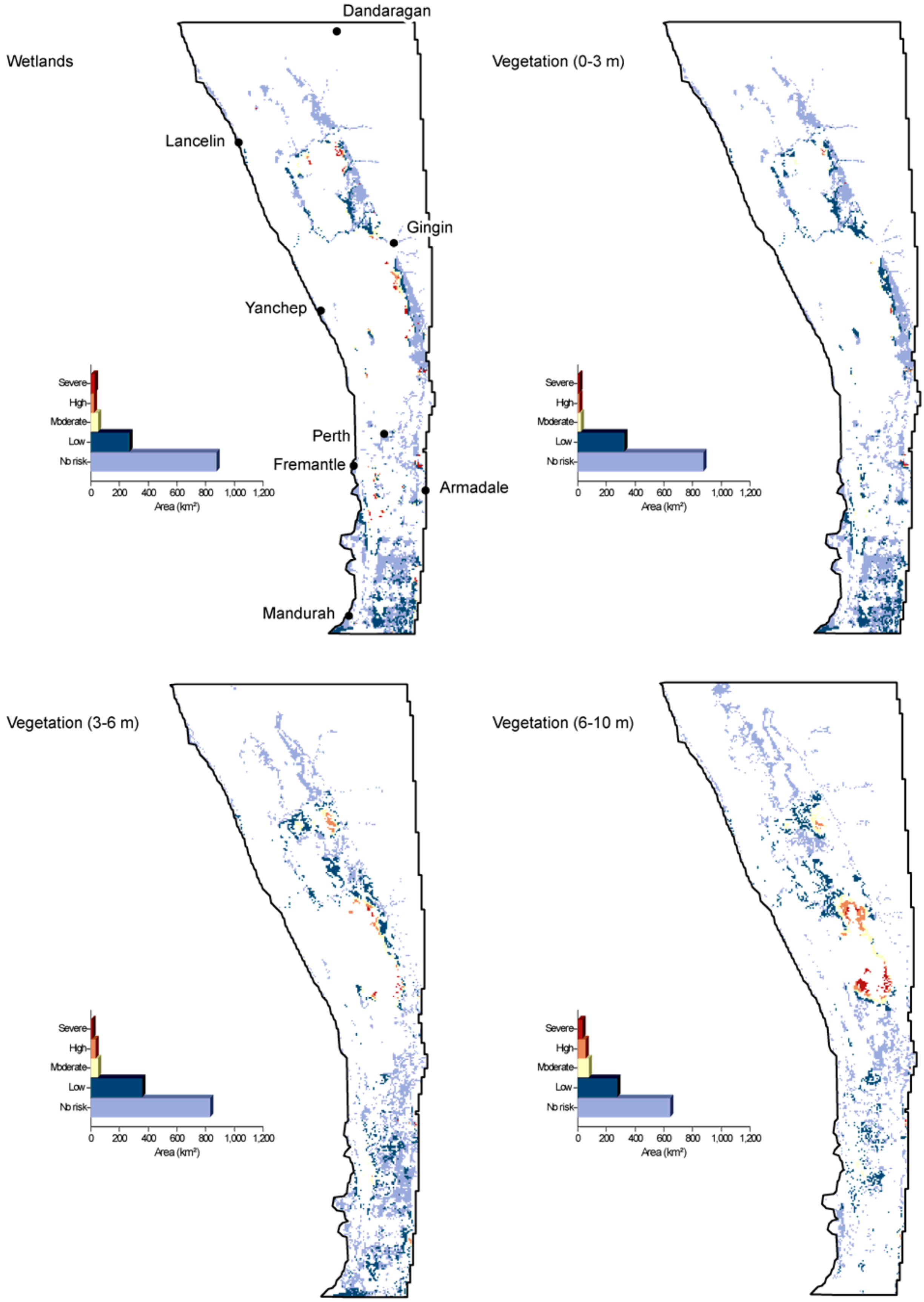

Figure 5-3. The risk category associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario Cmid

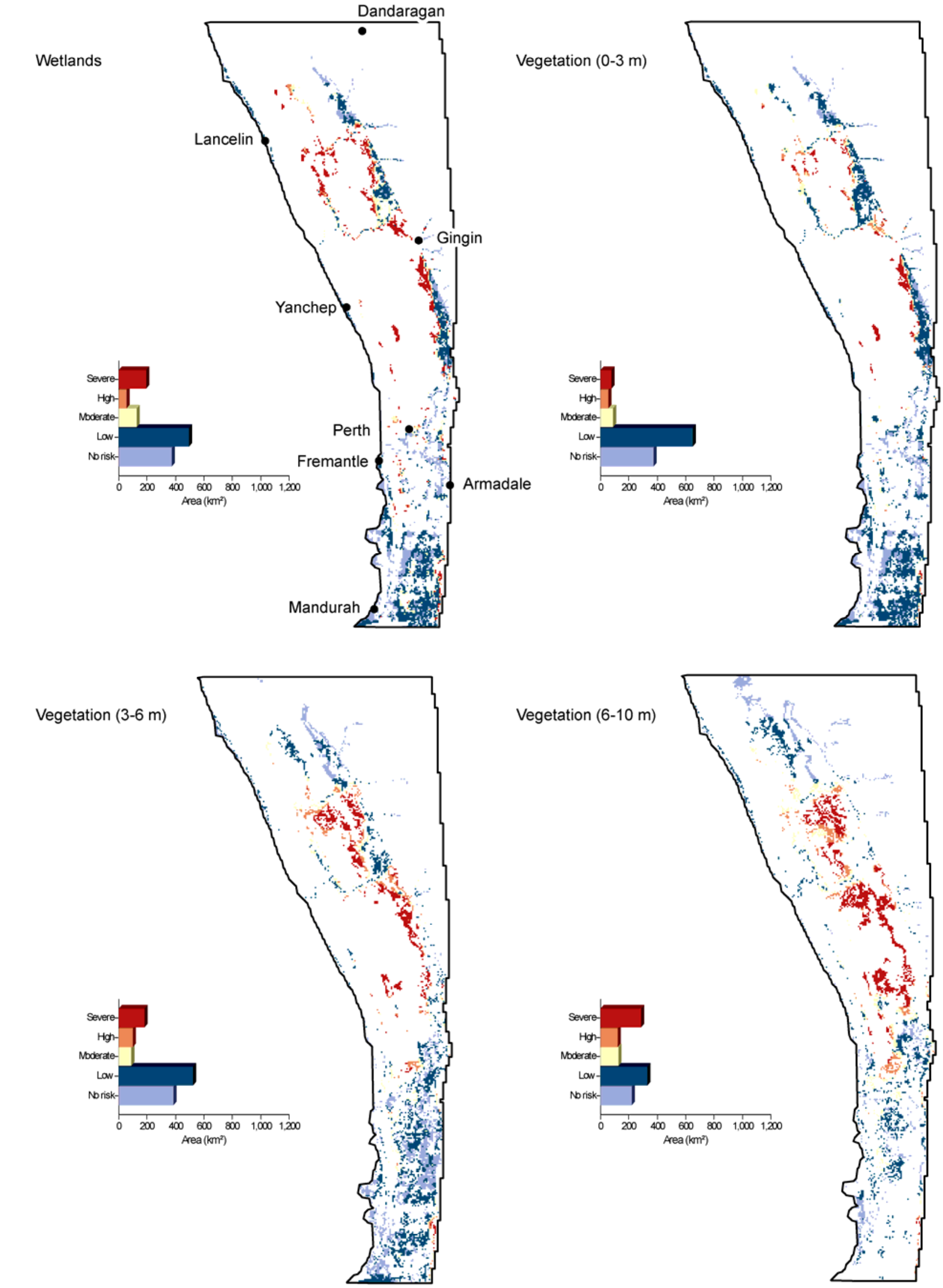

Figure 5-4. The risk category associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario Cdry

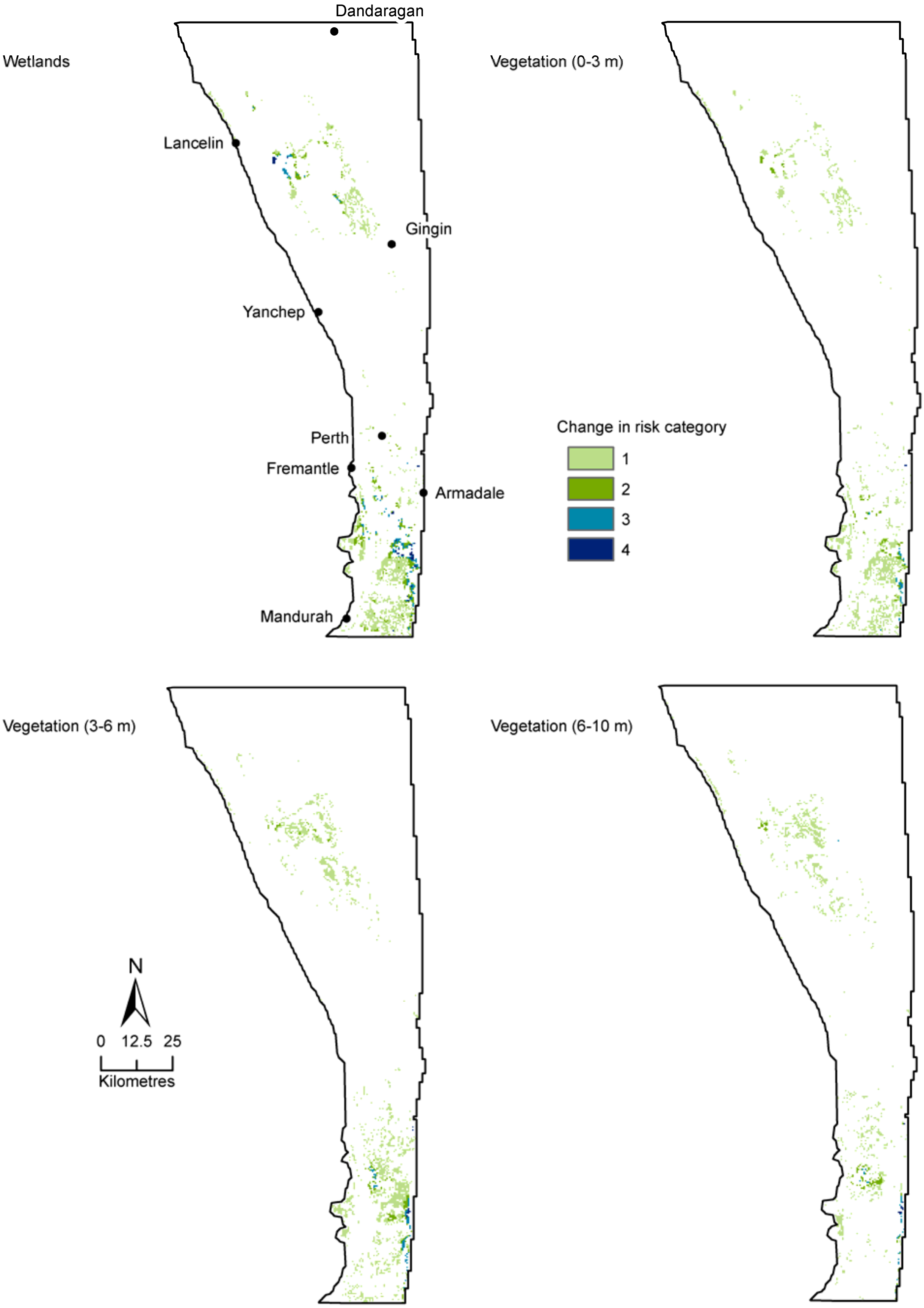

Figure 5-5. Change in risk category for each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario D

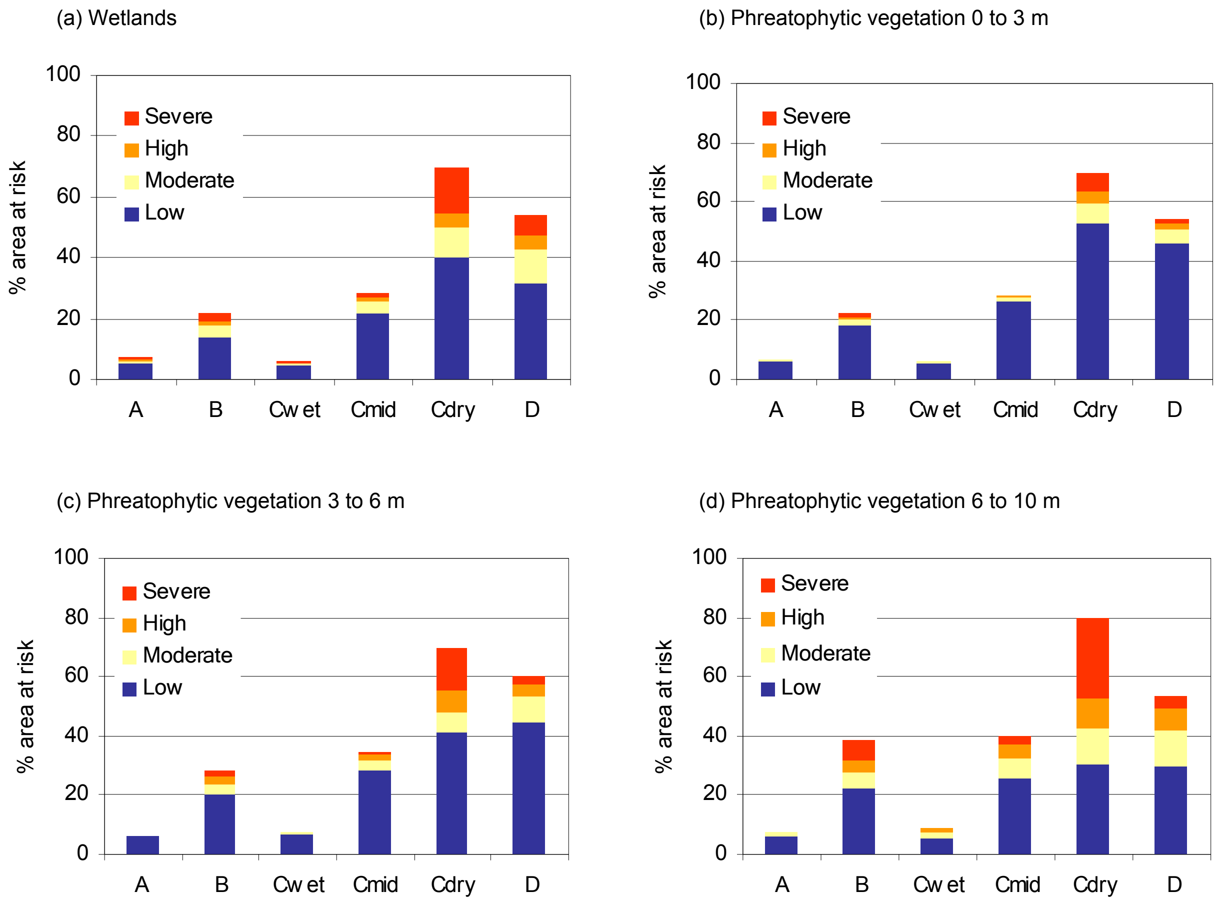

Figure 5-6. Percentage of total area in specified risk category for each type of groundwater dependent ecosystem in the Central Perth Basin: (a) wetlands, and phreatophytic vegetation with depths to watertable of (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m

5.5.2 Caves

In the Central Perth Basin area there are a number of caves (Figure 5-7) listed in the Australian Government National database TOPO 250K and in Yesertener, 2006. Groundwater hydrographs were derived from the groundwater model for the locations of individual caves as identified by the database (Figure 5-8). Climate impacts on groundwater levels are low where the areas are within high transmissivity limestone and close to the ocean (Figure 5-8(a)). The range of the groundwater level variations at these locations is low for both the historical climate (1975 to 2007) and most climate scenarios. If these future hydrograph are accurate, these caves are at a lower risk from climate change and abstraction than those located further south.

The effect of climate on groundwater levels is greater, where caves occur at a high elevation and likely to be within groundwater recharge zone, and is lesser, where caves occur at a low elevation and likely to be within groundwater discharge zone. As shown in Figure 5-8(b–d), during the last decade there has been a noticeable decline in groundwater levels in the vicinity of the caves and water level appears to fall between 1 and 2.5 m. Similar impacts are likely under scenarios B and Cdry. However under scenarios A and Cwet no further reduction in groundwater level is expected. This area is considered to have a moderate to high risk, particularly under Scenario Cdry.

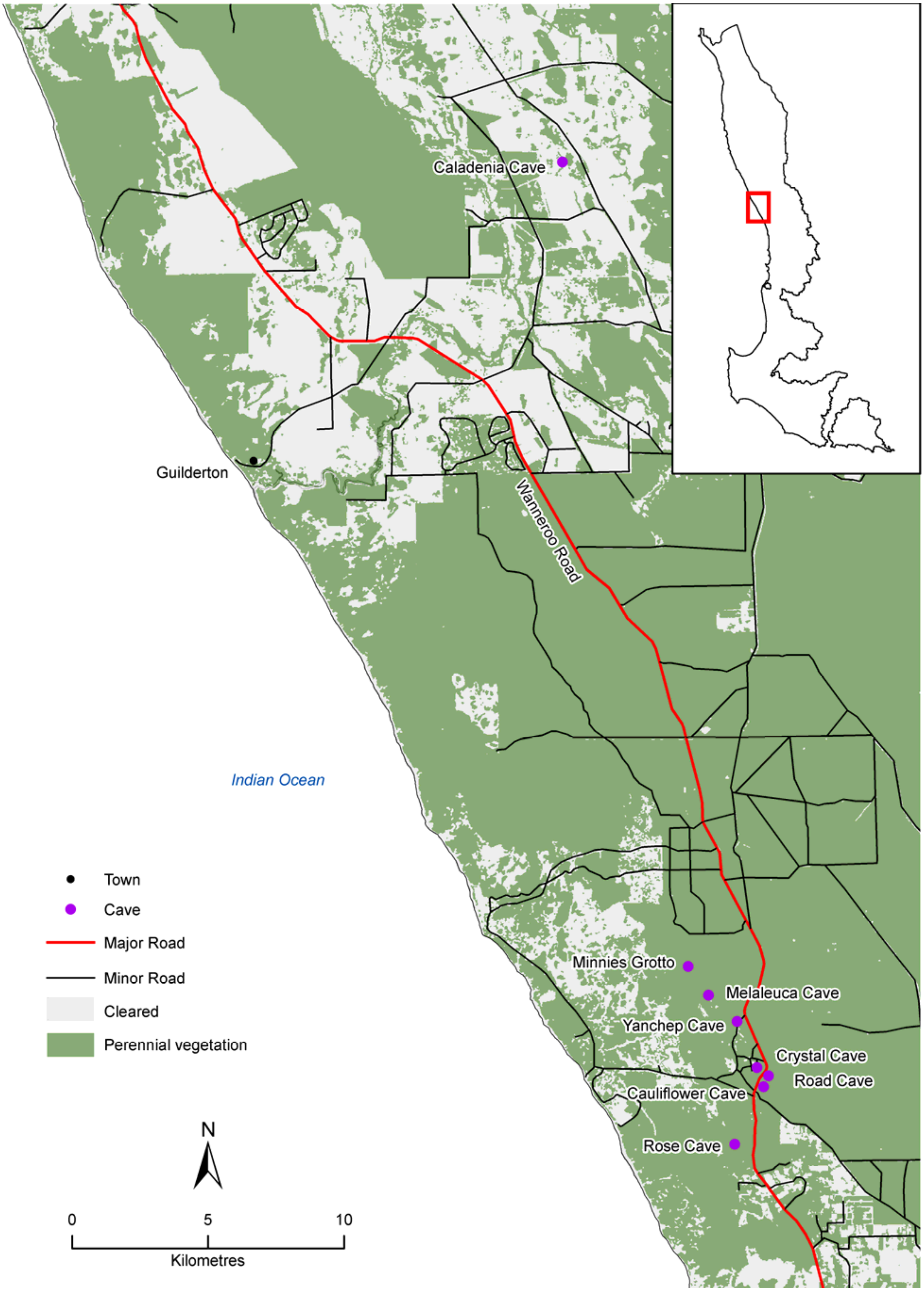

Figure 5-7. Location of caves in the Central Perth Basin

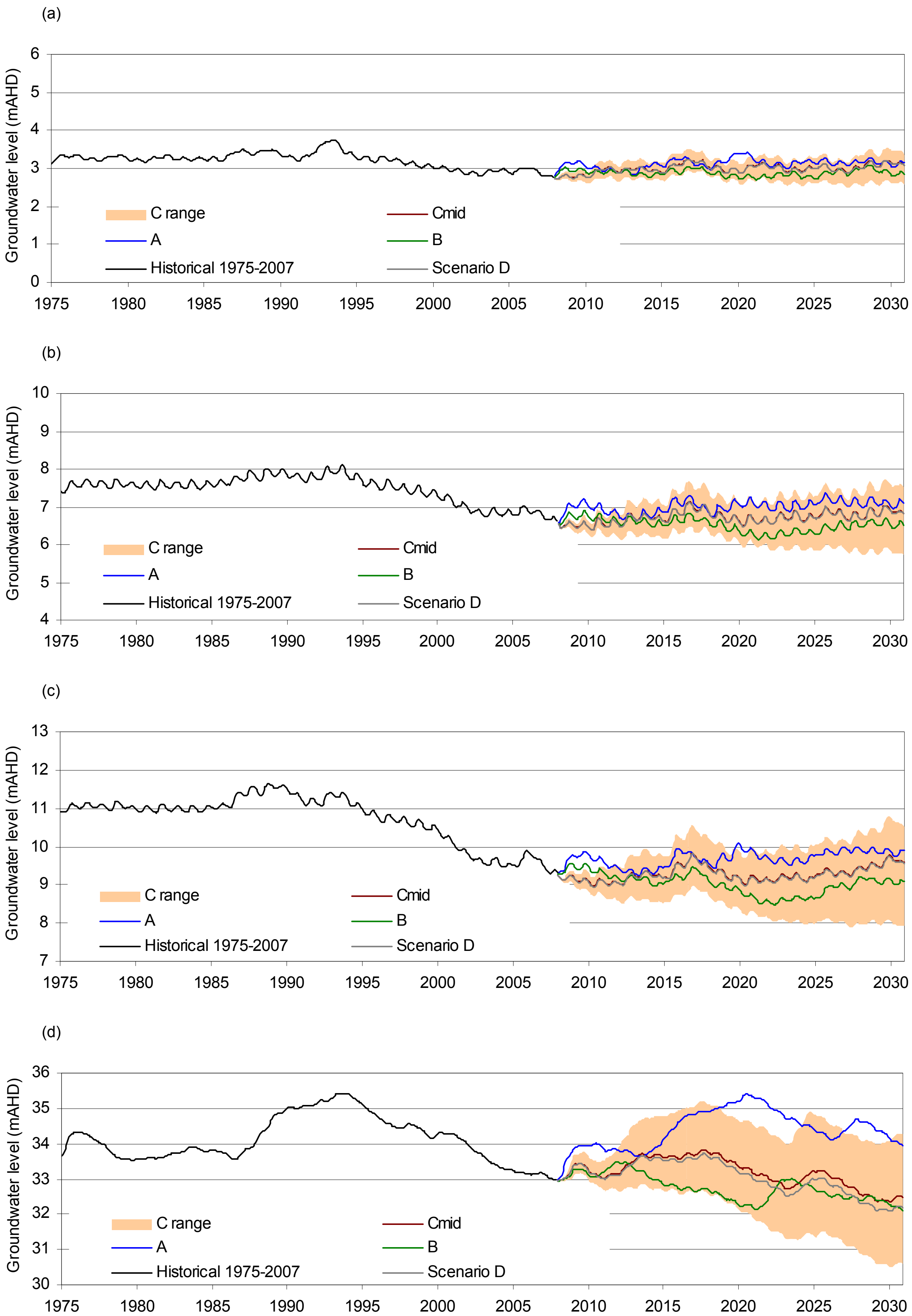

Figure 5-8. Observed and modelled groundwater hydrographs typical for (a) Melaleuca Cave, Road Cave and Minnies Grotto; (b) Yanchep Cave; (c) Cauliflower Cave, Crystal Cave and Rose Cave; and (d) Caladenia Cave

5.6 Risks to groundwater dependent ecosystems in the Peel-Harvey Area

Significant GDEs in the Peel-Harvey Area as shown in Figure 2-18 include a RAMSAR site (the Peel-Yalgorup System). The areas where various types of GDEs may potentially occur, based on the simulated minimum groundwater levels for 2007, are show in Figure 5-9. Land use is likely to have had a significant impact on GDEs ecological functions: the area is mostly cleared for agriculture as shown on Figure 2-16 (Chapter 2). Some remanent vegetation remains in the vicinity of coastal lake of the Peel-Yalgorup System.

The potential variation in the area of the four GDE types under Scenario Cmid is illustrated in Figure 5-9 and summarised in Table 5-4. The highest level of changes in GDE area is associated with GDEs with the shallowest groundwater (zero to 3 m depth to watertable). A loss of 65 km^2 in the area where wetlands may occur under this scenario is possible. There may also be a loss of about 18 km^2 in areas with a depth to watertable of 3 to 6 m and a net loss of 7 km^2 of areas with 6 to 10 m depth to watertable, but overall there may be net gains of these areas with 65 km^2 and 18 km^2 area increase respectively.

Table 5-4. Changes in the areas associated with groundwater dependent ecosystems in the Peel-Harvey Area under Scenario Cmid

	Phreatophytic vegetation in the area with the specified depth to watertable		
	zero to 3 m	3 to 6 m	6 to 10 m
Area in 2007 (km^2)	973	512	170
Area in 2030 (km^2)	909	559	181
Reduction in area between 2007 and 2030 (km^2)	65	18	7
Increase in area between 2007 and 2030 (km^2)	0	65	18
Area unchanged between 2007 and 2030 (km^2) and % total area in 2007	909 (93%)	494 (97%)	163 (96%)

As shown in Figure 5-10 and Table 5-5, though there is overall high percentage of the area with potential ecological risks for all considered GDEs (more than 80 percent of the area), the dominant risk category is 'low'. Only areas, where wetlands may potentially occur, have a high to severe ecological risk, but within a limited area (3 percent). Moderate risk for this GDE type is associated with 11 percent of identified area with potential wetlands occurrence. High and severe risks are not expected for other GDEs classes on a regional level. The wetlands overall has a much greater level of the ecological risks in this region (Figure 5-10).

Table 5-5. Percentage of total area with groundwater dependent ecosystems in the specified risk category in the Peel-Harvey Area under Scenario Cmid

Risk category	Wetlands		Phreatophytic vegetation in the area with the specified depth to watertable					
			zero to 3 m		3 to 6 m		6 to 10 m	
	Total area (%)	Total area	Total area (%)	Total area	Total area (%)	Total area	Total area (%)	Total area
Severe	1%		0%		0%		0%	
High	2%		0%		0%		0%	
Moderate	11%		1%		1%		4%	
Low	69%		81%		79%		93%	
No risk	18%		18%		1%		3%	
Total area (km^2)		973		973		512		170

Overall the risk to GDEs under Scenario Cmid is dominated by 'low' risk category with the exception to the areas near Harvey and further north. Similar effects were associated with Scenario A and B (Appendix D). Cwet scenario causes even lesser risk with areas unaffected are more than 60 percent for phreatophytic vegetation with a depth to watertable of 3 to 6 m and 6 to 10 m depth to watertable (Figure 5-13). The potentially affected area covers in the eastern and central part of region, including area of the Peel-Yalgorup System.

The effect of the driest future climate scenario is most evident for wetlands areas (Figure 5-11), where severe and high risk area increases from 3 percent (Cmid) to 11 percent (Cdry), which moderately affected area increase from 11 percent (Cmid) to 21 percent (Cdry).

The effect of the increased groundwater abstraction up to the current Allocation Limits is greater for wetlands and phreatophytic vegetation with a depth to watertable of zero to 3 m, when the total area under ecological risk increases from 82 to 92 percent relative to Scenario Cmid (Figure 5-12 and Figure 5-13). Additionally area under high and severe risk increases for all GDE classes from virtually non-existing to 10-26 percent of the area (Figure 5-13). However the risk is likely to be low with 45 to 70 percent of the areas.

The rise in the risk level resulting from the increased groundwater abstraction is shown in Figure 5-13 and is particularly evident in the north-east and in the area of coastal lakes. Areas in the north-west have lower risks but may contain more important GDEs. In some areas the increase in abstraction results in a greater increase in ecological risk than changes under the climate scenarios.

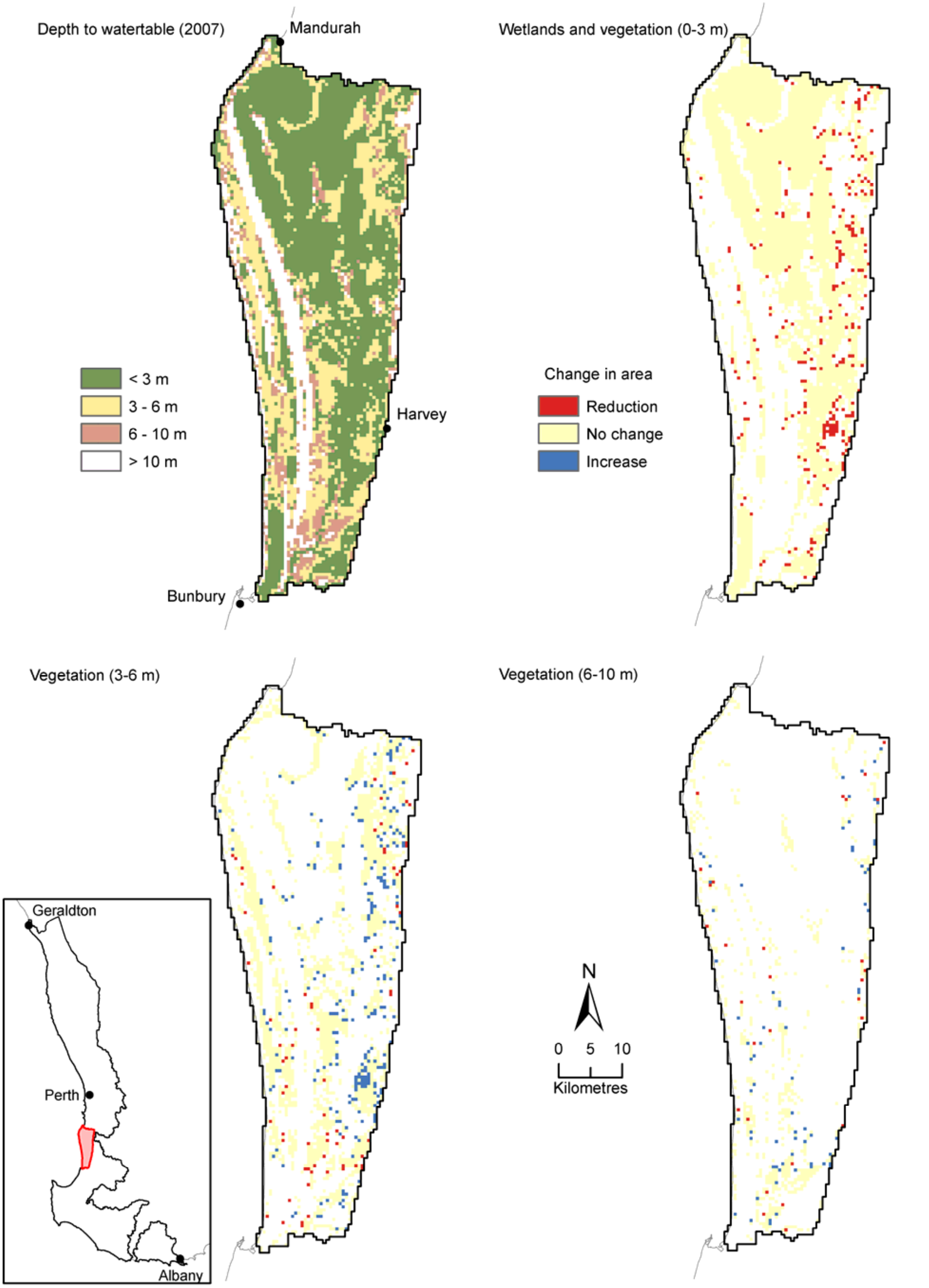

Figure 5-9. Depth to watertable (2007) and change in area associated with each type of groundwater dependent ecosystem in the Peel-Harvey Area under Scenario Cmid

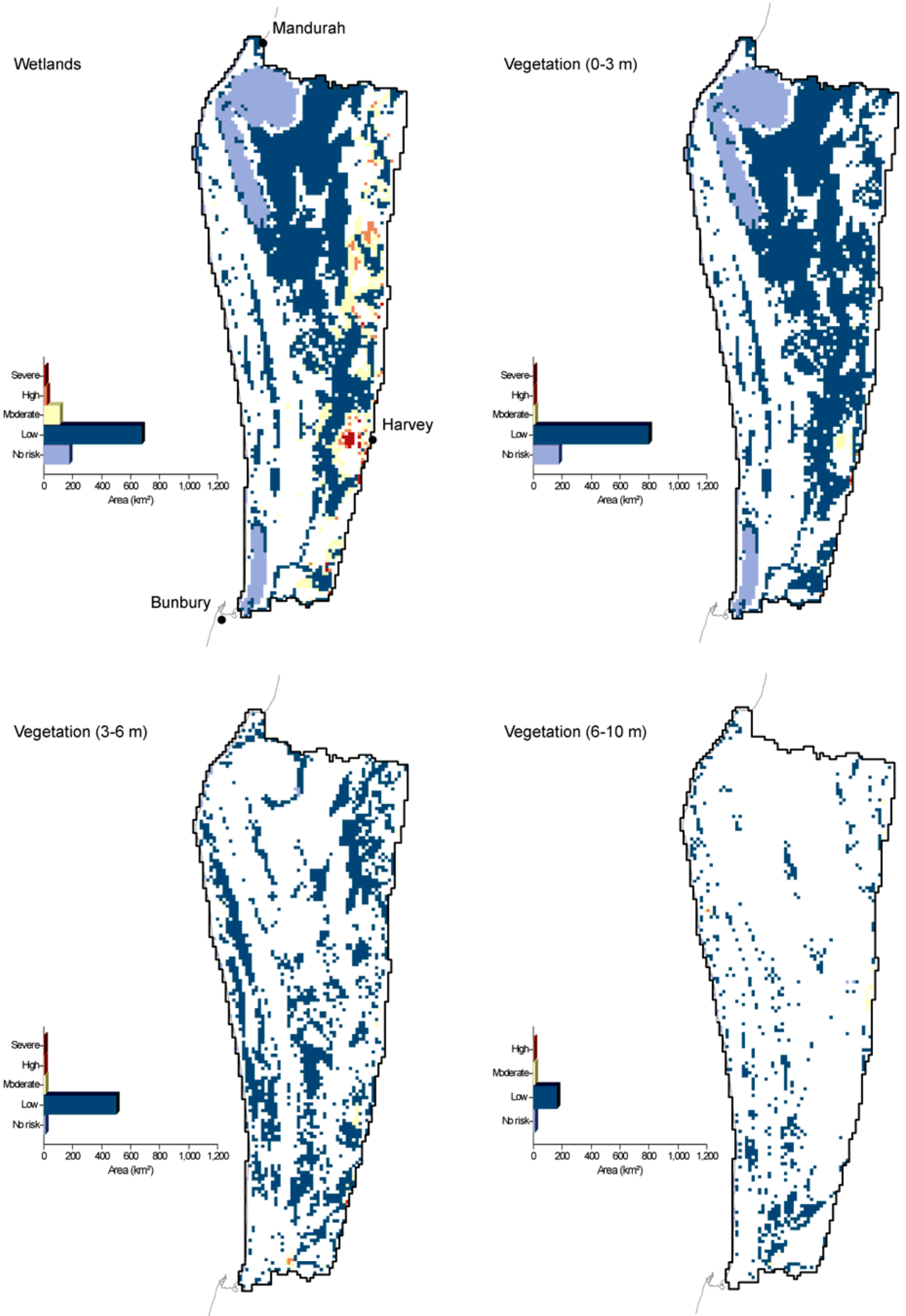

Figure 5-10. The risk category associated with each type of groundwater dependent ecosystem in the Peel-Harvey Area under Scenario Cmid

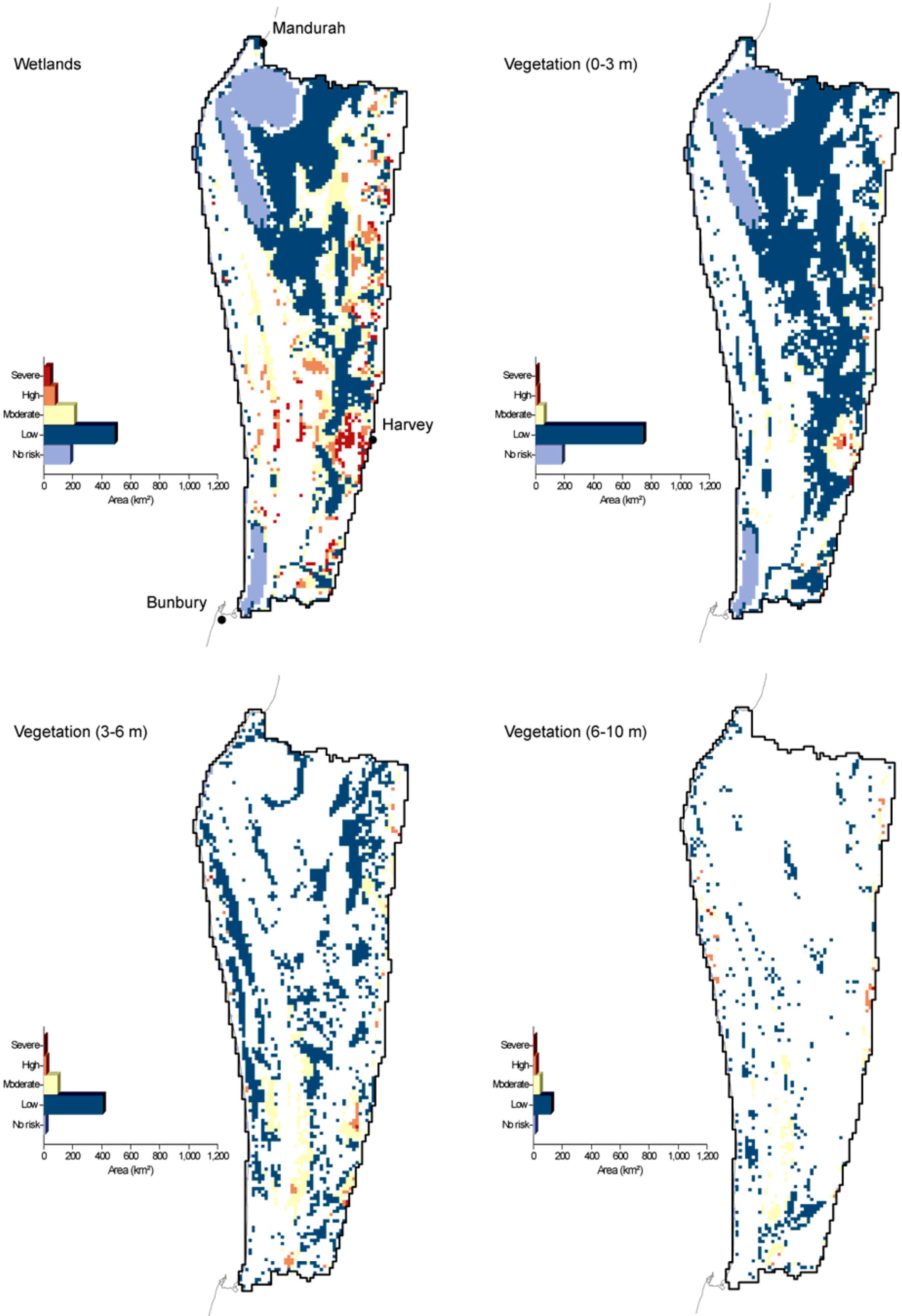

Figure 5-11. The risk category associated with each type of groundwater dependent ecosystem in the Peel-Harvey Area under Scenario Cdry

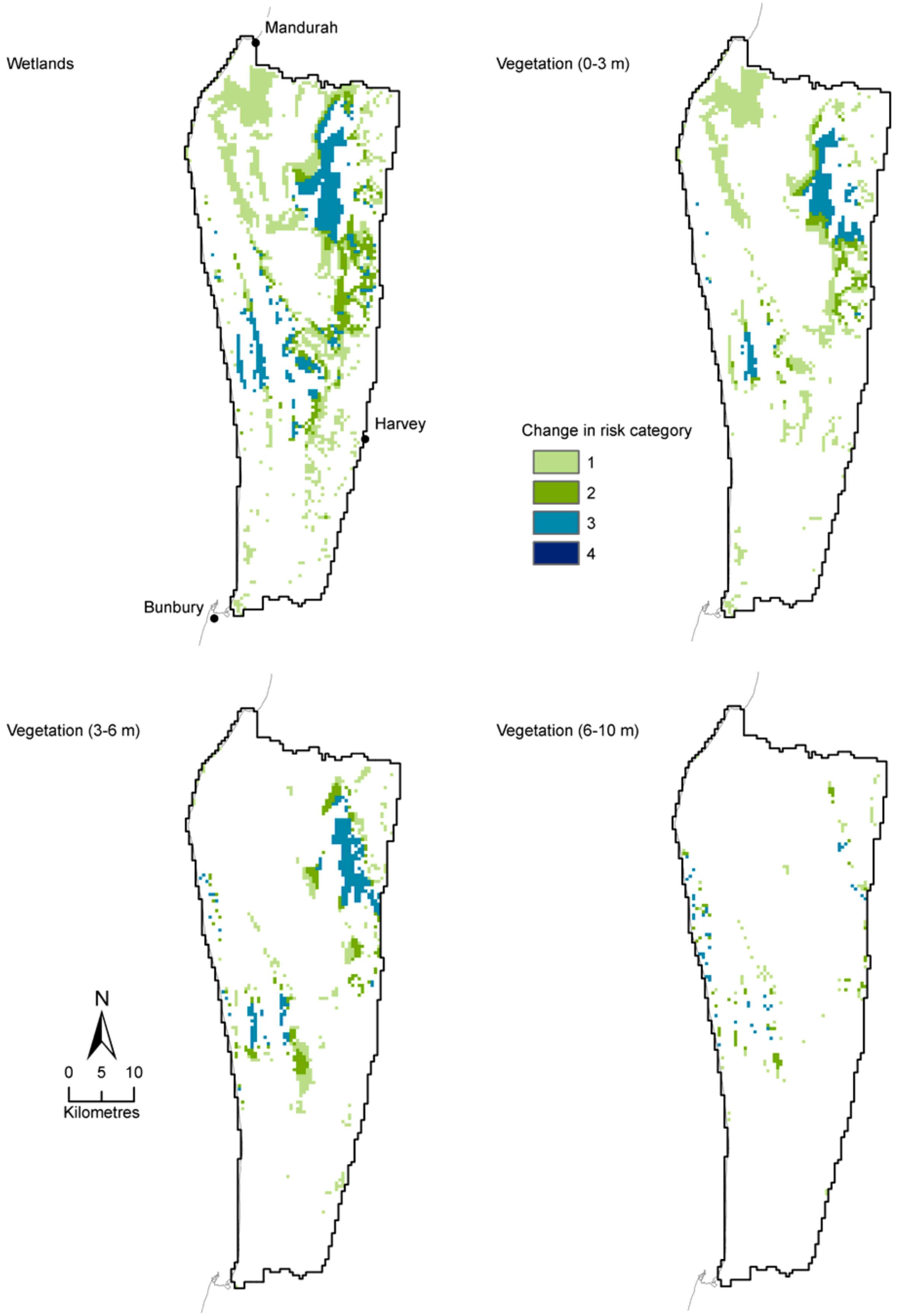

Figure 5-12. Change in risk category for each type of groundwater dependent ecosystem in the Peel-Harvey Area under Scenario D

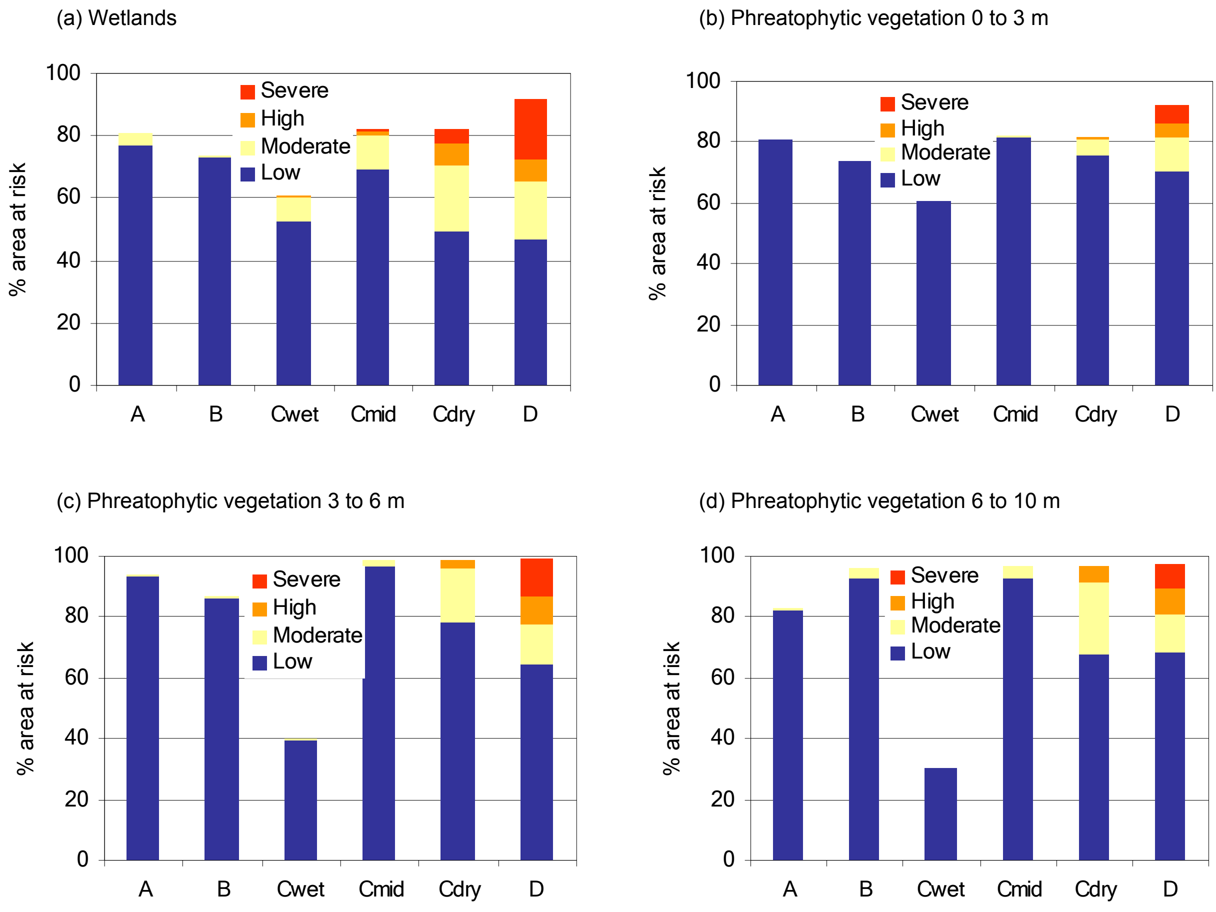

Figure 5-13. Percentage of total area in specified risk category for each type of groundwater dependent ecosystem in the Peel-Harvey Area: (a) wetlands, and phreatophytic vegetation with depths to watertable of (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m

5.7 Risks to groundwater dependent ecosystems in the Southern Perth Basin

Significant water dependent ecosystems in the Southern Perth Basin are also shown in Figure 2-18, including the Ramsar-listed Vasse-Wonnerup System. The areas where GDEs may potentially occur, are illustrated in Figure 5-14 and are based on the simulated minimum groundwater levels for 2007. Land use is likely to have had a significant impact on GDEs ecological functions coastal plains areas, which are mostly cleared for agriculture as shown on Figure 2-16 (Chapter 2).

The potential changes in the area of the four GDE types under Scenario Cmid are shown in Figure 5-14 and summarised in Table 5-6. This shows that a loss of 298 km^2 of the area where wetlands may potentially occur (zero to 3 m depth to watertable) under Scenario Cmid is possible with most of this loss being in the Scott Coastal Plain but also with losses on the Blackwood Plateau. There will also be a loss of about 445 km^2 in areas with a depth to watertable of 3 to 6 m and a loss of only 541 km^2 of areas with 6 to 10 m depth to watertable. As in other regions losses in one depth category are gained in the area of the GDE type dependent on a deeper groundwater levels. When net changes in areas are considered the net losses are only associated with the area with depth to watertable less than 3 m. Other areas are likely to experience the net gain in areas with relevant GDEs.

The ecological risk maps for each GDE type under Scenario Cmid are given in Figure 5-15 and further summarised in Table 5-7. These show that more than 90 percent of areas where wetlands and phreatophytic vegetation with depth to watertable less than 6 m may have no ecological risk. The areas where some ecological risk occurs are in the western and eastern parts of the Scott Coastal Plain. Overall the relatively higher risk is associated with phreatophytic vegetation with depth to watertable 6 to 10 m, where 7 percent of area may be within severe or high risk category.

Table 5-6. Changes in the areas associated with groundwater dependent ecosystems in the Southern Perth Basin under Scenario Cmid

	Phreatophytic vegetation in the area with the specified depth to watertable		
	zero to 3 m	3 to 6 m	6 to 10 m
Area in 2007 (km^2)	1353	672	230
Area in 2030 (km^2)	1330	568	134
Reduction in area between 2007 and 2030 (km^2)	62	138	120
Increase in area between 2007 and 2030 (km^2)	39	34	24
Area unchanged between 2007 and 2030 (km^2) and % total area in 2007	1226 (91%)	270 (40%)	169 (73%)

Table 5-7. Percentage of total area with groundwater dependent ecosystems in the specified risk category in the Southern Perth Basin under Scenario Cmid

Risk category	Wetlands		Phreatophytic vegetation in the area with the specified depth to watertable					
			zero to 3 m		3 to 6 m		6 to 10 m	
	Total area (%)	Total area	Total area (%)	Total area	Total area (%)	Total area	Total area (%)	Total area
Severe	3%		2%		1%		6%	
High	1%		0%		1%		1%	
Moderate	1%		1%		1%		3%	
Low	3%		5%		6%		8%	
No risk	92%		92%		91%		82%	
Total area (km^2)		2768		2768		1071		1031

The wetlands that occur on the Swan Coastal Plain have a lower ecological risk, possibly because reductions in recharge are offset by reductions in both drainage and evapotranspiration.

Following the undertaken analysis it appears that under Scenario Cmid the area with identified ecological risks is lesser than for scenarios A for all considered GDE classes (Figure 5-18, and also Appendix D), but particularly for wetlands and phreatophytic vegetation with depth to watertable less than 3 m. This differ this region from the Central Perth and Peel-Harvey areas, where Scenario Cmid resulted in a slightly greater ecological risk than Scenario A. The least ecological risk is associated with Scenario Cwet (Appendix D), when overall less than 10 percent of the areas where GDEs may potentially occur are at risk.

As for the Central Perth Basin and the Peel-Harvey Area, Scenario Cdry has the most profound changes in groundwater levels (Figure 2-23, Chapter 2). This identifies the maximum ecological risk to GDEs in the Southern Perth Basin (Figure 5-16) with the highest percentage of the area at risk of severe and high category at 31 percent of area with wetlands and phreatophytic vegetation with depth to watertable zero to 3 m, 28 percent of areas with phreatophytic vegetation with depth to watertable 3 to 6 m and 41 percent of area with phreatophytic vegetation with depth to watertable 6 to 10 m (Figure 5-18).

It is important to mention here that despite this the total area of all risk categories (from low to severe) is greater for Scenario B (Figure 5-18), but in this case the area under low ecological risk dominates.

In this region the potential effect of increased groundwater abstraction on GDEs is less than the effect of the driest climate scenario. However the risk is still greater than under Scenario Cmid. The potentially affected area has approximately doubled relative to Scenario Cmid for all GDEs types, The greater increase in the level of ecological risk is associated with wetlands under severe risk (from 1 to 7 percent) (Figure 5-17). The increase in the risk level resulting from the groundwater abstraction is particularly evident south of Bunbury, east of Busselton and in the eastern part of the Scott Coastal Plain.

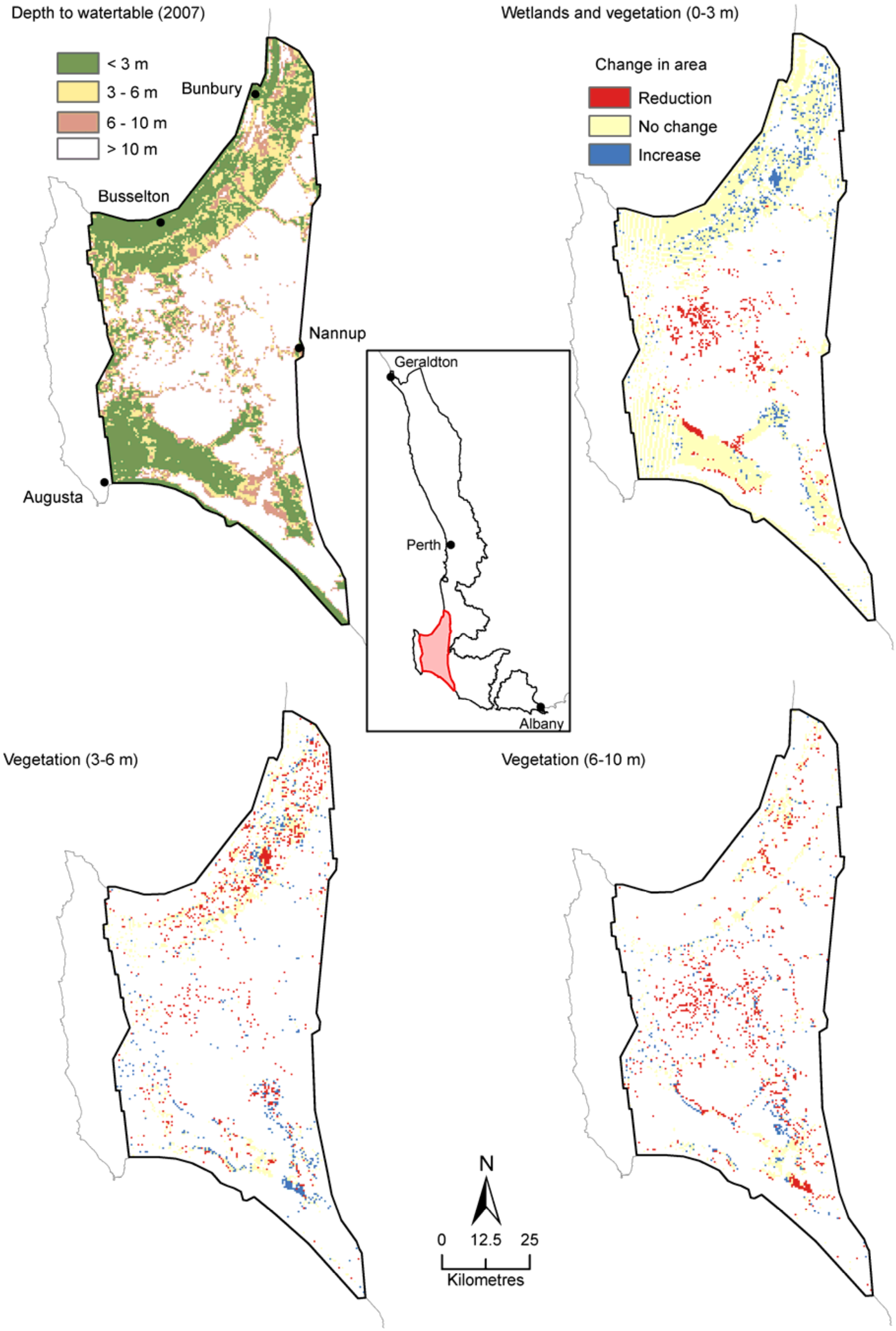

Figure 5-14. Depth to watertable (2007) and change in area associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario Cmid

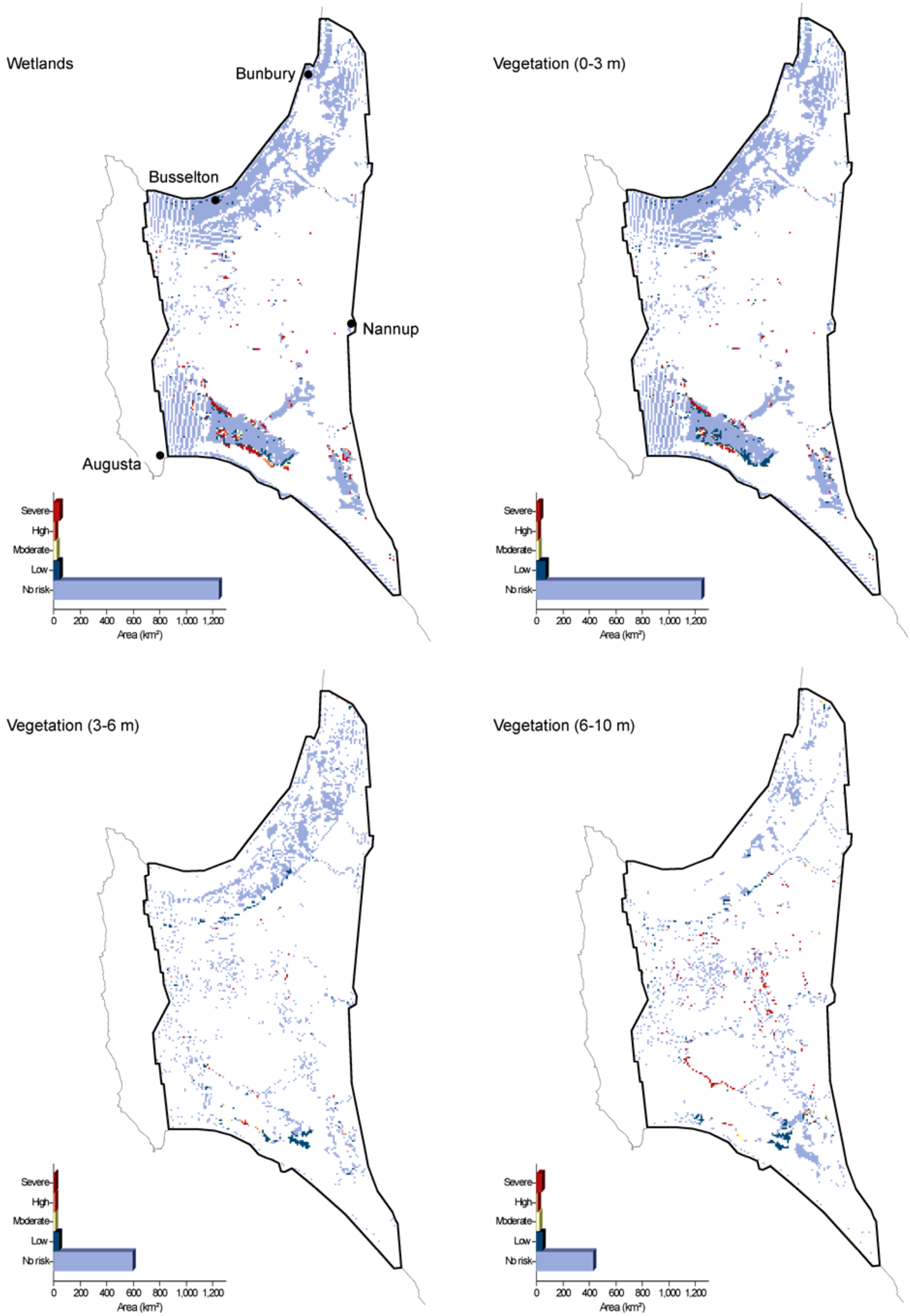

Figure 5-15. The risk category associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario Cmid

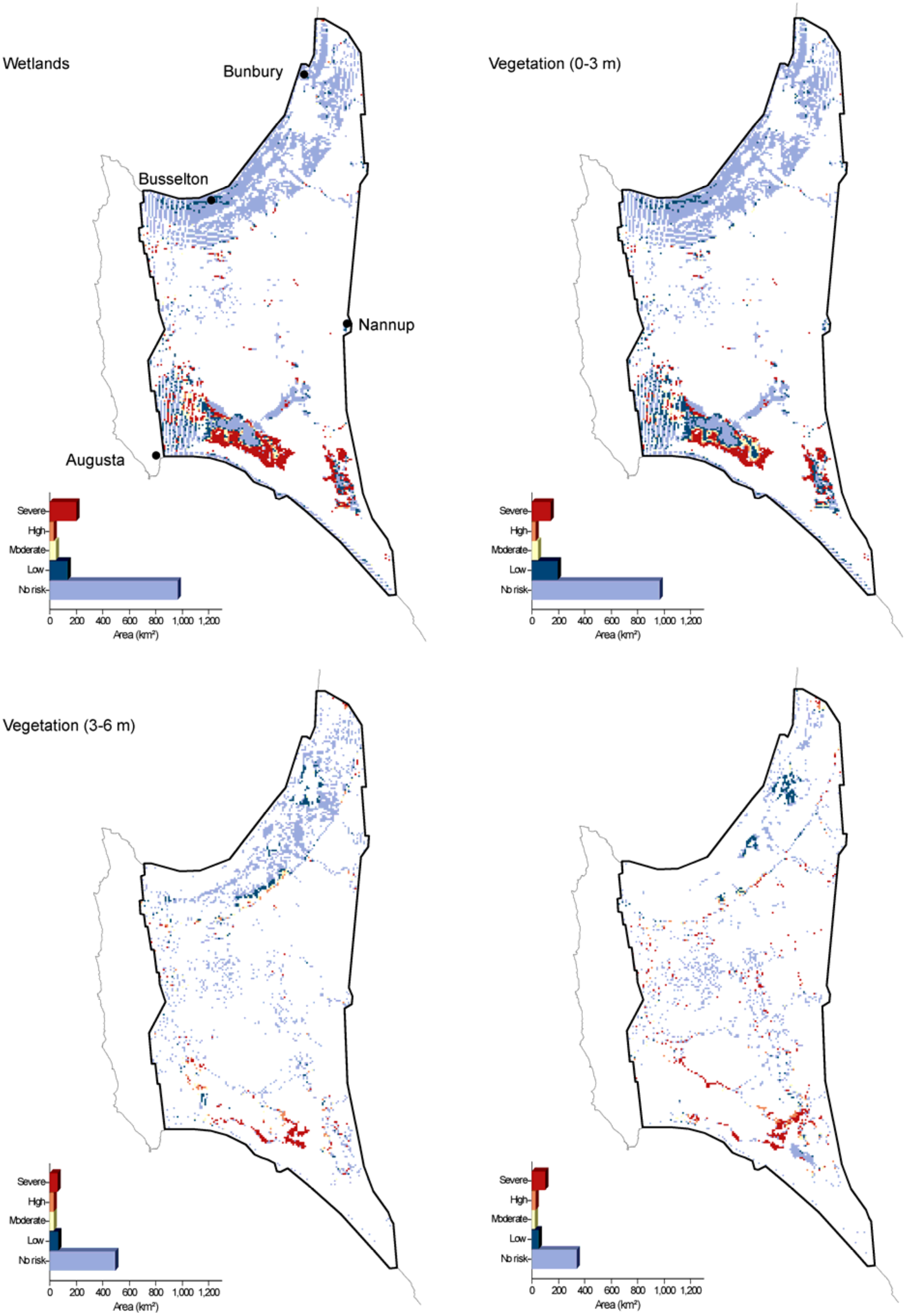

Figure 5-16. The risk category associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario Cdry

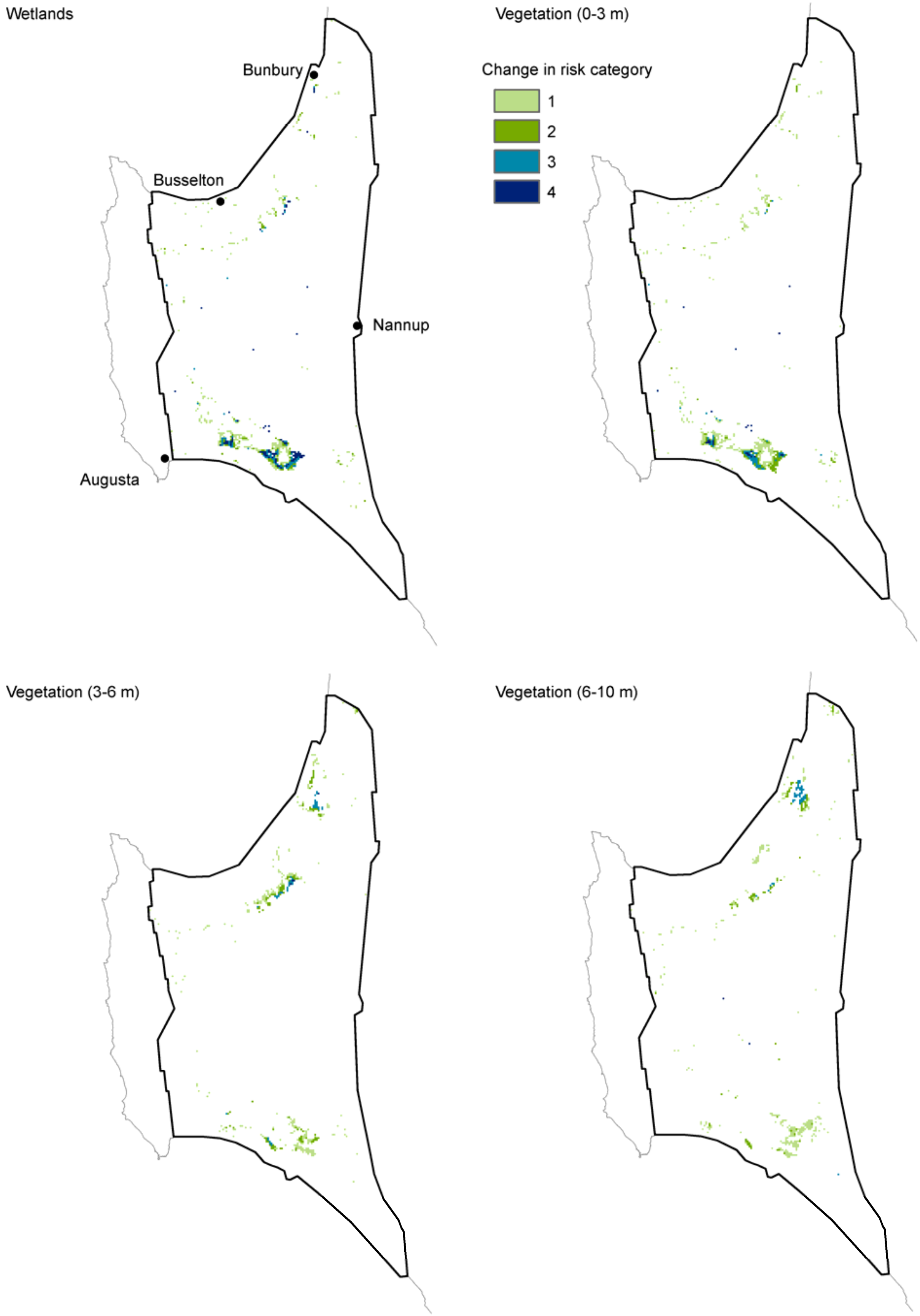

Figure 5-17. Change in risk category for each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario D

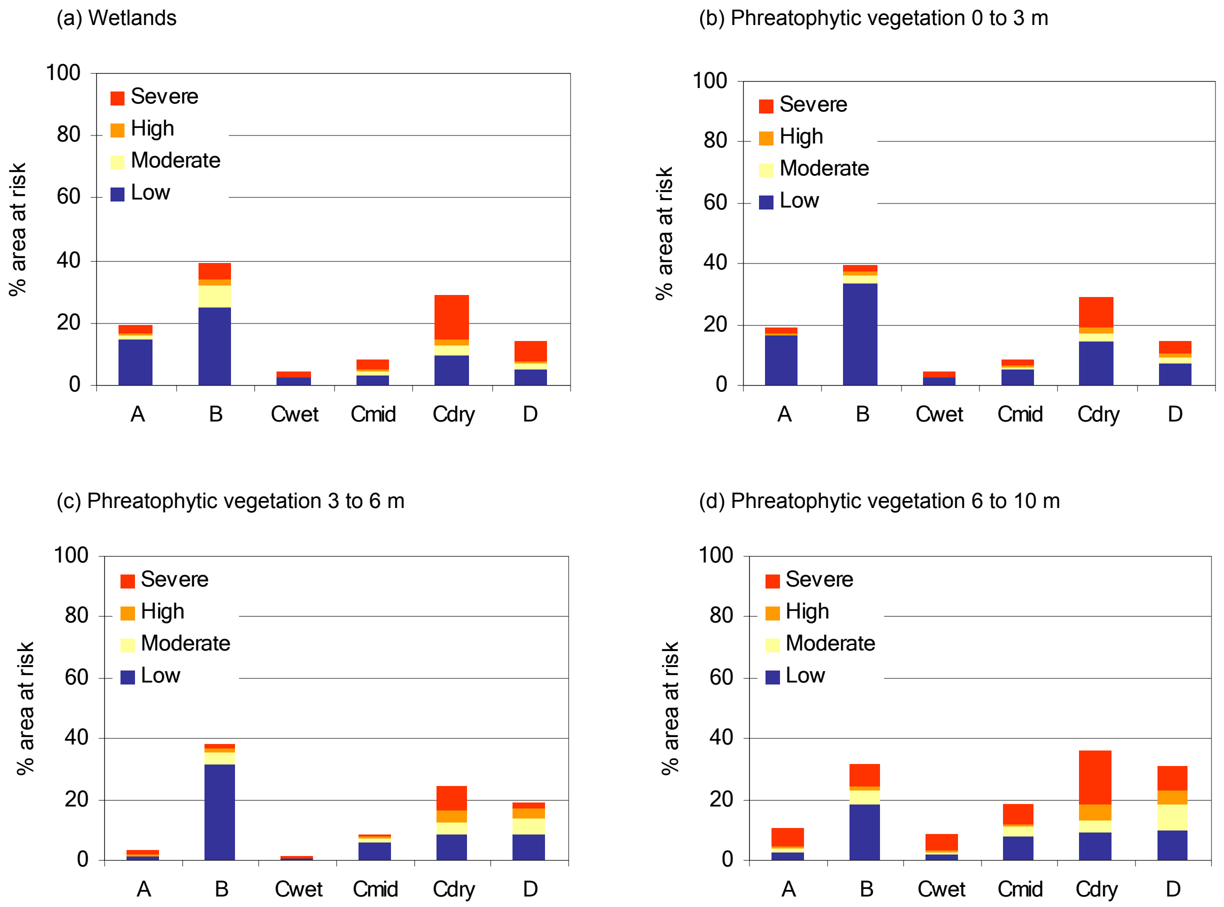

Figure 5-18. Percentage of total area in specified risk category for each type of groundwater dependent ecosystem in the Southern Perth Basin: (a) wetlands, and phreatophytic vegetation with depths to watertable of (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m

5.8 Northern Perth Basin and the Albany Area

Since groundwater models were not available for the Northern Perth Basin and Albany Area, WAVES modelling and statistical analysis of hydrographs of representative bores was used to assess the impact of future climates on recharge and groundwater levels respectively. The outcomes are briefly described below.

5.8.1 Northern Perth Basin

The Northern Perth Basin has a number of very important aquifers, especially the Yarragadee, Leederville-Parmelia and Superficial aquifers (CSIRO 2009). They are under-utilised at present with only 41 percent or 125 GL/year out of 302 GL/year being licensed for use. The watertables are often more than 10 m below the ground surface and locally known to be rising under dryland agricultural land uses. The basin had a series of very low rainfall years during the recent (1997 to 2007) period, but also occasional heavy summer or autumn rainfalls and it is unclear if groundwater levels will continue to rise if these conditions persist.

The WAVES model indicates that recharge is likely to reduce substantially if the future climate is hotter and drier than at present. For example, under Scenario Cmid, groundwater recharge in the area with annual crops and pastures may reduce by 15 and 25 percent in the Geraldton and Three Springs climate zones respectively (CSIRO 2009). Under Scenario Cdry, the groundwater recharge reduction may be 40 and 66 percent respectively and recharge would cease under deep-rooted grasses or trees.

Results of hydrograph analysis indicate that there are some geographic patterns to groundwater level trends in the region. Bores located in the north-west indicate few if any changes in groundwater levels by 2030. Bores in the mid-west indicate a slight decline in levels is possible under most scenarios. Only two locations (OB1-75 and EL1C) indicate strong rising trends over the historical (1975 to 2007) period and under most of scenarios (CSIRO, 2009).

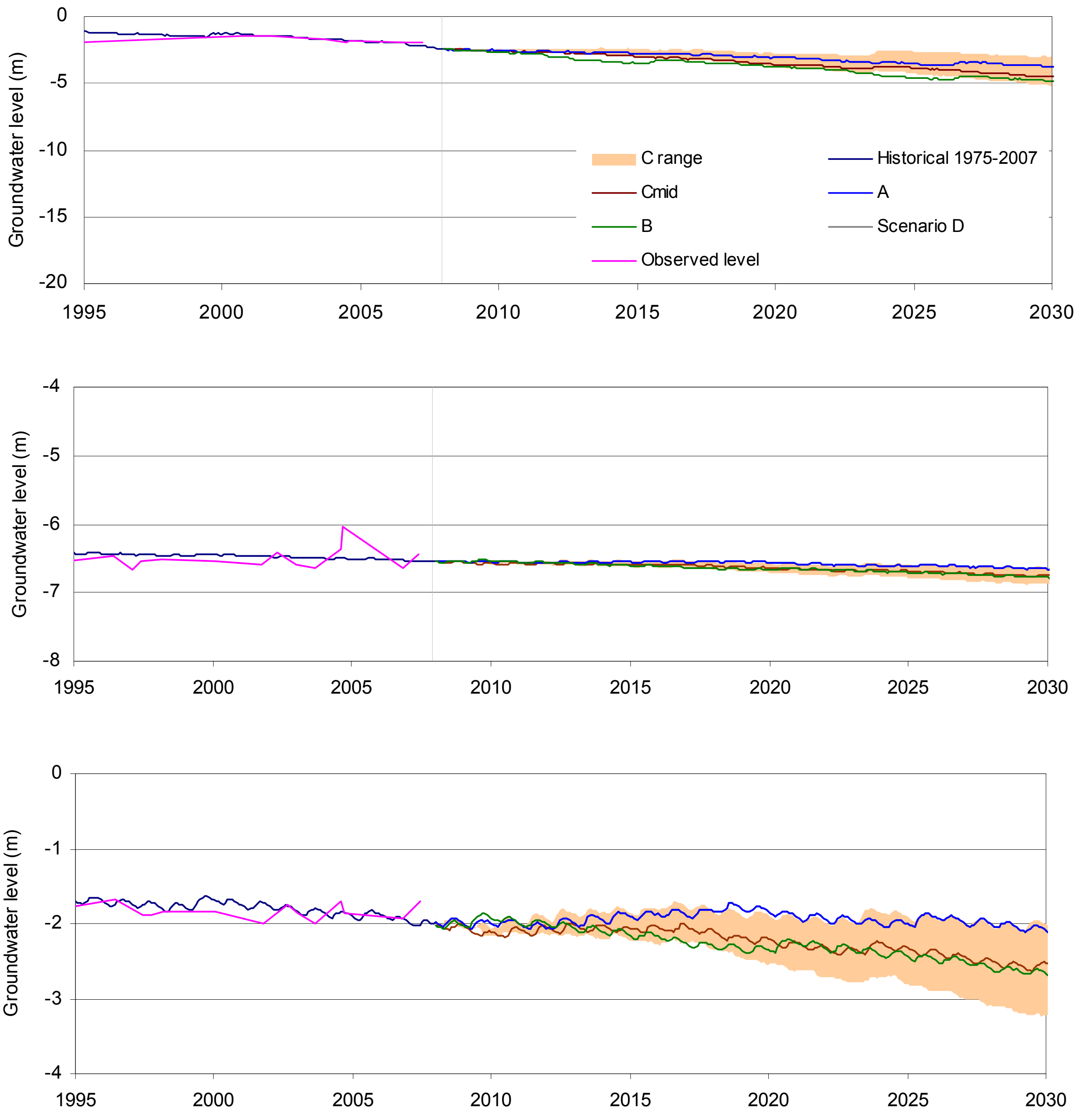

Figure 5-19. Observed and modelled hydrographs for bores in the Geraldton climate zone (LS31B) and the Lancelin and Geraldton Airport climate zones (LS18B, LS12A) in the Northern Perth Basin

However in the area where shallow groundwater (less than 10 m depth to watertable) was monitored, the hydrograph analysis indicates moderate watertable declines by 2030 under all scenarios (Figure 5-19). Watertable remains stable under scenarios A and Cwet (LS12A) and slightly decline under scenarios B, Cmid and Cdry. Under Scenario Cwet the watertable may decline by 0.5 m (LS31B) whereas under Scenario Cdry the watertable declines by 1 to 2 m. Under scenarios B and Cmid the downward watertable trends are similar.

Based on this limited information, it is unlikely that significant ecological risk for any GDE classes will occur if the historical climate (Scenario A) were to continue until 2030. Climate scenarios B, Cwet and Cmid show and increase in risk levels. Under Cdry climatic conditions the GDEs ecological risk is likely to be high. Increases in groundwater abstraction may increase these risks further but it was not feasible to evaluate Scenario D without a groundwater model.

5.8.2 Albany Area

The Albany Area groundwater resource is very valuable for supplying the City of Albany and surrounding areas but it is technically over allocated if all used and reserved water is considered.

The recent climate in the Albany Area (1997 to 2007) is only about 3 percent drier than the historical climate (1975 to 2007) whereas estimates of future climate indicate that the rainfall near the coast could decline by about 10 percent (range of 4 to 15 percent) (CSIRO, 2009). Scenarios A and B are wetter in comparison to Scenario C for all bores. In the absence of a suitable groundwater model, estimates of the impact of a hotter, drier climate on recharge indicate that there could be a decrease of about 35 percent (range of 19 to 49 percent) under deep-rooted trees on the coast in areas where the current wellfields exist. Thus for every 1 percent reduction in rainfall, recharge may reduce by 3 to 5 percent.

Hydrograph analyses for selected bores, where the depth to watertable is currently within 10 m of the ground surface, shows an overall falling trends under all climate scenarios apart from Scenario A, when almost no changes occur. A 1 m greater decline is expected under Scenario B in comparison with Scenario A. The impact under Scenario Cwet is similar to that under Scenario B. Under the drier Scenario Cmid the groundwater level decline was estimated to be up to 5 m, while In the case of the driest scenario (Cdry) the greatest drawdown of up to 8 m is expected.

In summary, a more severe future impact under drier climate scenarios is expected for shallower groundwater systems where GDEs are more likely to occur. The analysis indicates that it is unlikely that significant ecological risk for any GDE classes occurs under Scenario A. Under Scenario B the risk level may potentially increase. However under scenarios Cwet, Cmid and Cdry the ecological risk to GDEs is likely to be high or severe.

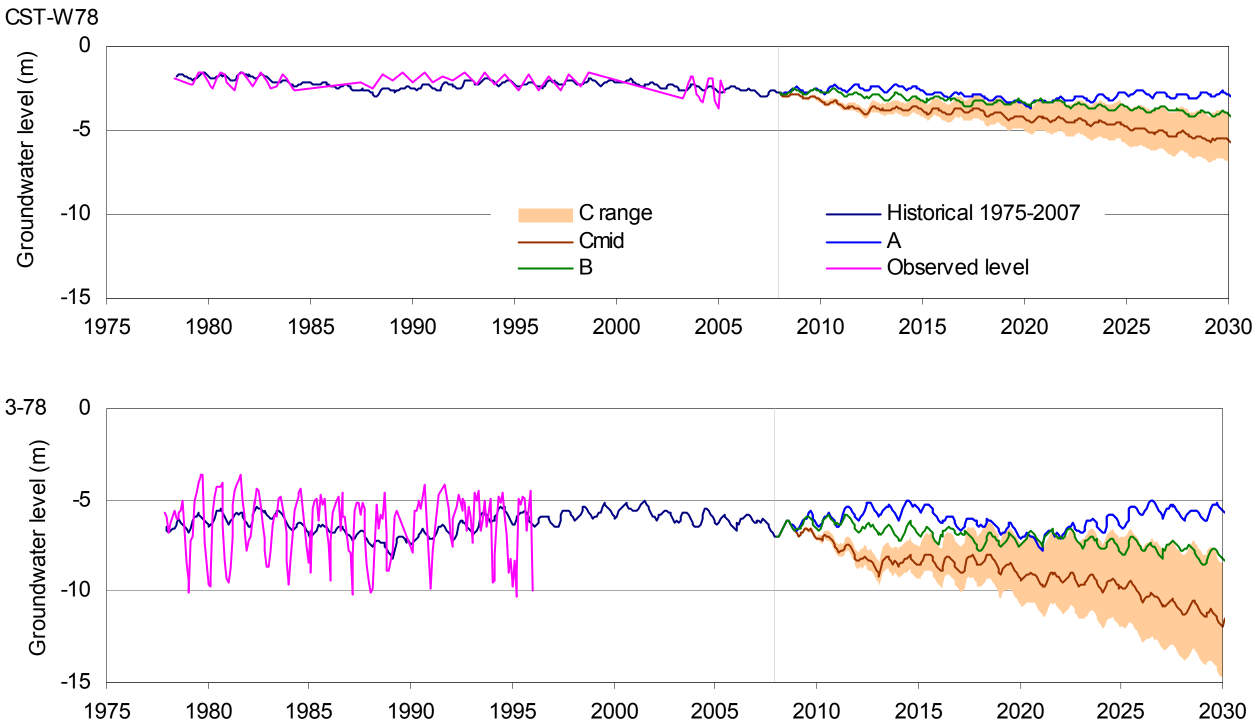

Figure 5-20. Observed and modelled hydrographs for bores in the Grassmere climate zone in the Albany Area

5.9 Confidence, variability and uncertainty

The main sources of uncertainty relate to the inherited modelling uncertainty, which includes estimates of the future climate as well as how well the groundwater models translate this into future groundwater levels, and limitation related to the risk analysis approach that was used.

5.9.1 Model uncertainties

The project assessed future groundwater levels under a number of scenarios and there is still uncertainty about the ability of global climate models to predict future conditions. Therefore extrapolations of past climates were included through scenarios A and B as well as outcomes of all available daily climate models (Scenario C).

The limitations of the groundwater modelling are discussed in details in Chapter 13 of the Groundwater Report (CSIRO, 2009), but in summary they are related to limitation in hydrogeological information available for some key area: along the Darling Scarp, in the western boundaries of the model as groundwater discharge area in the ocean; hydrogeological features of major fault systems and long term monitoring data of hydraulic heads and discharge surface water network. In addition there was a concern that the VFM modelling may have resulted in recharge rates that are high when compared with chloride and carbon-14 techniques.

A groundwater model will be developed for the Northern Perth Basin in 2010/11 so these estimates, especially the Vertical Fluxes Model (VFM) results, will be a useful input and the model can be used to test these estimates of the likely impact of climate and development on future groundwater levels.

Without a groundwater model it is difficult to check VFM estimates. The results were instead checked using the statistical hydrograph analysis and by comparing chloride concentrations in groundwater with estimates of rainfall chloride concentrations.

5.9.2 Uncertainty of the adopted risk assessment

The method used to assess the stress of lower groundwater levels on wetlands and groundwater dependent phreatophytic vegetation was based on results obtained in the Gnangara Mound area and extrapolated to the entire project area. At this stage it is not possible to estimate what level of uncertainty this induces to the analysis.

Simplification of water requirements into minimum depths to watertable without recognition of other hydrological variables important to the ecology of the system can lead to an underestimation of water requirements; for example duration, timing and rate of seasonal flooding/drying and the episodic nature of extreme flooding/drying events need to be considered in addition to just groundwater level. However the regional nature of the model characteristics may be too coarse for assessment of the climate impact on individual GDEs. No account was also taken of water quality and other factors that may affect the viability of GDEs.

5.10 Discussion

GDEs are diverse, uniquely adapted features of the Western Australian landscape which require careful water management practices for their retention and a continuation of the ecological services which they provide.

The reported results of undertaken analysis of climate and development effect on GDEs are based on the results of climate and groundwater modelling and as such they inherit the assumptions, limitation and uncertainty of relevant modelling briefly described in Sections 2.9.2. and 5.9 of this report and also in CSIRO, 2009 and Charles et al., 2010. The undertaken analysis is considered as a first approximation to the risk posed to GDEs from future climate scenarios and development, which aims to highlight potentially impacted areas relative to 2007. The adopted method used in this study determines "risk of impact" rather than potential impact: "severe risk" means there is a severe risk of any impact, not that the impact will be severe.

This analysis focuses on wetlands and three types of phreatophytic vegetation with the depths to watertable of zero to 3, 3 to 6 and 6 to 10 m. Currently the modelled area of the Central Perth Basin, Peel-Harvey Area and South Perth Basin, where wetlands can potentially occur, cover over 3540 km^2 of the area. The outcomes provide a quantitative indication of the potential pressures to ecosystems from climate and groundwater consumptive use in a regional scale. No individual GDEs were considered.

In the Central and Southern Perth basins high and severe ecological risks may occur over 17 to 19 percent of areas where wetlands can potentially occur under Scenario Cdry. The main risks in the Central Perth Basin are on the Gnangara Mound and Darling Scarp while in the Southern Perth Basin they are on the Scott Coastal Plain.

In the Peel-Harvey Area the climate and development scenario D results in a potentially high impact on GDEs indicating this area is sensitive to abstraction. The affected areas are the coastal lakes and Harvey.

GDEs associated with caves may be highest for those more distant from discharge areas.

Groundwater levels are expected to rise in the northern part of the Perth Central Basin and an increase in areas with GDEs may occur, especially for phreatophytic vegetation with depths to watertable between 6 and 10 m. However the deployed method is applicable for GDEs where declining groundwater level is a threat. As discussed in Section 5.2 in some instances an increasing water table can be a risk for the ecological values of some GDEs (waterbird wading habitat, soil salinisation and inundation).

Since the approach was only used at a regional scale, it used to assess ecological risk utilising only some aspects of a methodology developed by the Froend and Loomes (2004), and as such it does not include considerations of conservation value of environmental assets and historical groundwater level change prior to 2007. It is well documented that a large proportion of GDEs on the Swan Coastal Plain (and in particular, on the Gnangara mound) have suffered groundwater level decline over the last 30 years and change to the ecological values identified and endorsed before major groundwater abstraction schemes commenced. However the analysis only includes areas within the specified depths to watertable in 2007, and as such it allows estimation of potential ecological risks to environmental assets which may potentially occur in those areas under future climate and development scenarios in a regional scale. The approach was not used to investigate any other risks outside the identified time period.

The analysis could also be applied to acid sulfate soil risks which are associated with the areas with a shallow watertable that may fall under a future scenario.

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6 Water demands

6.1 Key findings

- Total water use in the project area is currently about 1200 GL/year, of which 71 percent is self-supplied and three-quarters is groundwater.
- About 35 percent of the water use is for irrigated agriculture. Elsewhere in Australia irrigation uses a higher percentage (66 to 75 percent) and most is scheme-supplied surface water.
- There is relatively little ‘low-value’ agricultural water use in the project area compared to other parts of Australia and, as a result, the flexibility to transfer water from low- to high-value uses is limited.
- Growth in demand for water by 2030 is expected to be about 10 percent under the low demand scenario, 35 percent under the medium demand scenario and 57 percent under the high demand scenario.
- Demand at 2030 for the Water Corporation’s Integrated Water Supply Scheme has been estimated as 350, 380 and 439 GL/year under the low, medium, and high demand scenarios respectively.
- Growth in demand for self-extraction, mainly for irrigation, is expected to grow by over 300 GL/year or over 25 percent by 2030.
- The highest areas of demand growth are the Harvey and Collie management areas for surface water and the Perth and Gingin management areas for groundwater.

6.2 Background

A major objective of this project is to compare water yields under potential climate change and alternative economic development scenarios with the amount of water that will be required to meet both environmental and consumptive demands for fresh water, so that stresses on resources may be estimated and taken into account in water planning and allocation. This chapter considers prospective growth in water use in the absence of future water or land constraints. Chapter 7 then addresses the options for reconciling prospective yields with anticipated ‘unconstrained’ demand.

There have been only a few studies of water use at the level of detail required for the South-West Western Australia Sustainable Yields Project. Three authoritative studies are: (i) Review ’85 (AWRC, 1987) undertaken as a part of the National Review ’85 statistical compilation of water resources and water use; (ii) Water 2000 Study, undertaken as a part of the National Land and Water Resources Audit (WRC, 2000); and (iii) Western Australia Water Futures Study, by Resource Economics Unit (REU) commissioned by the Department of Water (REU, 2008). The Australian Bureau of Statistics has also published water accounts for the whole of Western Australia based on user surveys (ABS, 2006).

Water use in south-west Western Australia (SWWA) accounts for approximately half of all water used in the state. In contrast to many other regions of Australia, urban, industrial and mining uses dominate. These accounted for about 61 percent of all diversions in the SWWA in 2008 to 2009 (this project), an increase from 57 percent of total use in 1985 (AWRC, 1987). There has also been a significant shift away from pasture irrigation and a large proportion of agricultural water use today is for high-value horticultural uses. There is relatively little ‘low-value’ agricultural water use in SWWA compared to other parts of Australia (Brennan, 2006). As a result, the flexibility to transfer water from low- to high-value uses is limited.

Since 1985 water use in SWWA has almost doubled, growing by an annual average 2.3 percent per year (this project). Between 1999 and 2008 the growth rate increased in response to economic development to over three percent per year. Growth in the use of natural water resources would have been even higher had it not been for: (i) increasingly comprehensive restrictions on urban water use, and (ii) the commencement of seawater desalination and wastewater recycling in Perth.

Growth in water use has been accompanied by a substantial proportional increase in the use of groundwater. Whereas approximately 56 percent of water used in SWWA had been supplied from surface sources in 1985, by 2009 this had fallen to just 26 percent, the balance of 74 percent coming from groundwater. In absolute terms, surface water use has remained relatively constant while virtually all the growth in demand has been supplied from groundwater. As very few potential surface water resources remain for meeting future growth in demand, and climate change might depress surface water yields even further, this emphasises the importance of quantifying the potential impacts of climate change on groundwater as well as on surface water.

6.2.1 Definition of water use

For the purpose of this chapter, 'water use' has been interpreted to mean 'abstraction', i.e. the taking of fresh water from the environment, including the diversion of surface water or the abstraction of groundwater and including mine dewatering. All demands are 'gross'. Return flows to the environment have not been deducted, though they are taken into account in the licensing process. The Integrated Water Supply Scheme (IWSS) exports water outside of SWWA whereas all self-abstraction is used locally. Use within the IWSS includes the water produced by desalination plants or re-use.

The following items are specifically excluded from this definition of 'use':

- licensed water storage
- reservations for future use
- discharges to the environment following water diversion, e.g. return flows from mine dewatering or from hydro-electricity generation are not netted out
- environmental allocations
- abstractions of brackish or saline water
- any unused allocations of urban scheme water suppliers and irrigation cooperatives. These typically occur when physical water availability falls short of the licensed amount, e.g. as has happened in recent years with the reservoirs of the Darling Range used by the Water Corporation and Harvey Water.

6.2.2 User groups

For the purposes of this project 14 user groups were defined:

- household bores
- parks and recreation
- commercial and institutional
- general industry
- mining
- power generation
- pasture irrigation
- perennial horticulture (including grapes, fruit trees and irrigated plantations)
- vegetables and other annual horticulture
- rural – domestic and stock uses
- rural – other uses
- local town supply
- urban scheme supply
- irrigation scheme supply.

These groups are broadly consistent with the classification of water uses in Review '85 (AWRC, 1987), as well as with the Australian and New Zealand Standard Industrial Classification (ANZSIC).

6.2.3 Demand regions and water management areas

Eight large demand regions were defined by Resource Economic Unit (REU,2008) to reflect the geography of SWWA and the major concentrations of water use. Their boundaries conformed closely to Western Australia's regional planning boundaries and the Australian Geographical Classification System used by the Australian Bureau of Statistics. The demand regions are used as reporting units in this chapter.

To gauge potential gaps between demand and yields of fresh water in the light of alternative climate scenarios, 45 water management areas were defined (Figure 6-1). The water management areas contain mutually exclusive sets of surface water and groundwater users which can be summed into the eight demand regions. Within demand regions the boundaries of groundwater areas and surface water catchments generally do not conform to each other. Note that those parts of the surface water management areas that lie to the east of the demand region boundaries running southwards from the Swan River to the Donnelly River are largely comprised of forest in the upper reaches of closed catchments. Water use in these areas is negligible. Also, in the north of SWWA the inland parts of the Moore and Greenough demand regions were excluded (because they were not modelled).

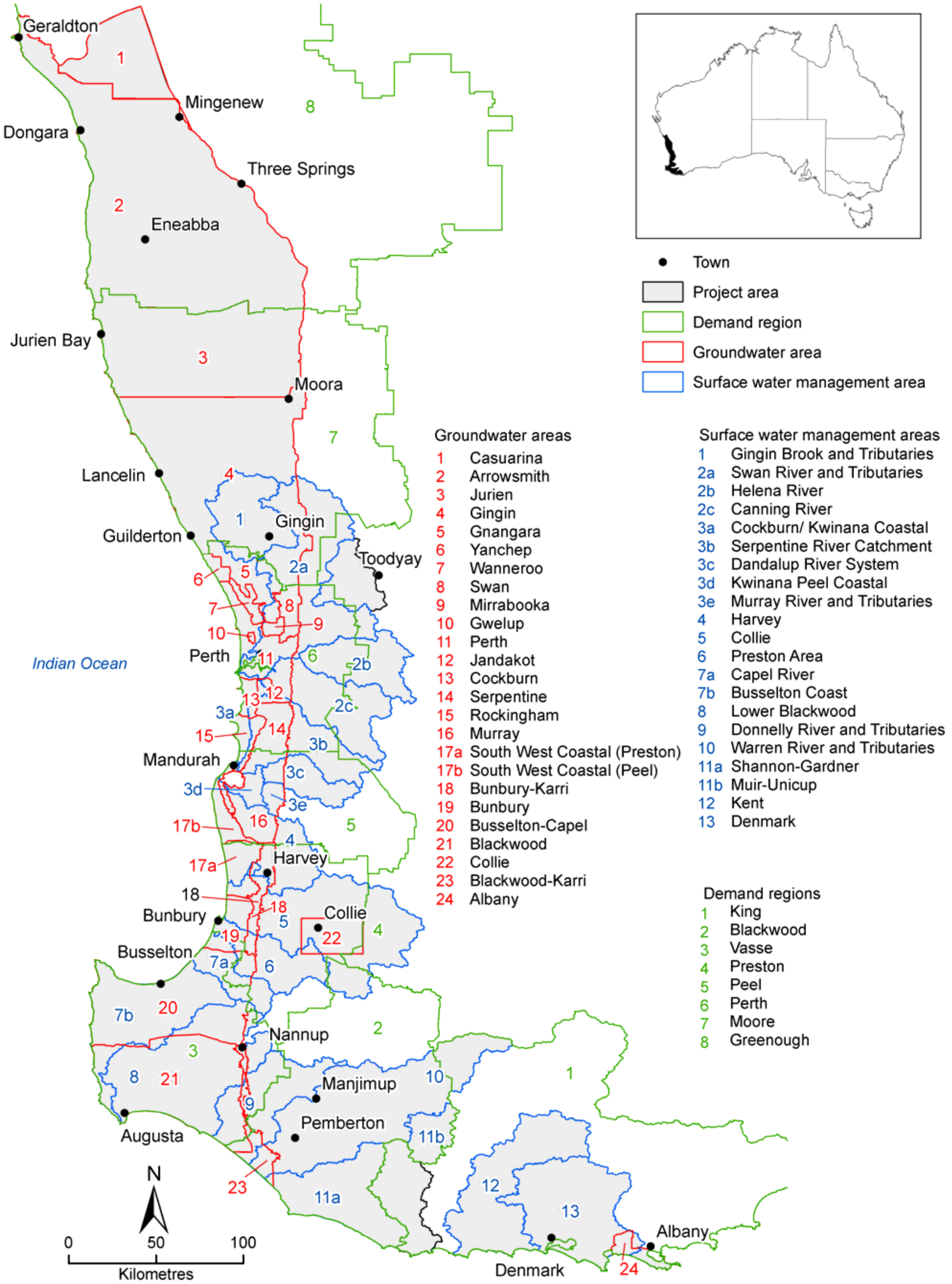

Figure 6-1. Map of surface water management areas, groundwater management areas and demand regions in south-west Western Australia

6.3 Current (2008) water use

6.3.1 Method

Estimates of current (2008) water use in each of the 22 surface water management areas and 23 groundwater areas were made by the following method.

1. Licensed surface water and groundwater allocations in each water management area were abstracted from the Department of Water (DoW) Water Resources Licensing (WRL) database and classified into 14 'User Groups' using a translation algorithm. Licensed allocations were then converted to estimates of actual water use. Private licence holders were assumed to use all their allocation. Independent data were used to determine actual water use of scheme suppliers, including the WA Water Corporation, AQWEST (Bunbury Water Board), Busselton Water Board, and Harvey Water (see below).
2. Typical abstractions for the IWSS were estimated by reference to current yields. In practice, the operation of the IWSS will lead to significant inter-annual fluctuations in abstractions.
3. Typical irrigation scheme water use was obtained from recent statutory reports by Harvey Water to the Department of Water under its licensing provisions.
4. Estimates were made of unlicensed uses including: (i) urban household bores and (ii) farm dams in unproclaimed areas, which are used for irrigation or rural stock and domestic requirements. The estimates take account of recent research within the Department of Water on farm dam use; a consultancy report on farm dams in the Preston, Vasse and Blackwood demand regions (SKM, 2007); data from the Agricultural Census, 2006 (ABS, 2008a;b); a paper on the dietary water requirements of stock (Marwick, 2007); and studies of the growth of domestic bore ownership undertaken by DoW (2008), ABS (2004, 2007) and REU (2008).

6.3.2 Use in 2008 to 2009

Total estimated water abstractions in SWWA during the period 2008 to 2009 are shown in Table 6-1. These totalled 1201 GL of which 857 GL was self-supplied and 344 GL was diverted for use in either urban or irrigation scheme supplies. In addition, 38 GL was produced by sea water desalination and re-use.

Table 6-1 also shows that urban and industrial uses accounted for 600 GL (50 percent) of total water abstracted in the SWWA. Urban uses include domestic bores, parks and recreation, commercial and institutional, general industry, power generation, local town supplies and diversions for the IWSS.

The mining and mineral processing sector, which is largely self-supplied, accounted for a further 84 GL (7 percent) of total diversions.

Irrigated agriculture used an estimated 454 GL (38 percent) mainly from self-extraction, both licensed and unlicensed. Use in the irrigation sector is predominantly for intensive horticulture including fruit, vegetables, and grapes, accounting for 61 percent of irrigation use. Irrigation of pasture occurs mainly within the Harvey Water cooperative scheme, but is declining. Outside of the irrigation sector, rural use for domestic, stock and intensive animal production, including aquaculture, pigs and poultry, is estimated to have been 26 GL (2 percent) of total use in the SWWA.

Table 6-1. Water use by user group in south-west Western Australia for the period 2008 to 2009

User group	Water use	
	GL	percent
Domestic	126	11%
Parks and recreation	94	8%
Commercial and institutional	10	1%
General industry	60	5%
Mining	84	7%
Power generation	9	1%
Pasture irrigation	76	6%
Perennial horticulture	122	10%
Vegetables and other horticulture	159	14%
Rural domestic and stock	13	1%
Rural other	14	1%
Local town water supply	54	5%
Irrigation Scheme supply	97	8%
IWSS	246	21%
Total	**1163**	**100%**
IWSS desalination and re-use	38	
Total water use	**1201**	

6.3.3 Regional distribution of water use

Table 6-2 shows the regional distribution of diversions. The Perth demand region had the largest use of water in SWWA accounting for about 44 percent of the total, followed by Preston (22 percent) and Moore (14 percent).

Two demand regions exported water to regions lying outside of the SWWA. Perth exports water to the central agricultural areas and goldfields through the Goldfields and Agricultural Water Supply Scheme, now incorporated into the IWSS. The operations of the IWSS mean that water exported from, for example, the Peel or Preston demand regions to Perth contributes to Perth's capacity supply to the goldfields and agricultural areas. Further south, the Preston region exports water to the Great Southern Towns Water Supply Scheme.

Table 6-2. Regional distribution of water diversions in each demand region in south-west Western Australia in 2008

Demand region	Self-extracted*	IWSS abstractions	Irrigation scheme supplies	Total resource use	
	GL				percent
King	14.6	0.0	0.0	14.6	1%
Blackwood	33.7	0.0	0.0	33.7	3%
Vasse	90.4	0.0	0.0	90.4	8%
Preston	122.6	30.6	97.3	250.5	22%
Peel	25.9	20.7	0.0	46.6	4%
Perth	313.3	195.0	0.0	508.3	44%
Moore	163.3	0.0	0.0	163.3	14%
Greenough	56.1	0.0	0.0	56.1	5%
Total	**819.9**	**246.2**	**97.3**	**1163.4**	**100%**

* Including local town supplies.

Table 6-3 shows the estimated composition of use in each demand region in 2008 to 2009. Significant points are: (i) the large level of abstractions for the IWSS, domestic bores, parks & recreation, and irrigated agriculture in Perth; (ii) significant use for irrigation scheme supply, mining and industry in the Preston region; (iii) dominance of intensive irrigation in the Moore region; (iv) dominance of irrigation uses in the Vasse and Blackwood regions; and (v) the diversity of uses in the King and Greenough demand regions.

Table 6-3. Water use by user group in each demand region in south-west Western Australia for the period 2008 to 2009

User group	King	Black-wood	Vasse	Preston	Peel	Perth	Moore	Green-ough	Total	
	GL									percent
Domestic	0	0	2.8	3.9	4.2	112.7	0.4	2.1	126.1	**11%**
Parks and recreation	0.2	0.1	2.8	5.3	4.7	76.1	1.8	2.6	93.6	**8%**
Commercial and institutional	0	0	0.3	0.2	2.8	4.8	1	1.2	10.3	**1%**
General industry	0	0	1.1	30.4	5.4	22.9	0.2	0	60	**5%**
Mining	0	0	10.8	31.2	1.6	4.8	18.9	16.5	83.8	**7%**
Power generation	0	0	0	9	0	0	0	0	9	**1%**
Pasture irrigation	0	0.7	17.9	4.4	2.5	28.3	14.3	7.4	75.5	**6%**
Perennial horticulture	3	0.7	18.2	6	2.1	12.5	66.9	12.5	121.9	**10%**
Vegetables and other horticulture	3.3	28.1	22.1	16.8	0.4	39.2	47.3	1.6	158.8	**14%**
Rural domestic and stock	3.5	1.1	3	2	0.4	1.8	0.9	0.1	12.8	**1%**
Rural other	0.1	0.8	1.3	0.3	0.7	4.8	5.2	0.4	13.6	**1%**
Local town water supply	4.5	2.1	10.2	13	1.2	5.4	6.2	11.6	54.2	**5%**
Irrigation Scheme supply	0	0	0	97.3	0	0	0	0	97.3	**8%**
IWSS	0	0	0	30.6	20.7	195	0	0	246.3	**21%**
Total	**14.6**	**33.7**	**90.4**	**250.5**	**46.6**	**508.3**	**163.3**	**56.1**	**1163.5**	**100%**

Figure 6-2 records growth in demand on the IWSS since 1980. The graph demonstrates that there was a reduction in late 2001 when sprinkler restrictions were placed on garden watering in the Metropolitan Area. The continuing growth in the population and economy of the SWWA is not reflected in the slower rates of growth in IWSS water demand that were recorded between 2002 and 2008. Some reduction in IWSS demand may have been substituted for by increased self-supply garden bores which were granted a subsidy to reduce the demand for IWSS water between 2003 and 2009.

It is possible that growth in IWSS water demand may return to its earlier high level.

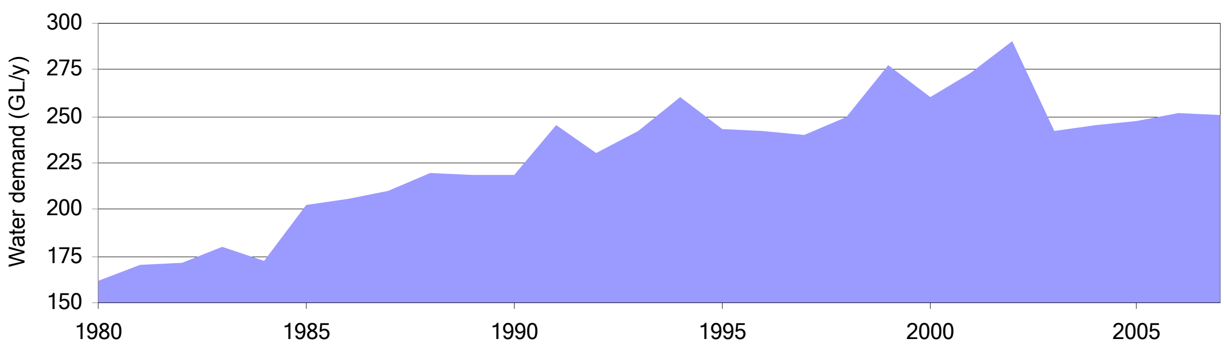

Figure 6-2. Trends in water use from the Integrated Water Supply Scheme over the period 1980 to 2007

6.3.4 Sources of water

Table 6-4 shows the volumes of surface and groundwater that were diverted in each demand region. Most notable are the large volumes of groundwater abstracted in Perth; the larger volumes of surface water diverted in the more southerly regions of Peel, Preston, Vasse, Blackwood and King, and the virtual absence of surface water diversion in the more northerly regions of Greenough and Moore. Surface water catchments were not modelled in these two regions for this reason.

Table 6-4. Surface water and groundwater diversions in each demand region for the period 2008 to 2009

Demand region	Surface water	Groundwater	Total	Surface water	Groundwater	Total
	GL			percent		
King	9.3	5.3	**14.6**	3%	1%	**1%**
Blackwood	33.7	0	**33.7**	11%	0%	**3%**
Vasse	25.1	65.4	**90.4**	8%	8%	**8%**
Preston	151	99.5	**250.5**	50%	12%	**22%**
Peel	22.6	23.9	**46.6**	8%	3%	**4%**
Perth	52.8	455.5	**508.3**	18%	53%	**44%**
Moore	4.8	158.4	**163.3**	2%	18%	**14%**
Greenough	0	56.1	**56.1**	0%	6%	**5%**
Total	**299.3**	**864.1**	**1163.4**	**100%**	**100%**	**100%**

6.4 Future water demands – methodology

6.4.1 Economic model

Potential 'unconstrained' water demand in the year 2030/31 in each demand region was estimated under four scenarios ('high demand', 'medium demand', 'low demand' and 'climate-dependent demand') by multiplying the 2008/09 base year water use by a mean annual rate of growth for each of the 14 user groups. Growth rates were derived from REU (2008). That study considered 61 user groups in 19 demand regions across the whole of Western Australia, of which eight were in SWWA.

The growth rates applied in this project were weighted mean annual percentage changes taken from the 61 groups provided in the MONASH-TERM Computable General Equilibrium economic model (Dixon and Rimmer, 2002; Horridge et al., 2005). This model provided projections of value-added and employment for 55 industries in each demand region that were used as indicators of prospective growth in water use. An additional six demand categories were used for items – mainly population-related – that were estimated separately. The MONASH-TERM model is very large. At its core in this application was a set of 55 x 55 input-output tables describing transactions between industries. It estimates where each industry obtains its inputs (e.g. from other industries, employees, owners and imports) and where it sells its outputs, whether to other industries or to 'Final Demand'. Sales to Final Demand include households, government, capital formation, stock building or exports. It is also possible to identify key macro-economic aggregates such as consumers' expenditure, investment or the balance of trade. For the 'Water Futures' study (REU, 2008) four input-output tables were estimated. These were (i) Perth; (ii) FarmWA (covering all regions in the south-west outside of Perth); (iii) MineWA (covering the rest of the state); and (iv) rest of Australia. National and inter-national transactions across the boundaries of these four economies were modelled. The 'General Equilibrium' aspect involved the solution of a large number of equations that ensure that all markets are cleared, e.g. the labour market is cleared through assumptions about wages and employment; and imports and exports assume a certain exchange rate. The model has been applied in a wide range of government and industry enquiries including applications to water demand and supply (e.g. ATSE, 1999; Horridge et al., 2005).

6.4.2 Demand scenarios

The four demand scenarios were defined as follows.

Low demand scenario

- Demographics: population trends in each demand region were adjusted downwards to reflect lower net immigration to Western Australia
- Economy: the resources boom was assumed to continue until around 2012, but to be followed by a more rapid 'cooling off' period, with growth rates after 2020 at around the historical lows for Western Australia. Unit water uses were assumed to remain constant.

Medium demand scenario

- Demographics: the population of Western Australia and each demand region was assumed to follow the path indicated in the Department of Planning and Infrastructure's publication 'WA Tomorrow' (DPI, 2005)
- Economy: the recent rapid growth of the resource-based industries was assumed to decline to historical average rates of growth. Unit water uses would remain constant under this scenario

High demand scenario

- Demographics: population trends in each demand region are adjusted upwards to accommodate industry requirements for labour
- Economy: the resources boom was assumed to continue for longer and a high, but historically plausible, rate of growth for the Western Australian economy was sustained through to the year 2030. Considering long-term trends in the Australian and Western Australian economies, any higher growth rate after the year 2020 than was assumed in this scenario would be unlikely. Unit water uses were assumed to remain constant.

Climate-dependent demand scenario

- A fourth scenario attempted to anticipate the effects of perceived climate changes on the demand for water, through changed unit water use or through possible structural economic effects. As the results were found to be intermediate between those under the medium and high demand scenarios it was not used in the gap analysis reported in Chapter 7 of this report. However, a brief summary of the results of this scenario is given in Section 6.5.6.

6.4.3 Indicators

The volume of water used by any particular group in a water management area or demand region was expressed as the product of three variables:

- an 'indicator' of water use – either industry value added ($million in constant prices), industry employment (jobs) or residential population
- the expected value of the indicator in future – multiplying the base year indicator value by a series of future growth rates produced an estimate of future levels for each indicator
- a coefficient that relates the water use estimate to the indicator value – expressed as kL/$million or kL/employee. Base year coefficients were obtained by dividing the base year water use in each user group by the corresponding indicator value.

Industry value added was chosen where water use is expected to follow trends in output. The industries that satisfied this criterion included irrigated agriculture, mining, process industries such as refineries and several of the higher-water-using service industries such as construction, power generation, transport, wholesale distribution and leisure industries. The latter employ production systems which are as water-intensive as some manufacturing and processing industries. As a broad generalisation real value added tends to increase at a faster rate than employment or population as a result of productivity improvement.

Industry employment which is an indicator of industry inputs rather than outputs, was used in industries where the level of physical activity is better reflected by employment levels, even if the value of output increases faster than employment. Examples include furniture manufacturing, metal fabricating and assembly, mechanical repairs, finance, banking, business services, public administration, health, education and personal services.

Projected population was used as the indicator for growth in residential water use from both scheme supply and self-supply. Future household water use from scheme supplies was estimated using population projections by the Department of Planning and Infrastructure (DPI, 2005). The Department is currently revising its projections to take account of more recent information. The scenario projections in this project incorporate the DPI's revised projection for the Perth demand region, but not for the rest of the state, for which the assumptions remain based on DPI (2005). The projections in this report assume that per capita demand on the IWSS will remain constant, which is in line with Water Corporation planning.

Physical output measures such as areas irrigated, or mine production might be considered to offer an alternative to value added or employment as indicators of trends in water use. However, it is difficult to establish datasets and trends in physical output across the complete range of water-using activities. Further, any prediction of physical measures would likely rely on some underlying predictive economic model. With further research to produce valid econometric models it might prove possible to obtain more accurate predictors of change in water demand taking account of such factors as water pricing, technology change and substitution patterns of households, industry or agriculture. However at present value added, employment and population are considered to be the most reliable predictors of water use in long-term regional studies such as this.

6.4.4 Population growth assumptions

Table 6-5 shows the anticipated growth in population of SWWA by 2030 and Figure 6-3 show the annual growth in SWWA population over the period 2008 to 2030 under the low, medium and high demand scenarios. It is expected that the Perth-Peel areas will grow slightly faster than other areas within SWWA. Nevertheless, with the exception of the Blackwood region, most population centres are expected to share in SWWA's population increase.

Table 6-5. Current (2008) and anticipated future (2030) population for each of the eight demand regions in south-west Western Australia

Demand region	2008	2030	2008	2030
	population		percent	
Greenough	47,904	53,075	3%	2%
Moore	14,099	19,092	1%	1%
Perth	1,544,752	2,176,555	82%	82%
Peel	88,248	154,975	5%	6%
Preston	76,938	95,962	4%	4%
Vasse	53,439	77,266	3%	3%
Blackwood	15,426	15,000	1%	1%
King	44,649	51,597	2%	2%
Total	**1,885,456**	**2,643,522**	**100%**	**100%**

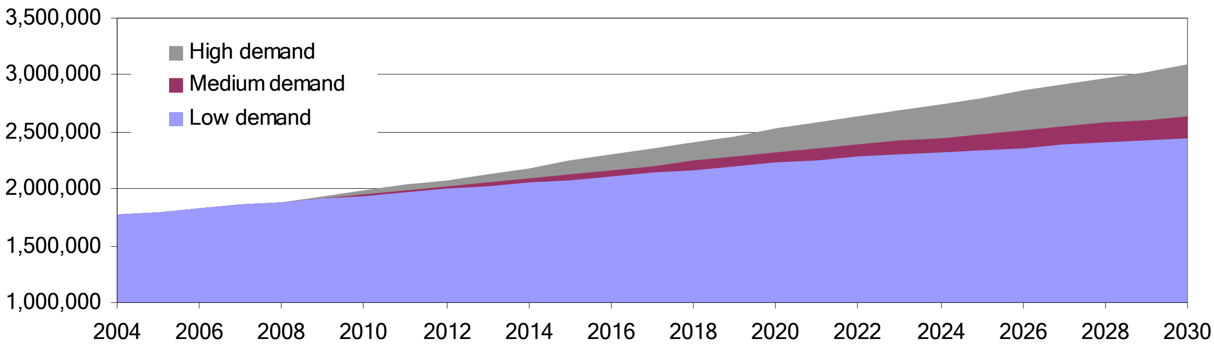

Figure 6-3. Population for south-west Western Australia between 2004 and 2030 under the low, medium and high demand scenarios

6.4.5 Economic growth assumptions

Assumptions about the contribution of SWWA to the Western Australian gross state product are shown in Figure 6–4 which shows trends in real value added, and which shows annual percentage changes.

The graphs suggest continuous growth, but with a declining trend in the percentage growth rate as the Western Australian economy increases in size. The effect is a convergence of the assumed growth rates with broader experience in the Australian economy as a whole.

Under the high demand scenario the economy in SWWA in 2030 is approximately 16 percent larger than under the medium demand scenario. Conversely under the low demand scenario SWWA's contribution to gross state product is reduced by about 12 percent compared with that under the medium demand scenario.

The projections of economic growth were compiled before the global financial crisis commenced in July/August 2008. While the growth in output, employment and capital investment in Western Australia will be affected in the following two to three years, world demand and the Western Australian economy may rebound in a fashion that could compensate for depressed growth in later years. The modelled growth rates for key commodities for 2008 to 2013 were significantly lower than those experienced between the boom years of 2004 and 2008. Therefore the assumptions about growth and the resultant impact on water demand to 2030 under the medium demand scenario are still considered to be valid.

Figure 6-4 and show the assumed economic slow-down in the state economy in 2013 to 2018 following the preceding period of exceptional growth between 2003 and 2008.

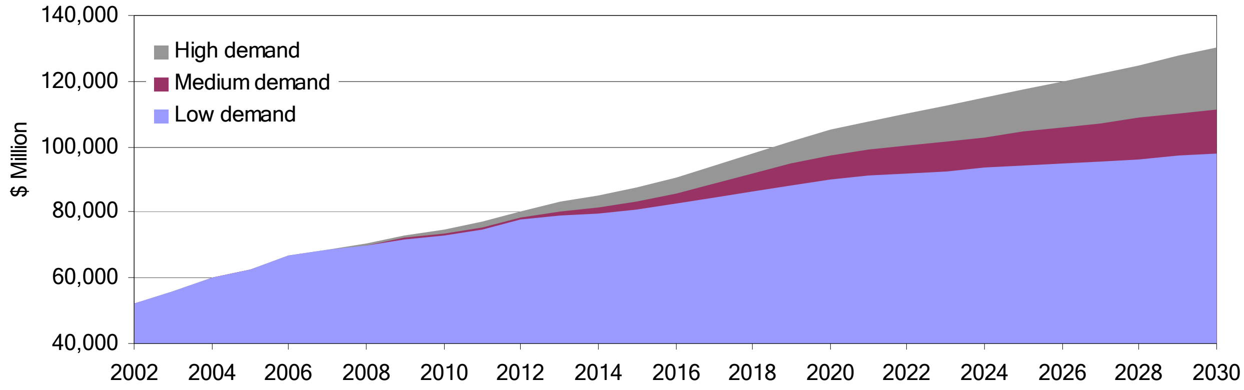

Figure 6-4. Contribution of south-west Western Australia to gross state product between 2002 and 2030 under the low, medium and high demand scenarios

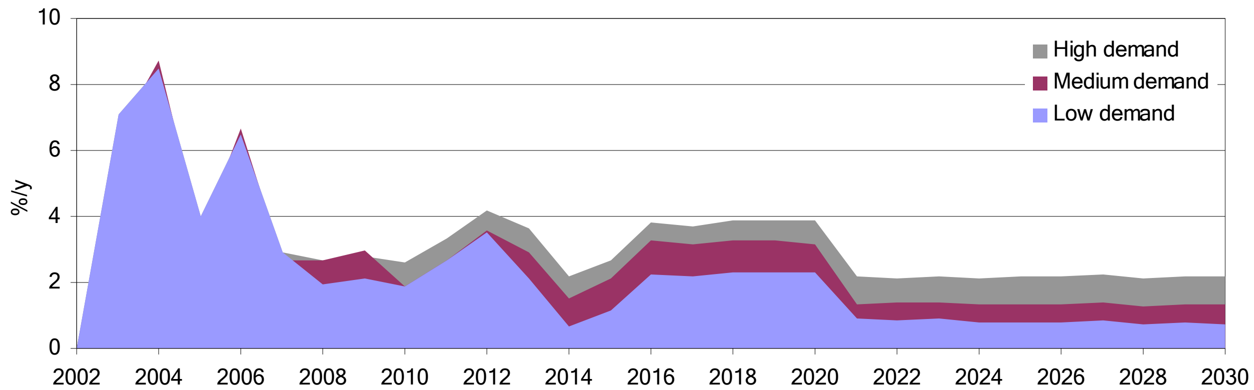

Figure 6-5. Assumed annual rates of change in real value added in south-west Western Australia between 2003 and 2030 under the low, medium and high demand scenarios

6.4.6 Economic structure of south-west Western Australia

The projections depict a Western Australian economy that while still dominated by the services sector will increasingly be driven by the resources sector (Table 6-6 and Figure 6-6). The economy of SWWA would be about 53 percent larger than it is now, with a projected real value added of $108 billion at 2008 prices in 2030 compared with $71 billion now. Table 6-6 shows projected mean annual growth rates for value added at constant prices in the principal economic sectors of the SWWA economy between 2008 and 2030.

Table 6-6. Mean annual projected growth rates of the principal economic sectors in south-west Western Australia at constant prices over the period 2008 to 2030 under the medium demand scenario

Economic sector	Increase
	percent
Agriculture, forestry and fishing	2.3%
Mining	6.0%
Manufacturing	1.5%
Services	2.2%
Gross SWWA Product	2.4%

All sectors are projected to grow over the time frame of this project. The services sector would remain the largest sector in terms of value added and employment, emphasising that Perth and urban demands generally will continue to grow in pace with the state's economy. The minerals and energy sector's share of the total would increase significantly, but the share of manufacturing and processing industries would decline. The agriculture sector would maintain its share of the growing economy indicating that its unrestricted water demand could increase by around 50 percent over the projection period. The growth rates for irrigation uses obtained from the MONASH-TERM model are comparable to those suggested by other studies in Western Australia (e.g. Brennan, 2006).

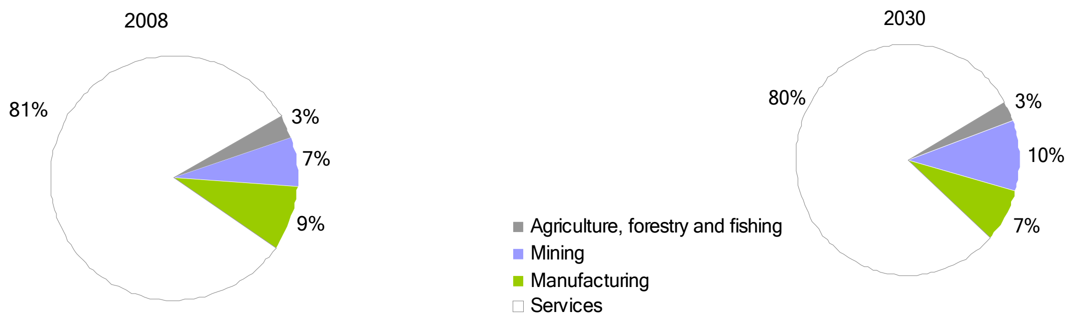

Figure 6-6. Shares of the principal economic sectors in gross product of south-west Western Australia in 2008/09 and 2030/31

6.4.7 Regional distribution of economic activity

The resulting relative size and growth of the project SWWA's sub-regional economies is summarised in Figure 6-7. The Perth region is projected to continue to attract the greater part of the project SWWA's economic growth. The fastest growing region in relative terms is Greenough which benefits from development of its mineral resources. Towards the end of the scenario period, growth of economic activity in the Preston demand region is estimated to flatten reflecting low anticipated growth for pasture-based agriculture and related industries. Broadly, however, the rates of growth in water use are very similar across the demand regions. This reflects the broad nature of the underlying economic model and the diversity of water uses in each region. In other words, there is no demand region that has an economic structure that would cause a significant divergence from the general trend.

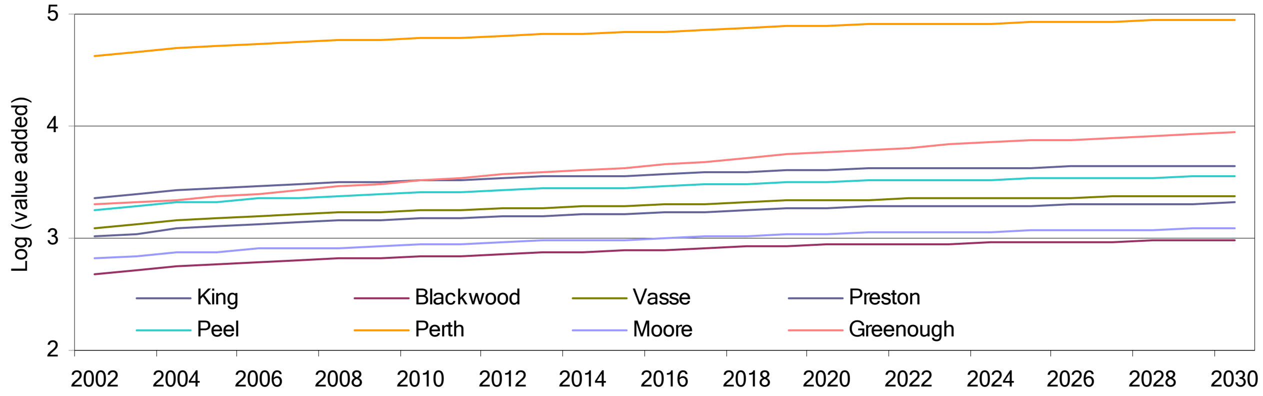

Figure 6-7. Projected growth in real value added by each demand region expressed in log values (original data in $million)

6.5 Future water demand – results

6.5.1 Separation of self-extracted from Integrated Water Supply Scheme uses

Results of the scenario projections are given separately for: (i) self-extracted uses; and (ii) demands on the IWSS. The reason for this separation is that users who extract water for themselves are in fixed locations. The economic projections – which are independent of any water or land availability constraints – give an indication of the extent of demand for self-extraction that may be expected in each location, if water and land availability permit. However it is clearly unrealistic to assume that future IWSS requirements can be met by growth in diversions at the current points of extraction. Therefore IWSS demand was projected as an aggregate to be able to assess how future IWSS demand can be met or modified. Chapter 7 considers future options for the IWSS and locations where the economic projections of 'unconstrained' demand appear to violate water and land constraints.

6.5.2 Projected growth in Integrated Water Supply Scheme demand

The Water Corporation of Western Australia has produced estimates of likely IWSS demands under varying assumptions about future per capita water use (Water Corporation, 2009). For the purposes of this project, the Corporation's estimates were used for the medium demand scenario. The Corporation took an estimated 145 kL/person/year as an indication of likely IWSS consumption, and a population served of 2.31 million in 2030, giving a potential IWSS demand from all sources of 380 GL in the absence of improved water use efficiency.

Under the high demand scenario IWSS demand in 2030 could be some 12 percent greater than under the medium demand scenario. For the low demand scenario a reduction in IWSS growth of 8 percent in 2030 was assumed. Demand at 2030 for the IWSS was estimated as 350 GL/year, 380 GL/year, and 439 GL/year under the low, medium and high demand scenarios respectively. The medium demand scenario estimate for the IWSS was found to be similar to published demand estimates contained in Water Forever (Water Corporation, 2009).

6.5.3 Projected growth in self-extracted water use by demand region

Table 6-7 shows the projected future self-extraction under the medium demand scenario for 13 user groups, i.e. excluding the IWSS. The greatest demands occur for vegetables and other annual horticultural crops (Perth and Moore regions), domestic self-supplied water (Perth), perennial horticulture (Moore), parks and recreation (Perth), mining (Preston, Peel, Moore and Greenough) and irrigated pastures (Perth, Vasse and Moore).

Table 6-7. Projected self-extraction in 2030 by demand region and user group under the medium demand scenario

Demand region	King	Blackwood	Vasse	Preston	Peel	Perth	Moore	Greenough	Total
	GL								
Domestic	0	0	5.6	6.7	9.9	156.3	0.8	3.2	**182.5**
Parks and recreation	0.2	0.2	4.1	7.8	7	120.3	2.6	4.3	**146.5**
Commercial and institutional	0	0	0.4	0.2	3	5.7	1	2.1	**12.4**
General industry	0	0	1.2	40	6.9	29.8	0.3	0	**78.2**
Mining	0	0	13.8	38.3	2.2	10.1	26.6	22.5	**113.5**
Power generation	0	0	0	9.2	0	0	0	0	**9.2**
Pasture irrigation	0.1	1	25.1	6.5	3.6	42.6	21	11.1	**111**
Perennial horticulture	3.4	0.9	24.5	8	2.9	17.7	88.4	16.6	**162.4**
Vegetables and other horticulture	4.1	34.1	26.8	20.4	0.4	48.6	57.3	2.1	**193.8**
Rural domestic and stock	5.1	1.7	4.4	2.9	0.6	2.6	1.3	0.2	**18.8**
Rural – other	0.1	1.1	1.5	0.3	0.8	8.5	6.1	0.5	**18.9**
Local town water supply	5.4	2.4	13.9	16.2	1.9	7.6	8.2	14.8	**70.4**
Irrigation scheme supply	0	0	0	112	0	0	0	0	**112**
Total	**18.3**	**41.4**	**121.2**	**268.5**	**39.3**	**449.8**	**213.7**	**77.6**	**1229.8**

6.5.4 Projected growth in self-extracted water use by water management areas

Using the methods and assumptions outlined in the preceding sections of this chapter, self-extraction demand was estimated for each of the 45 water management areas in 2008/09 and in 2030/31 under the three demand scenarios (Table 6-8). Significant growth in irrigation water demand in the Collie and Harvey surface water management areas is assumed by the method that has been used.

Table 6-8. Estimated self-extraction demand in each water management area under the low, medium and high demand scenarios

	Water management area	Demand region	Base 2008/09	Demand scenarios (2030)		
				Low	Medium	High
			GL			
Surface water management areas						
1	SW1 Denmark	King	3.5	3.3	4.2	4.6
2	SW2 Kent	King	5.8	6.4	7.6	8.3
3	SW3 Muir-Unicup	Blackwood	0.0	0.0	0.0	0.0
4	SW4 Shannon-Gardner	Blackwood	5.2	4.3	6.4	7.3
5	SW5 Warren River	Blackwood	21.6	18.1	26.5	30.2
6	SW6 Donnelly River	Blackwood	6.8	5.7	8.5	9.6
7	SW7 Lower Blackwood	Vasse	10.0	8.9	12.9	14.5
8	SW8 Busselton Coast	Vasse	9.6	9.3	12.6	14.2
9	SW9 Capel River	Vasse	5.5	4.8	7.2	8.2
10	SW10 Preston	Preston	5.0	4.4	6.4	7.5
11	SW11 Collie	Preston	50.9	39.9	60.0	85.5
12	SW12 Harvey	Preston	64.5	51.3	76.2	130.7
13	SW13 Murray River	Peel	1.3	1.1	1.7	1.9
14	SW14 Kwinana-Peel Coastal	Peel	0.0	0.0	0.0	0.0
15	SW15 Dandalup River System	Peel	0.7	1.0	1.0	39.8
16	SW16 Serpentine River Catchment	Perth	0.9	0.8	1.2	28.3
17	SW17 Cockburn-Kwinana Coastal	Perth	0.0	0.0	0.0	0.0
18	SW18 Canning River	Perth	0.8	0.8	1.2	39.9
19	SW19 Helena River	Perth	0.0	0.0	0.0	15.6
20	SW20 Swan River	Perth	1.3	1.4	1.9	2.1
21	SW21 Swan Coastal	Perth	0.0	0.0	0.0	0.0
22	SW22 Gingin Brook	Moore	4.8	4.1	6.9	7.3
	Total surface water		**198.1**	**165.5**	**242.3**	**455.3**
Groundwater areas						
23	GW1 Albany	King	5.3	5.9	6.6	7.7
24	GW2 Blackwood	Vasse	10.0	7.8	13.6	16.1
25	GW3 Busselton-Capel	Vasse	55.4	57.0	74.9	86.0
26	GW4 Bunbury	Preston	32.3	37.1	43.5	46.3
27	GW5 Collie	Preston	43.4	49.0	51.9	58.1
28	GW6 SW Coastal (Preston)	Preston	23.8	21.0	30.5	34.6
29	GW7 SW Coastal (Peel)	Peel	9.4	15.2	17.2	18.5
30	GW8 Murray	Peel	14.5	15.5	19.3	22.8
31	GW9 Serpentine	Perth	15.5	15.1	22.9	25.5
32	GW10 Rockingham	Perth	33.1	40.2	46.8	61.9
33	GW11 Cockburn	Perth	41.1	46.9	56.0	69.6
34	GW12 Jandakot	Perth	33.7	42.5	47.2	83.4
35	GW13 Gwelup	Perth	2.4	3.0	3.3	38.9
36	GW14 Mirrabooka	Perth	23.5	29.7	32.9	74.3
37	GW15 Perth	Perth	73.3	98.7	113.1	209.1
38	GW16 Wanneroo	Perth	36.3	35.0	49.5	65.5
39	GW17 Gnangara	Perth	14.7	19.6	21.1	94.9
40	GW18 Yanchep	Perth	1.5	2.1	2.4	4.0
41	GW19 Swan	Perth	35.2	38.5	50.4	62.0
42	GW20 Gingin	Moore	140.8	129.4	183.1	206.6
43	GW21 Jurien	Moore	17.7	19.6	23.7	27.0
44	GW22 Arrowsmith	Greenough	55.0	64.3	76.1	69.4
45	GW23 Casuarina	Greenough	1.1	1.2	1.4	1.6
	Total groundwater		**719.0**	**794.2**	**987.5**	**1,383.7**
	Total self-extraction		**917.2**	**959.7**	**1,229.8**	**1,839.1**

6.5.5 Summary of total water use projections

Total use in SWWA is projected to be 1617 GL by 2030/31 under the medium demand scenario (Table 6-9). This represents a mean annual growth of 1.36 percent.

Table 6-9. Summary of water use projections for each demand region and Integrated Water Supply Scheme under the low, medium and high demand scenarios

Demand region	Base	Demand scenarios (2030)			Demand scenarios (2030)		
	2008/09	Low	Medium	High	Low	Medium	High
	GL				percent change from base		
King	15	16	18	21	6%	25%	41%
Blackwood	34	28	41	47	-17%	23%	40%
Vasse	90	88	121	139	-3%	34%	54%
Preston	220	203	269	318	-8%	22%	45%
Peel	26	32	39	44	22%	52%	71%
Perth	313	374	450	558	20%	44%	78%
Moore	163	153	214	241	-6%	31%	47%
Greenough	56	66	78	86	17%	38%	54%
Total self-extraction	917	960	1230	1454	5%	34%	59%
IWSS	284	356	387	433	25%	36%	53%
Total water use	1201	1316	1617	1888	10%	35%	57%

Under the high demand scenario total water use in SWWA could rise to 1888 GL/year. Under the low demand scenario water demand would be limited to only 1316 GL in 2030/31. However, in the light of trends in the growth in water use since the early 1980s and considering the potential increased demand as a result of a hotter, drier climate this scenario appears the least likely. The medium demand scenario remains the best estimate, with the probability of a higher rate of growth being more likely than a lower one.

Surface water and groundwater management areas likely to experience the highest growth in demand for water resources are shown in Figure 6-8 and Figure 6-9. These are the Harvey and Collie management areas for surface water and the Perth and Gingin management areas for groundwater. The Warren catchment is also likely to experience a growth in demand for surface water and the Arrowsmith area for groundwater.

These figures show volumes and are therefore affected by the area over which this volume is extracted. The small management areas in the Perth area have very large volumes being extracted and this is not reflected when shown in this manner.

6.5.6 Impacts of climate change on water demand

For the 'climate-dependent demand' scenario a review was made of available literature (up to early 2008) on potential climate change in Australia (REU, 2008). A preliminary assessment was then made of the implications for future water demand in SWWA, considered as a modification of the medium growth assumption.

The following assumptions were made in compiling the climate-dependent demand scenario.

- **Unit water demands (e.g. the amount of water used per household, per dollar of real value added or per employee).** In the northern half of SWWA from Greenough to Peel, unit water demands were assumed to increase by around 12 percent by 2030/31 in response to reduced rainfall and increasing temperature and evapotranspiration. Further south, unit water demands were assumed to increase, but more slowly, by about 7 percent by 2030. In the demand regions of the south coast, unit water demands were assumed to remain at 2008 levels.
- ***Structural economic change.*** A 5 percent reduction was assumed in Western Australian exports in 2030/31 due to reduced international demand. However, the negative effect of this on total economic activity was

counteracted by a second assumption that large defensive expenditures (public works) would be needed after 2020 to combat rising sea levels and increased cyclonic activity. This had the effect of stimulating the economy.

- **Impacts of greenhouse policies on economic activity and land use**. It was assumed that there would be a gradual shift of energy production from coal to gas. The possible conversion of farmland to forestry plantations with possible consequences on water demand was not examined.

As already stated, the total water demand in SWWA under the climate-dependent demand scenario was intermediate between that under the medium and high demand scenarios. The gap analysis in Chapter 7 therefore considers the implications under the high demand scenario rather than under the climate-dependent demand scenario. It should be noted, however, that a combination of climate change with high demographic and economic growth in SWWA would result in an even higher water demand under the high demand scenario.

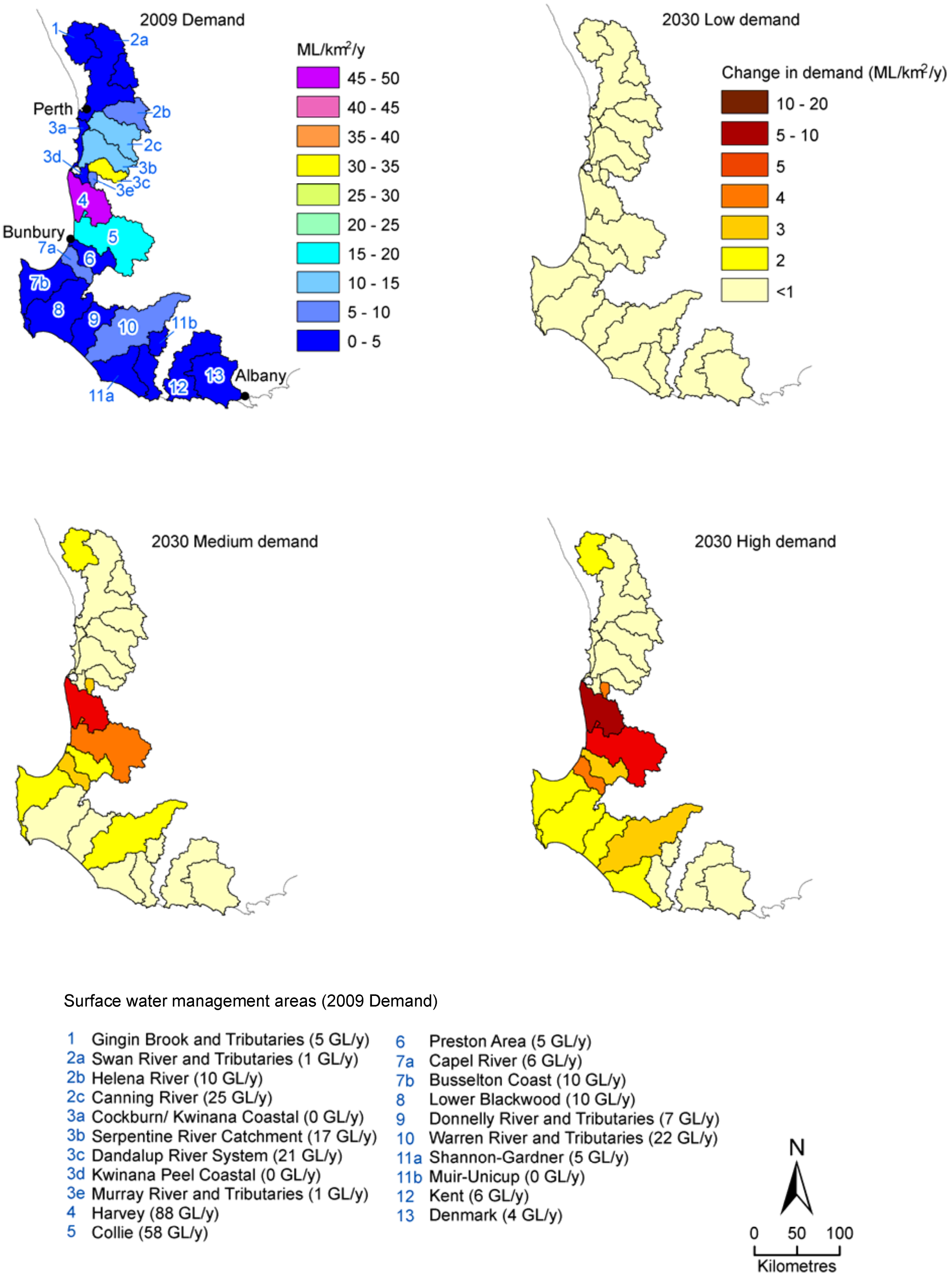

Figure 6-8. Current demand and change in demand under the low, medium and high demand scenarios by surface water management area

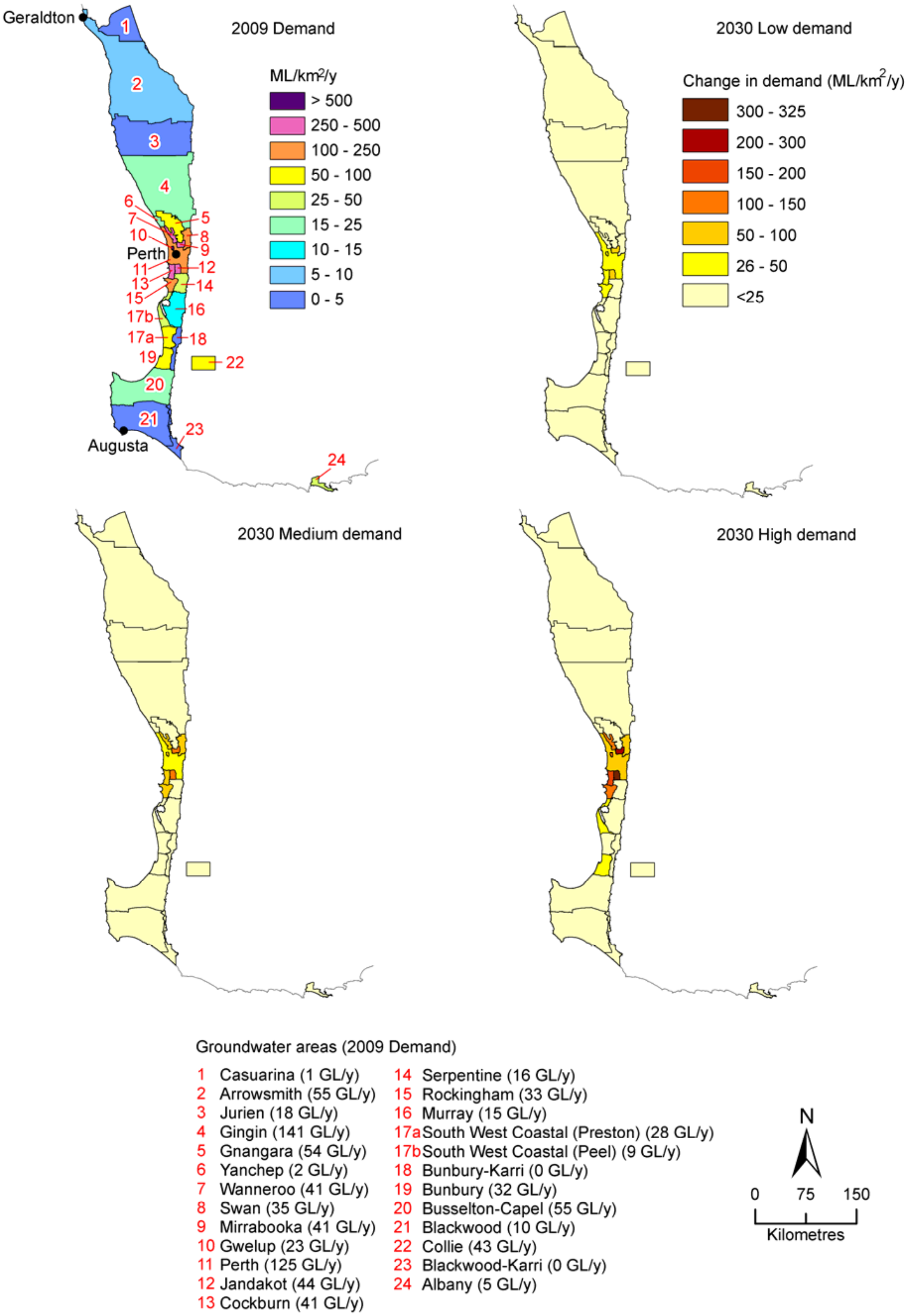

Figure 6-9. Current demand and change in demand under the low, medium and high demand scenarios by groundwater area

6.6 Discussion

The scenarios of future demands in this project are based on a model that considers plausible trends in value added, employment and population on a sub-regional basis and gives an indication of potential future water use in the absence of land or water constraints. Results are broadly consistent with observed long-term historical trends.

Where there are constraints to the growth of water-using activities these will reduce the economic potential of those industries currently resident in a particular location. This applies particularly to irrigated agriculture. The issue that then needs to be addressed is whether the additional growth can be accommodated in an alternative location. An example is the growth potential of horticulture in the Metropolitan Region where the resource is already fully allocated, if not over-allocated. The adjacent Moore demand region can, and does, provide an alternative source of land and water to meet this growth so the unconstrained economic projections for the two regions need to be considered together. Alternatively, the scenarios might signal the need for new sources of water to be developed or imported into the region (e.g.Science Matters and Economics Consulting Services, 2008). If the growth cannot be accommodated by accessing alternative water sources then the estimates of demand will be overestimated. The method outlined in Chapter 7 takes into account future water yields under climate change scenarios so the water component of growth is constrained.

Another qualification is that the model does not attempt to anticipate demand management policies. An example is the imposition in 2002 of sprinkler restrictions on the use of public water supplies in the Perth Metropolitan Area. This produced a step-change in residential water use trends that could not be anticipated by earlier economic modelling. Future changes in the technologies applied by water users may also falsify the projections. For example, piping the irrigation delivery channels by the Harvey Water irrigation cooperative has reduced irrigation delivery losses substantially and enabled water to be traded to the metropolitan area to meet another demand.

Similarly, no attempt has been made to anticipate the potential effects of water trading. REU (2007) reviewed current and prospective arrangements for water trading in Western Australia, and suggested that there is considerable scope for a widening of current transferability legislation as part of the Water Reform package in Western Australia. This would ease the process of adjustment within the irrigation sector in response to water scarcity. The implications for the level of water use in particular industries or locations are currently unknown.

The economic model makes no attempt to anticipate hydrologic variability. For example, since 2001 the Darling Range reservoirs that supply Perth have experienced historically low storage levels to the extent that neither urban nor rural irrigation water suppliers have been able to withdraw as much water as they did previously. Reduced water availabilities can be viewed as a frustrated economic demand for water. The impact of reduced inflows on water yields and reduced groundwater storage on reduced abstraction is considered in Chapter 7.

Finally, while the model can anticipate the impacts of macro-economic and micro-economic trends on existing industries, it cannot anticipate completely new activities. Major new economic development projects may therefore falsify the projections. For example, there is no large paper and pulp industry in SWWA. Should an industry be introduced it would represent a deviation from the model projections. There are two possible ways of dealing with this: either (i) the model can be re-run at regular intervals such as five years, taking account of unexpected developments; or (ii) water planners can use new information on major projects to modify model projections on the basis of best available knowledge. In practice a combination of the two approaches may be needed.

The art of plausible scenario generation must employ a mix of economic theory, well-grounded statistics and expert judgment. Chapter 7 will consider not only the potential gaps between projected ‘unconstrained’ demand and the modelled future yields of surface and groundwater resources under climate change, but also the potential for improvements in water use efficiency, water re-use and increased seawater desalination.

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7 Water yields and demand gaps

7.1 Key findings

- The total current surface water yield for the project area is 425 GL/year. Current demand is 299 GL/year of which 34 percent is currently for public water supply, 38 percent for scheme irrigation and 22 percent for self-supply use. The Harvey and Collie surface water management areas have the highest yields, contributing about 43 percent of the total.
- The total current groundwater yield for the project area is 1556 GL/year, more than 3.5 times the surface water yield. About 58 and 26 percent of the yield is from the Superficial and Yarragadee aquifers respectively, with the Leederville Aquifer providing a further 12 percent. The largest current yield is in the Gingin and Arrowsmith groundwater management areas which provide about 33 percent, not all of which is currently licensed or used.
- The surface water yield for the project area decreases by between 4 (under Scenario Cwet) and 49 percent (under Scenario Cdry), with a 24 percent decrease under Scenario Cmid. The high yield areas of Harvey and Collie show relatively high resilience with reductions of 15 and 22 percent respectively under Scenario Cmid. Further south the Donnelly and Warren rivers, which are largely self-supply areas, are some of the least robust with reductions of 39 and 36 percent respectively. Under Scenario Cdry, more than a third of areas have yield reductions of over 60 percent, with the largest being the Gingin Brook area with a reduction of 86 percent.
- Groundwater yields change from a 2 percent increase (under Scenario Cwet) to a 7 percent reduction (under Scenario Cdry) with a 2 percent reduction under Scenario Cmid. In the Integrated Water Supply Scheme, the Gnangara groundwater area is the least robust with a 6 percent yield reduction under Scenario Cmid. The largest yield reductions are in the Collie (15 percent), Blackwood (11 percent) and Albany (35 percent) areas. The small reductions in yield for groundwater management areas indicate that most allocation limits are able to accommodate a future drier climate.
- The Harvey and Warren surface water management areas may develop the greatest gap between surface water yields and demand while groundwater areas in the Central Perth Basin (with the exception of the Metro area) show the greatest vulnerability. The Harvey surface water management area currently has no spare capacity and is also likely to encounter the fastest rate of growth to 2030. The shortfall in yield to meet demand by 2030 is similar to the current yield of the Water Corporation's Harvey Dam.
- The Integrated Water Supply Scheme may develop a yield and demand gap of 116 GL/year by 2030 under Scenario Cmid and the medium demand scenario. With the Department of Water's pending reduction in groundwater yield availability to the Integrated Water Supply Scheme (-25 GL/year), the commissioning of the second desalination plant (50 GL/year) and forecast water use efficiency gains by 2030 (50 GL/year), this yield and demand gap reduces to 41 GL/year. This gap would increase to 80 GL/year under Scenario Cdry.
- Under Scenario Cmid and the medium demand scenario, annual surface water yields for the Integrated Water Supply Scheme reduce from 95 to 77 GL or 18 percent by 2030. Under the assumptions used in the analysis, groundwater yields reduce by only about 2 percent. Under Scenario Cdry, surface water and groundwater yield reduce by 45 and 12 percent respectively.
- With significant yield and demand gaps developing in many Central Perth Basin areas by 2030, there is expected to be increasing competition for groundwater for the Integrated Water Supply Scheme from self-supply users.

7.2 Introduction

South-west Western Australia (SWWA) is becoming water challenged because of reduced water yields, a rapid population growth and strong economic development.

The Integrated Water Supply Scheme (IWSS) distributes surface water, groundwater and desalinated seawater from the coastal strip to metropolitan centres and inland to agricultural and mining areas. The IWSS collects surface water from as far south as the Harris Dam near Collie, extracts groundwater from as far north as Yanchep, and meets drinking water demands as far east as Kalgoorlie and Kambalda. In addition to the IWSS, extensive self-supply use of surface water and groundwater also occurs for domestic, irrigation, and large-scale commercial use.

The assessment reported in this chapter used the results from the surface water and groundwater reports developed in this project (CSIRO, 2009b, a) to calculate current and future yields of groundwater and surface water systems and to assess the impacts of climate and development on these yields. The ability of these yields to meet existing and projected demands in the project area, as calculated in the previous chapter, is compared using a yield and demand gap analysis.

7.3 Methodology

Chapter 3 detailed how water management is carried out in Western Australia and Chapters 4 and 5 indicated how flows and groundwater levels may affect regional ecological assets. The water yields calculated and presented in this regional analysis are much less rigorous that the process undertaken by the Department of Water Western Australia (DoW) in setting and revising allocation limits for surface water and groundwater resources. Setting allocation limits for surface water and groundwater management areas is an evolving multidisciplinary process which is based on a number of physical, social, historical, cultural, economic and ecological factors. The limits for both surface water and groundwater are a result of expert analysis of competing risks and benefits with remaining uncertainty in a number of factors. If the resource is allocated slowly or the climate remains fairly constant the risks may be measured over time.

The analysis and methodology used in this project do not aim to replicate or to replace this groundwater and surface water allocation process. Rather the estimation of future surface water and groundwater yield for consumptive use presented in this report under the range of climate scenarios aims to provide information for water resource managers to better understand how changes in physical water yields may impact on how much water there may be to meet future demands. It provides some information about where increased management effort may be required if these changes in yields and demand do eventuate.

7.3.1 Establishment of water management areas and sub-areas

To enable the assessment of yields from the surface water and groundwater models, the project area was divided into 22 surface water management areas and 23 groundwater management areas (Figure 6-1). These areas are not discreet in that surface water boundaries may overlap groundwater area boundaries.

Groundwater management areas were based on groundwater area (GWA) boundaries proclaimed under the *Rights in Water and Irrigation Act 1914* as used by the DoW for water allocation planning and management. DoW groundwater management areas of Bunbury Karri (GMA 18) and Blackwood Karri (GMA 23) were excluded from this analysis as these areas are unproclaimed and no allocation limits or licensing currently exists for these areas.

Surface water management areas were based on the boundaries used for water allocation planning and management by the DoW, and are generally hydrologic basins or parts of basins.

Within each groundwater and surface water management area, sub areas were defined to assist in yield calculations. Groundwater sub areas were consistent with areas defined by the DoW for water allocation planning and management. For surface water areas, sub areas were selected to coincide with subcatchment areas identified in DoW surface water modelling for calculation of sustainable diversion limits, and also existing public water supply and irrigation dam storage catchment areas.

For analysis purposes, a further water management area was defined as the Water Corporation's Integrated Water Supply Scheme (IWSS). All yield and demand to the IWSS was aggregated to this water management area, including mining and agricultural demands of the Goldfields and Agricultural Areas Water Supply Scheme.

This enabled an analysis of the IWSS as a single entity, and also enabled a water balance of imported and exported water across water management areas to be maintained and assessed.

7.3.2 Estimating current surface water yield

In subcatchments and water management areas where allocation limits have been published by the DoW (or are currently in the process of being published) these were adopted in this project to reflect current surface water yields. This includes the Capel River, Busselton Coast, and Lower Blackwood water management areas covered by the Whicher Surface Water Allocation Plan (DoW, 2009) and the Gingin Brook and Tributaries water management area covered by the soon-to-be-released Gingin Draft Surface Water Allocation Plan.

To determine the current yield for each surface water management area which does not have an allocation limit the following approach was adopted with analyses being undertaken at a subcatchment level and results aggregated to each water management area:

- Yields were determined for subcatchments with existing public water supply and irrigation dams on the basis of reducing existing DoW licensed allocations in accordance with recent water use and reductions in mean annual flows since the allocations were established. The estimated current yields for these subcatchments were assessed as being representative of the recent climate, Scenario B.
- Subcatchments with annual rainfalls less than 900 mm were excluded on the basis that water quality was unlikely to be fresh or marginal in these areas. Surface water management areas such as the Upper Blackwood were excluded on this basis.
- For each subcatchment with annual rainfalls greater than 900mm, approximate estimates of current surface water yields were provided by DoW, based on the SDL methodology outlined in section 4.3. These are regionalised hydro-ecological based estimates considered acceptable for use in broad scale analyses but are not allocation limits adopted by the DoW. Current yield estimates on the basis of the SDL method are representative of the yield under Scenario A. These values were then reduced on the basis of the percentage of cleared vegetation within each catchment. This approach was used to ensure that land use constraints are considered within the yield estimation process and that artificially large yields are not reported for areas which have limited clearing or are in national parks and will have limited opportunity for surface water diversions in future.

The application of this methodology for the project area is shown in Figure 7-1.

Figure 7-2 and Table 7-1 show estimated current yields for all surface water management areas based on this methodology. The surface water yields in the area north of Gingin Brook were not modelled and have been assumed to be zero for the purposes of this project, although some self-supply use of surface water takes place in these catchments.

The total current surface water yield for the project area is 425 GL/year. Of this total surface water yield, 25 percent is the yield of existing public water supply dams and 27 percent the yield of dams for scheme irrigation.

The Harvey and Collie surface water management areas represent the highest yielding areas contributing about 182 GL/year or 43 percent of the total current surface water yield.

The total combined current yield for surface water sources supplying the Integrated Water Supply Scheme is estimated to be about 95 GL/year. This estimate is comparable to Water Corporation's Water Forever study (Water Corporation, 2009) which provided a current yield estimate of 90 GL/year for its surface water system. Given the different methods used in each estimate the amounts are remarkably similar.

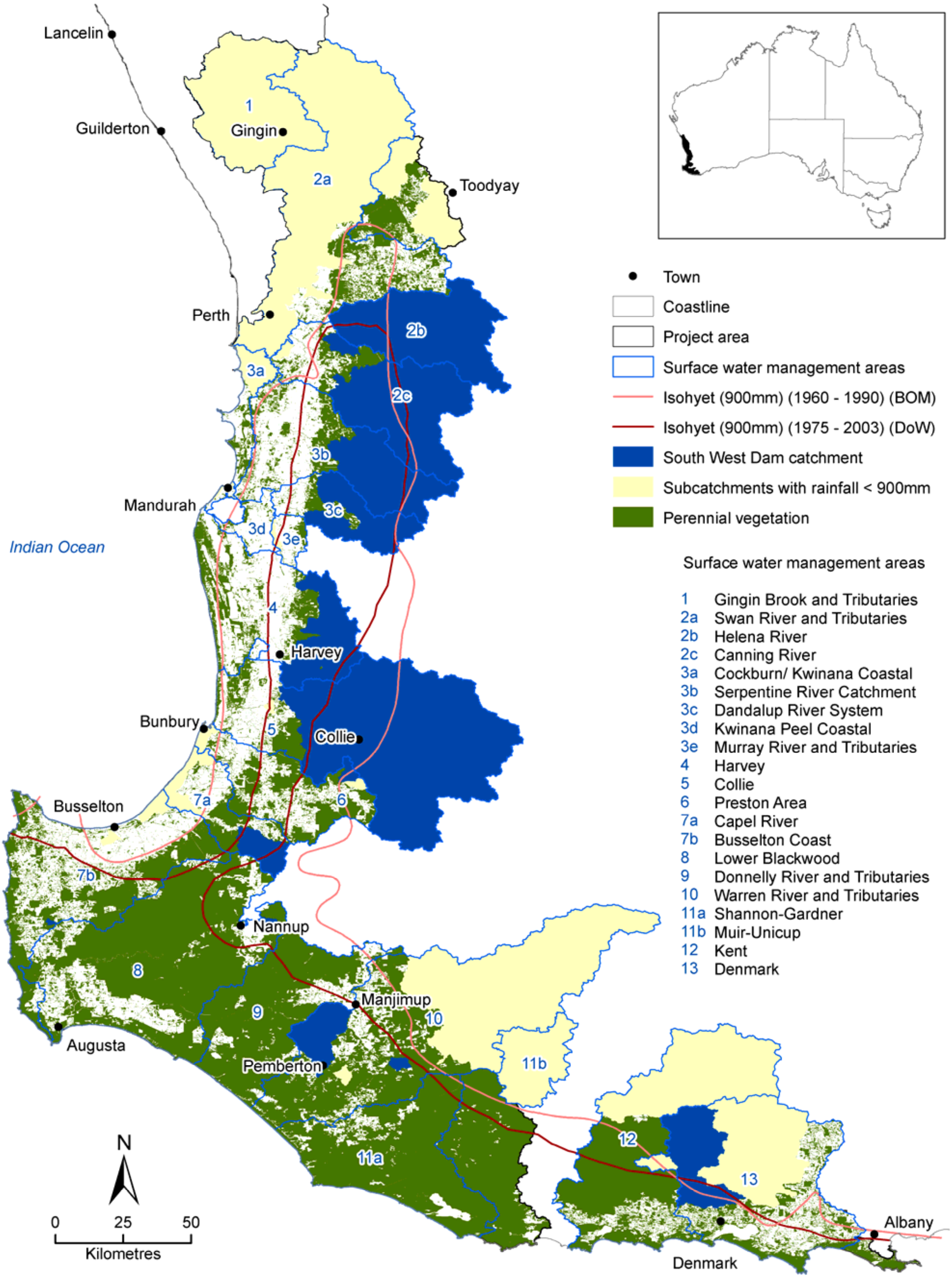


Figure 7-1. Areas adopted in the calculation of current surface water yields

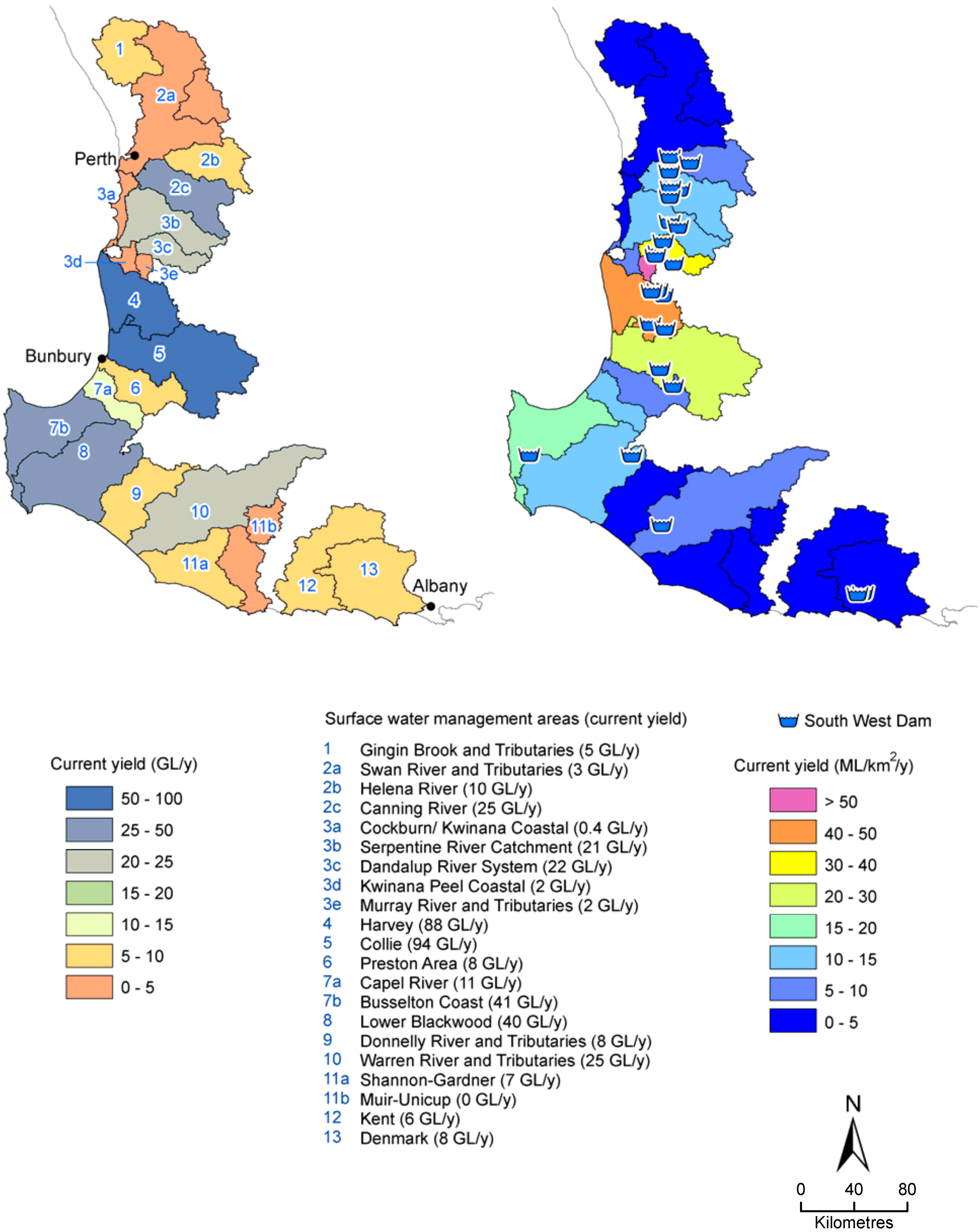


Figure 7-2. Map of current surface water yields by surface water management area

Table 7-1. Current surface water yields by surface water management area

Surface water management area	Water supply dam	Irrigation dam	Self-supply	Total
	GL/y			
Gingin Brook & Tributaries	-	-	5	**5**
Swan River & Tributaries	-	-	3	**3**
Helena	10	-	-	**10**
Canning River	24	-	1	**25**
Cockburn-Kwinana Coastal	-	-	0	**0**
Serpentine River Catchment	17	-	4	**21**
Dandalup River System	21	-	1	**22**
Kwinana-Peel Coastal	-	-	2	**2**
Murray River & Tributaries	-	-	3	**3**
Harvey	24	49	15	**88**
Collie	7	64	22	**93**
Preston	-	1	7	**8**
Capel River	-	-	11	**11**
Busselton Coast	0	-	40	**41**
Lower Blackwood	0	-	40	**40**
Donnelly River & Tributaries	-	-	8	**8**
Warren River & Tributaries	2	-	23	**25**
Shannon-Gardner	-	-	7	**7**
Muir-Unicup	-	-	-	**-**
Kent	-	-	6	**6**
Denmark	0	-	8	**8**
Total	**104**	**114**	**207**	**425**

7.3.3 Estimating future surface water yields

Estimates of future surface water yields were determined based on the following method:

- At existing public water supply and irrigation dams which usually capture all available runoff, future yields were determined by reducing current yields on the basis of calculated mean annual flow reductions based on hydrological model estimates for each climate scenario. Where specific information for a dam site was not available from a model, data from the nearest hydrologically similar modelled site were used. The assessment of yield change was made relative to yield under Scenario B which was assumed to be representative of the current yield.
- For sub-areas with current yields determined on the basis of SDLs, future yields were estimated on the basis of calculated changes in SDLs at 28 key gauging stations throughout the project area based on hydrological model results under each climate scenario using the methodology described in Sections 4.3.1 and 4.4. Results from the nearest hydrologically similar gauging station were then applied to sub areas on a percentage change basis. Assessments of yield changes were made relative to yield under Scenario A which was assumed to be representative of the current yield.

Table 7-2 and Figure 7-3 detail estimated future yields for all surface water management areas based on the above method. The total surface water yield for the project area was estimated to decrease from between 4 percent under Scenario Cwet to 49 percent under Scenario Cdry with a 24 percent reduction under Scenario Cmid.

The highest yielding areas of Harvey and Collie had a relatively high resilience to climate change with yield reductions under Scenario Cmid of 15 and 22 percent respectively. These catchments have a higher yield under Scenario A than currently because recent flows were used to estimate the current yields for all Water Corporation dams.

Further south the Donnelly and Warren River management areas which are largely self-supply areas have some of the least robust areas providing yield reductions of 39 and 36 percent respectively. The Gingin Brook and Kwinana-Peel Coastal catchments have 56 and 41 percent reductions but this is partly because they have low current yields.

Under Scenario Cdry, more than a third of the surface water management areas have yield reductions of over 60 percent. The largest yield reduction is for the Gingin Brook area which has a yield reduction of 86 percent. The allocation limit for this catchment was determined from the draft water allocation plan with future yields scaled according to the SDL method. This catchment has significant surface–groundwater interactions and it has been estimated that flows have already been reduced because of both reduced rainfall and lower groundwater levels (CSIRO 2009a). The magnitude of the reduction is very large and may not be suited to the assumptions made in this regional assessment.

Table 7-2. Current surface water yields by surface water management area and under scenarios A, B and C

Surface water management area	Current	A		B		Cwet		Cmid		Cdry	
		GL/y	% change	GL/y	% change	GL/y	% change	GL/y	% change	GL/y	% change
Gingin Brook & Tributaries	5.0	5.0	0	4.7	-6	4.2	-16	2.2	-56	0.7	-86
Swan River & Tributaries	2.6	2.6	0	2.6	0	2.3	-12	1.9	-27	1.1	-58
Helena	9.6	13.2	38	9.6	0	11.8	23	7.9	-18	3.9	-59
Canning River	25.4	28.8	13	25.4	0	26.6	5	21.1	-17	14.8	-42
Cockburn-Kwinana Coastal	0.4	0.4	0	0.4	0	0.4	0	0.3	-25	0.2	-50
Serpentine River Catchment	20.7	25.8	25	20.7	0	22.5	9	15.6	-25	9.1	-56
Dandalup River System	21.9	24.7	13	22.1	1	22.0	0	15.8	-28	9.6	-56
Kwinana-Peel Coastal	1.7	1.7	0	2.0	18	1.5	-12	1.0	-41	0.5	-71
Murray River & Tributaries	2.5	2.5	0	3.0	20	2.2	-12	1.6	-36	0.8	-68
Harvey	88.0	97.2	10	91.3	4	90.3	3	75.0	-15	58.7	-33
Collie	93.6	100.2	7	97.9	5	91.5	-2	72.9	-22	53.8	-43
Preston	8.1	8.1	0	10.8	33	7.0	-14	5.6	-31	4.2	-48
Capel River	10.6	10.6	0	15.1	42	9.3	-12	7.7	-27	4.2	-60
Busselton Coast	40.8	40.9	0	40.2	-1	36.0	-12	29.0	-29	16.3	-60
Lower Blackwood	40.4	40.4	0	40.9	1	35.1	-13	28.9	-28	18.1	-55
Donnelly River & Tributaries	7.9	7.9	0	7.9	0	6.3	-20	4.8	-39	2.7	-66
Warren River & Tributaries	24.7	25.0	1	25.5	3	20.6	-17	15.9	-36	9.4	-62
Shannon-Gardner	7.4	7.4	0	9.5	28	6.5	-12	5.3	-28	3.1	-58
Muir-Unicup	0.0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
Kent	5.8	5.8	0	6.2	7	5.2	-10	4.3	-26	3.1	-47
Denmark	8.3	8.4	1	8.6	4	7.6	-8	5.8	-30	3.1	-63
Total	**425.2**	**456.5**	**7**	**444.4**	**5**	**408.7**	**-4**	**322.6**	**-24**	**217.6**	**-49**

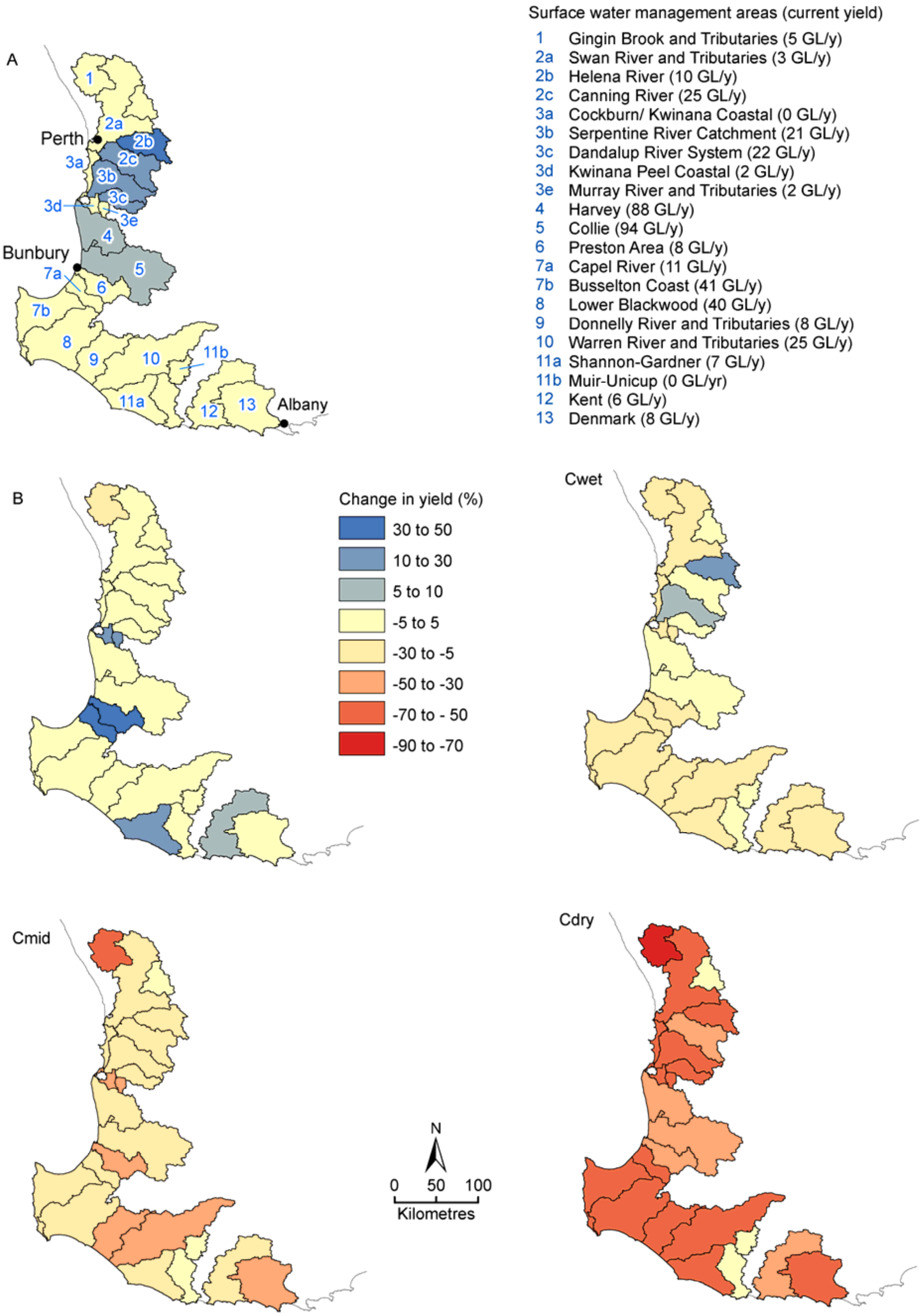


Figure 7-3. Map of changes in surface water yields by surface water management area under scenarios A, B and C

7.3.4 Estimating current groundwater yields

Current groundwater yields for each groundwater management area were based on existing allocation limits within the DoW Water Resource Licencing (WRL) database added to the estimated current unlicensed use within each of these areas. Allocation limits within the database reflect the current status of groundwater allocation planning as detailed in published DoW documents, many of which were reviewed in Chapter 3.

Current yields were determined by aggregating allocation limits for individual groundwater sub-areas to aquifer type within each groundwater management area. In the Grassmere sub-area of the Albany groundwater management area, where no allocation limit has been set for its sedimentary aquifer, the existing allocation was used as an estimate of the current groundwater yield for the purposes of this project.

Current groundwater yield estimates based on this method were considered representative of yield under Scenario A.

Table 7-3 and Figure 7-4 detail estimated current yields for all groundwater management areas based on this method. The total estimated groundwater yield for the project area is 1556 GL/year, more than 3.5 times the current surface water yield. About 58 and 26 percent of the total current groundwater yield is from the Superficial and Yarragadee aquifers respectively with the Leederville Aquifer providing a further 12 percent.

The largest current yield is in the Gingin and Arrowsmith areas with 326 and 187 GL//year. Together, these areas constitute 33 percent of all current groundwater yield. The total combined current yield for aquifers supplying the IWSS is estimated as 145 GL/year which is the same yield as that estimated in the Water Forever study (Water Corporation, 2009).

Table 7-3. Current groundwater yields by groundwater management area

Groundwater management area	Superficial Aquifer	Yarragadee Aquifer	Leederville Aquifer	Mirrabooka Aquifer	Fractured rock & other	Total
			GL/y			
Casuarina	0	16	0	0	0	16
Arrowsmith	27	160	0	0	0	187
Jurien	34	44	13	1	0	92
Gingin	255	25	39	8	0	326
Gnangara	34	5	15	0	0	54
Yanchep	11	0	0	0	0	12
Wanneroo	33	5	1	0	0	39
Swan	26	1	5	2	0	34
Mirrabooka	37	2	6	1	0	46
Gwelup	10	8	5	4	0	27
Perth	131	23	15	0	0	169
Jandakot	52	0	2	0	0	54
Cockburn	45	5	1	0	0	51
Serpentine	40	2	7	0	0	49
Rockingham	29	0	1	0	0	29
Murray	40	3	27	0	0	70
South West Coastal (Preston)	47	6	4	0	0	57
South West Coastal (Peel)	17	0	4	0	0	21
Bunbury	6	30	11	0	0	47
Busselton-Capel	17	50	20	0	0	87
Blackwood	6	20	6	0	0	31
Collie	0	0	0	0	56	56
Albany	5	0	0	0	0	5
Total	**900**	**402**	**182**	**15**	**57**	**1556**

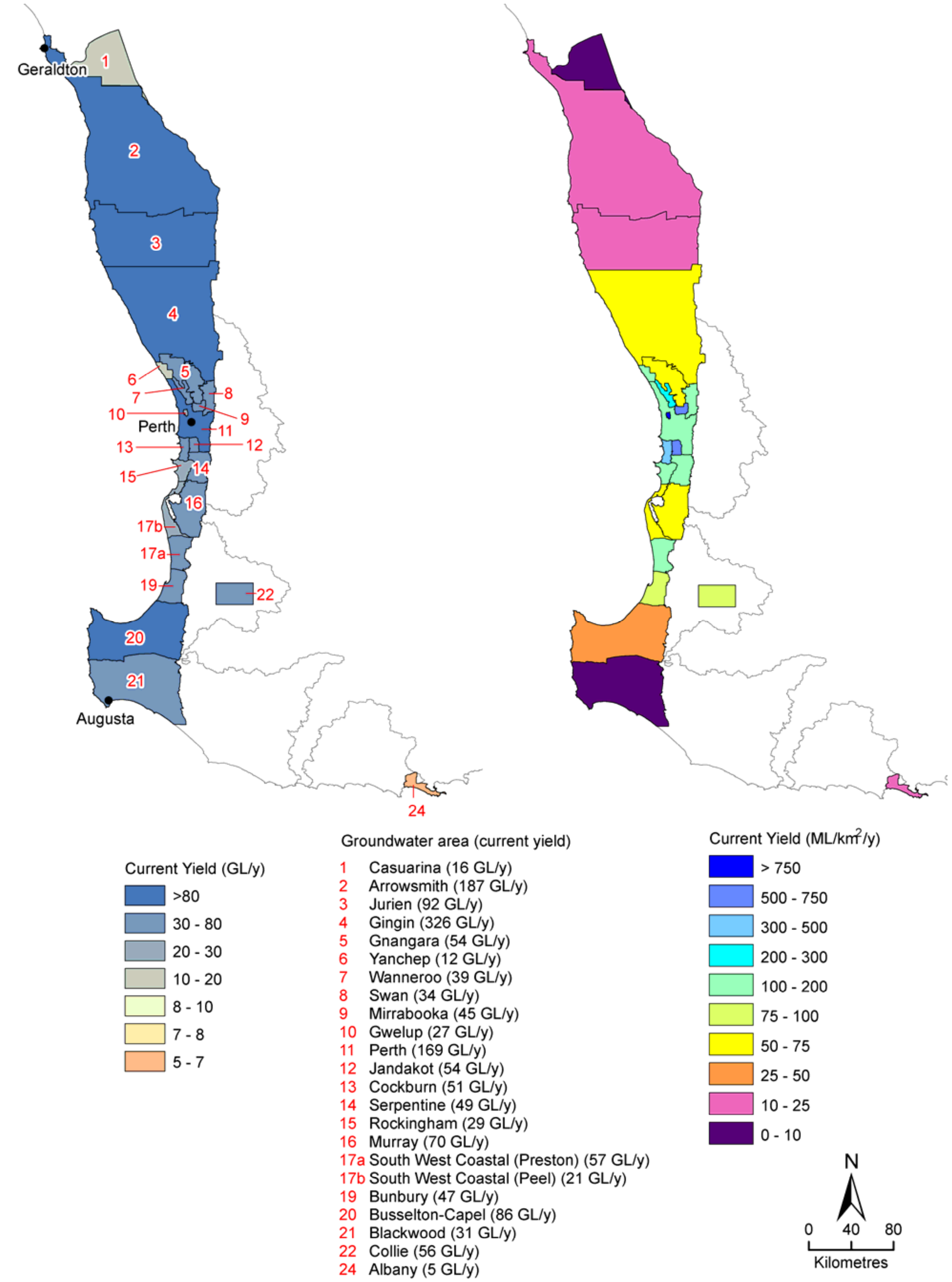


Figure 7-4. Map of current groundwater yields by water management areas

7.3.5 Estimating future groundwater yields

To estimate future groundwater yields, it was assumed that the current groundwater allocation limits were related to the existing storage within each aquifer in a groundwater sub area. For unconfined aquifers storage is directly related to levels and abstraction is limited by impacts on groundwater dependent ecosystems so this assumption has some validity.

Assessments of yield changes were made relative to Scenario A which was assumed to be representative of the current yield. Any change in the storage volume of the aquifer under scenarios B and C when compared with Scenario A were then directly related to the future groundwater yield. Rules were applied to determine the magnitude of the yield change to apply on the basis of the current performance of the aquifer:

- If the aquifer had increasing storages under Scenario A then a yield reduction was only applied if the modelled climate scenario resulted in a decrease in aquifer storage. This assumed that there would be no imperative to reduce limits if levels were rising in the aquifer. The amount of the yield reduction was set as the average annual storage decrease. This is a conservative assumption in that it assumes that all future reductions in storage would result in a commensurate reduction in abstraction and the environmental demands would still be met. A yield increase was applied if a climate scenario resulted in a storage increase above Scenario A.
- If the aquifer had a decreasing storage under Scenario A, then a yield reduction was applied equal to the average annual change in storage between the two scenarios.

For example under this approach, a 5 GL/year reduction in aquifer storage under Scenario B (relative to Scenario A), would equate to a 5 GL/year reduction in yield from that aquifer, if under Scenario A storage within the aquifer was decreasing. If storages in the same aquifer had been increasing at a rate of 4 GL/year under Scenario A, a yield reduction of only 1 GL/year would have been adopted.

The assumption that allocation is related to storage is not valid for confined aquifers which remain full but contain water at a lower pressure as water is removed (elastic storage). However reducing the pressure in confined aquifers can lower groundwater levels in connected unconfined aquifers. Using changes in recharge as a measure of future water yields was assessed but found to be unreliable because recharge will increase in areas with high watertables as groundwater levels fall and enable more water to enter the aquifer.

The method was applied to individual aquifers on a sub-area basis and the results aggregated to the groundwater management area scale for use in the yield and demand gap analysis.

Storage changes were obtained for individual aquifers at sub-area scale using the following groundwater models:

- Superficial, Leederville and Yarragadee aquifers in the Central Perth Basin used the Perth Regional Aquifer Modelling System (PRAMS)
- Superficial Aquifer in the Peel Harvey Area used the Peel Harvey Regional Aquifer Modelling System (PHRAMS)
- Superficial, Leederville, and Yarragadee aquifers in the Southern Perth Basin used the South West Aquifer Modelling System (SWAMS)
- Collie confined aquifers in the Collie Groundwater Basin used the Collie Groundwater Model.

Storage changes were not provided for all aquifers or groundwater sub-areas within the above groundwater model domains and the following approach was adopted to determined yield changes for these situations:

- yield changes for the Mirrabooka semi confined aquifer were assumed to be similar (in percentage terms) to those of the Yarragadee Aquifer in the same sub area
- yield changes for the Surficial and Fractured Rock aquifers were assumed to be similar (in percentage terms) to those of the Superficial Aquifer in the same sub-area.

These assumptions were considered reasonable at the sub-area level, given the aggregation of data to the groundwater management area scale for reporting and analysis purposes and the small quantities of water involved in these aquifers.

The abstraction of water from the Leederville and Yarragadee aquifers influences levels in the Superficial Aquifer in the PRAMS domain. To acknowledge this relationship, any loss of storage in the unconfined aquifer was used to reduce the Allocation Limits by 75 percent of the loss of storage to this aquifer and 25 percent to the confined aquifers. Where both the Leederville and Yarragadee aquifers were present in a Groundwater Management Area, 15 percent was allocated to the Leederville Aquifer and 10 percent to the Yarragadee Aquifer. It is recognised that the confined aquifers remain full so this assumption was made to prevent depressurising of them with consequent impacts on the unconfined aquifers that are in contact with them.

Two further methods were used to assess the yield changes in the Northern Perth Basin and Albany groundwater areas which lacked a suitable groundwater model:

- statistical hydrograph analysis using the HARTT method, which establishes statistical relationships between historical rainfall and groundwater levels where other factors are not influencing level s and uses this relationship and the future rainfall scenarios to predict groundwater levels in 2030
- recharge estimated using the WAVES model (CSIRO, 2009a).

No yield reductions in the management areas of the Northern Perth Basin (Casuarina, Arrowsmith and Jurien) were adopted for any of the climate scenarios based on application of these methods. Groundwater levels in a number of bores in dryland agriculture areas are rising (as are Dandaragan Plateau hydrographs), and allocation limits in the Northern Perth Basin were considered to be set at relatively conservative levels as a result of the generally low level of development and use (Chapter 3).

The groundwater report developed as part of this project provides further details on the analysis of how groundwater resources of each management areas respond to the future climate scenarios.

Table 7-4 and Figure 7-5 detail estimated future yields for all groundwater management areas and individual aquifers based on the above methodology. The current yield is the sum of all allocation limits. Under future climate, groundwater yields change from an increase of 2 percent under Scenario Cwet to a decrease of 7 percent under Scenario Cdry, with a 2 percent reduction under Scenario Cmid. With respect to the IWSS, the Gnangara groundwater area performs worst showing a 6 percent yield reduction. The largest yield reductions were experienced in the Collie (15 percent), Blackwood (11 percent) and Albany (35 percent) management areas. The latter estimate is based on very limited data.

The minor changes in yield for many areas implies current allocation limits are able to accommodate impacts of future climate on yields at least until 2030.

Table 7-4. Current groundwater yields by groundwater management area and under scenarios A, B and C

Groundwater management area	Current	A		B		Cwet		Cmid		Cdry	
		GL/y	% change	GL/y	% change	GL/y	% change	GL/y	% change	GL/y	% change
Casuarina	15.7	15.7	0	15.7	0	15.7	0	15.7	0	15.7	0
Arrowsmith	186.9	186.9	0	186.9	0	186.9	0	186.9	0	186.9	0
Jurien	91.7	91.7	0	91.7	0	91.7	0	91.7	0	91.7	0
Gingin	326.2	326.2	0	321.3	-2	344.0	5	323.7	-1	299.1	-8
Gnangara	54.3	54.3	0	43.1	-21	58.5	8	50.9	-6	34.3	-37
Yanchep	11.6	11.6	0	11.6	0	11.8	2	11.6	0	11.4	-2
Wanneroo	38.8	38.8	0	38.6	-1	38.8	0	38.6	-1	32.0	-18
Swan	33.5	33.5	0	33.5	0	33.7	1	33.5	0	32.0	-4
Mirrabooka	45.4	45.4	0	45.4	0	45.4	0	45.4	0	43.7	-4
Gwelup	26.7	26.7	0	26.7	0	26.7	0	26.7	0	26.5	-1
Perth	168.8	168.8	0	168.8	0	168.7	0	168.4	0	162.1	-4
Jandakot	53.8	53.8	0	53.8	0	53.8	0	53.7	0	53.7	0
Cockburn	51.0	51.0	0	51.0	0	50.9	0	50.6	-1	50.5	-1
Serpentine	49.0	49.0	0	49.0	0	49.0	0	49.0	0	48.9	0
Rockingham	29.3	29.3	0	29.3	0	29.3	0	29.2	0	29.2	0
Murray	70.0	70.0	0	70.3	0	69.9	0	69.6	-1	69.0	-1
South West Coastal (Preston)	57.2	57.2	0	57.9	1	57.2	0	55.8	-2	53.8	-6
South West Coastal (Peel)	20.8	20.8	0	21.1	1	20.8	0	20.4	-2	19.9	-4
Bunbury	46.7	46.7	0	45.8	-2	50.1	7	46.4	-1	44.2	-5
Busselton-Capel	86.4	86.4	0	86.1	0	91.2	6	84.2	-3	81.7	-5
Blackwood	31.1	31.1	0	29.3	-6	33.4	7	27.7	-11	18.6	-40
Collie	55.5	55.5	0	55.5	0	52.7	-5	47.0	-15	40.9	-26
Albany	5.1	5.1	0	4.6	-10	4.1	-20	3.3	-35	2.6	-49
Total	**1555.7**	**1555.7**	**0**	**1537.1**	**-1**	**1584.6**	**2**	**1530.2**	**-2**	**1448.8**	**-7**

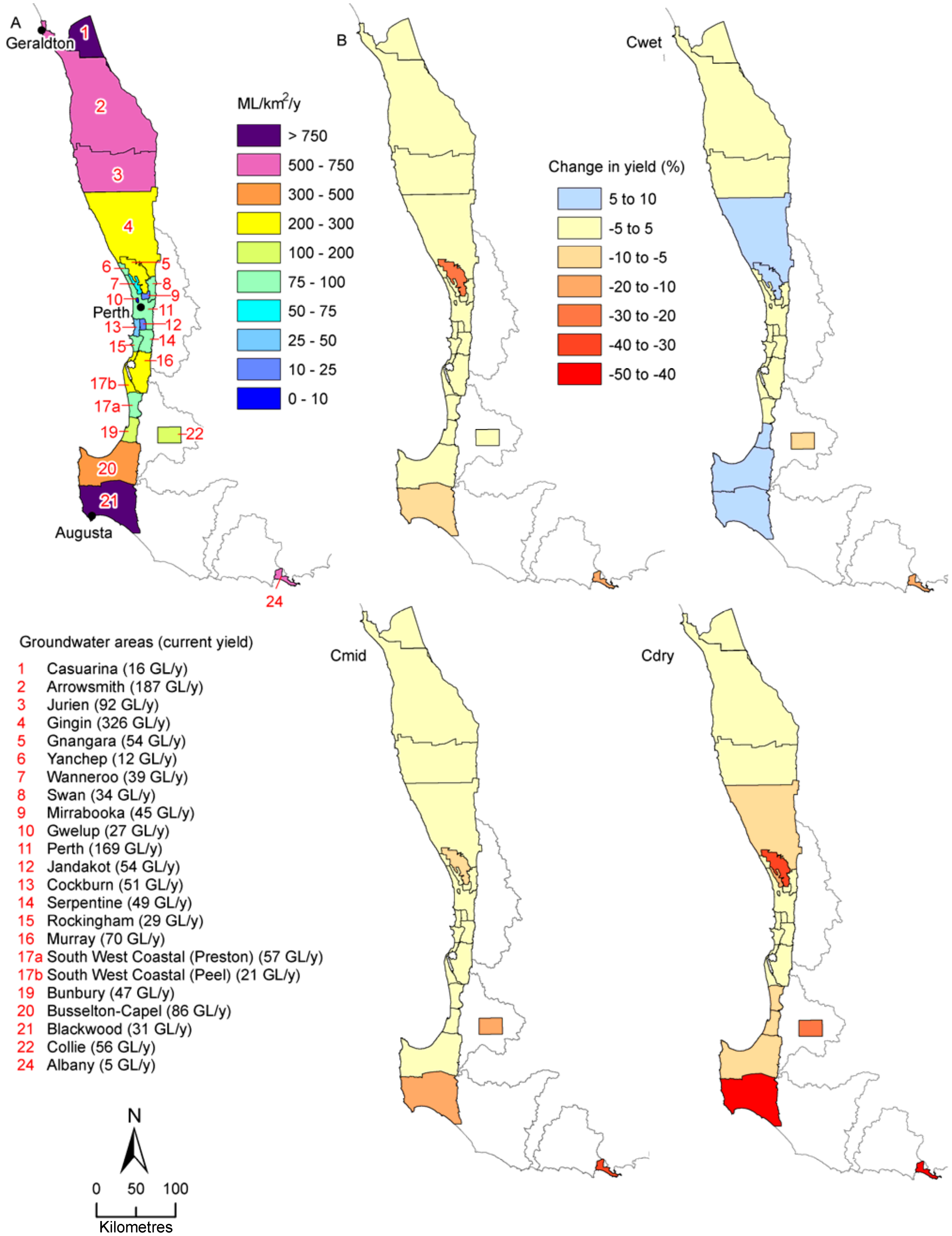


Figure 7-5. Changes in groundwater yield by groundwater management area under scenarios A, B and C

7.4 Yield and demand gap analysis

The following sections combine the current and future yield assessments for the scenarios with the current and projected demand scenarios to 2030.

For this analysis, a spreadsheet-based model, YGAP, was developed for the project area. The model enables the analysis and synthesis of water management demand and yields at water management area and sub-area scale and enables the aggregation of data to various user-defined reporting scales.

YGAP includes the capability and accounting for existing water transfers and modified future water transfers between water management areas. The model also enables management actions such as importing water, new sources, desalination, water use efficiency, and changes in water distribution, to be input and the assessment and evaluation of these actions in addressing a yield and demand gap to be quantified. While assessment of the management actions to address yield and demand gaps is outside the scope of this project, the framework was established to provide future capability for water resources managers at the completion of this project.

The results of the yield and demand gap analysis are presented at the following scales of water resource management in the following sections:

- the entire South-West Western Australia Sustainable Yields Project area
- surface water assessment aggregated to surface water management region
- groundwater assessment aggregated to groundwater management region
- Water Corporation's Integrated Water Supply Scheme.

Yield and demand gap analysis results for individual surface water and groundwater management areas are included in Appendix E to this report.

A regional synthesis of the yield and demand gap analysis findings is presented in Chapter 8.

7.4.1 Surface water in the Busselton Coast to Denmark region

The combined yield and demand gap analysis for the Busselton Coast to Denmark region, which includes all surface water catchments from Capel, south of Bunbury to the Denmark Basin west of Albany, is shown in Table 7-5 and Figure 7-6. Individual surface water management areas results are in Appendix E.

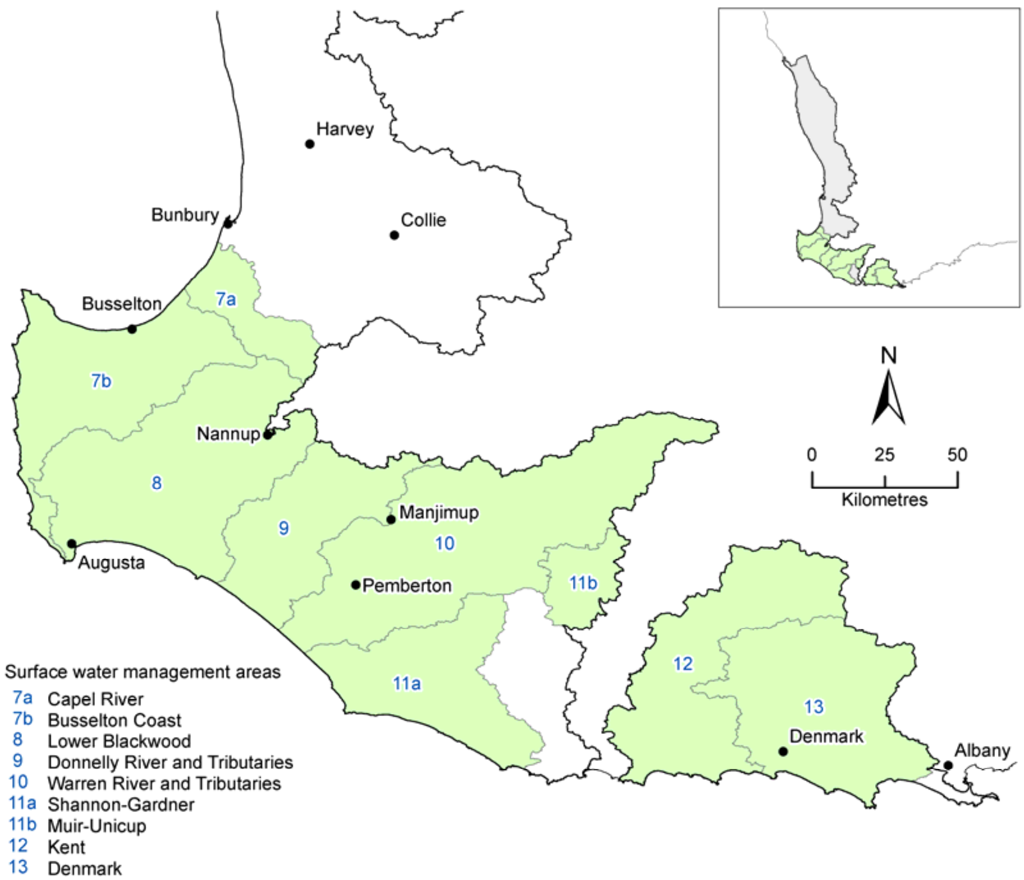
The region has sufficient surface water overall in terms of meeting expected demands to 2030, apart from under Scenario Cdry. This is despite significant surface water yield losses under Scenario C (e.g. regional average of 30 percent reduction in yield under Scenario Cmid). Flows will continue in the main rivers that drain large areas of state forest and national park but tributaries servicing self supply irrigation areas may not meet all future demand under a very dry scenario.

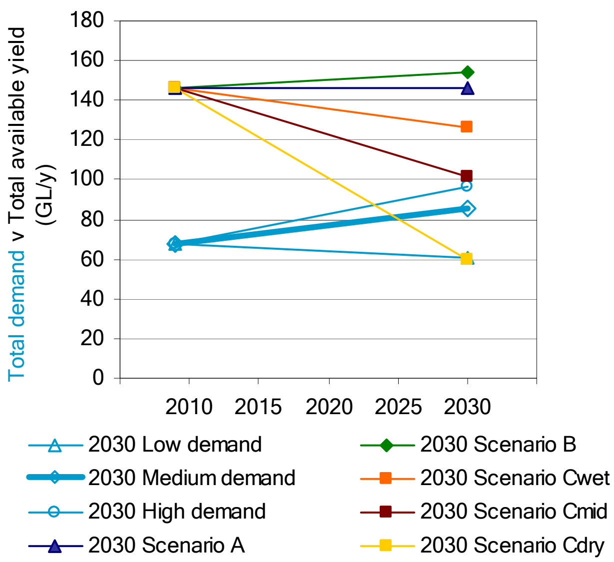
At the individual management area scale, the Kent, Shannon-Gardiner, Warren and Donnelly rivers are identified as areas where demand is likely to exceed yield by 2030, and in the case of the Warren and Donnelly rivers this is likely to be the case irrespective of any yield reduction due to climate change. The Warren River area is identified as the individual management area of the region likely to have the largest yield and demand gap by 2030, estimated as 11 GL/year by 2030 under Scenario Cmid.

The Busselton Coast, Capel River, Lower Blackwood and Denmark areas appear to have sufficient surface water resources to 2030 to meet demand under all scenarios other than Scenario Cdry.

Table 7-5. Summary of surface water yield and demand gap analysis for the Busselton Coast to Denmark region. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
			GL/y			
Current	78	78	86	59	34	-8
Low demand	85	86	93	66	41	-1
Medium demand	60	60	68	41	16	-26
High demand	49	49	57	30	5	-37





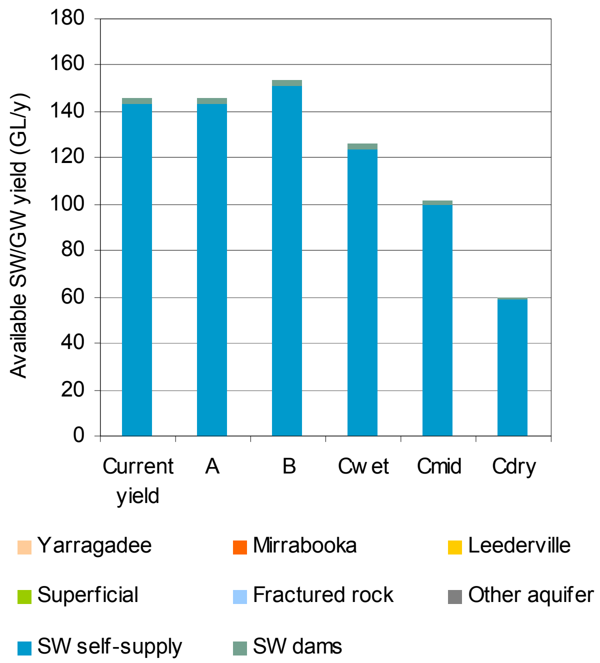


Figure 7-6. Yield and demand gap analysis for the Busselton Coast to Denmark surface water region

7.4.2 Surface water in the Harvey to Preston region

The Harvey to Preston region covers the area north of Bunbury to south of the Peel Harvey estuary which includes the major irrigation districts and a number of dams providing water to the IWSS. Most of the water in this region is used for irrigation and water supply purposes.

Table 7-6 and Figure 7-7 provide a summary of the results of the combined yield and demand gap analysis. Individual surface water management areas yield and demand gap analyses are in Appendix E.

The results indicate the region has a yield and demand gap of 29 GL/year under the medium demand scenario and Scenario Cmid, and high growth would result in a yield and demand gap irrespective of the climate. These results indicate future stresses on the water resources of this region to meet demand, possibly within ten years. This deficit may be partly a function of the assumption that horticultural areas will expand in a growing economy.

Of the three surface management areas within the region, the Collie and Preston appear the most robust to future demand increase and the climate scenarios while water in the Harvey management area is the most vulnerable. The Harvey area currently has no spare capacity between yield and demand and this region was identified using the Computable General Equilibrium model as one likely to encounter the fastest rate of growth in demand due to its mix of industries to 2030. As a result, this region is considered likely to experience considerable pressure on its water resources.

The shortfall in yield by 2030 to meet demand is of similar magnitude to the current yield of the Harvey Dam.

Table 7-6. Summary of surface water yield and demand gap analysis for the Harvey to Preston region. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
				GL/y		
Current	39	55	49	38	2	-34
Low demand	63	79	74	63	27	-9
Medium demand	7	23	18	6	-29	-66
High demand	-20	-5	-10	-21	-57	-93

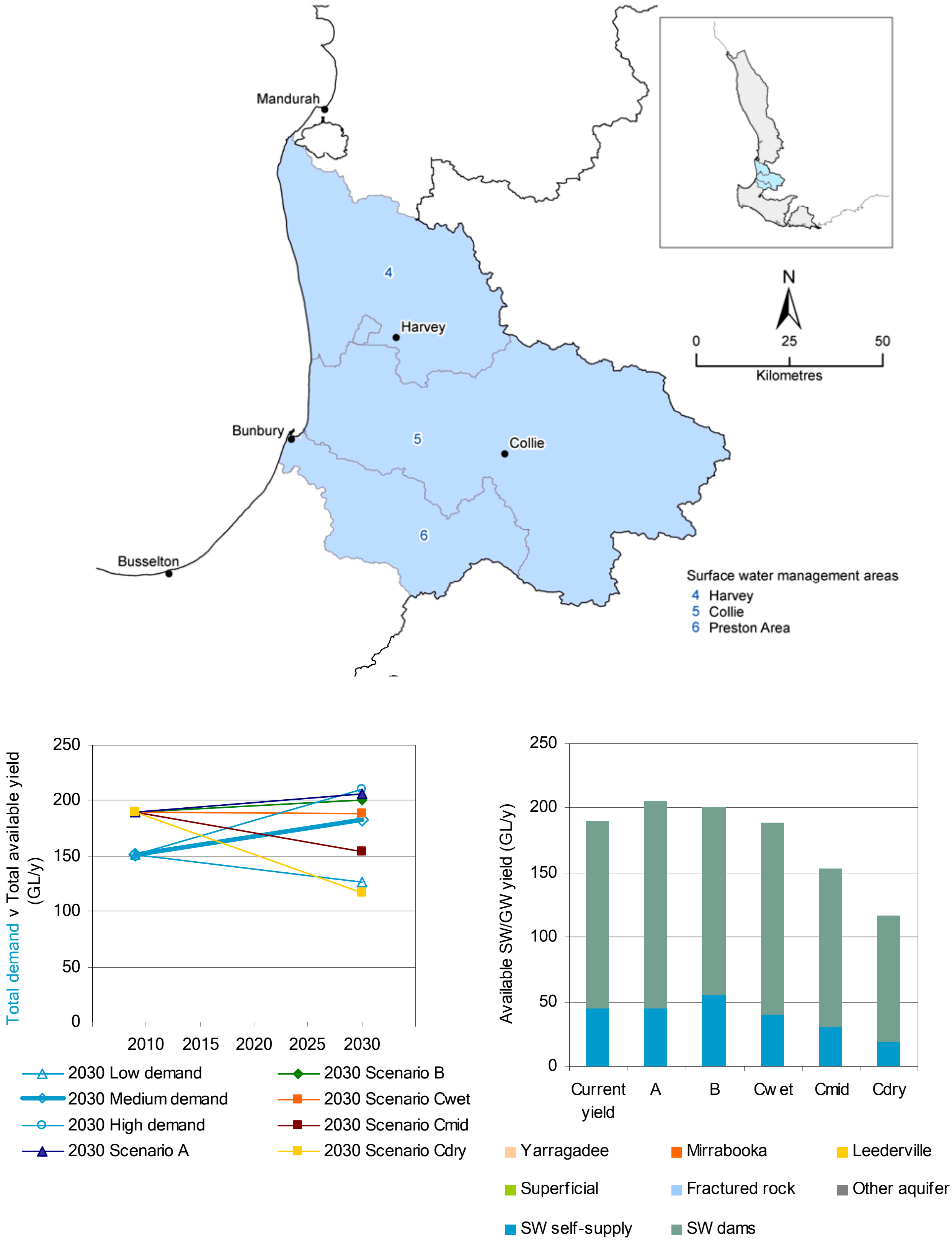


Figure 7-7. Yield and demand gap analysis for the Harvey to Preston surface water region

7.4.3 Surface water in the Gingin to Murray region

The Gingin to Murray region covers the area from the Peel Harvey Estuary south of Mandurah to Gingin north of Perth, and covers a total of 9 surface water management areas across 3 basins. The majority of water resources are used to provide water to the IWSS and the region includes the major Water Corporation Dams of Serpentine, North and South Dandalup, Canning and Mundaring.

Table 7-7 and Figure 7-8 provide a summary of the results of the combined yield and demand gap analysis for the region. Individual surface water management areas yield and demand gap analyses are in Appendix E.

The results indicate the region has a yield and demand gap of 17 GL/year under the medium demand scenario and under Scenario Cmid. There is a yield and demand gap irrespective of demand growth under both scenarios Cmid and Cdry, indicating the yield reductions due to reduced runoff mainly affects the yield and demand gap.

The majority of the yield reduction will be in catchments providing water to the IWSS and this is discussed further in Section 7.4.10.

Table 7-7. Summary of surface yield and demand gap analysis for the Gingin to Murray region. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
				GL/y		
Current	10	24	10	13	-13	-39
Low demand	10	25	11	14	-12	-39
Medium demand	6	20	6	9	-17	-43
High demand	4	19	5	8	-18	-45

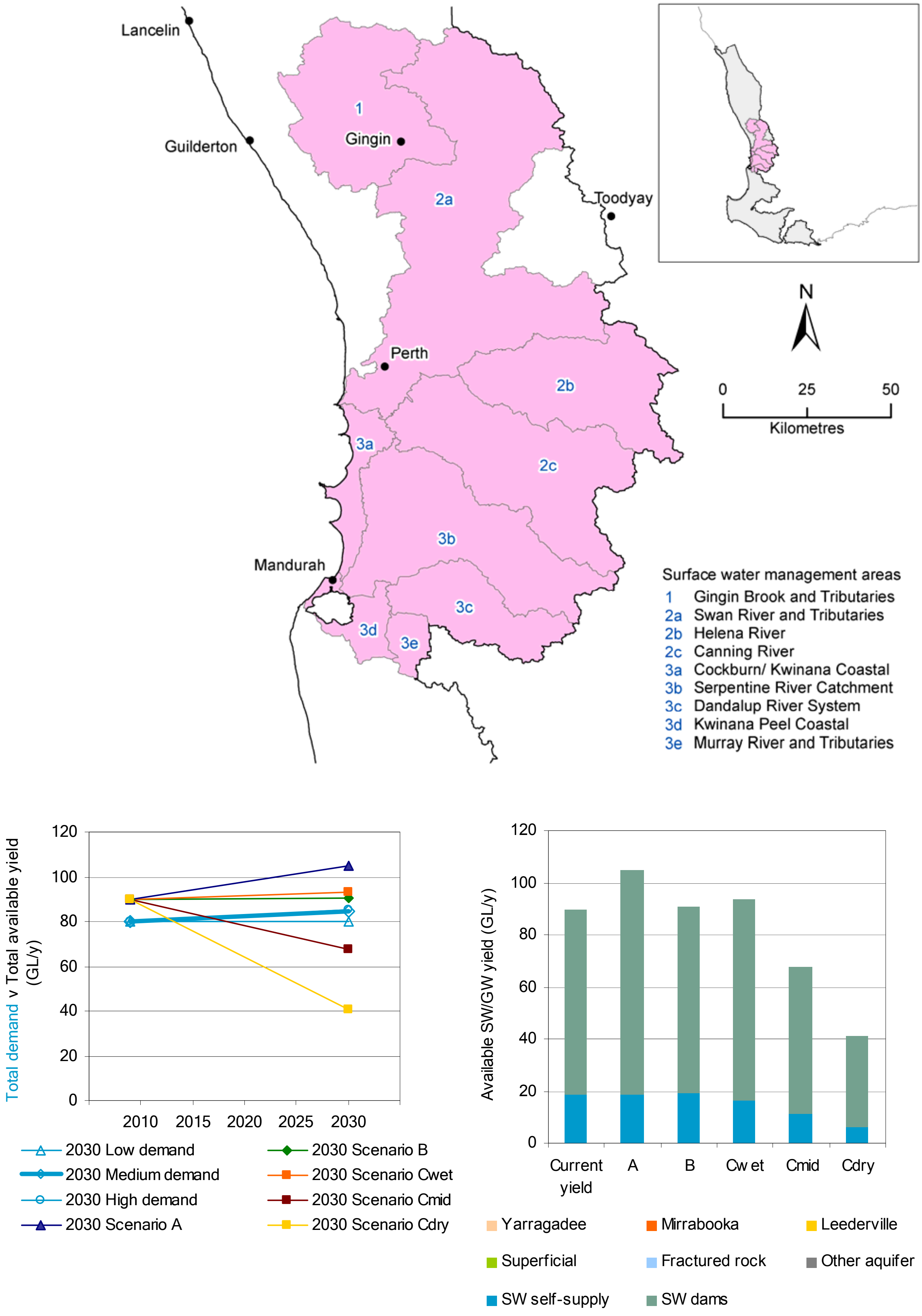


Figure 7-8. Yield and demand gap analysis for the Gingin to Murray surface water region

7.4.4 Groundwater in the Albany Area

Table 7-8 and Figure 7-9 show the results of the combined yield and demand gap analysis for the Albany Area. Individual groundwater management areas yield and demand gap analyses are in Appendix E.

DoW licensing information indicates the area is currently very close to full allocation, and future yields are considered likely to decrease significantly for all but Scenario A. However these analyses are based on WAVES and HARTT modelling only and therefore may not be reliable.

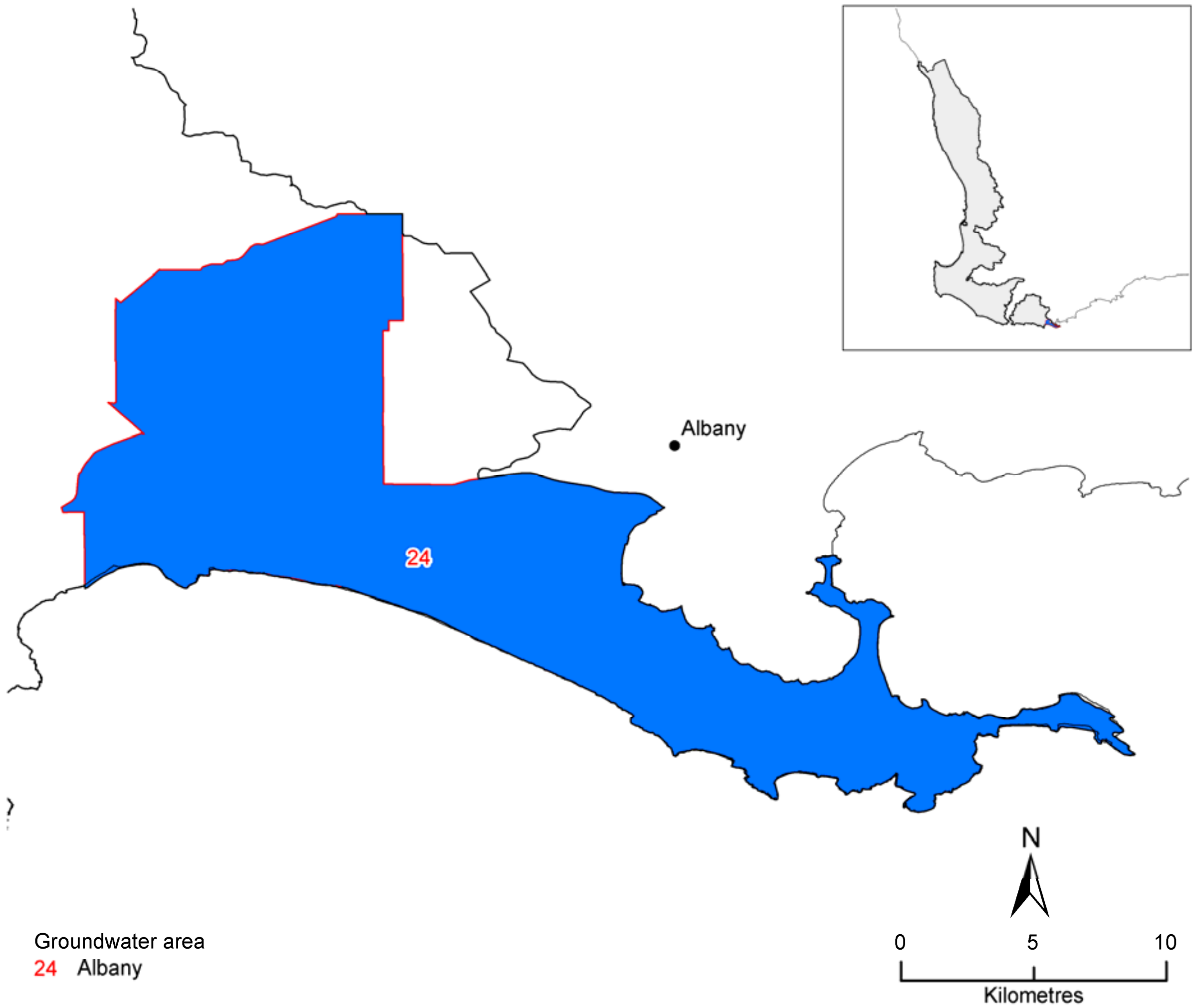
Albany has a yield and demand gap under all climate and demand scenarios. The results indicate the region has a yield and demand gap of 3 GL/year under the medium demand scenario and Scenario Cmid.

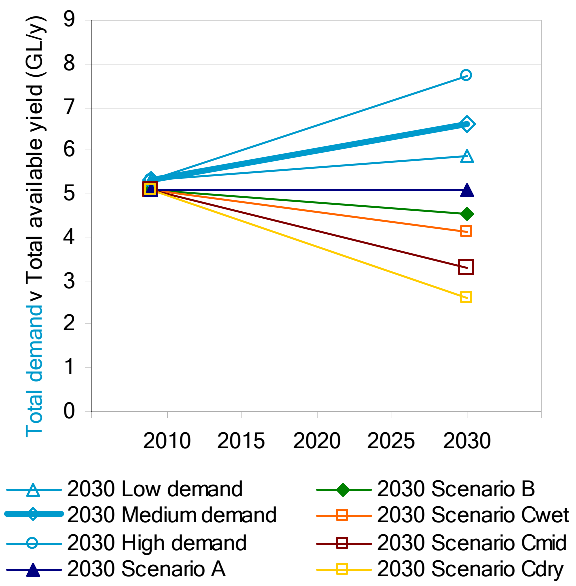
The yield and demand gap may be closed by using surface water.

As mentioned previously, this project does not however consider management options that may address any yield and demand gap between future possible supplies and demands.

Table 7-8. Summary of groundwater yield and demand gap analysis for the Albany Area. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
				GL/y		
Current	-0.2	-0.2	-0.8	-1.2	-2.0	-2.7
Low demand	-0.8	-0.8	-1.3	-1.7	-2.5	-3.3
Medium demand	-1.5	-1.5	-2.1	-2.5	-3.3	-4.0
High demand	-2.6	-2.6	-3.2	-3.6	-4.4	-5.1





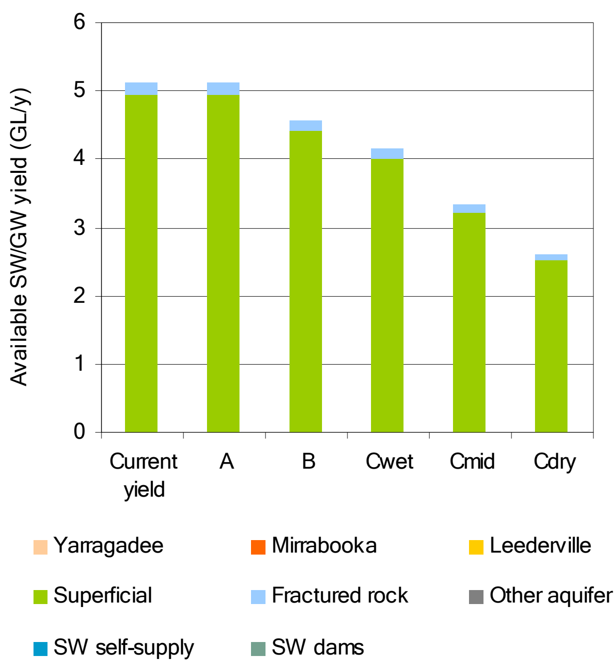


Figure 7-9. Yield and demand gap analysis for the Albany Area

7.4.5 Groundwater in the Southern Perth Basin

The Southern Perth Basin groundwater region includes the Bunbury, Busselton–Capel and Blackwood groundwater management areas. Medium growth in water demand in this region is estimated to be about 35 percent by 2030.

Table 7-9 and Figure 7-10 show the results of the combined yield and demand gap analysis for the region. Individual groundwater management areas yield and demand gap analyses are in Appendix E.

The region is seen to have a sufficient groundwater overall in terms of meeting expected demands to 2030, except under Scenario Cdry and under the high demand scenario. Decreases in yield can be seen to be mainly due to reductions in yield in the superficial aquifer, particularly under Scenario Cdry, although a reduction in yield in the confined aquifers may also occur.

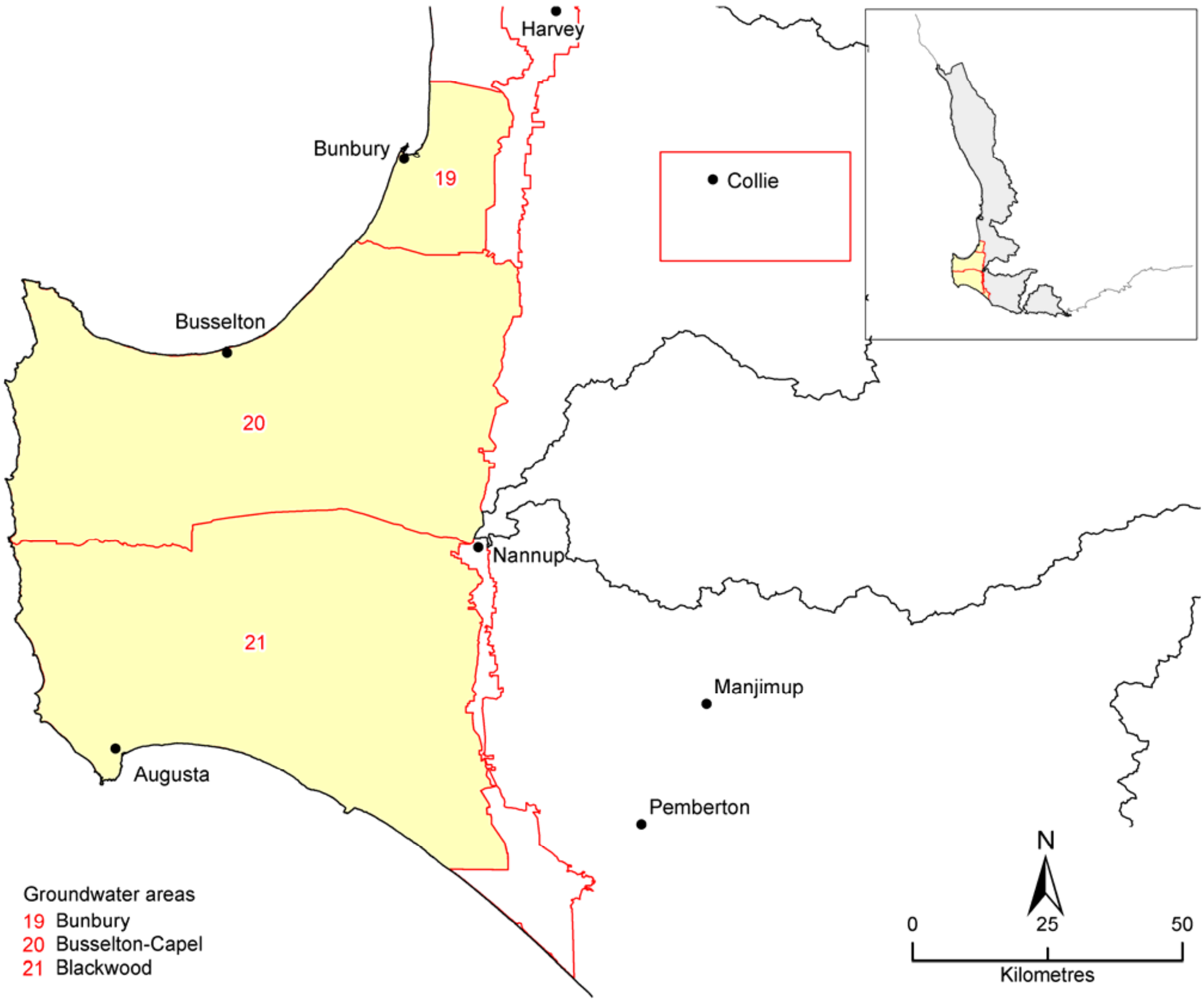
At the individual management area scale, the Blackwood groundwater management area experiences the largest yield variation due to the range of climate scenarios, with overall yields reducing by up to 40 percent under Scenario Cdry. However even with this yield reduction, this area has sufficient surface water to meet its projected demands, even under a high demand scenario.

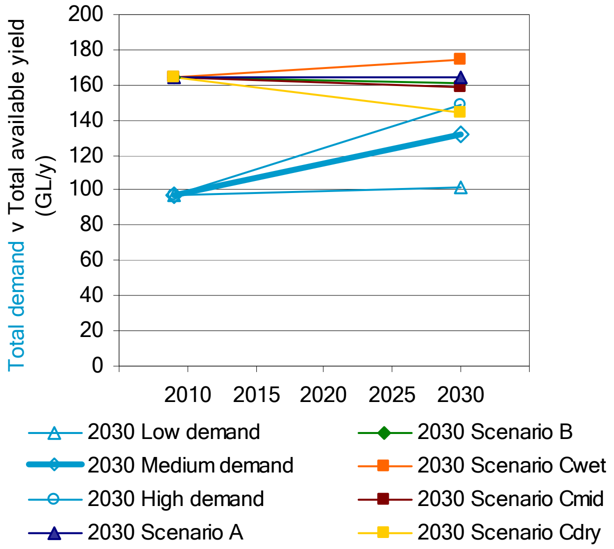
The Bunbury and Busselton–Capel management areas appear to have sufficient surface water resources to meet demands under all climate and demand scenarios other than the high demand scenario.

Additional water may also be available from the Blackwood-Karri unproclaimed groundwater area which has not included in this analysis.

Table 7-9. Summary of groundwater yield and demand gap analysis for the Southern Perth Basin. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
				GL/y		
Current	67	67	64	77	61	47
Low demand	62	62	59	73	56	43
Medium demand	32	32	29	43	26	13
High demand	16	16	13	26	10	-4





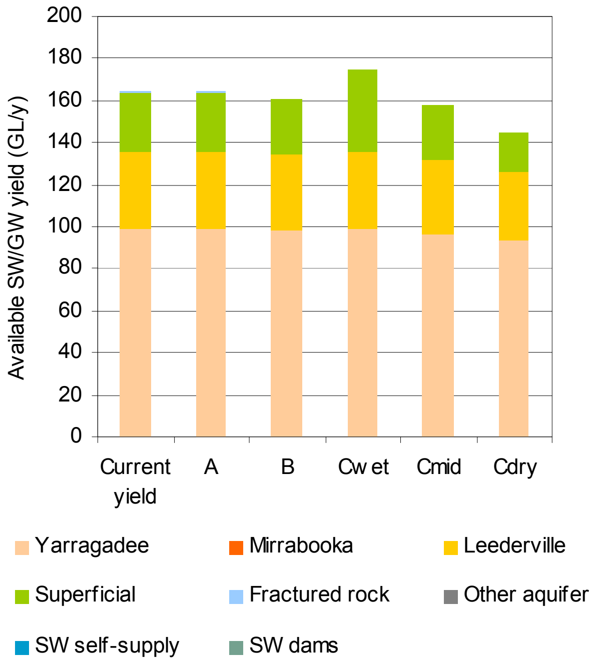


Figure 7-10. Yield and demand gap analysis for the Southern Perth Basin

7.4.6 Groundwater in the Collie Basin

Table 7-10 and Figure 7-11 show the results of the combined yield and demand gap analysis for the region. Individual groundwater management area yield and demand gap analyses are in Appendix E. The aquifers in the Collie Coal Basin are not found elsewhere in the project area so have been classified as ‘Other Aquifer’ in the figure.

The majority of current water use within the Collie groundwater Basin is for mine dewatering and energy generation purposes.

While the area has an estimated 12 GL/year of water currently available in excess of demand, the yield and demand gap analysis indicates a potential reduction in yield of up to 15 GL/year under Scenario Cdry and a similar demand increase of 15 GL/year under the high demand scenario over this period. A yield and demand gap is therefore likely to occur by 2030, even under Scenario Cmid and under the low demand scenario.

Any analysis of water yields and demands in this area is complicated by the interaction between the groundwater and surface water resources, and the possibility that water demand may be driven by energy requirements that may result in temporary over-allocations. Therefore these results need to be interpreted with caution.

Table 7-10. Summary of groundwater yield and demand gap analysis for the Collie Basin. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
				GL/y		
Current	12	12	12	9	4	-3
Low demand	7	7	7	4	-2	-8
Medium demand	4	4	4	1	-5	-11
High demand	-3	-3	-3	-5	-11	-17

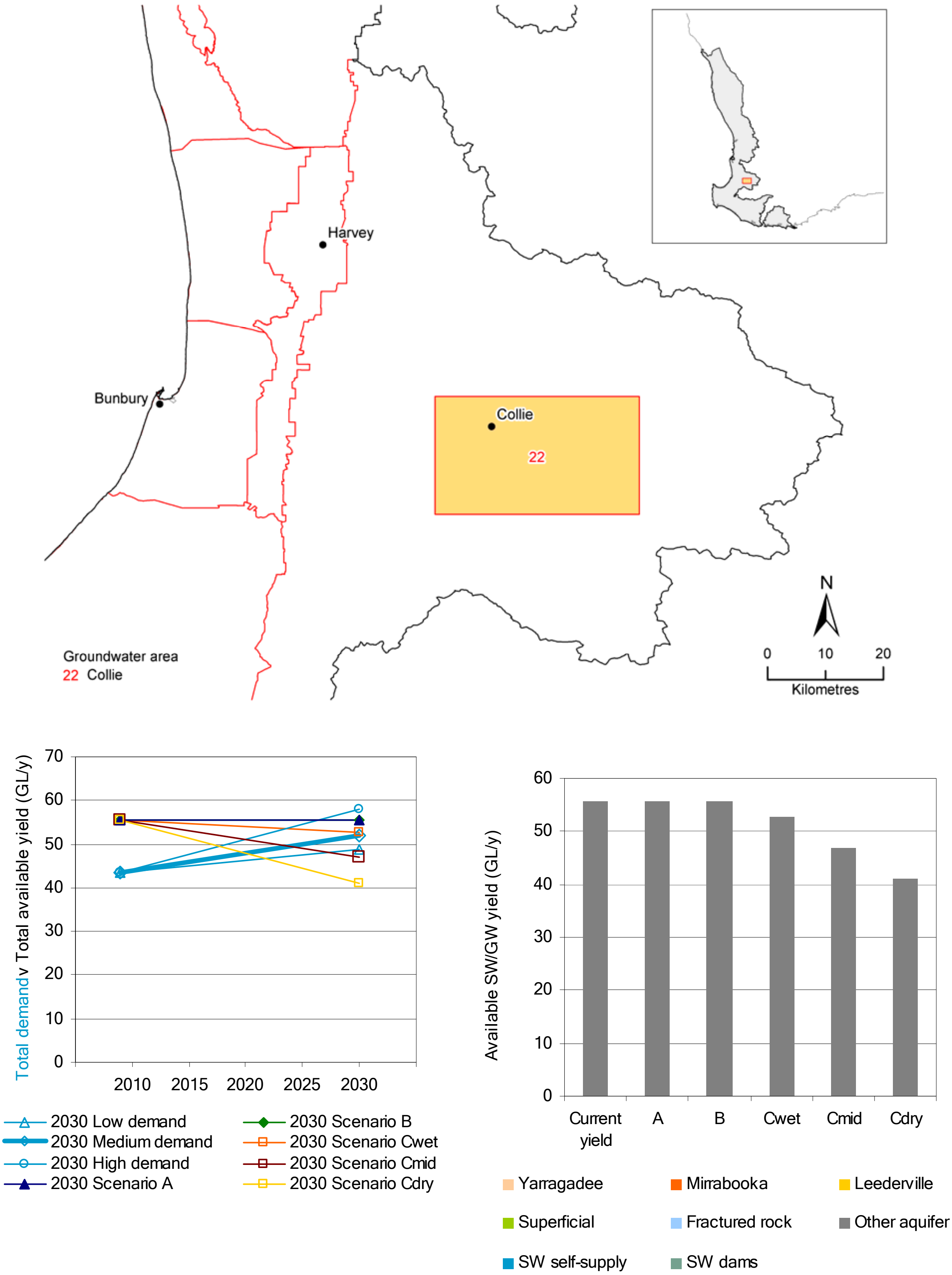


Figure 7-11. Yield and demand gap analysis for the Collie Basin

7.4.7 Groundwater in the Peel-Harvey Area

The Peel-Harvey Area includes the Murray and South West Coastal groundwater management areas. Medium demand growth for groundwater resources in this region is estimated to be about 42 percent above current levels by 2030.

Table 7-11 and Figure 7-12 show the results of the combined yield and demand gap analyses for the region. Individual groundwater management areas yield and demand gap analysis are in Appendix E.

The region has a high groundwater yield relative to demand for all climate and demand scenarios. Changes in yield to 2030 are likely to be minor. Lower groundwater levels over summer in this region under future climate scenarios that are hotter and drier enables more recharge over winter and less losses due to drainage and evapotranspiration because watertables will be lower.

This result is the converse to the result of the surface water management areas of Collie and Harvey, which are projected to have a high demand growth for surface water and yield susceptible to climate change.

This result implies groundwater of the Peel-Harvey Area may be considered as a possible source to meet projected future demands in the Collie and Harvey surface water management areas. Some groundwater resources may be too saline or distant from demand areas to be used in all applications however.

Table 7-11. Summary of groundwater yield and demand gap analysis for the Peel-Harvey Area. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
			GL/y			
Current	100	100	102	100	98	95
Low demand	96	96	98	96	94	91
Medium demand	81	81	82	81	79	76
High demand	72	72	74	72	70	67

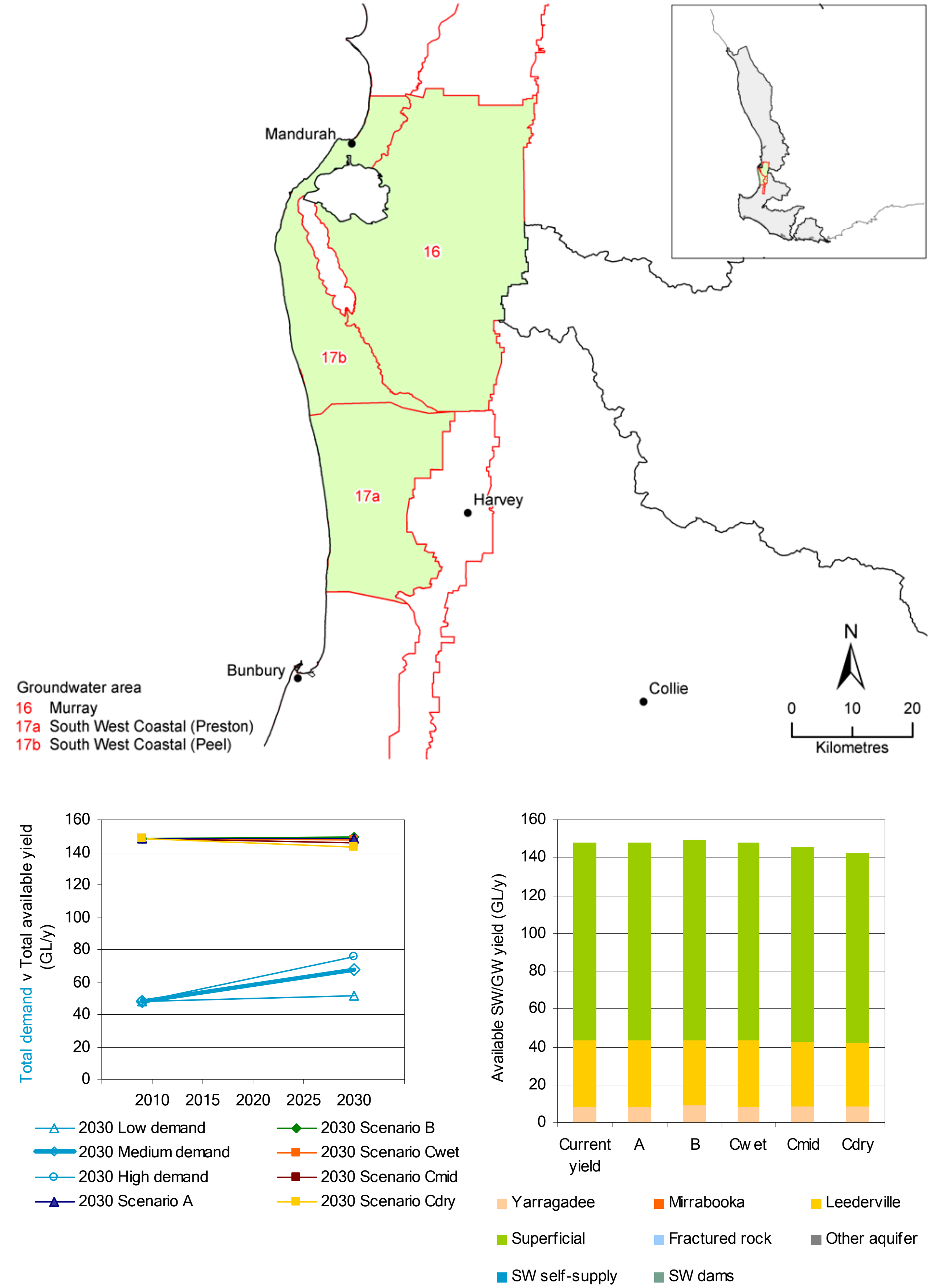


Figure 7-12. Yield and demand gap analysis for the Peel-Harvey Area

7.4.8 Groundwater in the Central Perth Basin

The Central Perth Basin groundwater region includes 12 groundwater management areas and extends from Mandurah in the south, to Moora approximately 180km north of Perth.

This region contains the highest demand growth of any of the groundwater regions to 2030. Under the medium demand scenario, demand is estimated to increase by 178 GL/year or by 30 percent by 2030.

Table 7-12 and Figure 7-13 show the results of the combined yield and demand gap analysis. Individual groundwater management areas yield and demand gap analyses are included as Appendix E.

The region is seen to have a sufficient groundwater overall in terms of meeting demand to 2030 under all climate scenarios, except under the high demand scenario.

At the individual management area scale, the yield and demand gap analysis results are spatially highly variable:

- Management areas such as Gingin, Yanchep, Gwelup and Serpentine have sufficient water resources for all future demand projections to 2030 under all modelled climate scenarios. In the case of Gingin, groundwater yield was found to exceed demand by 92 GL/year in 2030 even under Scenario Cdry and under the high demand scenario. This result for Gingin should, however, be viewed in the context that some groundwater in this area maybe saline and therefore have restricted potential use.
- Management areas such as Gnangara, Wanneroo, Swan and Rockingham may have insufficient water resources to meet future demand under any future demand projection. The combined total yield and demand gap for these areas, under Scenario Cmid and under the medium demand scenario, is about 60 GL/year. This result does not include any future increase in demand by the IWSS in these management areas.
- Other management areas (Mirrabooka, Perth, Jandakot and Cockburn) experience an emerging yield and demand gap to varying degrees under the different scenarios. In all of these areas, with the exception of Perth, a yield and demand gap occurs by 2030 under Scenario Cmid and a medium demand.

Table 7-12. Summary of groundwater yield and demand gap analysis for the Central Perth Basin. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
			GL/y			
Current	292	292	276	315	285	227
Low demand	243	243	226	265	236	178
Medium demand	115	115	99	137	108	50
High demand	-16	-16	-32	6	-23	-81

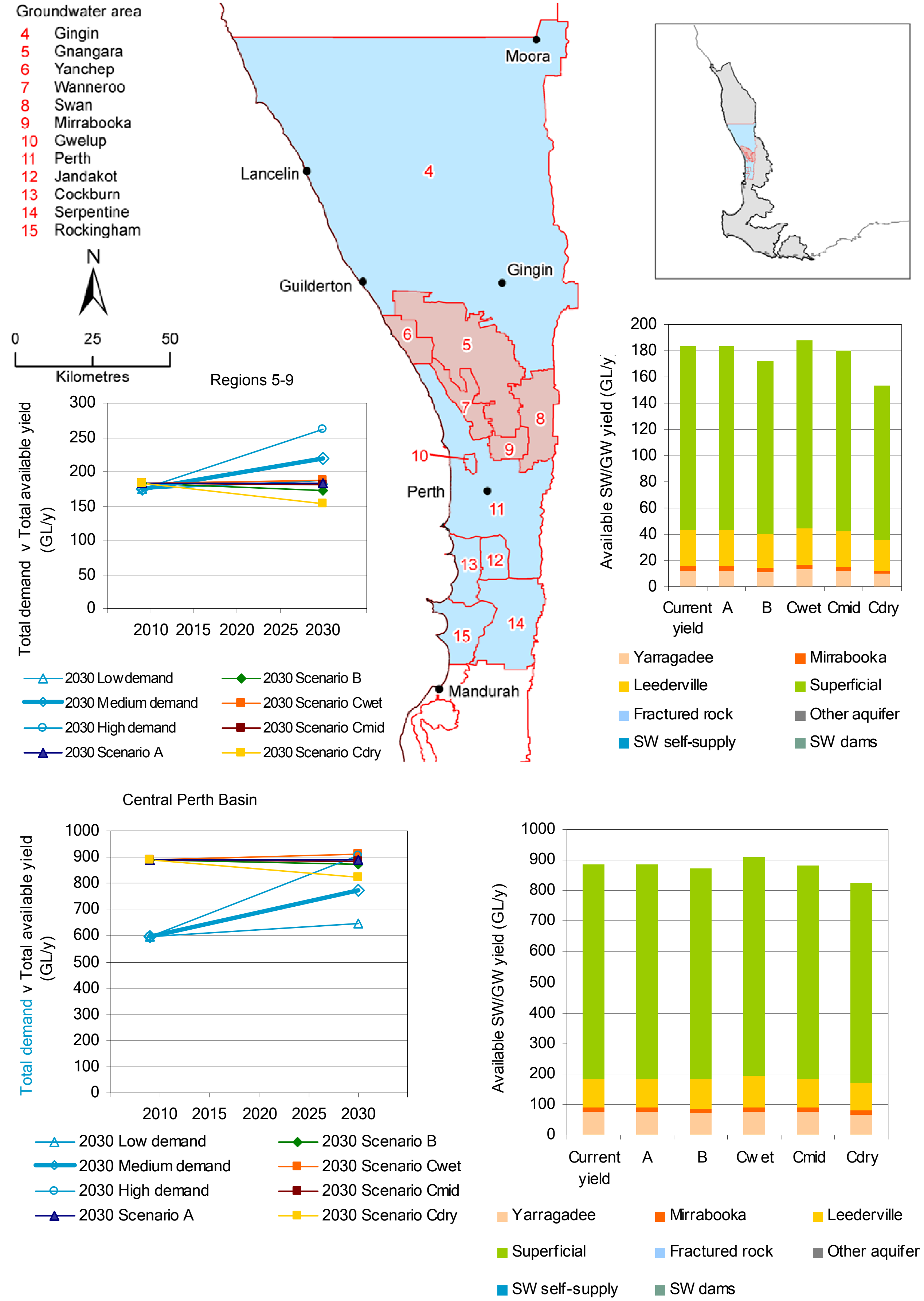


Figure 7-13. Yield and demand gap analysis for the Central Perth Basin

7.4.9 Groundwater in the Northern Perth Basin

The Northern Perth Basin includes the Jurien, Arrowsmith, and Casuarina groundwater management areas.

Table 7-13 and Figure 7-14 show the results of the combined yield and demand gap analysis. Individual groundwater management areas yield and demand gap analyses are in Appendix E.

The region has a very high groundwater yield relative to demand and groundwater yield exceeds demand under all climate and demand scenarios.

Table 7-13. Summary of groundwater yield and demand gap analysis for the Northern Perth Basin. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
			GL/y			
Current	221	221	221	221	221	221
Low demand	209	209	209	209	209	209
Medium demand	193	193	193	193	193	193
High demand	181	181	181	181	181	181

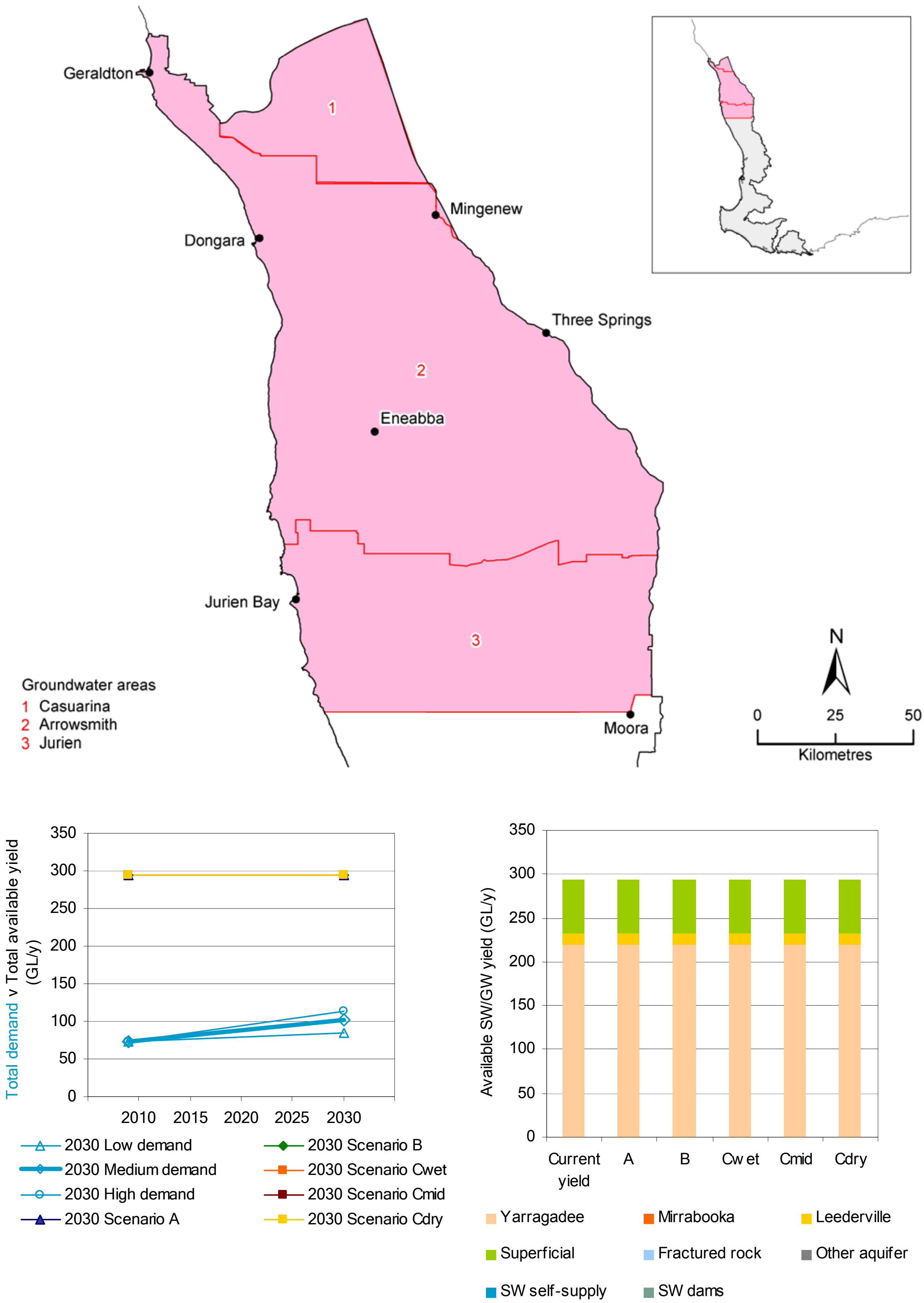


Figure 7-14. Yield and demand gap analysis for the Northern Perth Basin

7.4.10 Water Corporation's Integrated Water Supply Scheme

Table 7-14 and Figure 7-15 detail the results of the water yield and demand gap analysis with respect to the Water Corporations Integrated Water Supply Scheme (IWSS).

The analysis indicates a yield and demand gap of 116 GL/year by 2030 under Scenario Cmid and a medium demand scenario. Surface water yields are calculated to reduce from 95 GL currently to 77 GL in 2030, representing an 18 percent reduction. This estimate is very similar to Water Forever (Water Corporation, 2009) which predicts a 75 GL/year yield for its surface water sources by 2030.

With respect to groundwater yields, the groundwater systems show little reduction for the period to 2030. Groundwater yields reduce from 145 GL/year currently to 142 GL/year under Scenario Cmid, a 2 percent reduction. Water Forever (Water Corporation, 2009) reports a potential groundwater reduction from 145 GL/year currently to 90 GL/year by 2030. The relatively small reduction in groundwater yields estimated in this project results from areas in the Central Perth Basin being predicted to have stable or even increasing groundwater levels as a result of high recharge under dryland agriculture, pine removal, urbanisation and a reduction in drainage and evapotranspiration losses as watertables fall. Some of these increased yields may not be available to the IWSS so caution needs to be placed on comparing these estimates. Land management issues have been addressed in the Gnangara Sustainability Strategy (Government of Western Australia 2009).

In addition, the results of the demand-yield analysis of the Central Perth Basin (Section 7.4.8) indicate significant yield and demand gaps in many water management areas because demand is expected to grow and some resources are already fully allocated or have declining groundwater levels. This increase in local demand places pressure on groundwater that may otherwise have been supplied to the IWSS.

Management responses for the IWSS yield and demand gap have already been previously identified and are in the process of implementation. With the DoW's proposed reduction in groundwater availability to the IWSS (-25 GL/year), the commissioning of a second desalination plant (50 GL/year) and forecast water use efficiency gains by 2030 (50 GL/year), the 116 GL/year yield and demand gap by 2030 under Scenario Cmid and medium demand reduces to 41 GL/year. This gap increases to 80 GL/year under Scenario Cdry.

This compares to a yield and demand gap of 70 GL/year requiring to be met by new sources predicted in Water Forever (Water Corporation, 2009).

Table 7-14. Summary of groundwater yield and demand gap analysis for the Integrated Water Supply Scheme. Positive numbers are a surplus of water; negative numbers are a deficit

Demand	Current	A	B	Cwet	Cmid	Cdry
				GL/y		
Current	7	26	0	18	-13	-52
Low demand	-66	-47	-73	-55	-86	-125
Medium demand	-96	-77	-103	-85	-116	-155
High demand	-155	-136	-162	-144	-175	-214

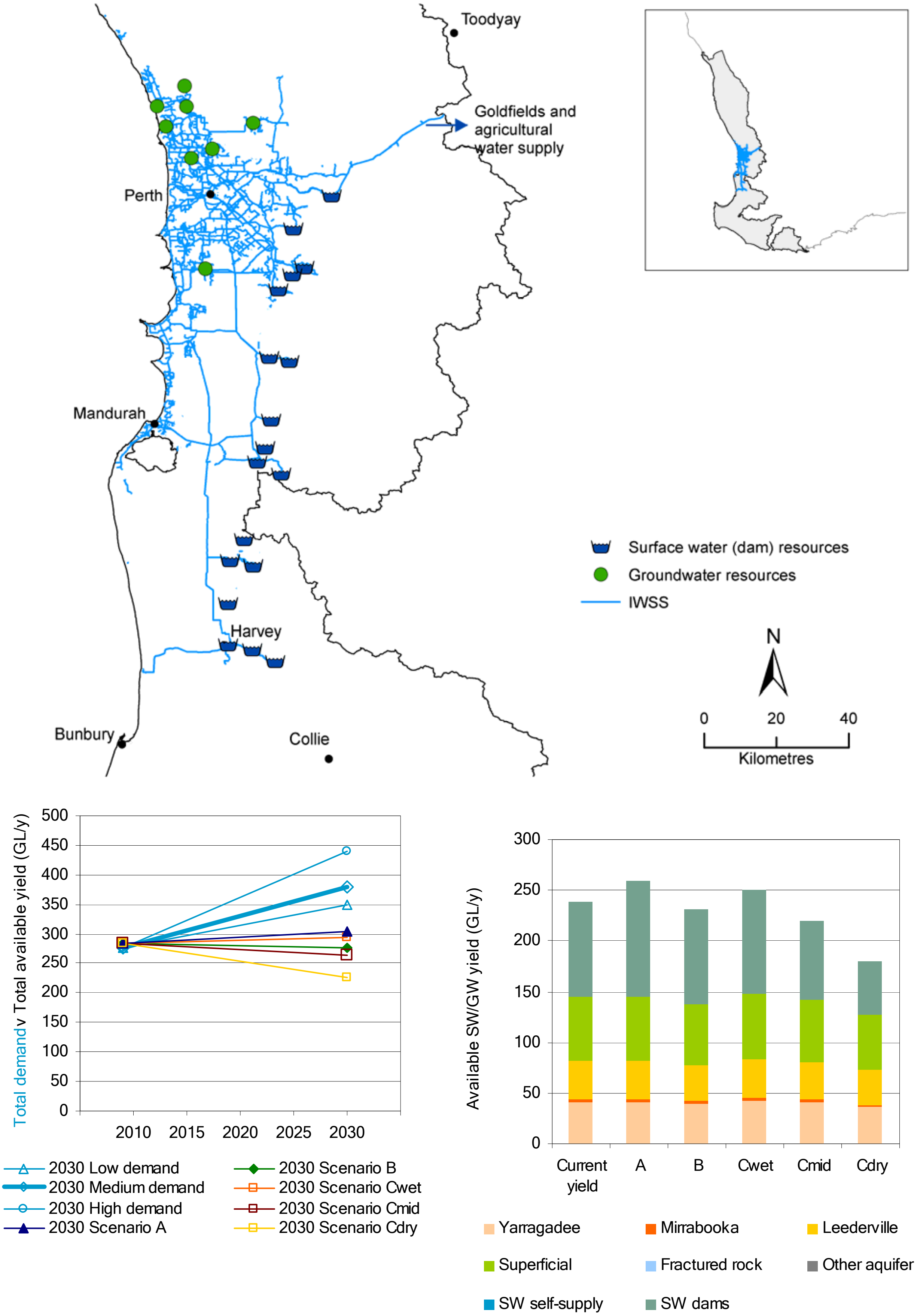


Figure 7-15. Yield and demand gap analysis for the Integrated Water Supply Scheme

7.5 Discussion

The results of the yield estimations and yield and demand gap are synthesised with the impacts on water dependent ecosystems in Chapter 8.

Water management areas that may be shown to have a surplus of water may result from sub-areas with surplus water offsetting sub-areas with a deficiency so the aggregated nature of these numbers need to be understood. The case of the Gnangara Mound is an example where groundwater levels may be rising after pines are removed but falling in areas where there is high abstraction or reduced recharge as a result of climate change or low recharge land uses.

The growth in surface water demands in the Harvey and Warren areas which may result in gaps developing is a function of the methods used whereby demand is assumed to grow where there are existing water using industries that are expected to respond to growth in population and the economy. The Harvey and Collie surface water basins contribute about 43 percent of all surface water, although this may include some irrigation tail-water and groundwater on the coastal plain. These basins are also relatively resilient to climate change compared with those to the north and south. The apparent availability of groundwater to meet this demand may be misleading as some of the groundwater is saline due to irrigation salinity and the natural concentration of salts in areas with high watertables.

The very high yielding groundwater area around Perth (250 to 550 $ML/km^2/y$) reflects the high yielding Superficial, Leederville and Yarragadee aquifers. They fortuitously coincide with the greatest demand for water for both the IWSS and private self supplies. For over one hundred years the Helena catchment immediately east of Perth has been supplying drinking water to the Wheatbelt and goldfields which is an indication of how water rich the area around the city has been. Climate change is reducing the yield of these northern jarrah forest catchments and also the aquifers, especially the Gnangara Mound which is largely covered with native vegetation and commercial pine plantations which restricts recharge (CSIRO 2009a). The main part of the Superficial Aquifer is relatively deep and distant from discharges which also make groundwater levels more susceptible to decline, especially if abstraction is also concentrated in this area.

The greatest gaps between supply and demand are in the Northern Perth Basin which reflects their vast size and the relatively small demands at present. Most of this area is also under dryland agriculture which usually results in rising groundwater levels. Poor water quality in some of these aquifers may preclude certain uses and demands may grow rapidly from mining industries so these estimates of unutilised groundwater in 2030 need to be treated with some caution.

About 56 percent of the Perth Basin is under dryland agriculture which is a high recharge land use which partially offsets the impact of climate change in these areas.

7.6 References

CSIRO (2009a) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. In prep.

CSIRO (2009b) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. In prep.

DoW (2009) Whicher surface water allocation limits: Methodology. Supporting information for the Whicher area surface water allocation plan. Water Resource Allocation and Planning Series, Report No 35, Department of Water, Perth, Western Australia.

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8 Regional synthesis

8.1 Key findings

- The methods used in this report provide a regional guide to the impact of future climate and development on water yields and the ability to meet future consumptive and environmental demands. The methods both under estimate and over estimate gaps between water supply and demand so they are neither optimistic nor pessimistic.
- The Central and Southern Perth basins appear to contain the groundwater dependent ecosystems (GDEs) that are most at risk under future climate and development despite the Peel-Harvey Area having the largest area of potential GDEs. The Peel-Harvey Area is relatively resistant to changes in groundwater levels because rainfall reductions are balanced by reduced drainage and evapotranspiration, and most of the Peel-Harvey Area has been cleared of native vegetation. However parts of this area may be sensitive to increased groundwater abstraction.
- Under the most extreme climate and development scenarios (scenarios Cdry and D), significantly higher risks of ecological damage are expected relative to the other scenarios. Wetlands on the Blackwood Plateau are affected even under Scenario A.
- The Harvey and Warren surface water basins may develop the greatest gap between surface water yields and demand while groundwater areas in the Central Perth Basin (with the exception of the Metro area) show the greatest vulnerability. The Harvey surface water basin currently has no spare capacity and is also likely to encounter the fastest rate of growth to 2030. The shortfall in yield to meet demand by 2030 is similar to the current yield of the Harvey Dam.
- The Integrated Water Supply Scheme (IWSS) may develop a gap of 116 GL/year by 2030 under Scenario Cmid and medium demand. Under this scenario, annual surface water yield yields are expected to reduce from 95 to 77 GL or 18 percent by 2030. Under the assumptions used in the analysis, groundwater yields were calculated to reduce by only about 2 percent. However with significant gaps developing in many Central Perth Basin areas by 2030, there is expected to be increasing competition for groundwater from self-supply users.
- Groundwater resources may continue to replace surface water resources in those parts of the project area where both are available for use. A possible exception to this may be the Albany Area where the groundwater resources appear more limited than nearby surface water resources under the assumptions made in this regional analysis.

8.2 Water management considerations

Water resources management and decisions on water allocation are based on complex multi-criteria considerations related to the environment and human water demands. These decisions need to take account of many values and be made with local knowledge.

This project is the first attempt to provide a scientific assessment of climate and development effects on both water dependent ecosystems and water resources available to meet the growing water demands in south-west Western Australia (SWWA). Using a consistent methodology for the entire region allows the estimation of relative changes in water regime under each scenario and the identification of key dependencies in water availability and demands, both environmental and human. This methodology is consistent with those used in three other parts of Australia and therefore it provides a national context. Additional work has estimated future demands and to compare these with possible future surface water and groundwater yields.

This project is regional in nature and therefore it can only give a broad and long-term planning context for management decisions that necessarily need to consider future climate and development, as well as many other factors.

There are many advantages of the project areas falling within one water management jurisdiction in that there is a regionally consistent set of data, management policies and plans. Wherever possible the methods used have either used or complemented the current management tools and processes so that the results may be more easily incorporated into future water management systems.

The rules-based method of amending future groundwater yields on the basis of reduced storage in aquifers as a result of the different climate conditions is approximate and is provided as a guide only. Using different assumptions would provide other assessments to the one provided in this report and provide further regional insights, and assessment of system behaviour and sensitivities.

8.3 Regional surface water dependant ecosystems

Surface water resources are defined as the amount of water that can be reliably harvested while enough remains to meet all environmental water provisions (EWPs). Two main methods are currently used to estimate the amount of a surface water resource that may be diverted without causing an unacceptable risk to the environment: establishment of site-specific ecological water requirements (EWR) in excess of which surface water can be harvested with a low risk to surface water dependent ecosystems; and regionally estimated sustainable diversion limits (SDL), based on statistical analyses of river daily flow hydrographs.

The annual EWRs estimated for nine river reaches comprise about 60 percent of the annual flow, which allows approximately 40 percent of runoff to be harvested at a low level of risk to surface water ecology. SDLs are commonly 10 to 13 percent of the mean annual flow, allowing more than 85 percent for environmental demands. To minimise environmental impacts, the abstraction is only allowed during the period from 15 June to 15 October, known as a winterfill period, when the main surface water resources are generated. In this analysis it was estimated that more than 80 percent of annual runoff is generated during this period.

Across the project area the climate conditions have a similar impact on runoff during the winterfill period. Relative to Scenario A, runoff reduces by 5 to 20 percent under Scenario Cwet, by 20 to 30 percent under Scenario Cmid, and by 40 to 50 percent under Scenario Cdry. However, under scenario B, runoff in most rivers remains unchanged or even increases. Climate effects are greater for the rivers in the most southern catchments of the project area (Kent and Denmark basins) and most in the most northern region (Gingin basin), where runoff reductions during both the winterfill period and the rest of the year may be 50 to 60 percent.

Climate has a slightly greater impact on runoff during the remaining year, when river flow is particularly important for in-river ecosystems. Overall the changes are 4 to 7 percent greater than during winterfill period.

Although the climate conditions may cause significant reductions in river streamflow, they do not commonly result in river flow cessation in the currently perennial rivers. When ecologically significant river flow rates are considered, reduction in their frequency is greater under scenarios Cmid and Cdry. The climate effect is more significant for the ecological river functions associated with low frequency river flow (high river flow rates), when relevant changes in frequency may reach up to 70 percent. The ecological river functions associated with high frequency river flow (low summer river flow rates) is less affected with relevant changes in frequency less than 15 percent.

In this project current Department of Water Western Australia (DoW) allocation limits and new ways of estimating environmental water needs (being considered by DoW, especially for application in self-supply areas) were used to assess climate impacts on surface water yields and environmental water. If adopted, the new approaches will lead to proportional reductions in allowable harvested volumes and environmental water, as streamflows decline in response to climate change.

8.4 Regional groundwater dependent ecosystem risks

The regional depth to watertable below the ground surface shows that most potential groundwater dependent ecosystems (GDEs), based on the depth to watertable, occur on the Swan and Scott coastal plains (Figure 8-1). Over the southern half of the Perth Basin, groundwater levels are within 3 m of the soil surface under 22 percent of the area, between 3 and 6 m under a further 14 percent, and between 6 and 10 m under another 10 percent. As shown in Figure 2-15, large parts of the Swan Coastal Plain have been cleared of native vegetation so that many of these potential GDEs have limited conservation value.

Figure 8-1. Depth to watertable in the southern half of the Perth Basin

Eastern parts of the Swan Coastal Plain have very high proportions of areas with shallow groundwater levels. These are associated with either the sandy Bassendean soil-landscape zone (zone 212, Figure 2-14) or the clayey Pinjarra zone (zone 213, Figure 2-15). Some of the latter GDEs may be supported by a perched groundwater system making the application of regional groundwater models to assess ecological risks due to changing groundwater levels problematic.

Areas with deep groundwater include the coastal Spearwood Dunes (zone 211, Figure 2-14), and the Dandaragan and Blackwood plateaux (Figure 2-12). However these landforms have important GDEs associated either within interdunal swales or riverine systems that cut down into the regional groundwater system.

Results from the three groundwater models that cover the southern half of the Perth Basin were combined to determine possible regional impacts of climate and development on GDEs.

The impact of the wettest climate, Scenario A, and the driest, Scenario Cdry, are compared in Figure 8-2. Almost all wetlands (zero to 3m depth to watertable) occur on the Swan and Scott coastal plains and many of these have no or low risk of impacts. However under Scenario Cdry there may be significant impacts on GDEs in the north-eastern Swan Coastal Plain and in the western and eastern Scott Coastal Plain.

A number of the areas on the eastern fringes of the Swan Coastal Plain are associated with Guildford clays and groundwater levels may decline in these areas while aquifers may remain perched over winter. The very extensive areas with high groundwater levels in the Peel-Harvey Area lack much native vegetation and therefore their environmental values have been largely lost through development.

Small but important wetlands on the vegetated Blackwood Plateau are impacted under both scenarios A and Cdry. Figure 8-2 can be used as an overview only and there may be significant impacts on wetlands that cover only one of these 500 x 500 m or 25 ha pixels.

Figure 8-3 shows the impact on GDEs (zero to 3m depth to watertable) of increasing abstraction from current levels to the maximum allowed by the allocation limits under Scenario Cmid. There will only be changes in the maps where there remains some available water for licensing. The areas with some impacts on this type of GDE occur in the eastern Peel-Harvey Area, near the coastal lakes in the Peel-Harvey Area, and in the western Scott Coastal Plain. As mentioned above, the change in groundwater levels in some parts of the Peel-Harvey Area may not result in the loss of important GDEs although the areas around the coastal lakes could be very important. The area in the western Scott Coastal Plain is known to contain acid sulphate soils so any long-term reduction in levels in this area may impact on surface water and groundwater quality.

The percentage of total areas at risk from future climate and development in the southern half of the Perth Basin is shown in Figure 8-4. About half of all types of wetlands in this 19,882 km^2 area may be affected to some extent under scenarios Cdry and D. About 40 percent will be affected if the recent climate were to continue until 2030 (Scenario B) which indicates how sensitive they are to climate change. GDEs with a 6 to 10 m depth to watertable may be most severely affected but it is likely that the change in vegetation species will be less noticeable to the public than will the loss of open water in wetlands.

The areas at high and severe risk are relatively small under scenarios A and Cwet and increase four- to eight-fold under scenarios Cdry and D (Figure 8-5). The Central Perth Basin with its deeper aquifers has the largest areas with GDEs with a 6 to 10 m depth to watertable at high and severe risk and the shallow Peel-Harvey Area has a very small area with this type. Increasing abstraction mainly impacts on the Central Perth Basin and Peel-Harvey Area for all GDE types.

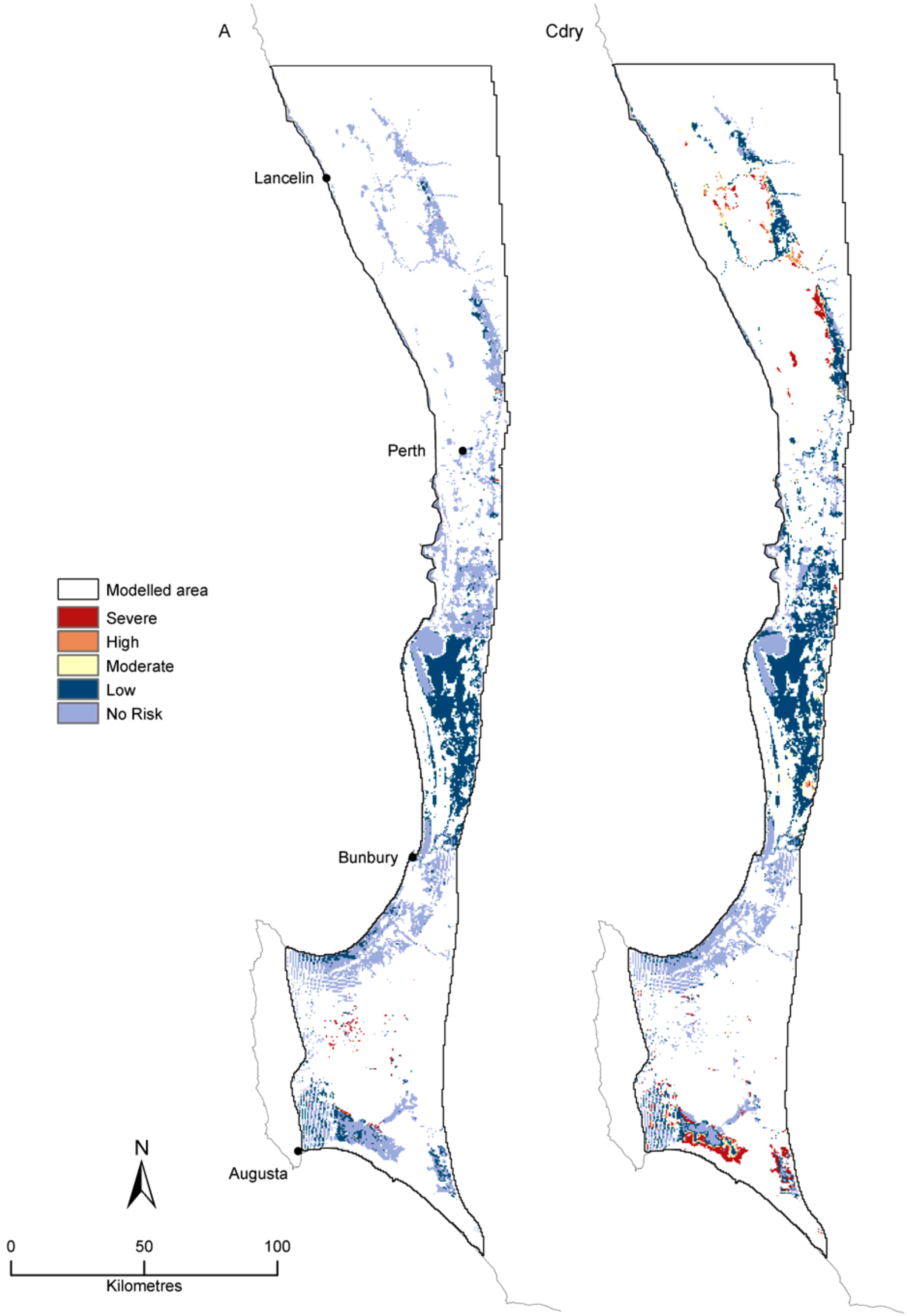

Figure 8-2. The risk to groundwater dependent ecosystems (zero to 3 m depth to watertable) in the southern half of the Perth Basin under scenarios A and Cdry

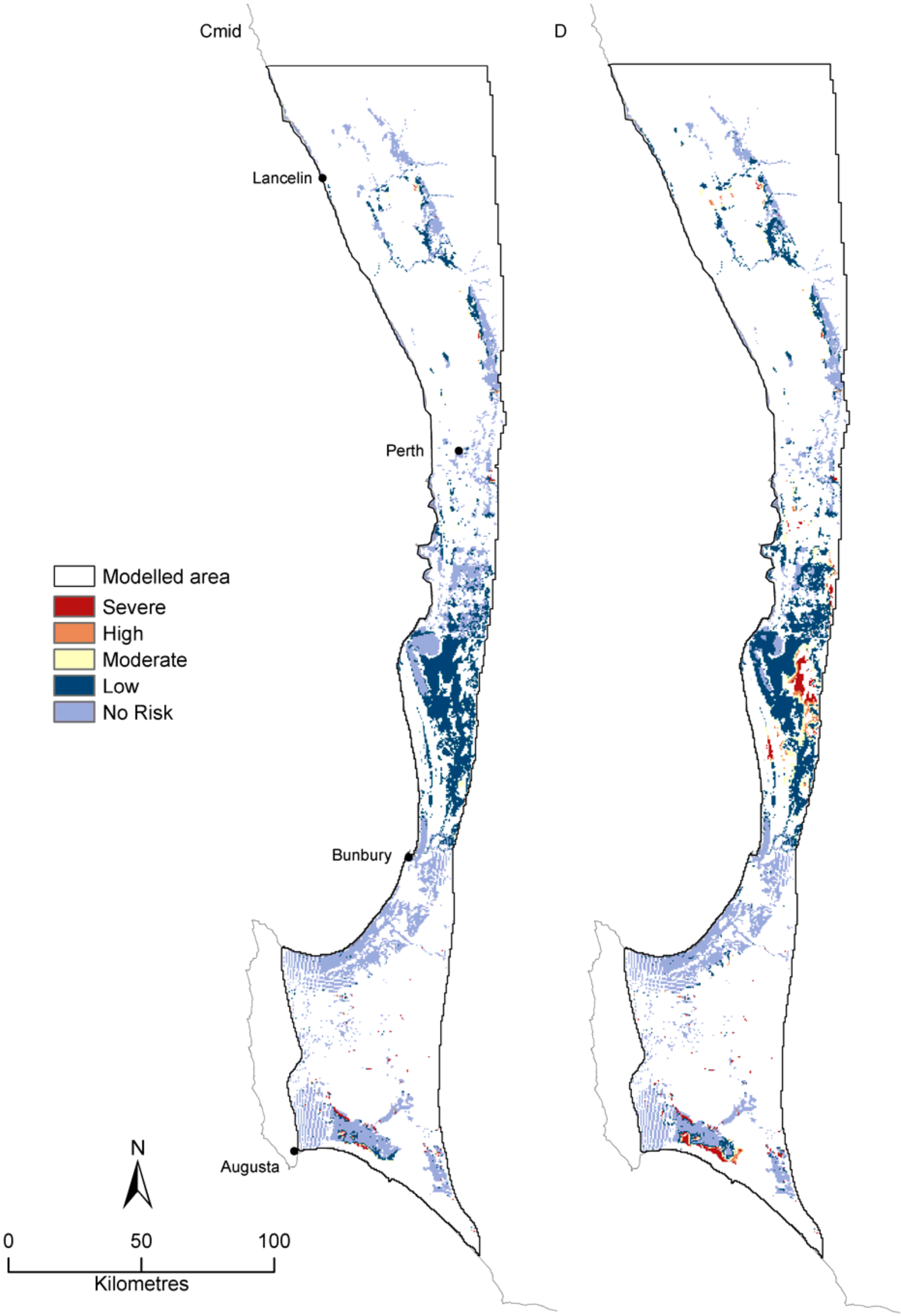

Figure 8-3. The risk to groundwater dependent ecosystems (zero to 3 m depth to watertable) in the southern half of the Perth Basin under scenarios Cmid and D

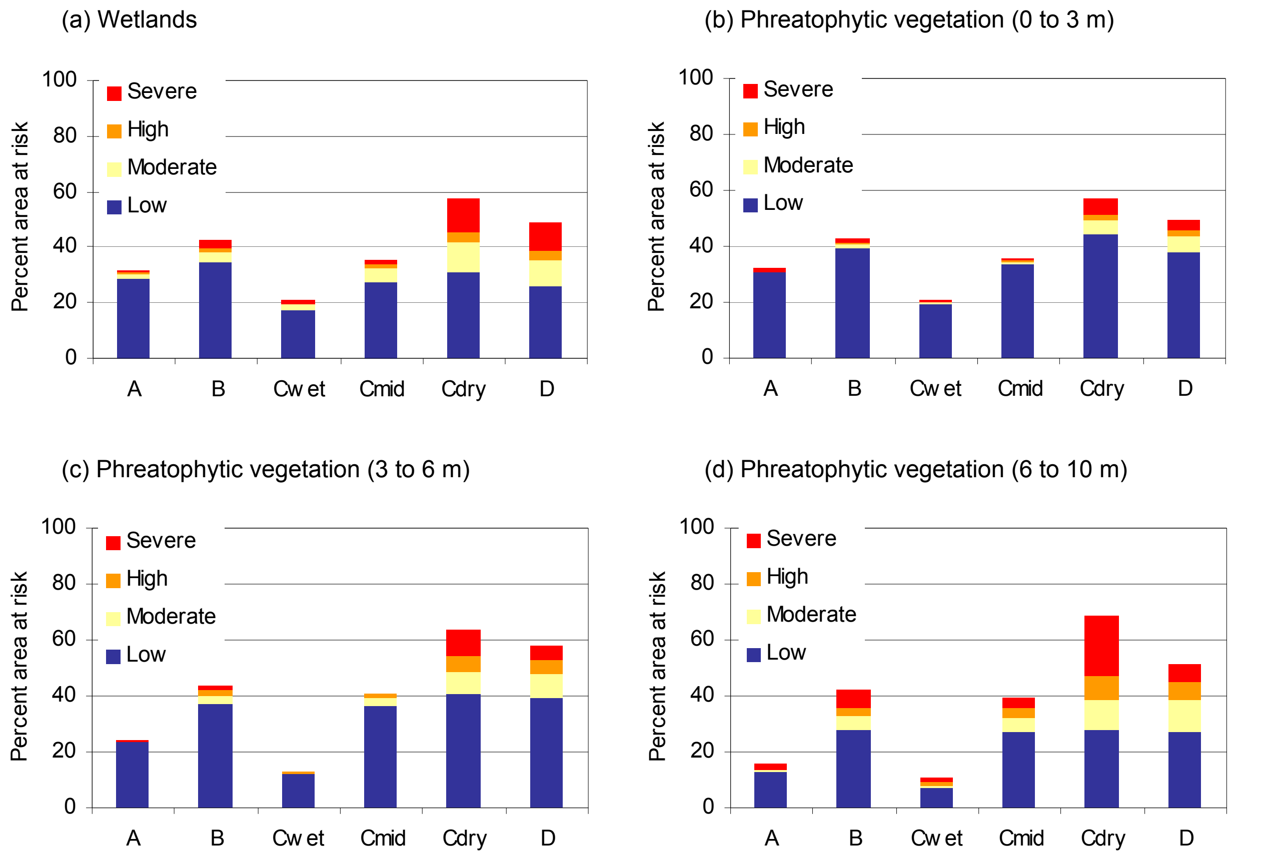

Figure 8-4. Percent of the total area at risk for four groundwater dependent ecosystem types in the southern half of the Perth Basin: (a) wetlands; and phreatophytic vegetation within (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m depth to watertable

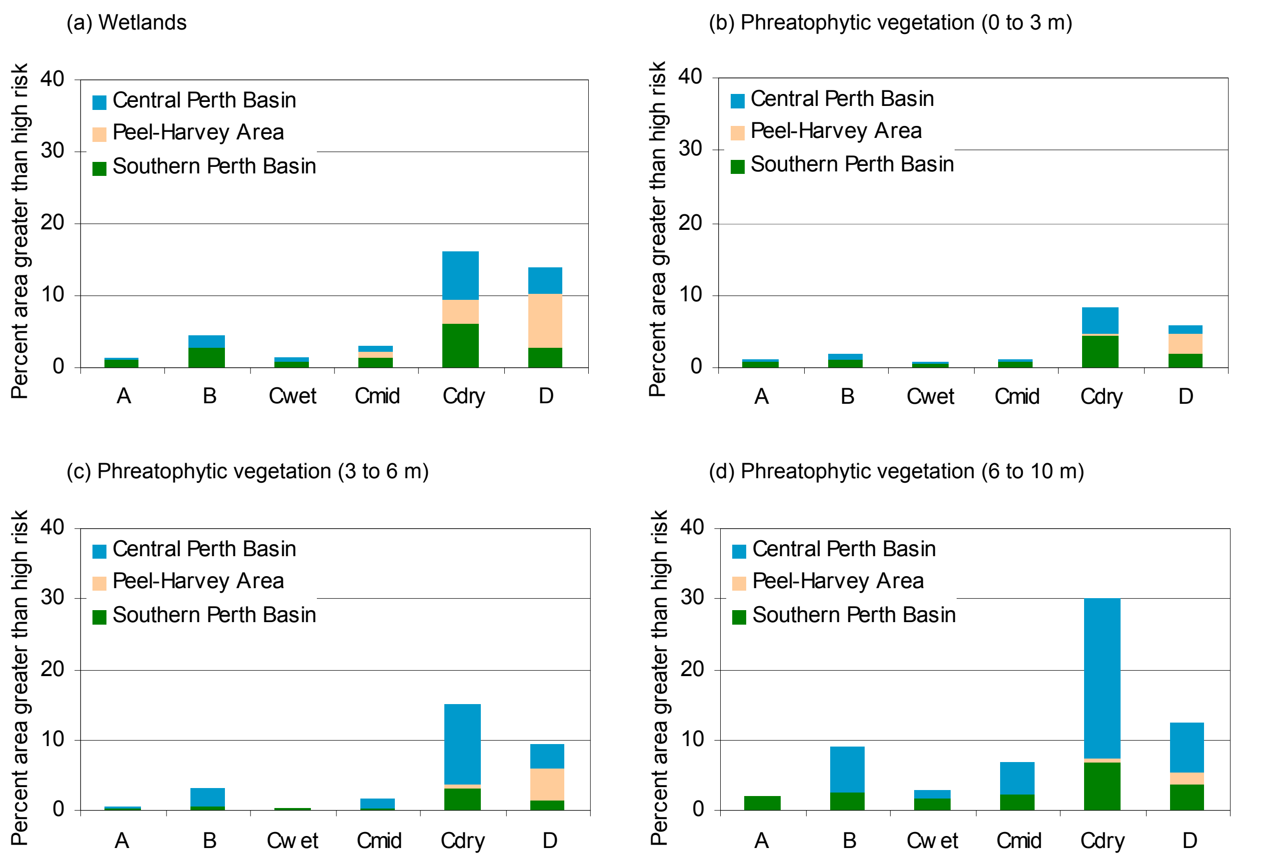

Figure 8-5. Percent of areas at high and severe risk for four groundwater dependent ecosystem types in the southern half of the Perth Basin: (a) wetlands; and phreatophytic vegetation within (b) zero to 3 m, (c) 3 to 6 m, and (d) 6 to 10 m depth to watertable

8.5 Gaps between yields and demands in the project area

8.5.1 Assessment of combined water resources by division

Gaps between yields and demands were assessed for Australian Bureau of Statistics (ABS) statistical divisions covered by the project area which enables analysis of the gap between demands and yields for aggregated surface water and groundwater resources. The ABS statistical divisions are shown as the eight demand regions in the project area in Figure 2-3.

Appendix E contains a series of figures detailing the geographical extent of each of the ABS statistical divisions and the results of the yield and demand gap analysis for the combined resources.

Table 8-1 summarises the gap analysis results under Scenario Cmid and medium demand. In summary:

- The Perth, Preston, Blackwood and King divisions may have a total demand greater than the total available yield of the division by 2030. While Perth has the greatest volumetric gap (40 GL/year), the deficit in the Blackwood division is the largest in relation to its projected demand (37 percent of demand).
- The Greenough, Moore, Peel and Vasse divisions are estimated to all have surplus water in 2030, with the Greenough and Moore regions north of Perth having the largest surpluses.

These results exclude consideration of future IWSS demand growth which is considered in Section 8.5.2. Aggregation to high levels such as an ABS division can hide areas where demands may not be able to be met by local supplies.

Table 8-1. Summary of gap analysis under Scenario Cmid and under the medium demand scenario by Australian Bureau of Statistics division

ABS division	Current yield	Current demand	Demand under Scenario Cmid (2030)	Available yield (2030)	Yield less demand (gap)
			GL/y		
Greenough	202.6	56.1	77.6	202.6	125.1
Moore	423.0	163.3	213.7	417.6	203.9
Perth	620.9	508.2	644.7	604.5	-40.1
Peel	116.9	46.6	59.9	108.4	48.5
Preston	349.1	250.5	308.3	302.7	-5.7
Vasse	209.3	90.4	121.2	177.5	56.3
Blackwood	39.9	33.7	41.4	26.0	-15.4
King	19.2	14.6	18.3	13.5	-4.9

8.5.2 Project area

The history of meeting water demands in Western Australia since about 1975 has been one of substituting reducing supplies of surface water with groundwater (Figure 2-16) and more recently with desalinated seawater. Most of the preceding analysis examined surface water and groundwater resources separately while this section looks at them in combination.

Figure 8-6 and Table 8-2 show the results of the combined yield and demand gap analysis for the project area for all surface water and groundwater resources. Overall, the area may have a surplus of water to meet demands to 2030, except under scenarios Cmid and Cdry under high demand. Under Scenario Cmid and medium demand, an overall surplus of 266 GL/year exists.

Figure 8-6 shows that mainly surface water yields are anticipated to decline under the future climate. However the yield of the Superficial Aquifer is expected to decrease under Scenario Cdry especially.

Such a high-level analysis ignores local shortages and issues such as water quality, the economics of moving water between supply and demand areas, and local impacts on important ecosystems that may preclude a resource from being fully developed. More details about the limitations of the method are provided in Chapter 9.

The spatial distribution of the gap between demand and yield under medium demand is shown for all surface water basins in Figure 8-7 and for all groundwater areas in Figure 8-8.

These figures indicate potential hotspots for water resource managers in the project area for the period to 2030. Under the assumptions made about future yields and demands, the Harvey and Warren basins appear likely to have the greatest surface water demand and yield gap while the groundwater areas in the Central Perth Basin and Collie Basin show the greatest vulnerabilities.

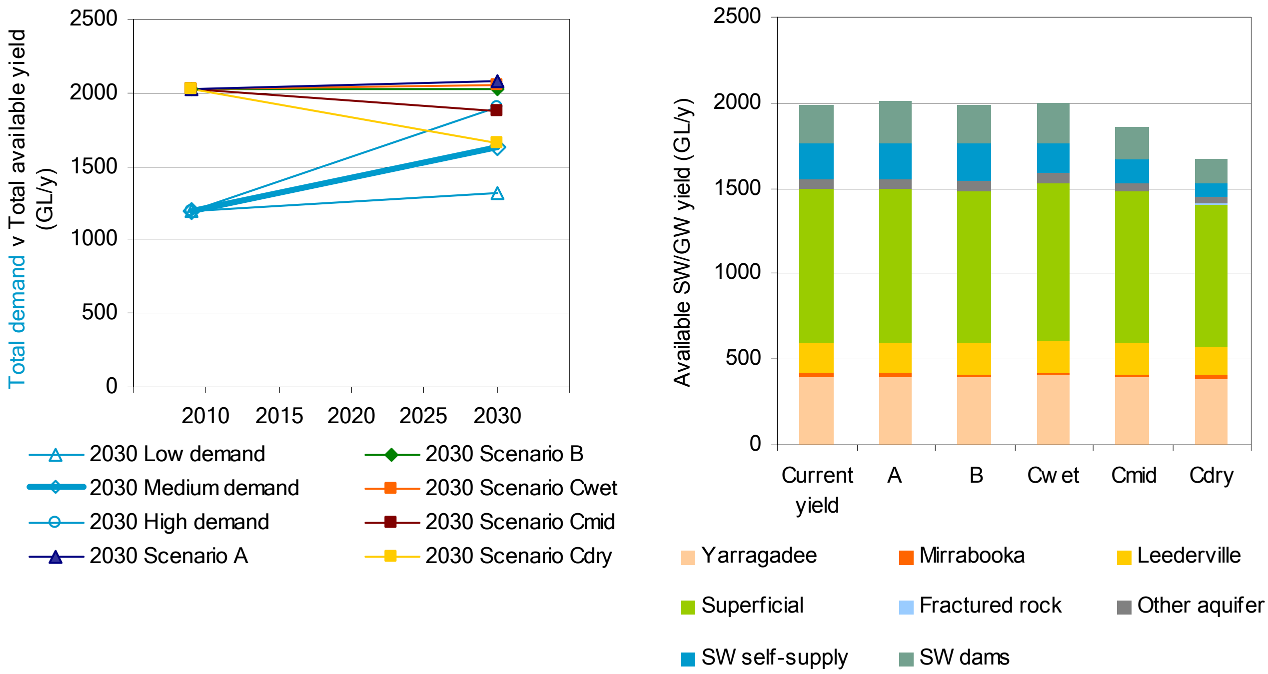

Figure 8-6. Gaps between yield and demand in the entire project area

Table 8-2. Summary of gaps between yield and demand for the entire project area. Positive numbers are a surplus of water; negative numbers are a deficit

	Yield less demand (gap)			
	Current demand	Low demand (2030)	Medium demand (2030)	High demand (2030)
	GL/y			
Current available yield	824.7	709.2	399.9	125.7
Scenario A	875.1	759.6	450.4	176.1
Scenario B	817.8	702.3	393.0	118.8
Scenario Cwet	847.8	732.3	423.0	148.8
Scenario Cmid	676.9	561.4	252.1	-22.1
Scenario Cdry	451.2	335.7	26.4	-247.8

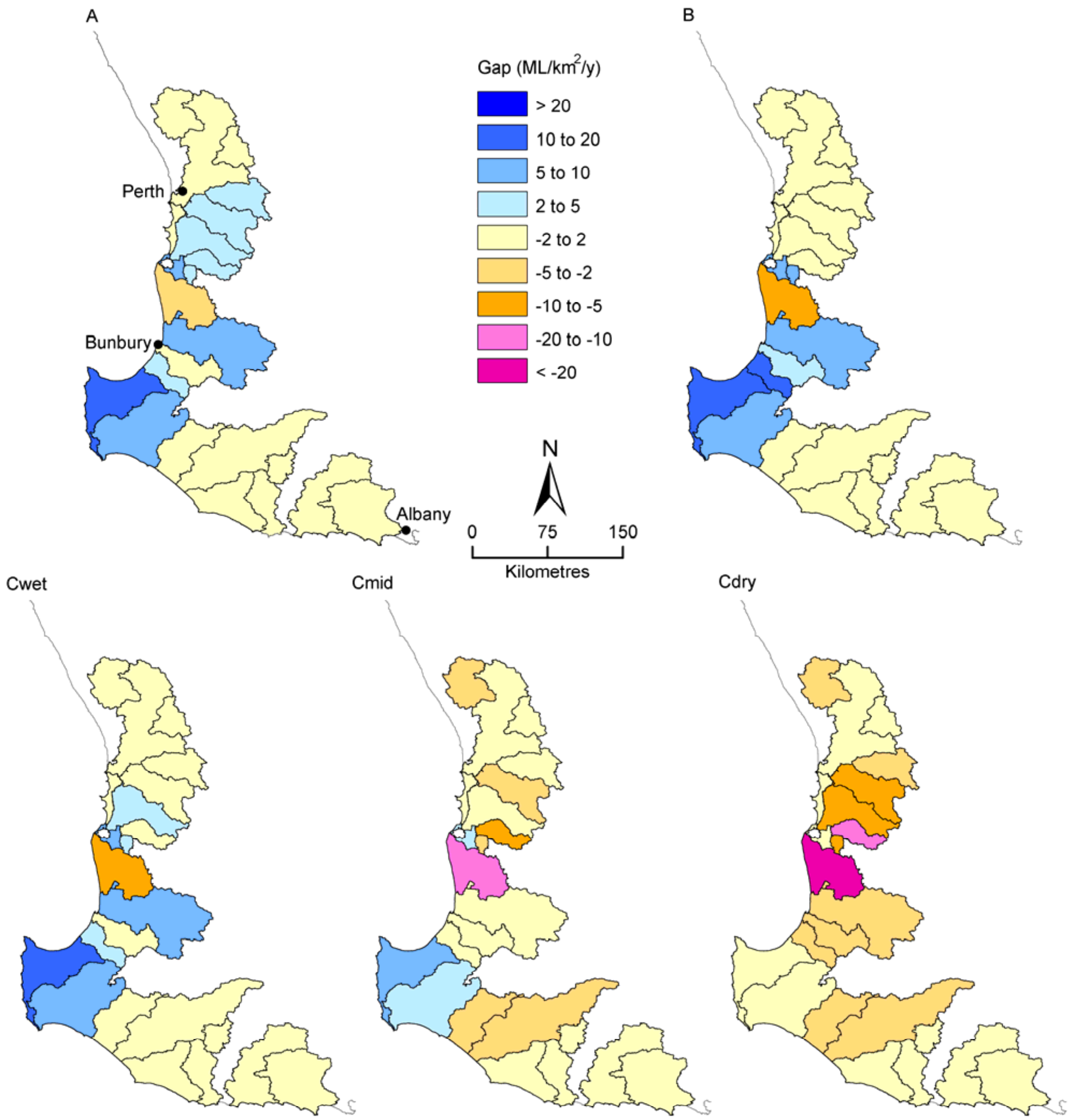

Figure 8-7. Spatial distribution of gaps between yield and demand for surface water basins under scenarios A, B and C and under the medium demand scenario

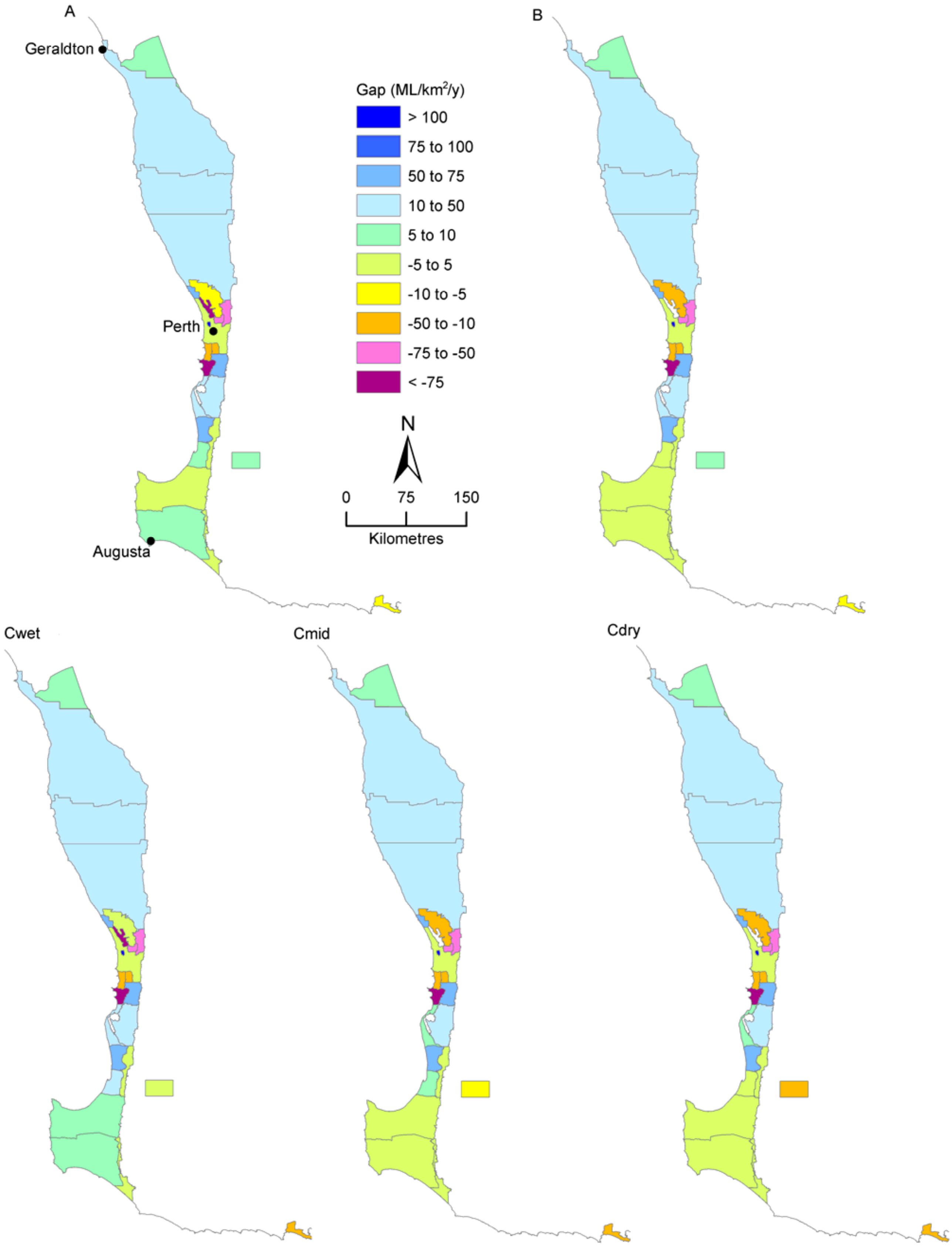

Figure 8-8. Spatial distribution of gaps between yield and demand for groundwater areas under scenarios A, B and C and under the medium demand scenario

8.6 Discussion

The difference between the estimated greater reductions in yield for surface water resources (22 percent under Scenario Cmid) compared with groundwater (2 percent) as a result of climate change can be explained by several factors.

Firstly groundwater yields are about 1556 GL/year and surface water only 425 GL/year so the difference in yield reductions between the two resources is about 3-fold rather than 11-fold in terms of volume.

All reductions in runoff are assumed to result in reduced surface water yields, although these reductions are shared with the environment under the sustainable diversion limit method used to estimate yields.

Reductions in recharge may be offset by reductions in evapotranspiration where groundwater levels are high. Figure 8-1 shows that over half of the Swan and Scott coastal plains have groundwater levels within 10 m of the surface, and most of this is within 3 m. In addition, reductions in recharge may be offset by reductions in drainage to artificial drains, rivers and the ocean. It is only when there is room in an aquifer that recharge can occur.

That recharge can remain significant under the right conditions is illustrated by rising groundwater levels under the cleared and sandy Dandaragan Plateau even though the annual rainfall in this areas is about 600 mm compared with about 900 mm in the vegetated and clayey Blackwood Plateau. Although the groundwater model does not have a high reliability, levels are expected to rise under the Dandaragan Plateau even under Scenario Cdry (Figure 2-21). This estimate is supported by recharge resulting in rising groundwater levels and dryland salinity throughout the Western Australian Wheatbelt, even though the rainfalls are about half of that on the west and south coast and the soils are usually clayey within 1 m of the surface.

Also as mentioned in the previous chapter, the fact that groundwater storages and yields may be constant over a groundwater area does not mean that some sub-areas will not have falling levels within them and significant impacts on GDEs.

The analyses presented in Chapters 7 and 8 confirm some prior understandings while providing much more detail. Under Scenario Cmid, surface water resources in all except the Vasse Demand Region have a gap between yield and demand by 2030. In contrast under the assumptions made in this analysis, groundwater is expected to be available to meet most demands over many parts of the project area except in the area around Perth and the Collie Basin. This conclusion needs to be tempered with the understanding arising from the analyses shown in Chapter 5 that a number of GDEs may be impacted as a result of future climate and further development and therefore abstraction may need to be reduced in these areas.

The trend for groundwater to progressively replace diminishing surface water resources looks likely to continue if these scenarios are an accurate indication of what may eventuate.

The demand for water in the Perth area is expected to continue to grow and further exceed available surface water and groundwater supplies under all future scenarios. The Perth region has high-yielding aquifers compared to all other parts of the project area but the reduction in streamflows and increased competition from self-supply groundwater users is likely to require further water imports and water from desalination to close the gap between yield and demand.

Similarly the Harvey basin is relatively well endowed in surface water but has increasing demands. As a result, development is likely to be limited by water, and current surface water users may switch to lower quality groundwater where it can meet their needs. Mainly, however, it is expected to result in increased water use efficiencies and demand being unmet.

The most northern and southern parts of the Perth Groundwater Basin appear to have enough water to meet foreseeable needs but a rapid expansion in mining in the area inland from Geraldton could change the situation. Neither of these resources is very well understood at present and therefore the allocation limits that have been set may need to be revised in future years. Some aquifers also contain water that is not fresh enough to be suited for all uses. The cost of transporting water from areas of surplus to those with a demand may be prohibitive, especially for low value uses.

The Collie groundwater area and Collie surface water basin are too complex in terms of their hydrology and management impacts to be understood at a regional level. At this stage it can be concluded that a future drier climate and high future abstraction for mining and power production could result in changes to the surface water – groundwater system in the sedimentary basin. More detailed studies are underway which will provide a better understanding of this situation.

Future groundwater resources may be reduced by climate change in the Albany Area. However there may be surface water resources further west which are within the sustainable diversion limits for these catchments. A more detailed local analysis would need to be carried out to confirm the relative impacts of climate change on water resource availability in this area.

8.7 Confidence, variability and uncertainty

The method adopted assumes that the impacts of extraction on runoff regimes and groundwater levels are taken into account in the setting of the allocation limits for the water resources. This analysis assumes that water demands arising from population and economic growth are not restricted by supplies, which is not always the case, especially by 2030. The method is conservative in that it assumes that the 2030 climate will start on 1 January 2008 and all groundwater loss of storages will be compensated for by a reduction in abstraction – that is, there is no sharing of losses with the environment. Groundwater levels have fallen around GDEs as a result of climate change, abstraction and land uses that reduce recharge so many GDEs may already be impacted. Only additional impacts are considered in this analysis. If current extraction is excessive, then the allocation limits and therefore yields used in this project will be set too high under Scenario A.

The consequences of even a small change in levels around a GDE may be catastrophic and therefore a conservative approach to management levels is probably warranted. A case may be made that Scenario Cdry may be the more appropriate climate to assume for estimating future water yields in such cases. This may be supported by the predictions of the Intergovernmental Panel on Climate Change usually tracking on the upper limits when compared in subsequent climate assessments.

The surface water estimates of sustainable diversion limits assume that self-supply irrigators have the capacity to divert water according to daily flow regimes. In practice most irrigators have gully dams that take all flows until they fill and spill into the downstream channel. This affects early streamflows when dams are depleted due to use over the summer period but may enable later seasonal flows to be almost unhindered.

The groundwater models used in the analysis are regional in nature and cannot be used to assess individual wetlands. The models may reproduce trends well but be out by several metres in level, the total depth of many wetlands. Only local area models that accurately depict the relationship between the wetlands and the surrounding groundwater will be able to properly assess these impacts.

8.8 References

Water Corporation (2009) Water Forever, Directions for Our Water Future - Draft Plan.

9 Knowledge and information gaps

9.1 Key findings

- The tools and data to accurately evaluate the impacts of climate and development on water yields for consumptive and environmental use are barely able to keep up with the rate of change in the water resources that are being impacted by rapid climate change and development pressures.
- The regime that is required to maintain water dependent ecosystems is well known for only a limited number of species and communities. This may require management systems to be conservative and limit water availability unnecessarily. Alternatively the risks to the environment may be higher than is acknowledged and a combination of climate and development pressures may result in the loss of important species.

9.2 Knowledge gaps

This section reviews the main knowledge gaps that have become apparent in developing this report. They are mainly gaps in our understanding of processes and in the methods that have been applied, as opposed to information or data gaps which are covered in the next section.

Scenarios Cwet, Cmid and Cdry are generated by global climate models and are scaled from the historical climate (1975 to 2007) and therefore have the same number of rain days as the historical period. Comparison of Scenario B with Scenario A indicates that the time between rainfall events may be longer under a hotter drier future climate. This limitation of using scaled rainfall data needs to be understood, and if possible, overcome in future analyses.

Only nine reaches in six rivers have had ecological water requirements calculated for them in the project area. The sustainable diversion limit (SDL) has had to be applied to all remaining rivers to assess the likely impact of climate on surface water dependent ecosystems and water yields. This method is approximate and is also likely to be conservative in only allowing a relatively small percentage of water to be diverted for use.

Under the assumptions applied in this project, reductions in runoff are shared between diversion for use and the environment whereas any reduction in aquifer storage has been removed from the water available for abstraction. These assumptions could be varied to see how the gap between yields and demands may be affected in the project area.

The groundwater models used in this project – PRAMS, PHRAMS and SWAMS – have calibration errors as reported in the groundwater report (CSIRO, 2009a). Often the models reproduce the correct trends but there may be more than 2 m difference between the simulated and observed heads at any one point. Differences of this magnitude are important when assessing risks to groundwater dependent ecosystems (GDEs) based on the depth to watertable. Local area models with a higher spatial resolution are being progressively developed for key areas to address this deficiency.

The impact of groundwater level regimes on GDEs is probably better known on the Gnangara Mound than in many parts of Australia. However these relationships have been extrapolated from Gnangara to the rest of the project area with little or no additional information available. The largest areas of increased risk to GDEs is in the category with 6 to 10 m depth to watertable, but often the changes in woody vegetation are less obvious than that when watertables are at or close to the soil surface so these changes may be unnoticed unless vegetation species and densities are closely monitored.

There is a need for improved ecological information including the current distribution of species, communities and habitats, the condition of communities and habitats, and the resilience of species and communities to water regime alterations and thresholds of change. Influences of associated climate change variables such as temperature and humidity are also poorly known. Currently the analysis of impacts of a future climate is about the presence of absence of water but major changes can result from relatively small shifts in water regimes. Water quality effects are not dealt with in this analysis. The persistence of open water in wetlands during drier and hotter drier periods is poorly known at present, although the analyses that were carried out were based on minimum annual groundwater levels.

Some wetlands in the project area are perched and changes in regional groundwater levels estimated by the groundwater models may be unable to assess the impact of climate and development on their ecological health. A cost-effective method of assessing the dependency of wetlands on groundwater levels and of monitoring the health of all GDEs through time would greatly assist in prioritising management and monitoring programs.

The combined impacts of climate and development on water dependent ecosystems are poorly known in all but a few well studied and monitored sites. Given that environmental impacts pay a major role in deciding how much water can be licensed for use in water management areas, improving this area of knowledge would seem to be very worthwhile. This regional analysis has combined climate, hydrology and hydrological models with the best estimates of ecological risks to identify areas which may be at risk from a combination of climate and development changes. These analyses may be useful in regional water plans where local issues are not considered but broader and longer term considerations are able to be accommodated.

Surface–groundwater interactions are important in a number of areas in the project area and climate change is affecting both resources in complex ways. As surface water flows decrease, the role of baseflow may become more important, provided groundwater levels don't decrease more than the heads in the river channels. In such cases saline surface waters that currently cross the coastal plains after coming from the saline wheatbelt may recharge the fresher groundwater systems. This is the opposite problem in the Murray-Darling Basin where the streams are usually much fresher than the regional groundwater. In many cases the contamination of the aquifer is likely to be local but may have significant impacts on GDEs.

This project has largely ignored water quality in its consideration, apart from excluding the large rivers that drain saline inland catchments. Water yields may look adequate to meet demands but if the water is of poor quality for the intended use, or is expensive to access or transport, then the gap between yield and demand estimated in this approach may be larger than has been calculated.

Future temperatures, rainfalls and carbon dioxide levels may be outside the historical range used in the model calibration periods and result in changes that are unable to be accurately estimated using regional models as have been used in this project. Interactions between the future climate and perennial vegetation in particular may be important. This may impact in important ways on water dependent ecosystems and on the yield of water both seasonally and inter-annually.

It is noticeable that groundwater management areas and sub-areas are small in areas of high groundwater use such as Gnangara so that abstraction is able to be controlled so that it is not concentrated close to areas of high environmental value. The impact of additional development combined with climate change on groundwater levels in critical areas is an area of limited knowledge at present. It may require lower allocation limits to be set.

The demand estimation method used in this project is able to extend existing industries and estimate their likely water requirements. However the northern parts of the project area have new mining developments that may place large water demands that cannot be estimated using the CGE modelling approach. The conclusions reached that the northern Perth Basin aquifers will be able to meet foreseeable demands to 2030 may be invalid were several large new developments to commence in areas where there are limited demands at present.

The project has developed a spreadsheet which enables surface water and groundwater yields and demands to be matched for 45 demand areas. The method has the ability to incorporate transfers between water resource types and between demand areas. The usefulness of the method for regional water planning is yet to be assessed.

9.3 Information gaps

A more accurate digital terrain model will be released by 2010 and this may improve estimates of the depth to watertable on parts of the Swan Coastal Plain in particular.

The lack of a groundwater model for the Northern Perth Basin (an area of 17,093 km^2 or 46 percent of the groundwater component of the project area) has limited the ability to extend the results of GDE risk assessment. A model is planned for this area and it should be possible to use the vertical flux model developed as part of this project to extend the analyses carried out in this project to the northern half of the Perth Basin. Groundwater model improvements are underway for the Collie Basin and Albany Area.

Changes in groundwater levels are projected to occur on the Dandaragan and Blackwood plateaux but monitoring in these areas is too limited at this stage to be able to assess whether these estimates are accurate or not. Rising levels on the Dandaragan Plateau and on cleared agricultural land in the Northern Perth Basin may provide additional water for abstraction, especially where the watertable is close to the soil surface and may contribute to waterlogging and inundation problems. Currently these areas are poorly identified. Groundwater levels on the Blackwood Plateau have been falling for a number of years and the rate of decline may increase under some climate scenarios. The impact that this may have on surface water and groundwater dependent ecosystems may require close monitoring.

The Swan Coastal Plain contains a number of important wetlands and rivers that receive groundwater throughflow. The models used in this project project that evapotranspiration from these wetlands will decline, along with drain flows. It is possible that winter rainfall will be unable to refill the aquifers each winter if levels decline beyond a critical point and declines in groundwater levels accelerate. Monitoring drain flows and diverting them into aquifers that have storage may be an important management mechanism provided they are adequately monitored and modelled.

The location of salt water wedges in coastal areas where aquifers are deep and around the saline lakes in the Peel-Harvey Area may require more monitoring to be able to anticipate salt water intrusion problems that may result from a sequence of below average rainfall years and abstraction. The last significant salt water intrusion problem occurred in the 1977 to 1979 period which is the driest 3-year period in the historical climate sequence in parts of the project area. Under climate change the likelihood of a similar 3-year dry period may be higher than previous.

9.4 References

CSIRO (2009a) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project*.* CSIRO Water for a Healthy Country Flagship, Australia.

Appendix A List of project reports

Methods report

CSIRO (2008) Description of project methods: South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. 61pp.

Main reports

1. CSIRO (2009) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
2. CSIRO (2009) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
3. CSIRO (2009) Water yields and demands in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

Technical reports

1. Charles et al. (2010, *in prep.*) Climate analyses for the South-West Western Australia Sustainable Yields Project. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
2. Silberstein et al. (2010, *in prep.*) Surface water yields in south-west Western Australia: technical report. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
3. Ali et al. (2010, *in prep.*) Groundwater yields in south-west Western Australia: technical report. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
4. McFarlane et al. (2010, *in prep.*) Water yields and demands in south-west Western Australia: technical report. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

Summary reports

1. CSIRO (2009) Surface water yields in south-west Western Australia. Summary of a report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. 12pp.
2. CSIRO (2009) Groundwater yields in south-west Western Australia. Summary of a report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. 12pp.
3. CSIRO (2009) Water yields and demands in south-west Western Australia. Summary of a report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. 16pp.

Factsheets

CSIRO (2008) Estimating the water yield of south-west Western Australia under a changing climate. CSIRO Water for a Healthy Country Flagship, Australia. 4pp.

1. CSIRO (2009) Surface water yields in south-west Western Australia. CSIRO Water for a Healthy Country Flagship, Australia. 4pp.
2. CSIRO (2009) Groundwater yields in south-west Western Australia. CSIRO Water for a Healthy Country Flagship, Australia. 4pp.
3. CSIRO (2009) Water yields and demands in south-west Western Australia. CSIRO, Water for a Healthy Country Flagship, Australia. 4pp.
4. CSIRO (2009) Water in south-west Western Australia. CSIRO Water for a Healthy Country Flagship, Australia. 4pp.

Appendix B Glossary

This glossary was largely based on a list developed by the Department of Water Western Australia (DoW).

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality. Reference: Porteous A (1996) Dictionary of Environmental Science and Technology, 2nd Ed, John Wiley & Sons, Chichester, UK.
Allocation limit	The amount of water set aside for annual licensed use. In the Department of Water's current water licensing system, the allocation limit is a volumetric licensing limit. As such, the allocation limit does not always account for basic stock and domestic water rights which do not require a licence. However, the meaning of the term will become broader as the department's water accounting systems are developed. Note: Setting an allocation limit involves making a decision. The allocation limit is ordinarily equal to or less than the sustainable yield. If the sustainable yield is highly uncertain, the allocation limit is usually set to be conservative. A triple bottom assessment may, under some circumstances, result in a decision to set an allocation limit greater than the ecologically sustainable yield. Reference: Department of Water (2007) Water Allocation Planning Branch.
Aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Usually described by whether they consist of sedimentary deposits (sand and gravel) or fractured rock. Aquifer types include 'unconfined', 'confined' and 'artesian'. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Areal potential evapotranspiration (APET)	Areal potential evapotranspiration (APET) as calculated by Morton's (1983) wet environment areal evapotranspiration method. APET is defined as the evapotranspiration that would take place from a continually saturated surface that is large enough to render the effects of any upwind boundary transitions negligible, thus integrating local variations to an areal average. An estimate of potential evaporation is a required input for most rainfall-runoff models, and the specific method used in this project is given in a companion report (Charles et al., 2009).
Artesian aquifer	A confined aquifer in which the hydraulic pressure will cause water to rise in a bore or spring above the land surface. If the pressure is insufficient to cause the well to flow at the surface, it is called a sub-artesian aquifer. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Artesian well	A well, including all associated works, from which water flows, or has flowed, naturally to the surface. Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Australian Height Datum	The datum used for the determination of elevations in Australia. The determination used a national network of benchmarks and tide gauges, and set mean sea level as zero elevation. Reference: Australian Government Geoscience Australia (2004), Canberra, viewed 11 October 2007 <http://www.ga.gov.au/nmd/geodesy/datums/ahd.jsp>

Baseflow	The component of streamflow supplied by groundwater discharge. Reference: Australian Government National Water Commission, Australian Water Resources (2005), Canberra, viewed 11 October 2007 <http://www.water.gov.au/Glossary.aspx>.
Biodiversity	Biological diversity or the variety of organisms, including species themselves, genetic diversity and the assemblages they form (communities and ecosystems). Sometimes includes the variety of ecological processes within those communities and ecosystems. Reference: Government of Western Australia (1992) State of the Environment Western Australia.
Bore	A narrow, normally vertical hole drilled in soil or rock to monitor or withdraw groundwater from an aquifer (see 'Well'). Reference: Department of Environment (2001 onwards), Contaminated Sites Management Series.
Borefield	A group of bores to monitor or withdraw groundwater. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Capillary fringe	A zone of saturated water that is at a pressure that is less than atmospheric pressure (i.e. tension saturated) above a watertable. The top of the capillary fringe is the 'air entry point' (i.e. where the zone first become unsaturated) and the bottom is the watertable where the water is held at exactly atmospheric pressure.
Catchment	The area of land from which rainfall becomes runoff contributing to a single watercourse or wetland or recharge to an aquifer. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Climate change	A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. Reference: United Nations Framework Convention on Climate Change State of the Environment Advisory Council (1996), Australia: State of the Environment (1996).
Confined aquifer	An aquifer lying between confining layers of low permeability strata (such as clay, coal or rock) so that the water in the aquifer cannot easily flow vertically. see 'artesian aquifer'. Reference: Water and Rivers Commission (1998) Water Facts No. 1: Water Words.
Consanguineous wetlands	Wetlands that are distinctly related because of similarity in size, shape, soils, water, setting and design. Reference: Hill et al. (1996), Wetlands of the Swan Coastal Plain, Vol 2A.
Consumptive pool	The amount of a water resource that can be made available for consumptive use in a given water system under the rules of the relevant statutory water plan. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.

Consumptive use	The use of water for private benefit consumptive purposes including irrigation, industry, urban and stock and domestic use. Reference: Australian Government (2004), Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
Dam	An embankment constructed to store or regulate surface water flow. A dam can be constructed in or outside a watercourse. Reference: Water and Rivers Commission (1998) Water Facts No. 1: Water Words.
Degree of freedom	In hydrology, the number of degrees of freedom is the number of model parameters free to vary during model calibration.
Dewatering	Removing underground water to facilitate construction or other activity. It is often used as a safety measure in mining below the watertable or as a preliminary step to development in an area. Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Discharge	The water that moves from the groundwater to the ground surface or above, such as a spring. This includes water that seeps onto the ground surface, evaporation from unsaturated soil, and water extracted from groundwater by plants (see 'evapotranspiration') or engineering works (see 'groundwater pumping'). Reference: WA Department of Agriculture (2002) Salinity in the classroom: a Western Australian educational resource for teachers and students of the early, middle childhood and early adolescent phases of learning – glossary.
Discharge rate	Volumetric outflow rate of water, typically measured in cubic metres per second.
Domain	The area covered by a groundwater or rainfall-runoff model, e.g. the PRAMS domain.
Drawdown	The lowering of a watertable resulting from the removal of water from an aquifer or reduction in hydraulic pressure. Reference: WA Department of Agriculture (2002) Salinity in the classroom: a Western Australian educational resource for teachers and students of the early, middle childhood and early adolescent phases of learning – glossary.
Ecologically sustainable yield	The amount of water that can be abstracted/extracted over time from a water resource while maintaining the ecological values (including assets, functions and processes). Note: The ecologically sustainable yield will vary over time depending on seasonal, annual and longer term trends in rainfall, runoff and recharge caused by changes in climate and land use. In a pristine environment, with no water abstraction, all the water would be left in the system and there would be no need to define an ecologically sustainable yield. In modified environments, the ecologically sustainable yield is decided from a scientific assessment of the in situ water regime required to meet ecological needs. It may be defined volumetrically, or in terms of impacts to the flow regime. Depending on circumstances, the decision may be to maintain a current ecological state, or it may be to mimic the natural variations in a system over time. Reference: Department of Water (2007), Water Allocation Planning Branch.

Ecological values	The natural ecological processes occurring within water dependent ecosystems and the biodiversity of these systems. Reference: Water and Rivers Commission (2000) Statewide Policy No. 5, Environmental Water Provisions Policy for Western Australia.
Ecological water requirement (EWR)	The water regime needed to maintain the ecological values (including assets, functions and processes) of water dependent ecosystems at a low level of risk. Reference: Department of Water, Water Allocation Planning Branch (2007) adapted from the Water and Rivers Commission Statewide Policy No. 5, Environmental Water Provisions Policy for Western Australia (2000).
Ecosystem	A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. lake, to include all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources. Reference: Government of Western Australia (1992) State of the Environment Western Australia.
Environment	Living things, their physical, biological and social surroundings, and interactions between all of these. Reference: *Environmental Protection Act 1986 (WA).*
Environmentally sustainable water extraction regime	The level of water use in a particular system (including the volume, timing, location and management of flows and extraction) that provides a water regime that would support all key environmental assets and ecosystem services with a low level of risk. Note: When this water extraction regime occurs, the environmental water requirement (EWR), as determined through scientific studies, is fully met.
Environmental water provision (EWP)	The water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements. Reference: Department of Water (2007) Water Allocation Planning Branch adapted from the Water and Rivers Commission Statewide Policy No. 5, Environmental Water Provisions Policy for Western Australia (2000).
Evaporation	The process of converting water from a liquid to a vapour. Evaporation in the environment includes loss of water from water surfaces, from the soil surface and plant surfaces by vaporisation due to a combination of solar radiation and advected energy (wind). Reference: Adapted from: WA Department of Agriculture (2002) Salinity in the classroom: a Western Australian educational resource for teachers and students of the early, middle childhood and early adolescent phases of learning – glossary.
Evapotranspiration	The combined loss of water by evaporation and transpiration. It includes water evaporated from the soil surface, leaf surfaces and water transpired by plants. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.

Extraction	The taking of water, defined as removing water from or reducing flow of a waterway or from overland flow. Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Fit for purpose	Water use is matched to an appropriate quality. Reference: State Water Plan (2007).
Flow	Streamflow in terms of m^3/a, m^3/d or ML/a. May also be referred to as discharge.
Gigalitre	A measure equal to one million kilolitres or one billion litres. Reference: Water and Rivers Commission (1998) Water Facts No. 1: Water Words Fact Sheet.
Groundwater	Water which occupies the pores and crevices of rock or soil beneath the land surface with a pressure in excess of atmospheric pressure so that it is able to flow into a bore or well, or discharge at a spring. Reference: Adapted from: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Groundwater area (GWA)	The boundaries that are proclaimed under the *Rights in Water and Irrigation Act 1914* and used for water allocation planning and management. Also called Groundwater Management Area. Reference: Department of Water (2007) Water Allocation Planning Branch, adapted from the Water and Rivers Commission (1998) Water Facts No. 1: Water Words.
Groundwater basin	A sedimentary basin that contains aquifers, e.g. the Perth Basin, the Collie Basin.
Groundwater dependent ecosystem (GDE)	An ecosystem that is dependent on groundwater for its existence and health. Reference: Water and Rivers Commission (2000) Statewide Policy No. 5, Environmental Water Provisions Policy for Western Australia.
Groundwater mound	A mound-shape formation of the watertable resulting from rainwater trickling down into the open space between particles in an elevated area of deep sand or other porous material. Groundwater will move slowly away from the central area to discharge into wetlands, rivers and oceans. Reference: Based on definition provided in Glossary of Geology. 4th Edition, American Geological Institute.
Groundwater pumping	Extraction of water from saturated soil that is at greater than atmospheric pressure (groundwater) using an electric, wind powered or compressed air pump and bore hole. Reference: Adapted from: WA Department of Agriculture (2002). Salinity in the classroom: a Western Australian educational resource for teachers and students of the early, middle childhood and early adolescent phases of learning – glossary.
Groundwater recharge	The addition of water to an aquifer, often by unsaturated water that is added to a watertable by its pressure exceeding atmospheric pressure. (see ‘groundwater’; ‘capillary fringe’).
Groundwater sub-area	Areas defined by the Department of Water within a groundwater area (GWA), used for water allocation planning and management. Reference: Revised by Department of Water (2007), Water Allocation Planning Branch.

Hydrogeology	The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality. Reference: Environmental Protection Authority (2003) Deep and Shallow Well Injection of Liquid Industrial Waste, No. 4.
Hydrograph	A graph showing the height of a water surface above an established datum plane for level, flow, velocity, or other property of water with respect to time. Reference: Department of Water (2007, Water Allocation Planning Branch adapted from The Macquarie Dictionary online, viewed 11 October 2007, <http://www.macquariedictionary.com.au>.
Inflows	Surface water runoff; deep drainage to groundwater (groundwater recharge); and transfers into the water system (both surface and groundwater), for a defined area. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
Kilolitre	A measure equal to one thousand litres or one cubic metre. Abbreviated as kL. Reference: Water and Rivers Commission (1998) Water Facts No. 1: Water Words Fact Sheet.
Licence	A formal permit which entitles the licence holder to ‘take’ water from a watercourse, wetland or underground source. Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Megalitre	A unit of capacity (volume) in the metric system equal to one million litres, a thousand kilolitres or a thousand cubic metres. Abbreviated as ML. Reference: Based on The Macquarie Dictionary online, viewed 11 October 2007, <http://www.macquariedictionary.com.au>.
Non-artesian well	A well, including all associated works, from which water does not flow, or has not flowed, naturally to the surface but has to be raised, or has been raised, by pumping or other artificial means. Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Off-stream storage	Storages (such as farm dams, turkey’s nest dams) that are not on defined waterways or watercourses and primarily store water either extracted from rivers or aquifers, or from flood water emanating from rivers or from local catchment runoff. Reference: Australian Government (2004), Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
On-stream storage	Storages (such as farm dams) that are built on or within a defined waterway or water course. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.

Outlier	In statistics, an outlier is an observation that is numerically distant from the rest of the data. They can occur by chance in any distribution, but they are often indicative either of measurement error or that the population has a heavy-tailed distribution.
Over-allocated	Sum of water access entitlements is more than 100 percent of sustainable yield. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
Over-allocation	Refers to situations where with full development of water access entitlements in a particular system, the total volume of water able to be extracted by entitlement holders at a given time exceeds the environmentally sustainable level of extraction for that system. Reference: Australian Government (2004), Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>. Over-allocation occurs when the permitted water extraction regime could lead to a high risk of system failure through: • inability to provide water to avoid catastrophic or irreversible loss of key environmental assets or ecosystem services, and/or • inability to provide for critical human needs, and/or • inability to avoid failure of water dependent social and economic services, and/or • collapse of groundwater systems. Note: 1. 'Permitted water extraction regime' means the water extraction regime allowed under water plans or other regulatory arrangements. 2. Over-allocation can occur because: • the knowledge on which an environmental water provision (EWP) was established was subsequently shown to be inadequate and the EWP was placed inadvertently close to system failure, and/or • of unexpected circumstances that were not anticipated in the water plan, and/or • previous decisions on water entitlements have placed the system close to the point of system failure. 3. Neither the water extraction regime nor the environmental water regime are sustainable in overallocated systems. 4. The EWP in an over-allocated system is inadequate and will be close to or past the threshold beyond which there is a high risk of system failure.
Over-use	Over-use occurs where the actual water extraction regime results in the EWP not being achieved. Note: 1. This definition includes water taken under water entitlements and other water rights as well as illegal uses of water. 2. In systems where an Environmental Water Provision has not yet been established but a cap is in place, over-use is considered to occur where use exceeds the cap.

Partial area	In hydrology, partial area can be defined as the portion of catchment areas that are hydrologically active and contribute to the runoff.
Potential evaporation	The amount of energy available for the evaporation of water from a surface. It is the upper limit of the rate at which water that can evaporate from the land surface including vegetation and open water and is also termed ‘evaporative demand’ or ‘potential evapotranspiration’. In this project it is abbreviated as APET and estimated using the areal evapotranspiration method of Morton (1983).
Potential evapotranspiration	Usually used as an equivalent term to ‘potential evaporation’ or ‘evaporative demand’. In this project it is abbreviated as APET and estimated using the areal evapotranspiration method of Morton (1983).
Precautionary principle	Taking a cautious approach to development and environmental management decisions when information is uncertain, unreliable or inadequate. Reference: Parliamentary Commissioner for the Environment, New Zealand, viewed on the 16 October 2007, <http://www.pce.govt.nz/reports/pce_reports_glossary.shtml>.
Recharge	Water that infiltrates into the soil to replenish an aquifer. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Region	Any large area with the type of region being defined by the descriptors before or after the word, e.g. Vasse Demand Region, South West Regional Water Plan. Three surface water regions in this report have been defined as groupings of neighbouring surface water basins.
Regolith	The unconsolidated solid material covering the bedrock.
Reliability	The frequency with which water allocated under a water access entitlement is able to be supplied in full. Referred to in some states as ‘high security’ and ‘general security’. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
Riparian right	The right of a riparian land owner to take water from a watercourse that flows through their property, unlicensed and free of charge for the purpose of stock and domestic use, without sensibly diminishing the flow of water downstream. Reference: *Rights in Water and Irrigation Act 1914.*
Runoff	The portion of rainfall that reaches streams. This includes rainfall that flows directly off the land surface (surface runoff), water that infiltrates into the soil and makes its way laterally to the stream along impermeable subsurface layers (throughflow) and groundwater discharge to streams. Units are millimetres, to be in common with rainfall measurement, 1 mm is equivalent to 1 L per square metre of land surface, and 1 ML per square kilometre.
Runoff coefficient	The ratio of runoff to rainfall, also known as the ‘runoff ratio’.
Scheme supply	Water diverted from a source (or sources) by a water services authority or private company and supplied via a distribution network to customers for urban, industrial or irrigation use. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.

Self-supply	Water diverted from a source by a private individual, company or public body for their own individual requirements. Reference: Water and Rivers Commission (1998) Water Facts no. 1: Water Words.
Salinity	The measure of total soluble salt or mineral constituents in water. Water resources are classified based on salinity in terms of total dissolved salts (TDS) or total soluble salts (TSS). Measurements are usually in milligrams per litre (mg/L) or parts per thousand (ppt). Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Social value	A particular in situ quality, attribute or use that is important for public benefit, welfare, state or health (physical and spiritual). Reference: Revised by Department of Water (2007) Water Allocation Planning Branch.
Soak	An excavation below ground level that usually intercepts groundwater. Where a wall is also constructed above ground, a combination of surface runoff and groundwater may be captured. Soaks may also be constructed close to a watercourse to obtain water. Other names for soaks may include excavations, dugouts or sumps. Reference: Licensing Handbook, Department of Water.
Social water requirement	Elements of the water regime that are needed to maintain social and cultural values. Reference: Department of Water (2007) Water Allocation Planning Branch adapted from the Water and Rivers Commission Statewide Policy No. 5, Environmental Water Provisions Policy for Western Australia (2000).
South-West Western Australia Sustainable Yields Project area	The area where either surface water and/or groundwater assessments of the impact of climate change and development were made as part of this project. Abbreviated as the 'project area'.
Spring	A spring is where water naturally rises to and flows over the surface of land. Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Stemflow	That portion of the gross rainfall intercepted by the vegetation canopy which reaches the litter or soil surface by running down stems or trunks. Reference: Helvey and Patric, 1965.
Stock and domestic water use	Water that is used for ordinary domestic purposes associated with a dwelling, such as: water for cattle or stock other than those being raised under intensive conditions; water for up to 0.2 hectares (if groundwater) or 2 hectares (if surface water) of garden from which no produce is sold. This take is generally considered a basic right. (Note: 'Intensive conditions' under the Act means 'conditions in which the cattle or stock: (a) are confined to an area smaller than that required for grazing under normal conditions and (b) are usually fed by hand or by mechanical means'). Reference: *Rights in Water and Irrigation Act 1914* and Exemption and Repeal (Section 26C) Order (2001).

Streamflow reporting node (SRN)	Location on a stream at which modelled flow results are calibrated or reported. All gauged points with six digit AWRC numbers (e.g. 612043) were used in surface water model calibration, and a number that are not gauged have been given five digit codes (61202). In either case, the first three digits designate the AWRC Basin in which the location resides. The five digit code points are either dams or terminal wetlands, environmental water requirement locations, or ungauged basin outlets.
Sub-area	A sub-division within a surface or groundwater area, defined for the purpose of managing the allocation of groundwater resources. Sub-areas are not proclaimed and can therefore be changed internally without being gazetted. Reference: Revised by Department of Water (2007) Water Allocation Planning Branch.
Sub-region	Any sub-division of a region with the type of region being defined by the descriptors before or after the word.
Superficial aquifer	See ‘unconfined aquifer’.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape. Reference: Water and Rivers Commission (2001) Understanding Groundwater Fact Sheet.
Surface water basin	A group of surface water catchments that have the same Australian Water Resources Council (AWRC) code which designates major river catchments, e.g. 607, the Warren River Basin.
Surface water management area	Areas defined by the Department of Water, used for water allocation planning and management, that are generally hydrological basins or parts of basins. Reference: Revised by Department of Water (2007) Water Allocation Planning Branch.
Surface water management sub-area	Areas within a surface water management area defined by the Department of Water, used for water allocation planning and management, that are generally hydrologic catchments. Reference: Revised by Department of Water (2007) Water Allocation Planning Branch.
Sustainable diversion limit (SDL)	The maximum volume that can be diverted from a catchment while protecting the environmental values of the catchment’s waterways.
Sustainable water extraction regime	The level of water use in a water plan for a particular system (including the volume, timing, location and management of flows and extraction) that provides a water regime which maintains significant key environmental assets and ecosystem services at an acceptable level of risk and provides water for key consumptive uses. Note: 1. Determination of the sustainable water extraction regime is a triple-bottom-line decision which balances environmental requirements with social and economic needs. 2. When this water regime occurs, the environmental water provision (EWP) is met, and will be less than, or equal to, the EWR.
Sustainable yield	The sustainable yield is the level of water extraction from a particular system that, if exceeded, would compromise key environmental assets, or ecosystem functions and the productive base of the resource. Reference: Australian Government National Water Commission, Australian Water Resources (2005), Canberra, viewed 11 October 2007, <http://www.water.gov.au/Glossary.aspx>.

Transferable (tradeable) water entitlement	The ability to transfer or trade a water entitlement, or a part thereof, to another person within a common water resource. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
Unconfined aquifer	The aquifer nearest the surface, having no overlying confining layer. The upper surface of the groundwater within the aquifer is called the watertable. An aquifer containing water with no upper non-porous material to limit its volume or to exert pressure. See 'aquifer'. Reference: Environmental Protection Authority (2003) Deep and Shallow Well Injection of Liquid Industrial Waste, No. 4.
Watercourse	(a) Any river, creek, stream or brook in which water flows; (b) Any collection of water (including a reservoir) into, through or out of which any thing coming within paragraph (a) flows; (c) Any place where water flows that is prescribed by local by-laws to be a watercourse. A watercourse includes the bed and banks of anything referred to in paragraph (a), (b) or (c). Reference: *Rights in Water and Irrigation Act 1914 (WA).*
Water dependent ecosystems	Those parts of the environment, the species composition and natural ecological processes, of which are determined by the permanent or temporary presence of water resources, including flowing or standing water and water within groundwater aquifers. Reference: Water and Rivers Commission (2000) Statewide Policy No. 5, Environmental Water Provisions Policy for Western Australia.
Water entitlement	The quantity of water that a person is entitled to take annually in accordance with the *Rights in Water and Irrigation Act 1914* or a licence. Reference: *Rights in Water and Irrigation Act 1914* (WA).
Water regime	A description of the variation of flow rate or water level over time. It may also include a description of water quality. Reference: Australian Government (2004) Australian Intergovernmental Agreement on a National Water Initiative, National Water Commission, Canberra, viewed 11 October 2007, <http://www.nwc.gov.au/nwi/index.cfm#overview>.
Water reserve	An area proclaimed under the *Metropolitan Water Supply, Sewerage and Drainage Act 1909* or *Country Areas Water Supply Act 1947* to allow the protection and use of water on or under the land for public water supplies. See Groundwater and Surface Water Management Areas. Reference: Water and Rivers Commission (1998) Water Facts no. 10 – Groundwater Pollution.
Watertable	The upper saturated level of an unconfined groundwater where the water is at exactly atmospheric pressure. Wetlands in low-lying areas are often seasonal or permanent surface expressions of the watertable. See 'capillary fringe'. Reference: Adapted from Water and Rivers Commission (2001) Understanding Groundwater.
Waterways	All streams, creeks, stormwater drains, rivers, estuaries, coastal lagoons, inlets and harbours. Reference: Water and Rivers Commission (2001) Understanding Groundwater.

Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations. Reference: *Rights in Water and Irrigation Act 1914* (WA).
Wellfield	A group of wells to monitor or withdraw groundwater, including for scheme supply. Reference: Water and Rivers Commission (1998) Water Facts No. 1: Water Words.
Wetland	Wetlands are areas that are permanently, seasonally or intermittently waterlogged or inundated with water that may be fresh, saline, flowing or static, including areas of marine water of which the depth at low tide does not exceed 6 m. Reference: Water and Rivers Commission (2001) Understanding Groundwater.
Yield	The volume of water that may be drawn from a well or water supply system measured in cubic metres per day, gigalitres per year, or equivalent. Reference: Water and Rivers Commission (1998) Water Facts No. 1: Water Words.

Volumes of water

One litre	1 litre	1 litre	(L)
One thousand litres	1,000 litres	1 kilolitre	(kL)
One million litres	1,000,000 litres	1 megalitre	(ML)
One thousand million litres	1,000,000,000 litres	1 gigalitre	(GL)

Appendix C Choice of post-1974 as the historical climate period

The Murray-Darling Basin Sustainable Yields Project used 1895 to 2006 as its historical climate series (Scenario A) against which other scenarios were compared. The South-West Western Australia Sustainable Yields Project used the 33-year period from 1 January 1975 until 31 December 2007 as its historical climate series because climatologists and water planners believe that there was a significant climate shift in the mid-1970s that makes using earlier climate data unrepresentative.

There is now a significant body of literature describing how the post-1974 climate of south-west Western Australia (SWWA) is different to that of the earlier period of record. This document summarises this literature to address concerns that characterising historical climate using only post-1974 data may not be scientifically justifiable.

There is increasing evidence that large-scale atmospheric circulation changes occurred in the late 1960s to mid-1970s on a global to hemispheric scale (Baines and Folland, 2007; Frederiksen and Frederiksen, 2007). These circulation and resultant storm track changes have resulted in declines in winter rainfall amounts and inter-annual variability (Figure C-1). The Indian Ocean Climate Initiative (IOCI; <www.ioci.org.au>) has investigated aspects of these unprecedented changes in detail (Hope et al., 2006; IOCI, 2006; Li et al., 2005; Bates et al., 2008). IOCI (2006) concluded that 'the enhanced greenhouse effect was a primary, if not the only significant, cause of rainfall decrease' experienced in SWWA since the mid-1970s.

Frederiksen and Frederiksen (2007) concluded that the post-1974 rainfall reduction over SWWA has been caused by large-scale changes to southern hemisphere circulation resulting in a reduction in the intensity of cyclogenesis (i.e. fewer and weaker cold fronts), with storms being deflected southward. They suggest these observed changes are physically consistent with expected changes due to increased anthropogenic greenhouse forcing.

Correspondingly, a weakened Leeuwin Current (Feng et al., 2004) has been linked to a weakening in the Indonesian throughflow caused by a 1976 'shift' in Pacific Ocean sea surface temperatures (Wainwright et al., 2008). Two recent studies have concluded that these changes are due to the enhanced greenhouse effect, rather than natural multi-decadal variability (Alory et al., 2007; Vecchi et al., 2006).

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Comparison of synoptic climatology in the 1975 to 1994 period with that in the 1949 to 1968 period shows that a 20 percent decrease in subtropical jet strength over Australia has reduced storm development over SWWA (IOCI, 2006). Hope et al. (2006) concluded that both decreases in the frequencies and intensities of early winter rain-bearing synoptic systems account for 80 percent of the observed rainfall declines. Treble et al. (2005) and Fischer and Treble (2008) investigated isotopic records in cave stalagmites near Margaret River as proxies for rainfall variability over inter-annual to multidecadal timescales. They show that the prolonged winter drying trend and reduction in storm intensity experienced since the mid-1970s is well outside the range of natural rainfall variability recorded in the isotopic record of the last 250 years.

Cai and Cowan (2007), comparing observed rainfall to an ensemble of 71 climate model runs, determined that 50 percent of the SWWA winter rainfall decline is attributable to the enhanced greenhouse effect, with factors such as multidecadal variability accounting for the other 50 percent. They concluded, 'One of the most consistent results from climate models is that as CO_2 continues to increase, SWWA rainfall will continue to decrease … If multidecadal variability plays a significant part in the observed rainfall reduction, it means that there will be a period in which CO_2-induced reduction will be temporarily mitigated by the opposite phase of variability. On the other hand, it also means that CO_2 and multidecadal variability could conspire to produce an even greater rate of rainfall reduction in the future.'

Bates et al. (2008) highlight the consistencies between baroclinic instability theory (Frederiksen and Frederiksen, 2007), self-organised maps (Hope et al., 2006) and statistical downscaling (Figure C-2) applied across hemispheric, regional and local scales, respectively. They conclude that the strong consistencies between these three methods are evidence that the observed mid-1970s rainfall decline is, at least in part, attributable to changes in large-scale circulation and synoptic activity. As can be seen from Figure C-2, the frequency of a wet rainfall pattern has declined since the 1960s and stabilised at a lower level since the mid-1970s. Correspondingly, the dry rainfall pattern experienced a rapid increase in frequency in the early 1970s and a steady increase since then. This is also consistent with statistically downscaled climate change projections (IOCI 2006).

Li et al. (2005) is one study that found an earlier change point. They examined station extreme daily rainfall, finding 1965 to be a change point for winter rainfall reduction. The distinct separation between the distributions of 1930 to 1965 versus 1966 to 2001 is strikingly evident in their analysis (Figure C-3).

Given the significant contribution of studies showing that SWWA climate changed in the mid-1970s, and the corresponding consistency with climate change projections of further drying (Bates et al., 2008), it is justifiable to accept 1975 to 2007 (Scenario A) as a plausible current climate baseline for this project. There is no expectation of a return to the wetter conditions of pre-1975 in the literature. Although natural variability will result in sequences of wet and sequences of dry years, the overall evidence is that SWAA is in a different climate regime to that pre-1975 and that climate change projections are consistent with observed trends.

The Department of Water Western Australia (DoW) use hydrological data from 1975 in their water allocation planning. Surface water data exist for periods prior to 1975 but most groundwater monitoring data start after this date.

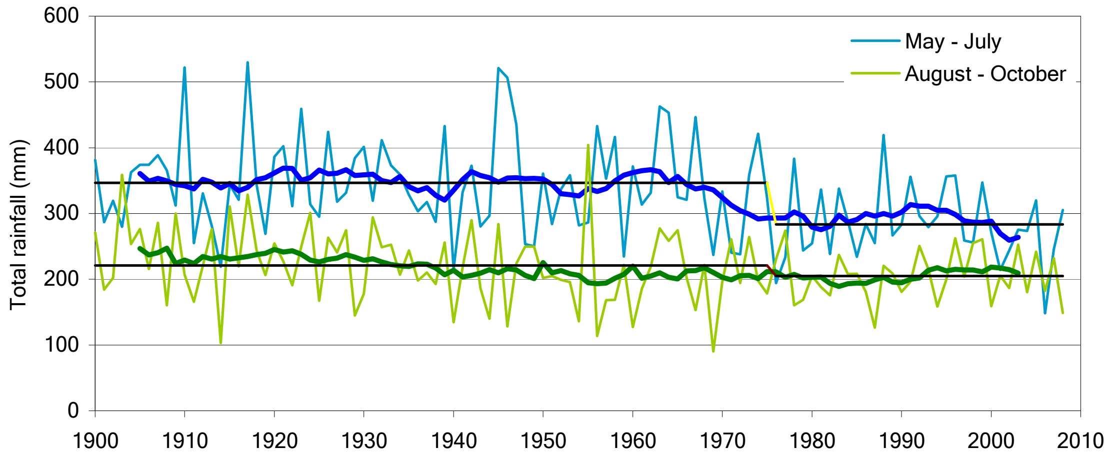

Figure C-1. Time series of rainfall in south-west Western Australia. Means for the periods 1900 to 1974 and 1975 to 2008 are represented by horizontal lines (Bureau of Meteorology data for the region south-west of a line joining 30ºS, 115ºE and 35ºS, 120ºE)

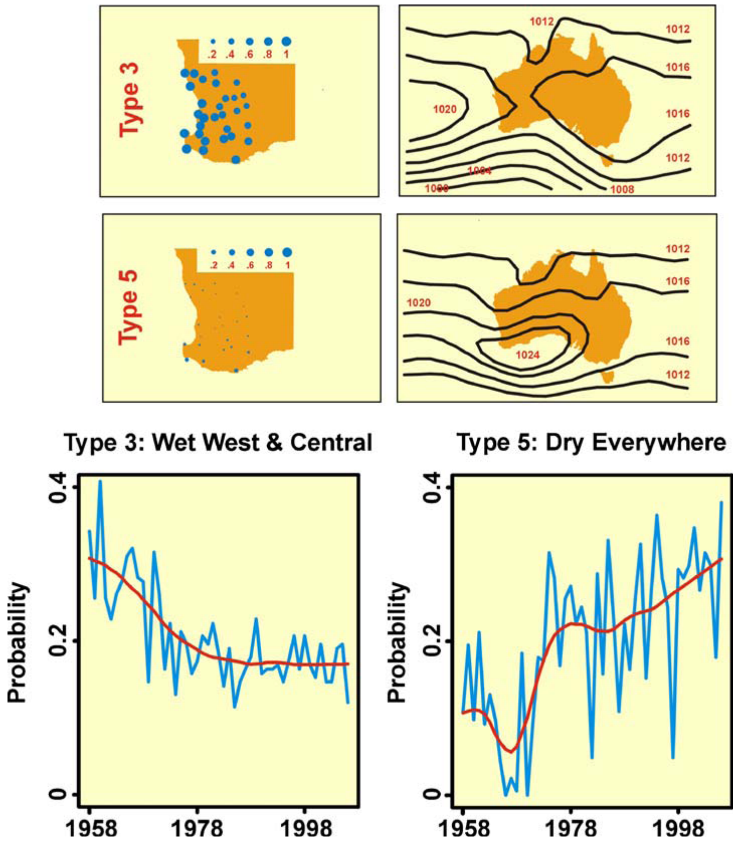

Figure C-2. Rainfall occurrence patterns and synoptic types associated with wet conditions in western and central south-west Western Australia (Type 3) and dry conditions (Type 5) for the winter half year (May to October) (from Bates et al. (2008))

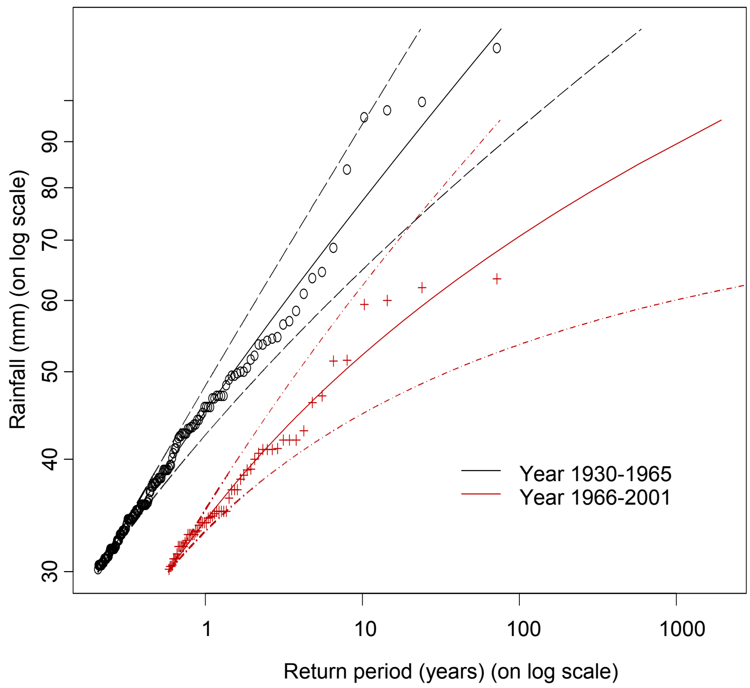

Figure C-3. Return periods of winter extreme daily rainfall at Manjimup. The solid curves represent the return period estimates with the 95 percent confidence interval given as a dashed line (from Li et al. (2005))

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Appendix D Environmental assets and impacts of changed water yields

This appendix provides information additional to Chapters 4 and 5 on surface water and groundwater dependent ecosystems and potential risks to them under future climate and development. The appendix has three sections which are described in Table D-1.

Table D-1. Explanation of the structure and content of Appendix D

Water dependent environmental assets	
A set of tables contains lists of most significant environmental assets in the project area including international, national and state-wide significant assets	
Effect of climate scenarios on surface water dependent ecosystems (for Chapter 4)	
The application of surface water modelling results (as reported in CSIRO, 2009a) for eight river reaches, illustrating the effect of climate on river flow regime significant for ecological river function. Information related to each site is given in a consistent form over two pages.	
Flow duration	A plot of flow duration curves under scenarios A, B and C, and the ecological flow thresholds for each river with the location of the flow estimation points shown on the insert map
Ecological flow thresholds	A table is given for each river defining the threshold flow rates associated with the identified ecological functions (as identified by Department of Water (DoW)), flow frequency under scenario A and the change under scenarios B, Cwet, Cmid and Cdry
Summary of the changes in flow frequency	Two plots are given for each river. The left-most plot illustrates the change in flow frequency, associated with the ecological function flow thresholds, under scenarios B, Cwet, Cmid and Cdry in comparison with Scenario A. The right-most plot shows the relative difference between flow frequency under scenarios A and Cdry
Variation in flow frequency under scenarios A, B and C	The series of figures illustrate the frequency of flow associated with the identified ecological functions (listed in the table) under scenarios A, B and C
Changes in total winter and summer runoff	Two plots are given for each river. Total streamflow during the winterfill period (15 June to 15 October) and the rest of the year is plotted under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years). Seasonal streamflow variation for each river under scenarios B, Cwet, Cmid and Cdry relative to Scenario A is also plotted.
Regional assessment of risk to groundwater dependent ecosystems (for Chapter 5)	
Risk maps	The maps show the risk category associated with the four types of groundwater dependent ecosystems in the Central Perth Basin, Peel-Harvey Area and Southern Perth Basin. This appendix contains maps under scenarios A, B, Cwet and D (while Chapter 5 contains maps under scenarios Cmid and Cdry)
Climate effect on groundwater level in the vicinity of caves located in Central Perth basin	Observed and modelled groundwater hydrographs are given for a number of caves

Table D-2. Internationally important environmental assets within the project area

Asset name	Class of asset	Type of asset	Easting	Northing
Thomsons Lake	Ramsar Wetland	Wetland	390835	6442485
Forrestdale Lake	Ramsar Wetland	Wetland	399256	6440354
Becher Point Wetlands	Ramsar Wetland	Wetland	382555	6416890
Vasse-Wonnerup System	Ramsar Wetland	Wetland	353598	6278482
Peel-Yalgorup System	Ramsar Wetland	Estuarial system	380728	6371134
Muir-Byenup Systems	Ramsar Wetland	Wetland	473508	6188179

Table D-3. Wetlands of National Significance as environmental assets within the project area

Asset name	Class of asset	Type of asset	Easting	Northing
Barlee Brook	Wetland of National Significance	Wetland	381750	6206625
Barraghup Swamp	Wetland of National Significance	Wetland	385835	6396737
Benger Swamp	Wetland of National Significance	Wetland	391394	6329699
Booragoon Swamp	Wetland of National Significance	Wetland	390701	6453872
Brixton Street Swamps	Wetland of National Significance	Wetland	404037	6456921
Broke Inlet System	Wetland of National Significance	Wetland	449847	6135727
Chandala Swamp	Wetland of National Significance	Wetland	400067	6517031
Chittering-Needonga Lakes	Wetland of National Significance	Wetland	413774	6522713
Doggerup Creek System	Wetland of National Significance	Wetland	417584	6151982
Ellen Brook Swamps System	Wetland of National Significance	Wetland	406392	6490075
Gibbs Road Swamp System	Wetland of National Significance	Wetland	397466	6441871
Gingilup-Jasper Wetland System	Wetland of National Significance	Wetland	353660	6204450
Guraga Lake	Wetland of National Significance	Wetland	362915	6584557
Hutt Lagoon System	Wetland of National Significance	Wetland	228583	6883102
Jangardup	Wetland of National Significance	Wetland	376700	6195575
Joondalup Lake	Wetland of National Significance	Wetland	385042	6487108
Karakin Lakes	Wetland of National Significance	Wetland	354559	6560603
Lake Jasper	Wetland of National Significance	Wetland	379750	6190500
Lake McLarty System	Wetland of National Significance	Wetland	379469	6380659
Lake Pleasant View System	Wetland of National Significance	Wetland	607927	6145667
Lake Thetis	Wetland of National Significance	Wetland	315009	6624557
Lancelin Defence Training Area	Wetland of National Significance	Terrestrial Vegetation	340382	6602459
Loch McNess System	Wetland of National Significance	Wetland	374799	6508739
Lower Blackwood River	Wetland of National Significance	Wetland	365200	6224260
Lower Murchison River	Wetland of National Significance	River Stream	221006	6934549
McCarleys Swamp Ludlow Swamp	Wetland of National Significance	Wetland	361192	6282091
Moates Lake System	Wetland of National Significance	Wetland	605029	6130167
Mt Soho Swamps	Wetland of National Significance	Wetland	496297	6154624
Owingup Swamp System	Wetland of National Significance	Wetland	505092	6126448
Oyster Harbour	Wetland of National Significance	River Stream	587708	6129475
Perth Airport Woodland Swamps	Wetland of National Significance	Wetland	404113	6466617
Poison Gully	Wetland of National Significance	Wetland	366720	6223550
RAAF Caversham	Wetland of National Significance	Terrestrial Vegetation	403249	6477102
Scott River National Park	Wetland of National Significance	Wetland	340570	6208620
Spectacles Swamp	Wetland of National Significance	Wetland	390488	6434887
Swan-Canning Estuary	Wetland of National Significance	River Stream	388257	6457836
Yalgorup Lakes System	Wetland of National Significance	Wetland	379850	6355920

Table D-4. Nationally significant environmental assets within the project area

Asset name	Class of asset	Type of asset	Easting	Northing
Tuart Forest National Park	National Park	Terrestrial Vegetation	357650	6279600
Blackwater Creek	Wild River	River	416271	6150016
Deep River Teds Pool 606001	Wild River	River	465762	6165930
Forth River	Wild River	River	450585	6144730
Inlet River	Wild River	River	460123	6135309
Shannon River	Wild River	River	443339	6162263

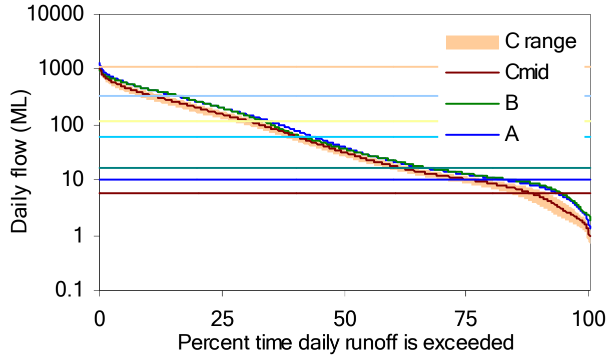
Table D-5. State environmental assets within the project area

Asset name	Class of asset	Type of asset	Easting	Northing
Arramall Cave	Cave	Cave	310272	6736468
Brown Bone Cave	Cave	Cave	320280	6615909
Cabaret Cave	Cave	Cave	375637	6509606
Caladenia Cave	Cave	Cave	368609	6542297
Calgardup Cave	Cave	Cave	317940	6230470
Capel Nature Reserve	Nature Reserve	Wetland terrestrial vegetation	364621	6283268
Carpark Cave	Cave	Cave	375249	6508443
Cauliflower Cave	Cave	Cave	376011	6508314
Crystal Cave	Cave	Cave	375762	6509018
Giants Cave	Cave	Cave	319731	6226115
Gilgi Cave	Cave	Cave	375685	6506740
Jewel Cave	Cave	Cave	324874	6205891
Lake Cave	Cave	Cave	318006	6227270
Mammoth Cave	Cave	Cave	318258	6229660
Melaleuca Cave	Cave	Cave	373983	6511681
Minnies Grotto	Cave	Cave	373234	6512737
Nambung Caves	Cave	Cave	321951	6619988
Ngilgi Cave	Cave	Cave	317719	6275634
River Cave	Cave	Cave	309091	6736078
Road Cave	Cave	Cave	376191	6508720
Rose Cave	Cave	Cave	374946	6506208
Stockyard Gully Tunnel	Cave	Cave	316452	6686252
Stockyard Tunnel	Cave	Cave	316355	6686578
Taylors Nature Reserve	Nature Reserve	Wetland terrestrial vegetation	333218	6263796
Twilight Cave	Cave	Cave	375780	6506795
Water Cave	Cave	Cave	374999	6508634
Weelawadgi Cave	Cave	Cave	315741	6701569
Yanchep Cave	Cave	Cave	375038	6510715
Capel Nature Reserve	Wetland terrestrial vegetation	Wetland terrestrial vegetation	364621	6283268
Fiegert Rd Barragup	Wetland	Wetland	388230	6400915
Taylors Nature Reserve	Wetland terrestrial vegetation	Wetland terrestrial vegetation	333218	6263796
Tutunup	Wetland	Wetland	367515	6273910
Upper Margret River swamps	Wetland	Wetland	350220	6252085

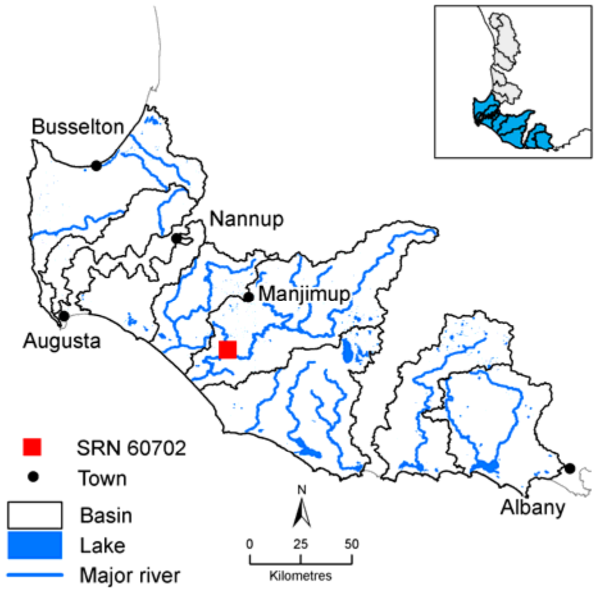
Table D-6. Selected environmental assets that are considered regionally significant within the project area

Asset name	Class of asset	Type of asset	Easting	Northing
Ambergate	Wetland terrestrial vegetation	Wetland terrestrial vegetation	345000	6265930
Bancell Brook Waterous 613007	River Stream	River Stream	401689	6354248
Bindiar Lake Cc 61710492	Terrestrial Vegetation	Terrestrial Vegetation	381894	6519778
Brunswick River Cross Farm 612032	River Stream	River Stream	383436	6319879
Canebreak Pool	River Stream	River Stream	341250	6249765
Canning River Seaforth 616027	River Stream	River Stream	407220	6448910
Collie South Branch	River Stream	River Stream	422189	6305498
Davies	Wetland	Wetland	318851	6211558
Demark River Mt Lindesay 603136	River Stream	River Stream	528789	6141697
Donnelly River Strickland 608151	River Stream	River Stream	388189	6200898
Ewart Swamp	Wetland	Wetland	568953	6123686
Gingin Brook Bookine Bookine	River Stream	River Stream	369354	6534189
Gingin Brook Gingin 617058	River Stream	River Stream	397039	6531699
Hay Park	Wetland	Wetland	373897	6307071
Hill River Hill River Springs	River Stream	River Stream	342890	6649375
Karnup Rd	Wetland	Wetland	400435	6418920
Kemerton	Wetland terrestrial vegetation	Wetland terrestrial vegetation	384926	6323325
Kent River Styx Junction 604053	River Stream	River Stream	507988	6139280
Lake Banbun Ec 61710486	Terrestrial Vegetation	Terrestrial Vegetation	394980	6522830
Lake Banbun Wc 61710483	Terrestrial Vegetation	Terrestrial Vegetation	394149	6522808
Lake Muckenburra MKB Ec 61710473	Terrestrial Vegetation	Terrestrial Vegetation	384349	6532059
Lake Muckenburra Wc 61710475	Terrestrial Vegetation	Terrestrial Vegetation	383956	6532234
Lefroy Brook	River Stream	River Stream	410889	6184748
Lower Collie Mt Lennard	River Stream	River Stream	397489	6309398
Lower Collie Rose Road	River Stream	River Stream	388239	6314898
Lower Collie Shentons Elbow	River Stream	River Stream	396189	6312148
Margret River Whicher Range	River Stream	River Stream	355938	6258198
Marrinup Brook	River Stream	River Stream	426551	6144692
Medulla Brook	River Stream	River Stream	406337	6425210
Moore Lower Quinns Ford	River Stream	River Stream	387225	6571755
Moore River Waterville Road	River Stream	River Stream	366139	6540209
PM4 HHW Ec 61611861	Terrestrial Vegetation	Terrestrial Vegetation	391111	6508186
PM4 HHW Wc 61611863	Terrestrial Vegetation	Terrestrial Vegetation	390360	6508146
Samson Brook Mt William	River Stream	River Stream	409661	6356039
Scott River Brennans Ford 609002	River Stream	River Stream	343709	6205927
Shannon River Dog Pool 606185	River Stream	River Stream	442839	6152647
Tangletoe Swamp TGT c 61710469	Terrestrial Vegetation	Terrestrial Vegetation	378663	6530399
The Spectacles SP1-1c 61419853	Terrestrial Vegetation	Terrestrial Vegetation	389952	6434937
Thomson Brook Woodperry Homestead 611111	River Stream	River Stream	402389	6278548
Wilson	River Stream	River Stream	382396	6189431
Wilyabrup Brook Woodlands 610006	River Stream	River Stream	316888	6258698
Yeal Wetland CYW c 61710480	Terrestrial Vegetation	Terrestrial Vegetation	385949	6526144

Lefroy Brook *SRN 60702* *Catchment area 92.1 km^2* *Busselton Coast to Denmark region*

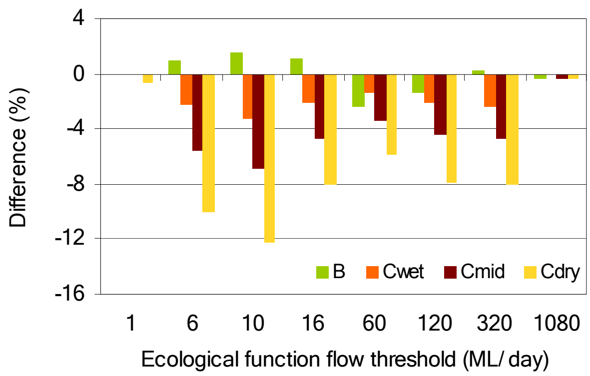


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

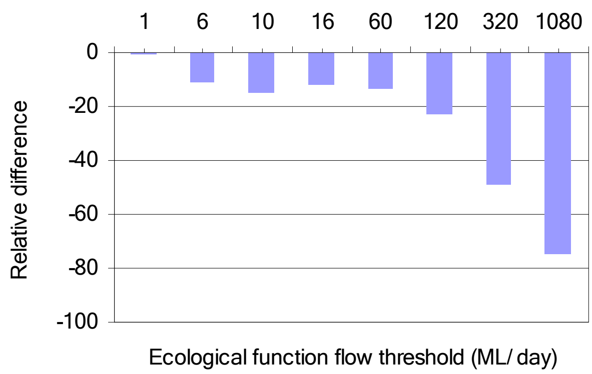


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Maintain pool habitat in summer	1	100.0%	0.0%	0.0%	0.1%	0.7%
Minimum flow to maintain pool quality	6	93.0%	-0.9%	2.2%	5.5%	10.1%
Upstream migration of small native fish	10	82.7%	-1.6%	3.3%	6.8%	12.3%
Summer habitat for invertebrates	16	67.1%	-1.1%	2.1%	4.7%	8.1%
Winter habitat for invertebrates	60	43.8%	2.4%	1.4%	3.4%	5.9%
Inundate trailing vegetation	120	34.3%	1.3%	2.1%	4.4%	7.9%
Inundate active channel	120	34.3%	1.3%	2.1%	4.4%	7.9%
Inundate low elevation benches	320	16.6%	-0.3%	2.4%	4.7%	8.1%
Inundate high elevation benches	1080	0.4%	0.3%	0.1%	0.3%	0.3%

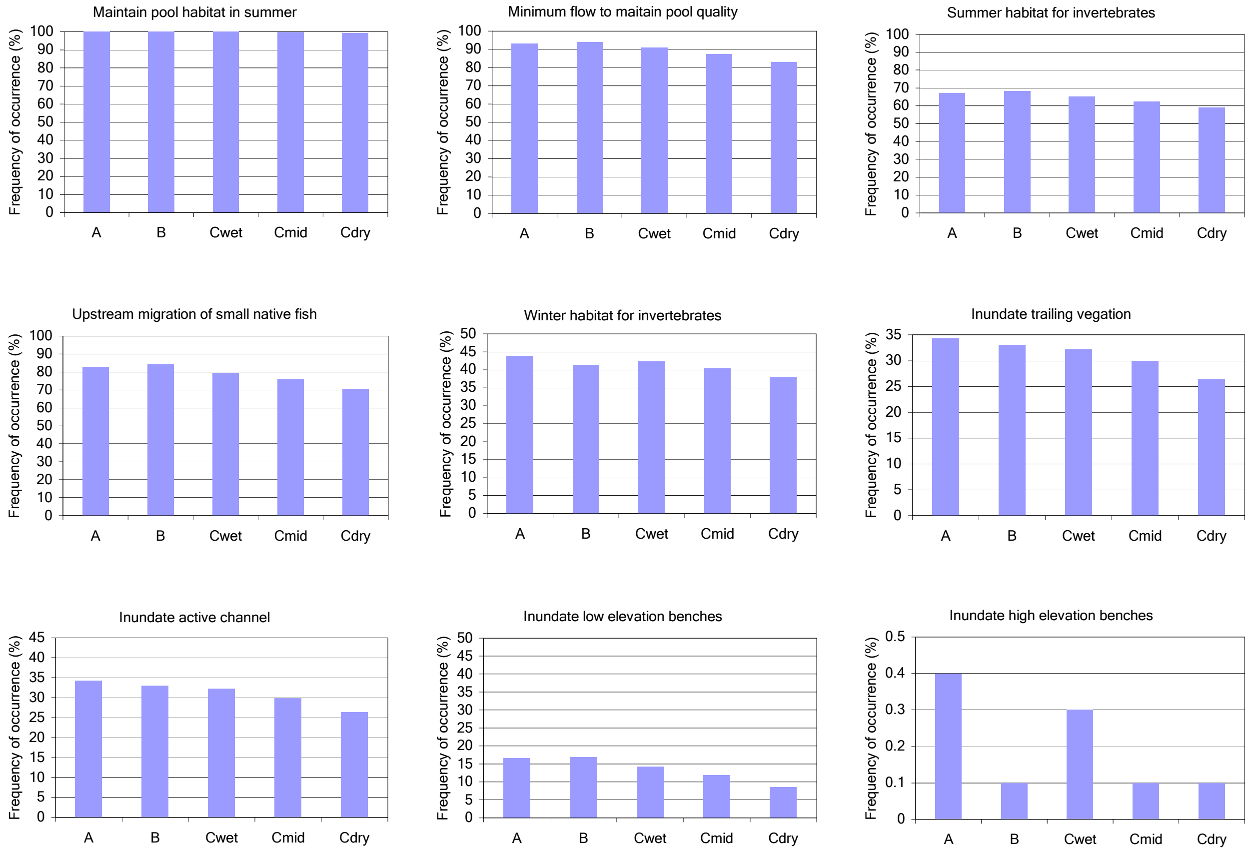


Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

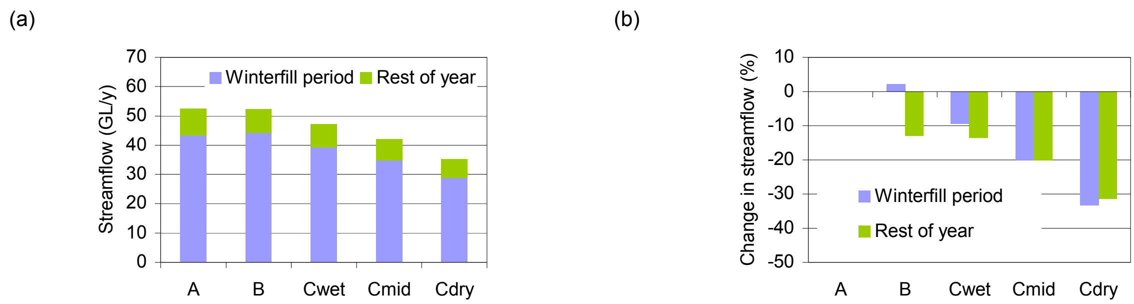


The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

Lefroy Brook ***SRN 60702*** ***Catchment area 92.1 km^2*** ***Busselton Coast to Denmark region***

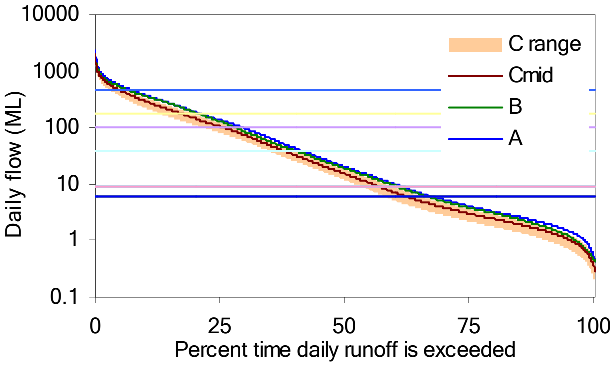


Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry



Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

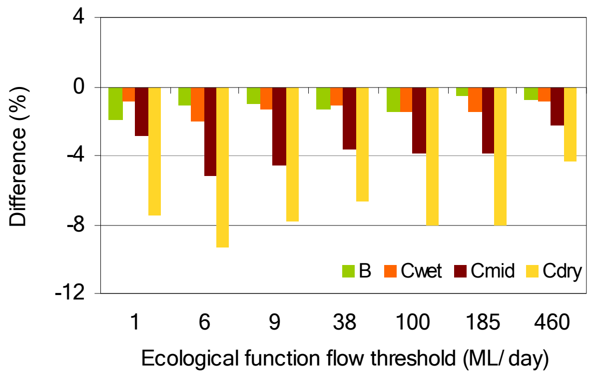
Chapman Brook	***SRN 609022***	***Catchment area 180 km^2***	***Busselton Coast to Denmark region***



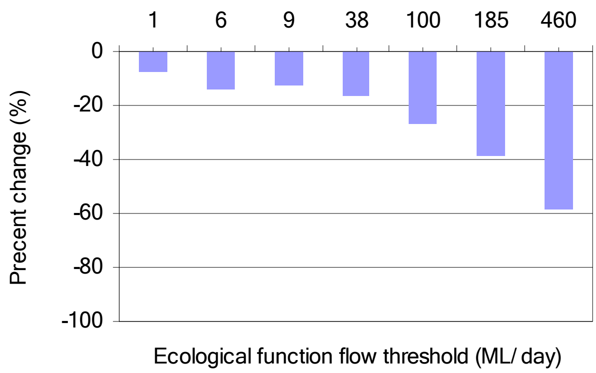
Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Maintain pool habitat in summer	1	98.1%	1.9%	0.9%	2.8%	7.5%
Minimum flow to maintain pool quality	6	67.6%	1.1%	2.0%	5.2%	9.3%
Summer habitat for invertebrates	6	67.6%	1.1%	2.0%	5.2%	9.3%
Upstream migration of small native fish	6	67.6%	1.1%	2.0%	5.2%	9.3%
Winter habitat for invertebrates	9	61.5%	1.0%	1.3%	4.6%	7.8%
Inundate trailing vegetation	9	61.5%	1.0%	1.3%	4.6%	7.8%
Inundate low elevation benches	9	61.5%	1.0%	1.3%	4.6%	7.8%
Riparian vegetation	9	61.5%	1.0%	1.3%	4.6%	7.8%
Upstream migration of large native fish	38	41.7%	1.3%	1.1%	3.6%	6.7%
Inundate medium elevation benches	100	29.7%	1.4%	1.5%	3.9%	8.0%
Inundate active channel	185	20.6%	0.5%	1.5%	3.9%	8.0%
Inundate floodplain	460	7.5%	0.8%	0.9%	2.3%	4.4%

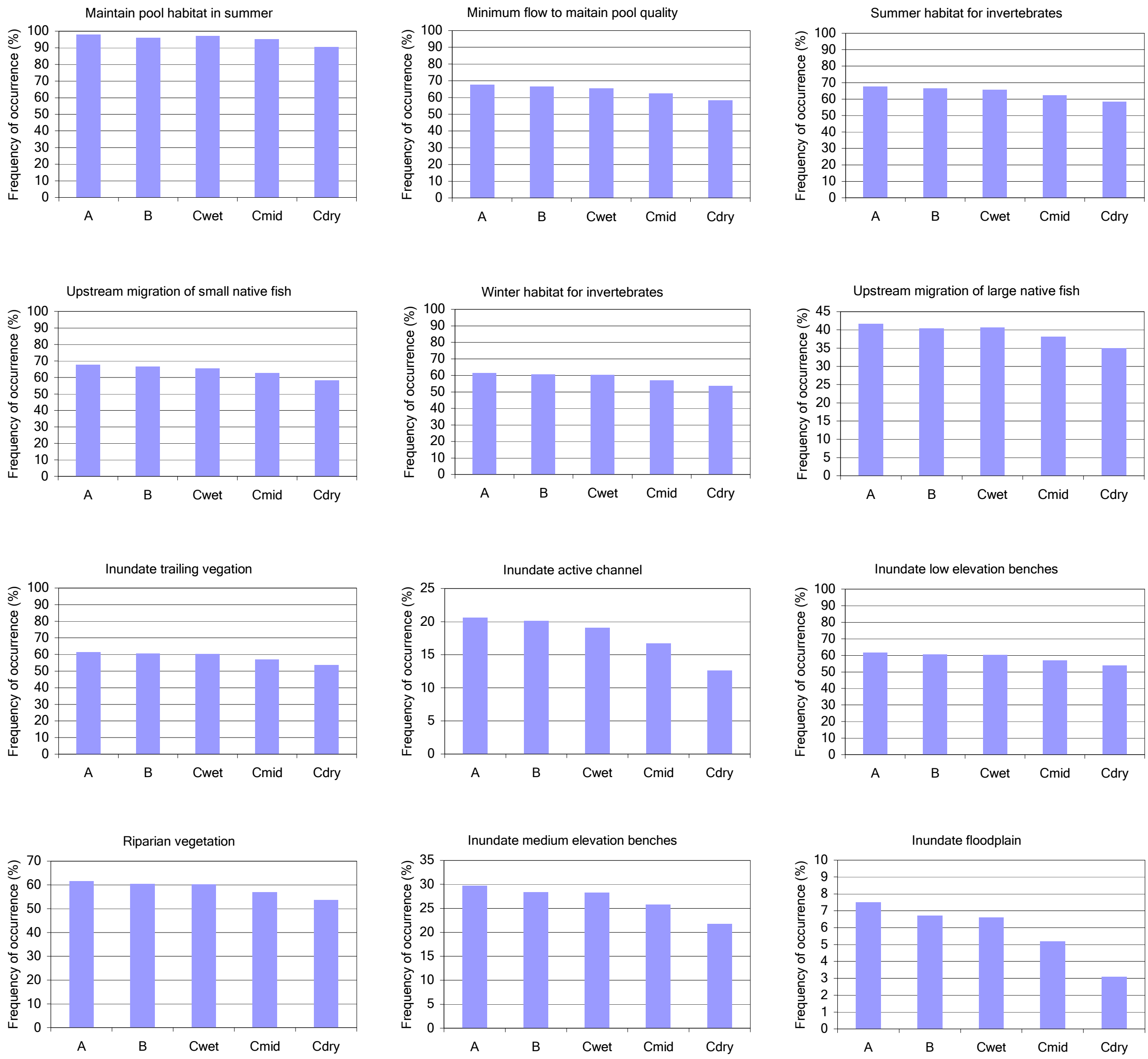


Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

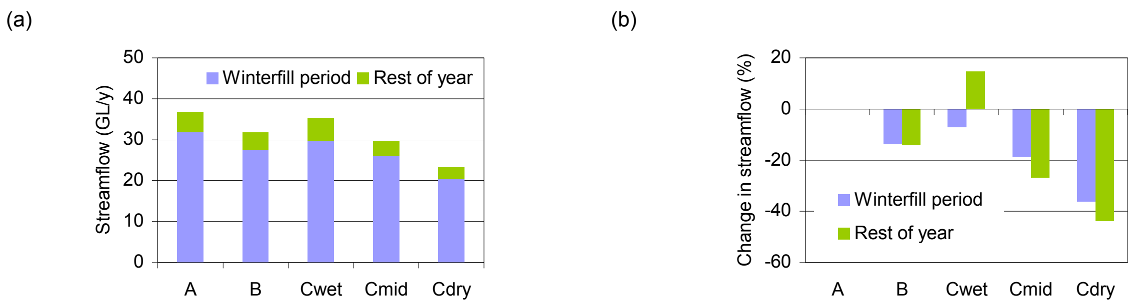


The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

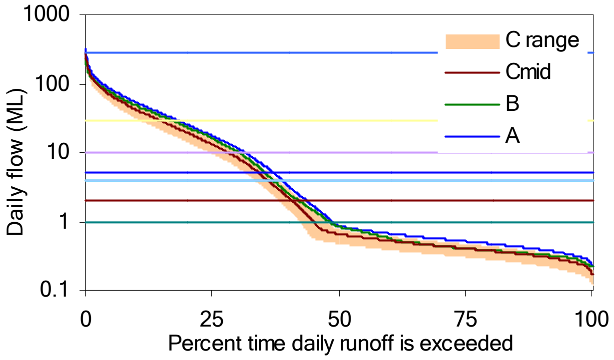
Chapman Brook ***SRN 609022*** ***Catchment area 180 km²*** ***Busselton Coast to Denmark region***



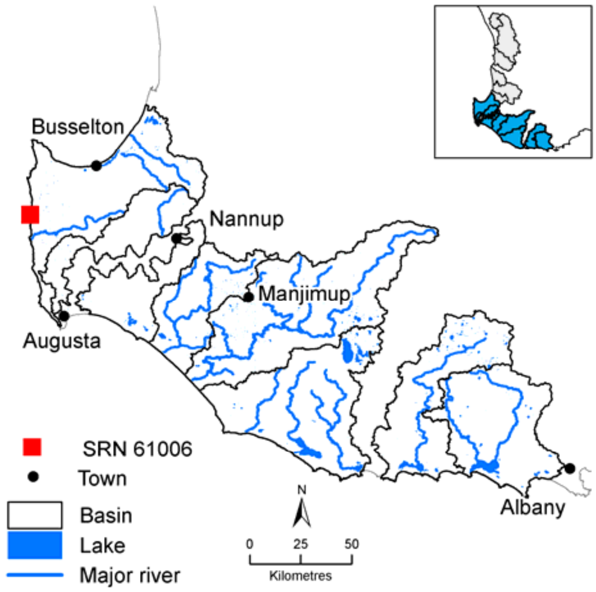
Variation in frequency of flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry



Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

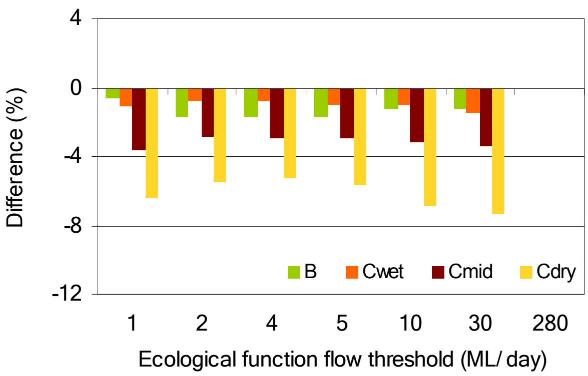


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

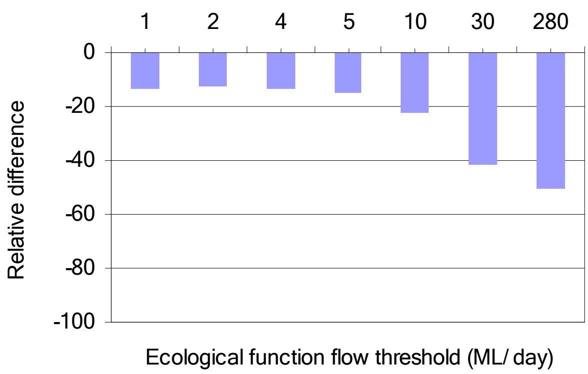


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

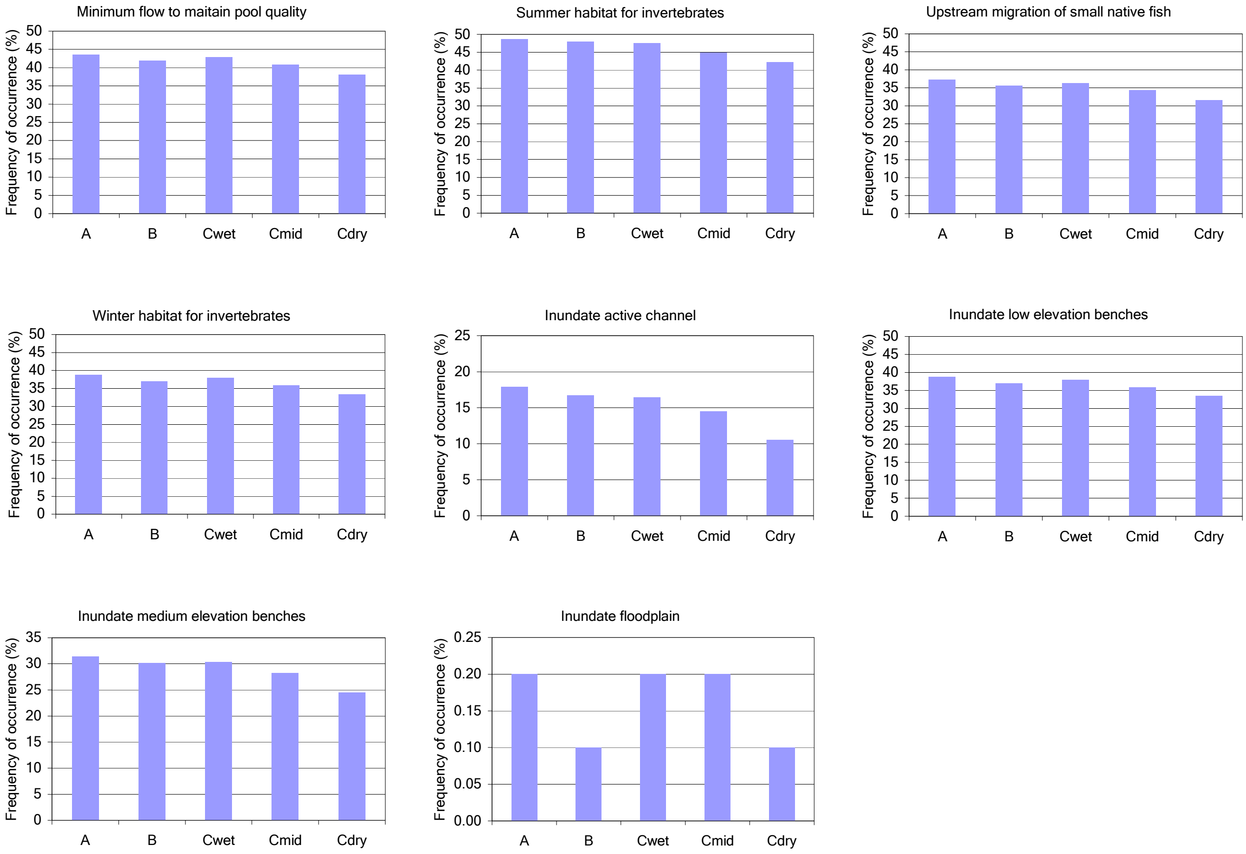
Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Summer habitat for invertebrates	1	48.6%	0.6%	1.1%	3.7%	6.4%
Minimum flow to maintain pool quality	2	43.6%	1.7%	0.7%	2.8%	5.5%
Winter habitat for invertebrates	4	38.7%	1.7%	0.8%	2.9%	5.3%
Inundate low elevation benches	4	38.7%	1.7%	0.8%	2.9%	5.3%
Upstream migration of small native fish	5	37.2%	1.7%	1.0%	2.9%	5.6%
Inundate medium elevation benches	10	31.4%	1.2%	1.0%	3.2%	6.9%
Inundate active channel	30	17.9%	1.2%	1.5%	3.4%	7.4%
Inundate floodplain	280	0.2%	0.1%	0.0%	0.0%	0.1%



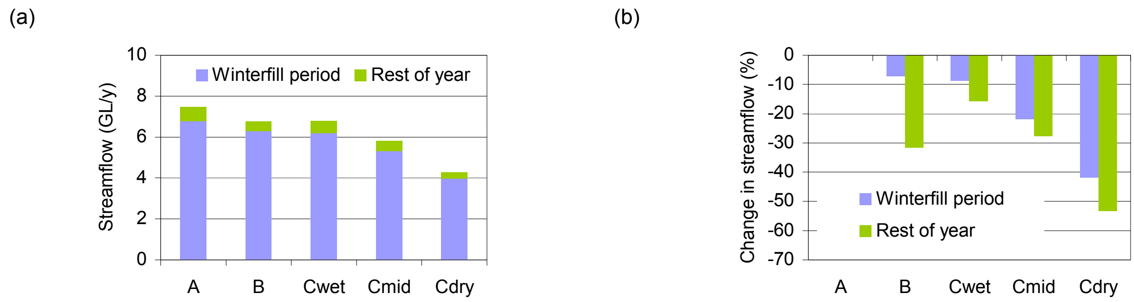
Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A



The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

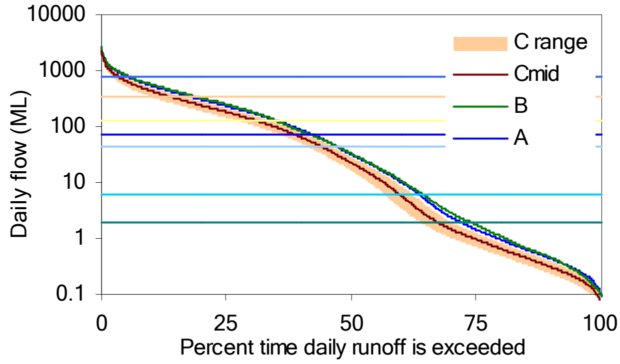


Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry

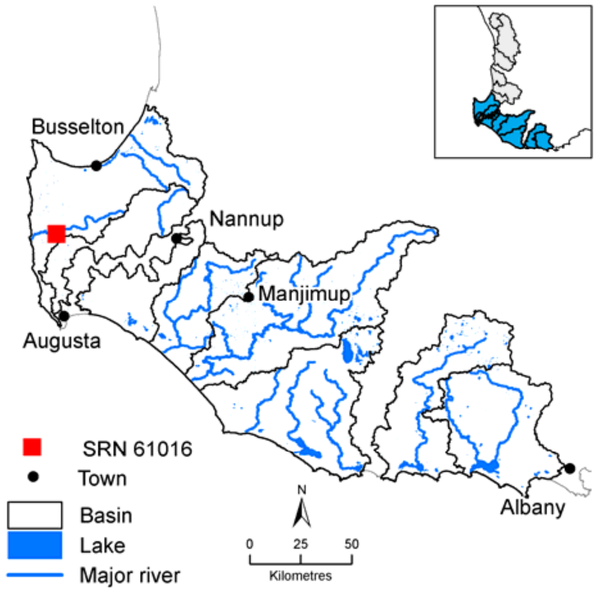


Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

Margaret River ***SRN 61016*** ***Catchment area 359.3 km^2*** ***Busselton Coast to Denmark region***

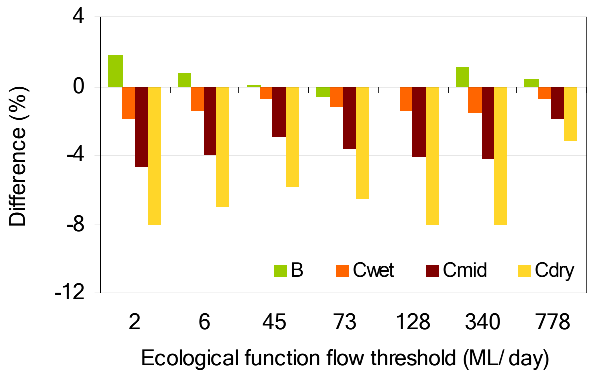


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

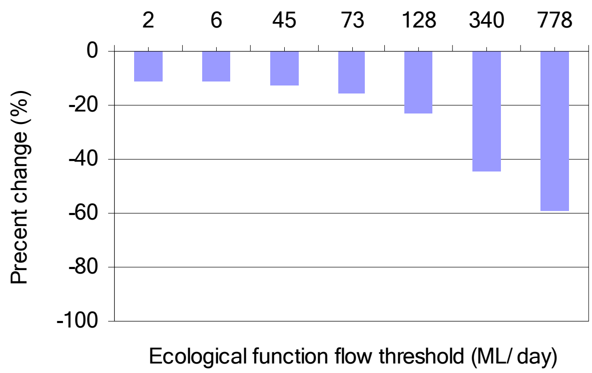


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

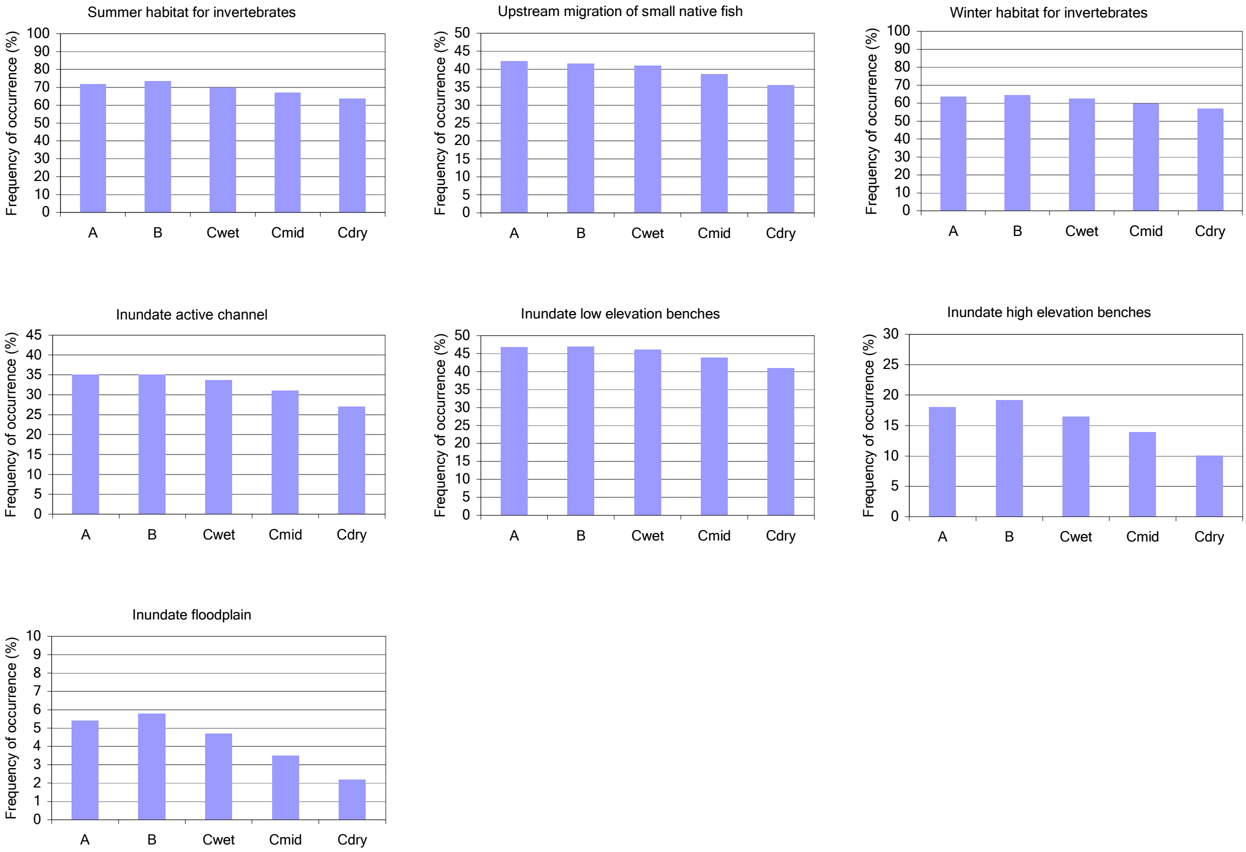
Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Summer habitat for invertebrates	2	71.8%	-1.8%	1.9%	4.7%	8.1%
Winter habitat for invertebrates	6	63.8%	-0.7%	1.4%	4.0%	7.0%
Inundate low elevation benches	45	46.9%	-0.1%	0.8%	3.0%	5.9%
Upstream migration of small native fish	73	42.2%	0.6%	1.2%	3.6%	6.6%
Inundate active channel	128	35.1%	0.1%	1.4%	4.1%	8.0%
Inundate high elevation benches	340	18.1%	-1.1%	1.6%	4.2%	8.0%
Inundate floodplain	778	5.4%	-0.4%	0.7%	1.9%	3.2%



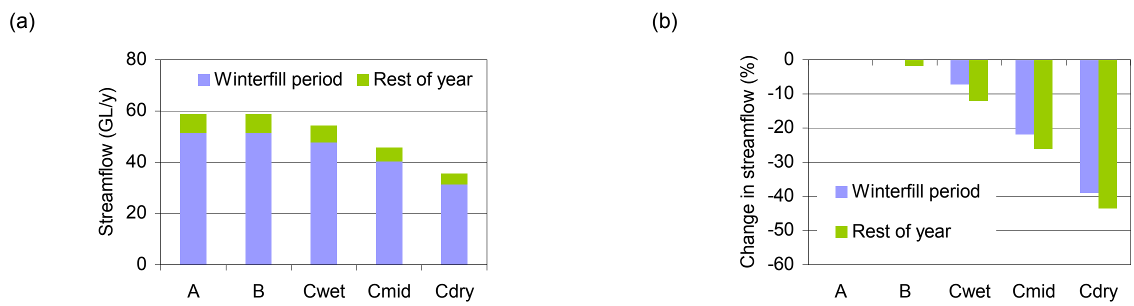
Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A



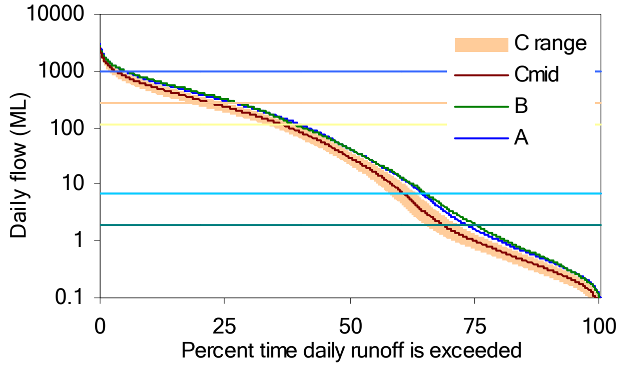
The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry



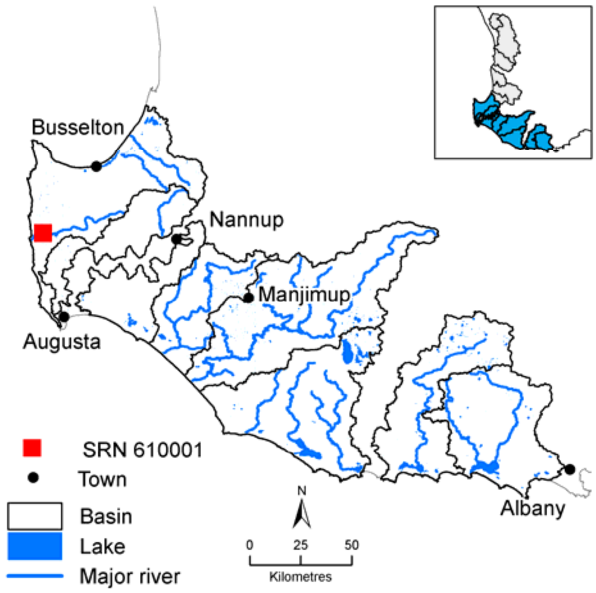
Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry



Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

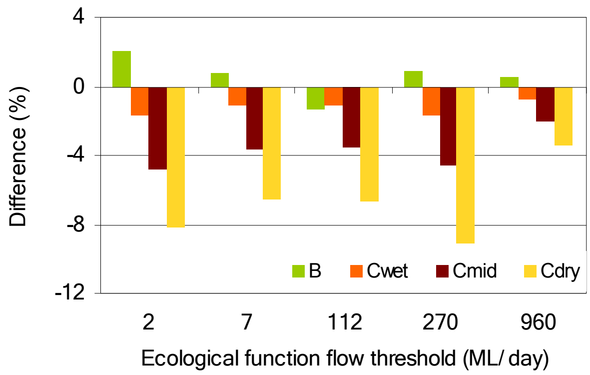


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

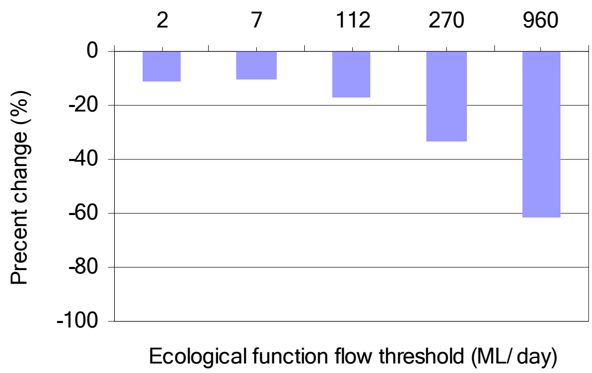


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Summer habitat for invertebrates	2	73%	-2.0%	1.7%	4.8%	8.2%
Upstream migration of small native fish	7	64.3%	-0.7%	1.1%	3.7%	6.6%
Winter habitat for invertebrates	7	64.3%	-0.7%	1.1%	3.7%	6.6%
Inundate active channel	112	40.2%	1.3%	1.1%	3.5%	6.7%
Inundate high elevation benches	270	27.1%	-0.9%	1.7%	4.6%	9.1%
Inundate floodplain	960	5.5%	-0.5%	0.7%	2.0%	3.4%

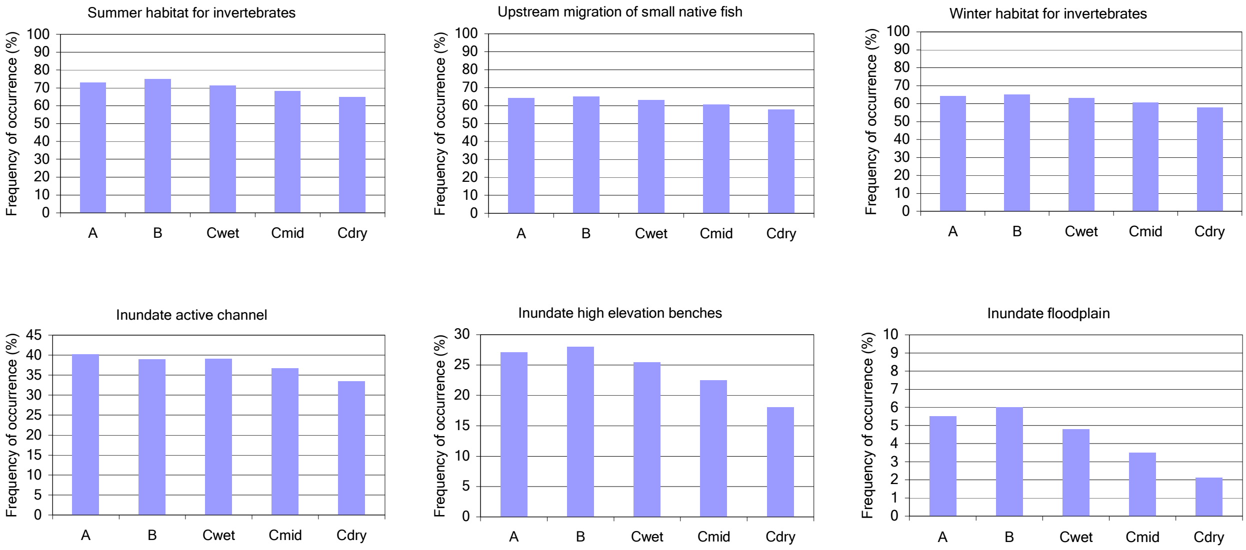


Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

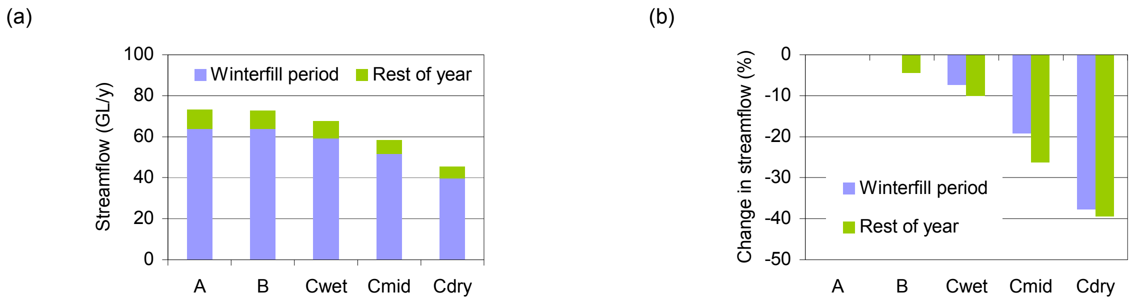


The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

Margaret River ***SRN 610001*** ***Catchment area 443 km²*** ***Busselton Coast to Denmark region***

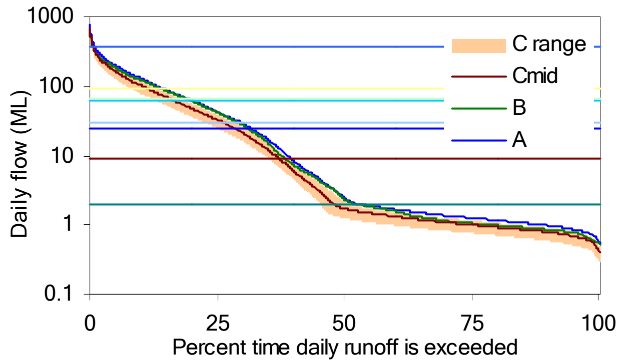


Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry

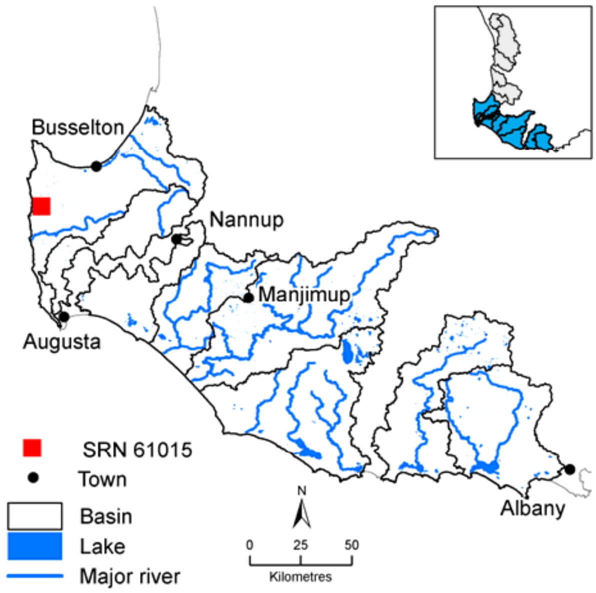


Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

Wilyabrup Brook ***SRN 61015*** ***Catchment area 43.6 km^2*** ***Busselton Coast to Denmark region***

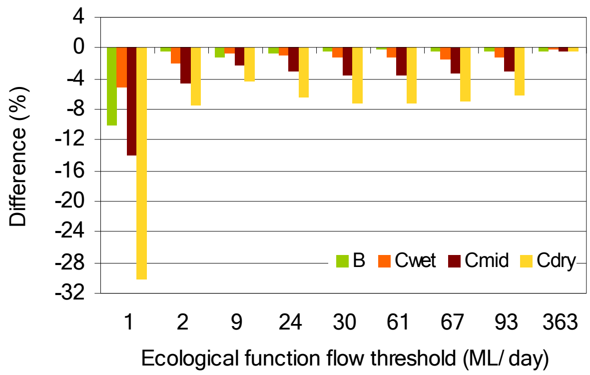


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

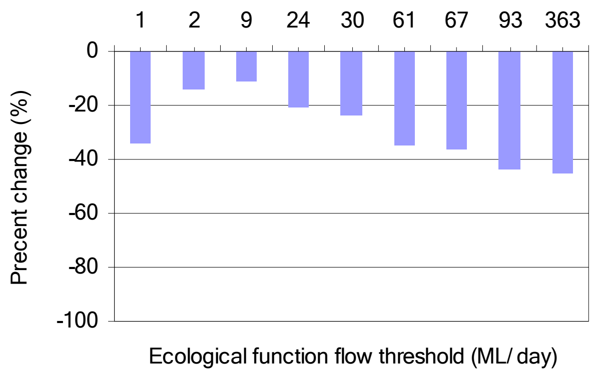


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Maintain pool habitat in summer	1	89%	10.1%	5.2%	14.0%	30.2%
Summer habitat for invertebrates	2	52.6%	0.5%	1.9%	4.7%	7.4%
Minimum flow to maintain pool quality	9	39.5%	1.1%	0.7%	2.3%	4.3%
Upstream migration of small native fish	24	31.9%	0.7%	1.0%	3.1%	6.5%
Inundate low elevation benches	30	29.7%	0.5%	1.3%	3.5%	7.1%
Winter habitat for invertebrates	61	20.3%	0.3%	1.2%	3.5%	7.1%
Inundate trailing vegetation	67	19.1%	0.4%	1.4%	3.4%	7.0%
Inundate active channel	93	14.3%	0.4%	1.1%	3.1%	6.2%
Inundate floodplain	363	1.1%	0.4%	0.1%	0.4%	0.5%

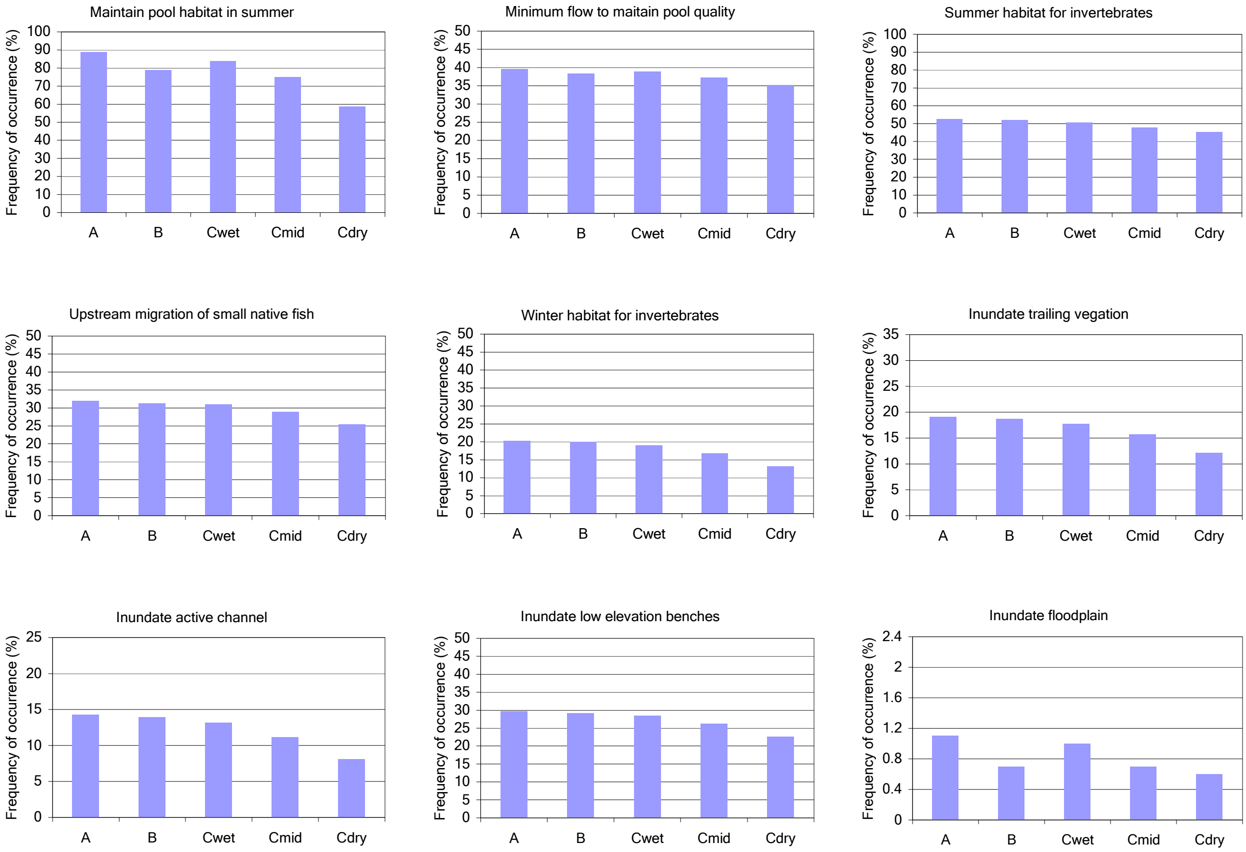


Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

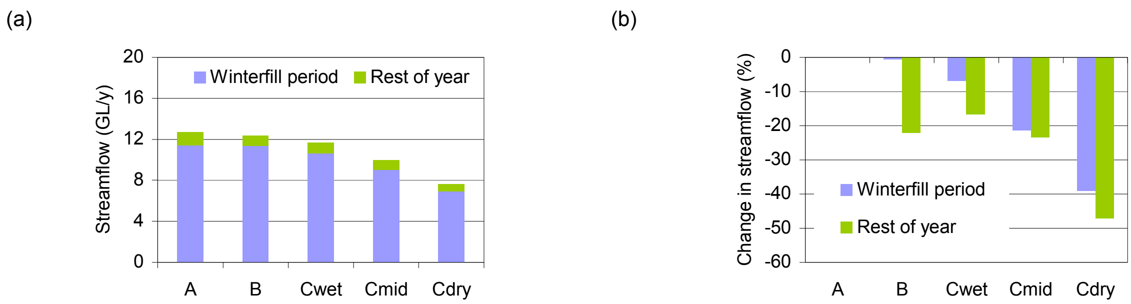


The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

Wilyabrup Brook ***SRN 61015*** ***Catchment area 43.6 km²*** ***Busselton Coast to Denmark region***

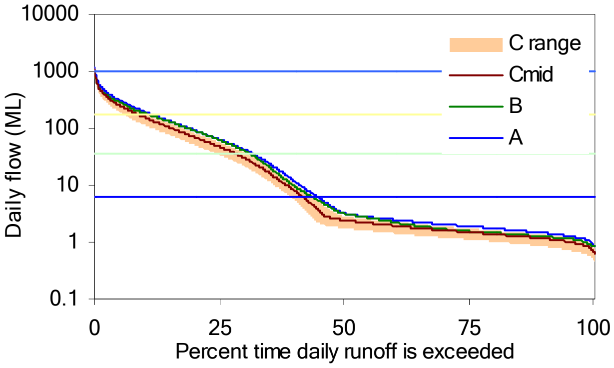


Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry

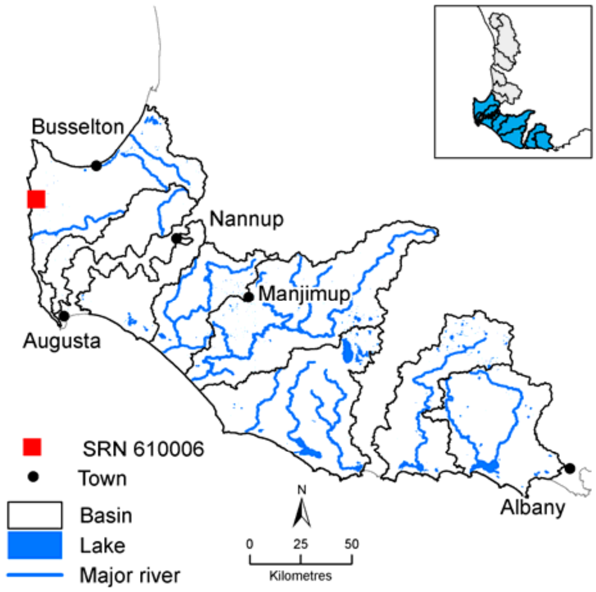


Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

Wilyabrup Brook ***SRN 610006*** ***Catchment area 82.3 km^2*** ***Busselton Coast to Denmark region***

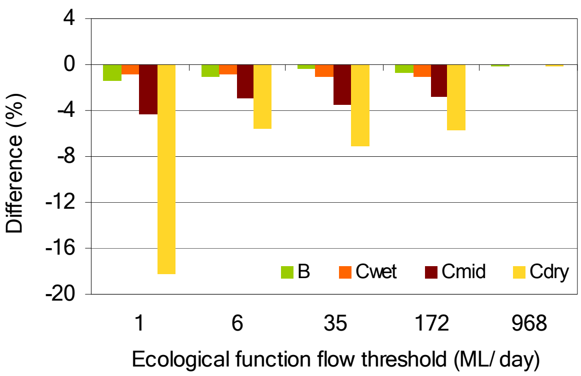


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

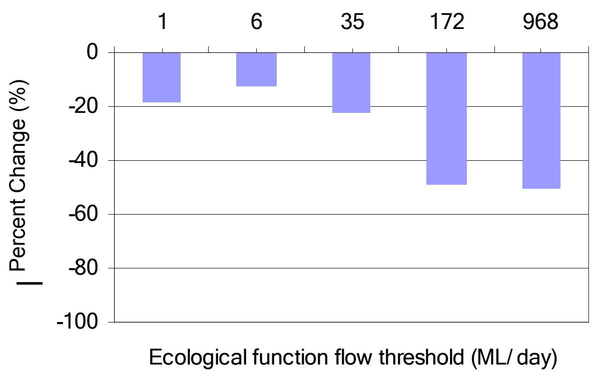


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Maintain pool habitat in summer	1	99.4%	1.4%	0.9%	4.4%	18.3%
Upstream migration of small native fish	6	44.9%	1.1%	0.9%	2.9%	5.5%
Inundate trailing vegetation	35	31.9%	0.4%	1.1%	3.4%	7.1%
Inundate active channel	172	11.7%	0.7%	1.0%	2.8%	5.7%
Inundate floodplain	968	0.2%	0.1%	0.0%	0.0%	0.1%

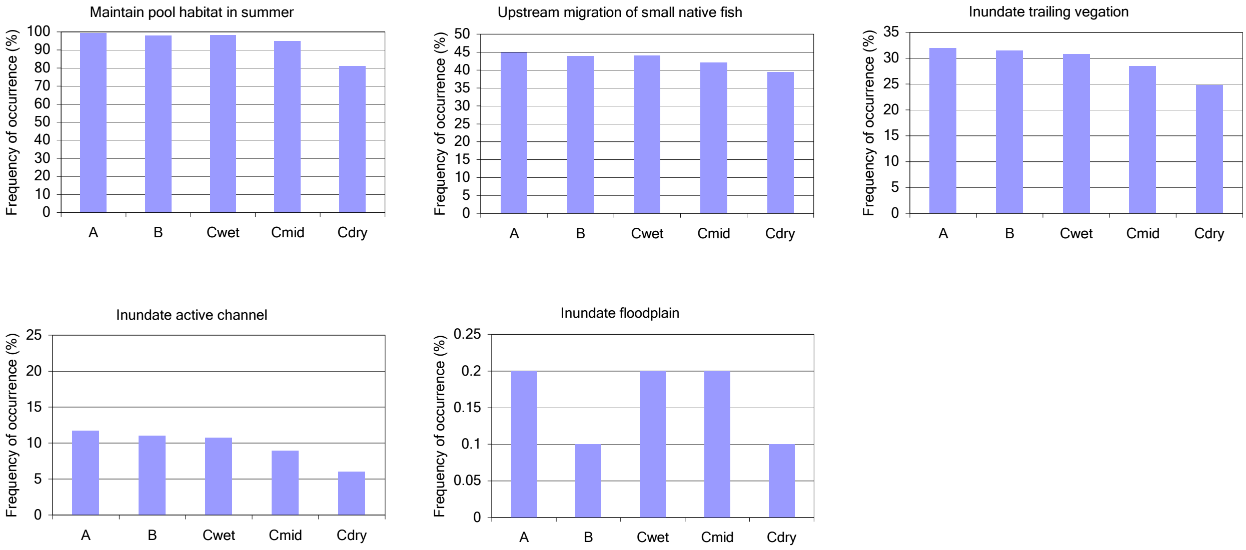


Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

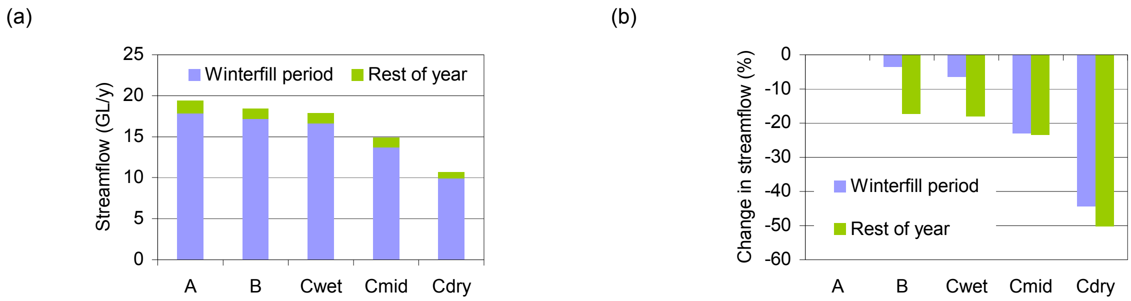


The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

Wilyabrup Brook ***SRN 610006*** ***Catchment area 82.3 km^2*** ***Busselton Coast to Denmark region***

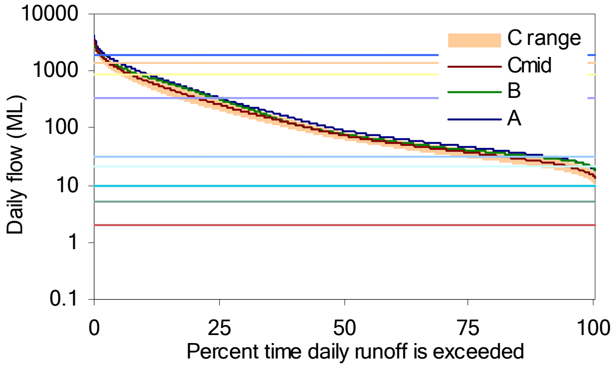


Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry

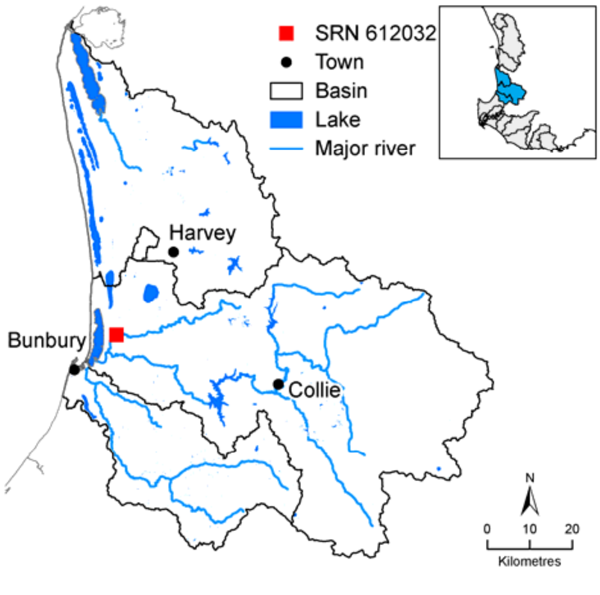


Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

Brunswick River ***SRN 612032*** ***Catchment area 509.4 km²*** ***Harvey to Preston region***

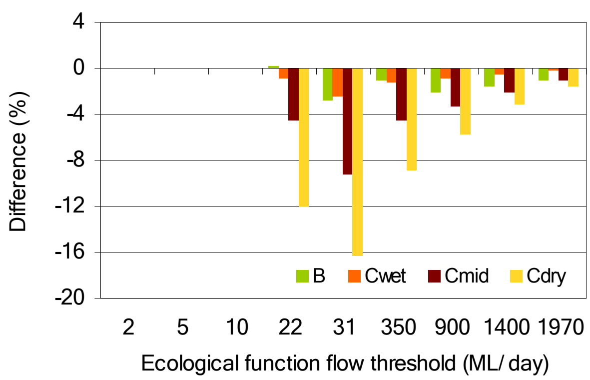


Flow duration curves under scenarios A, B and C, and the ecological flow thresholds (Column 2 in table)

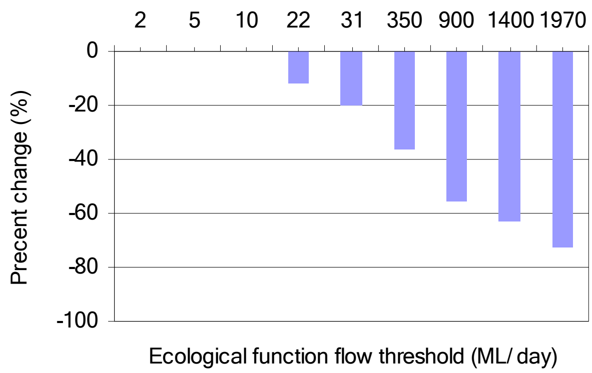


Threshold flow rates associated with the identified ecological functions, flow frequency under Scenario A and the change under scenarios B, Cwet, Cmid and Cdry relative to Scenario A

Ecological function	Flow threshold	Flow frequency				
		A	B	Cwet	Cmid	Cdry
	ML/day	percent	percent change from Scenario A			
Minimum flow to maintain pool quality	2	100%	0.0%	0.0%	0.0%	0.0%
Summer habitat for invertebrates	5	100%	0.0%	0.0%	0.0%	0.0%
Upstream migration of small native fish	10	100%	0.0%	0.0%	0.0%	0.0%
Winter habitat for invertebrates	10	100%	0.0%	0.0%	0.0%	0.0%
Upstream migration of large native fish	22	98.8%	-0.2%	0.9%	4.6%	12.0%
Inundate low elevation benches	31	91.9%	2.7%	2.4%	9.3%	18.2%
Inundate medium elevation benches	350	24.6%	1.0%	1.2%	4.6%	8.9%
Inundate active channel	900	10.5%	2.0%	0.9%	3.3%	5.8%
Inundate high elevation benches	1400	5.1%	1.6%	0.5%	2.0%	3.2%
Inundate floodplain	1970	2.2%	1.0%	0.1%	1.0%	1.6%

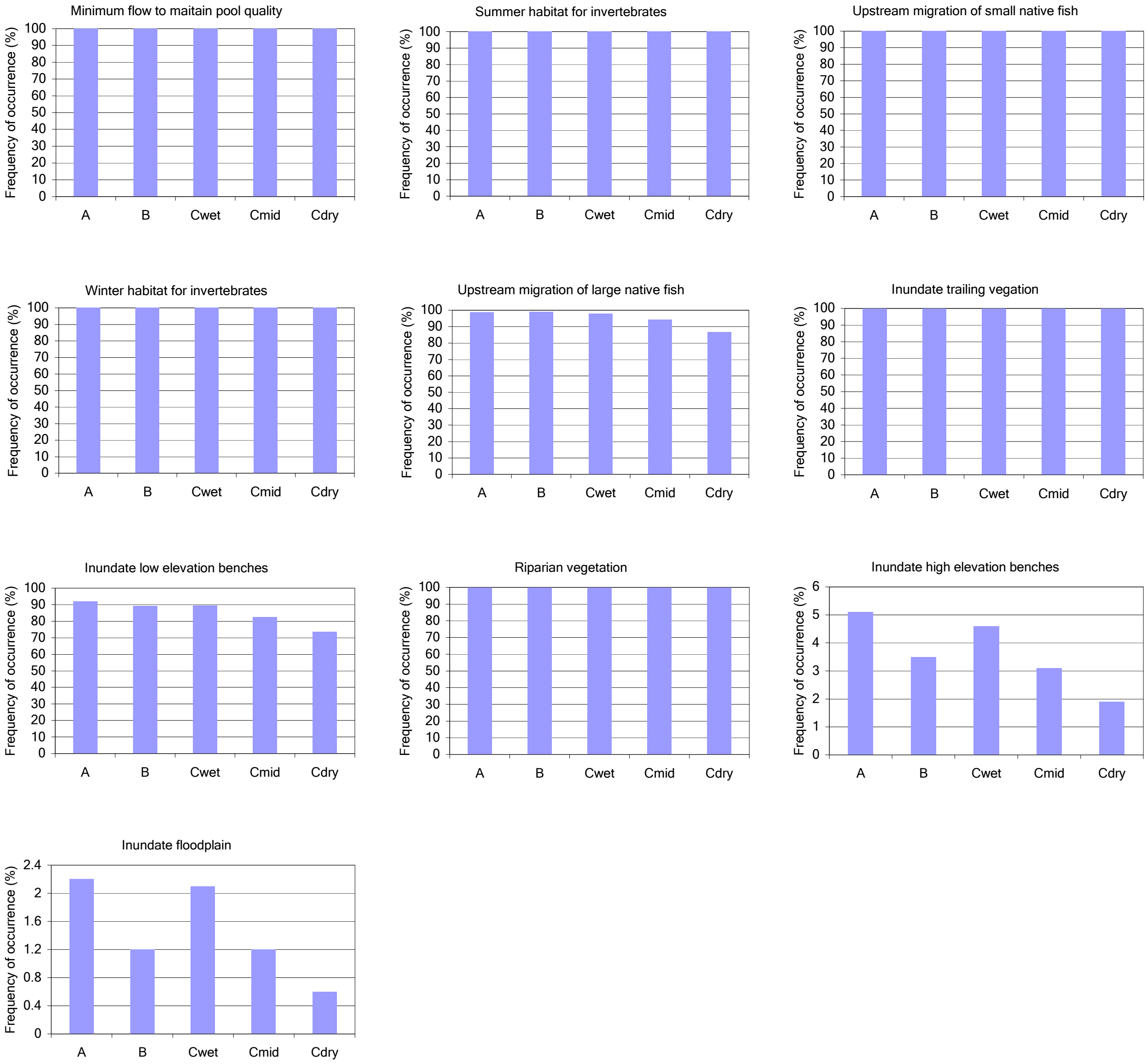


Change in flow frequency associated with the ecological function flow thresholds under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

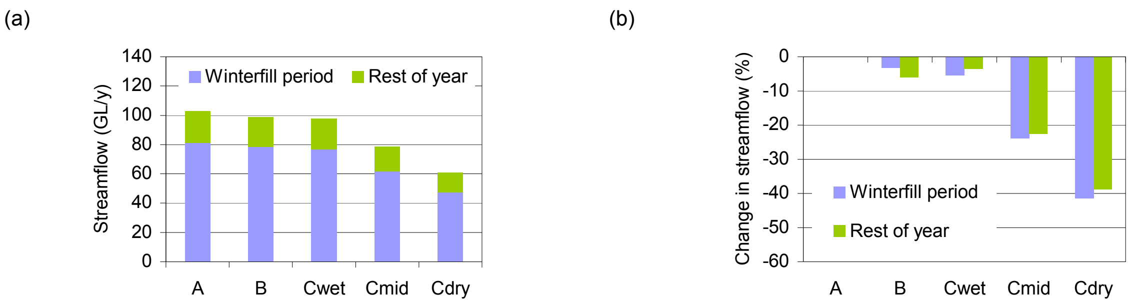


The relative difference in flow frequency associated with each ecological function flow threshold under Scenario A and Scenario Cdry

Brunswick River ***SRN 612032*** ***Catchment area 509.4 km^2*** ***Harvey to Preston region***



Variation in frequency of the flow associated with the identified ecological functions under scenarios A, B, Cwet, Cmid and Cdry



Estimated (a) streamflow during winterfill period (15 June to 15 October) and the rest of the year under scenarios A, B, Cwet, Cmid and Cdry (as median for 33 years) and (b) seasonal streamflow variation under scenarios B, Cwet, Cmid and Cdry compared to Scenario A

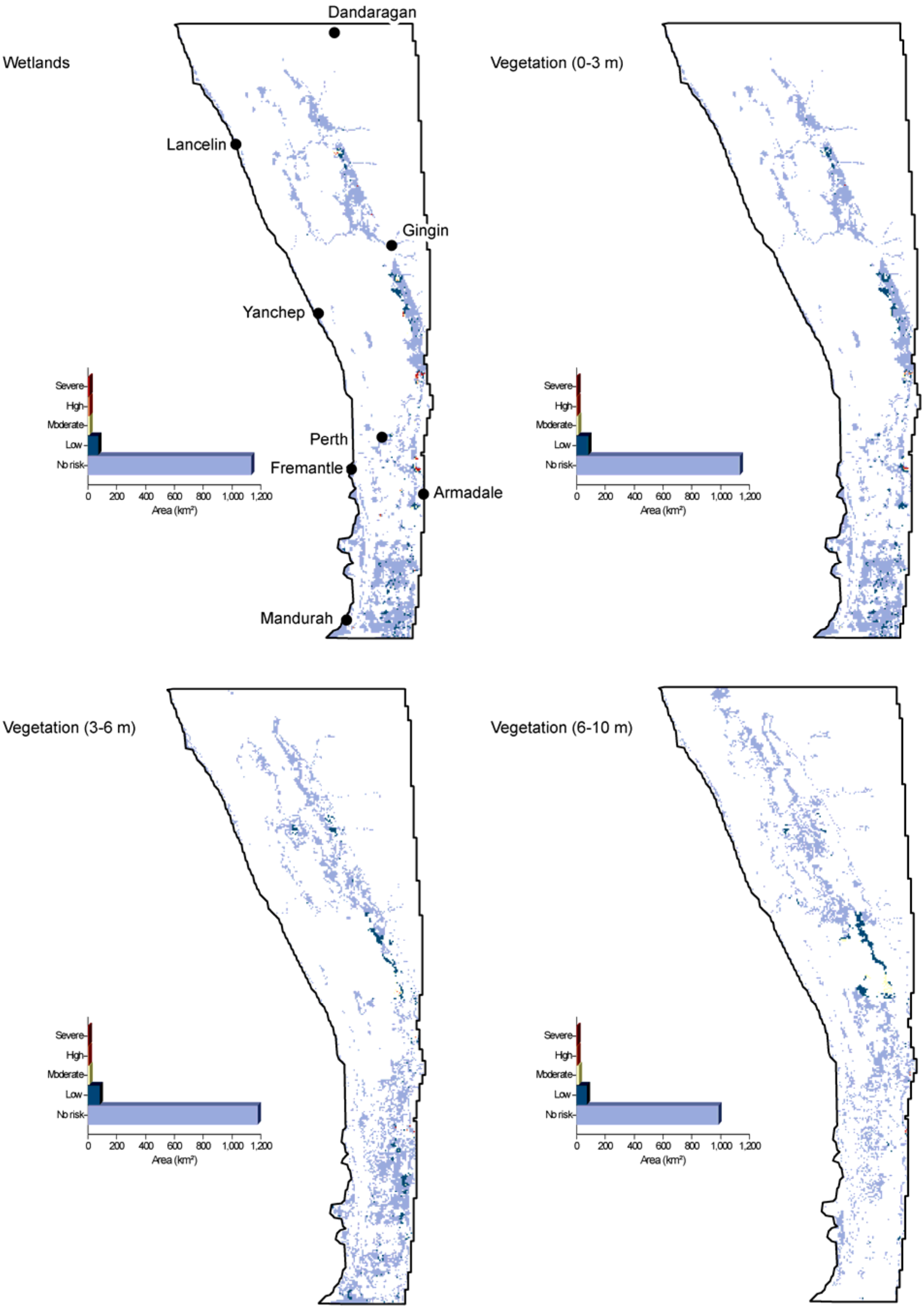


Figure D-1. The risk category associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario A

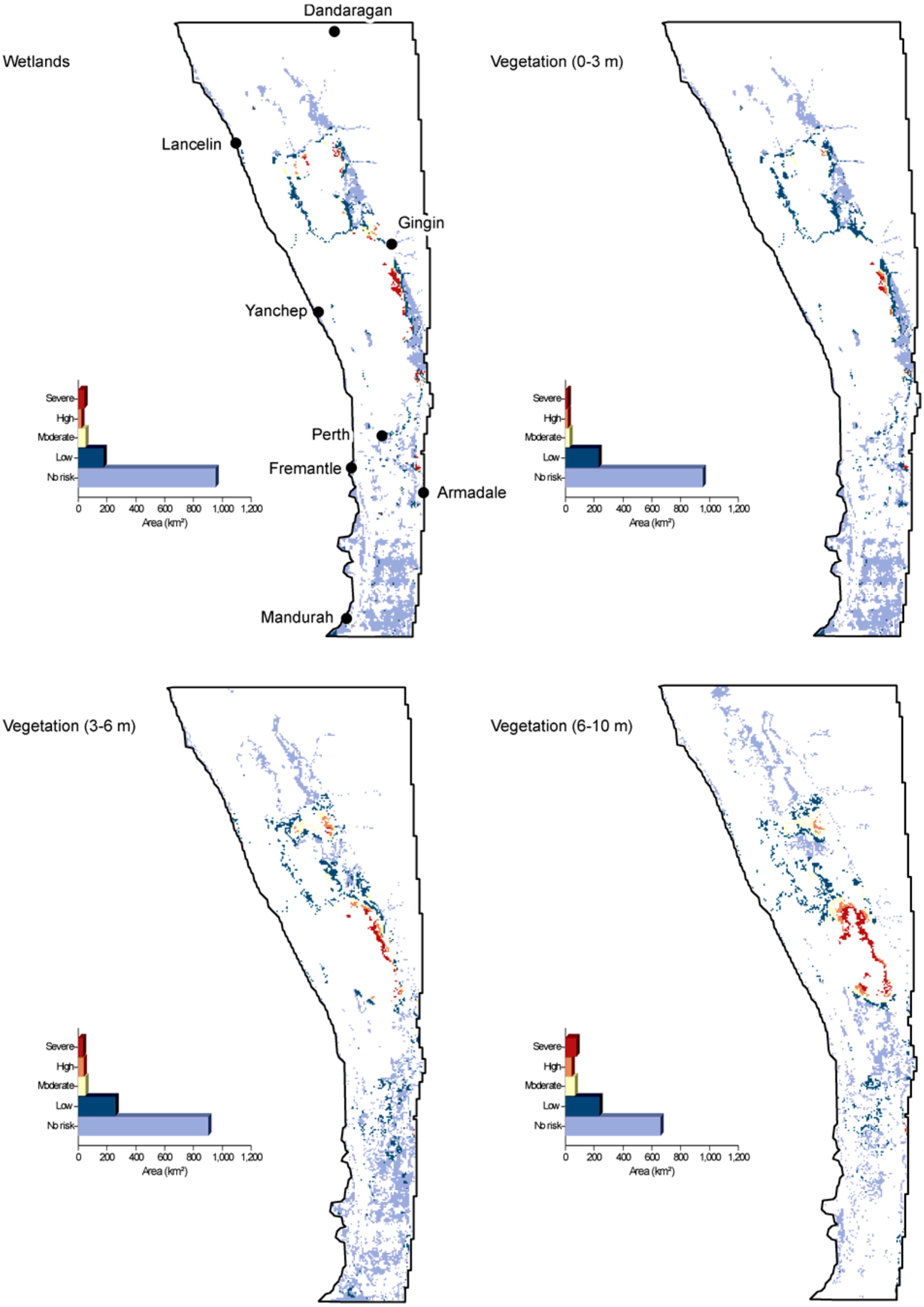


Figure D-2. The risk category associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario B

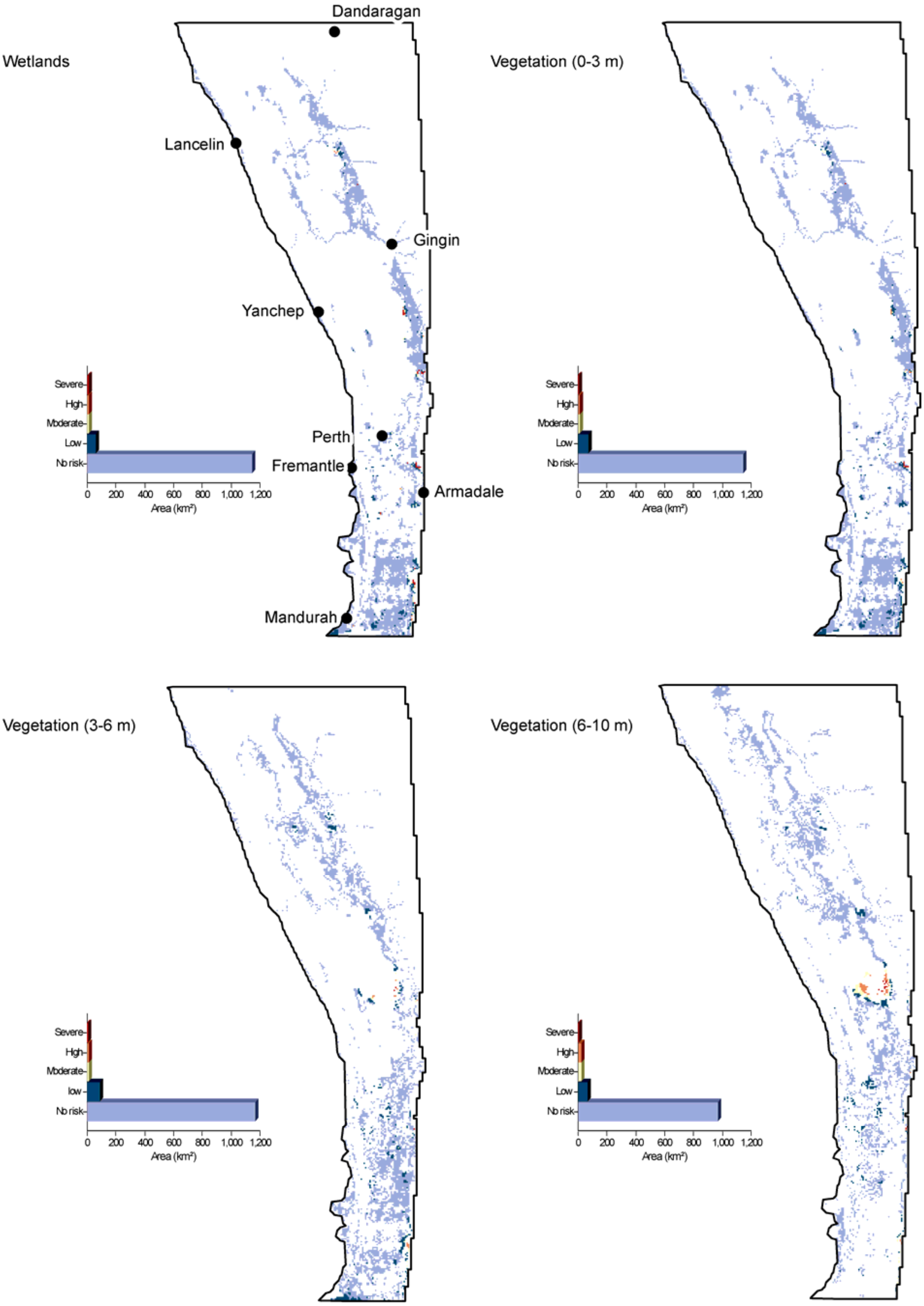


Figure D-3. The risk category associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario Cwet

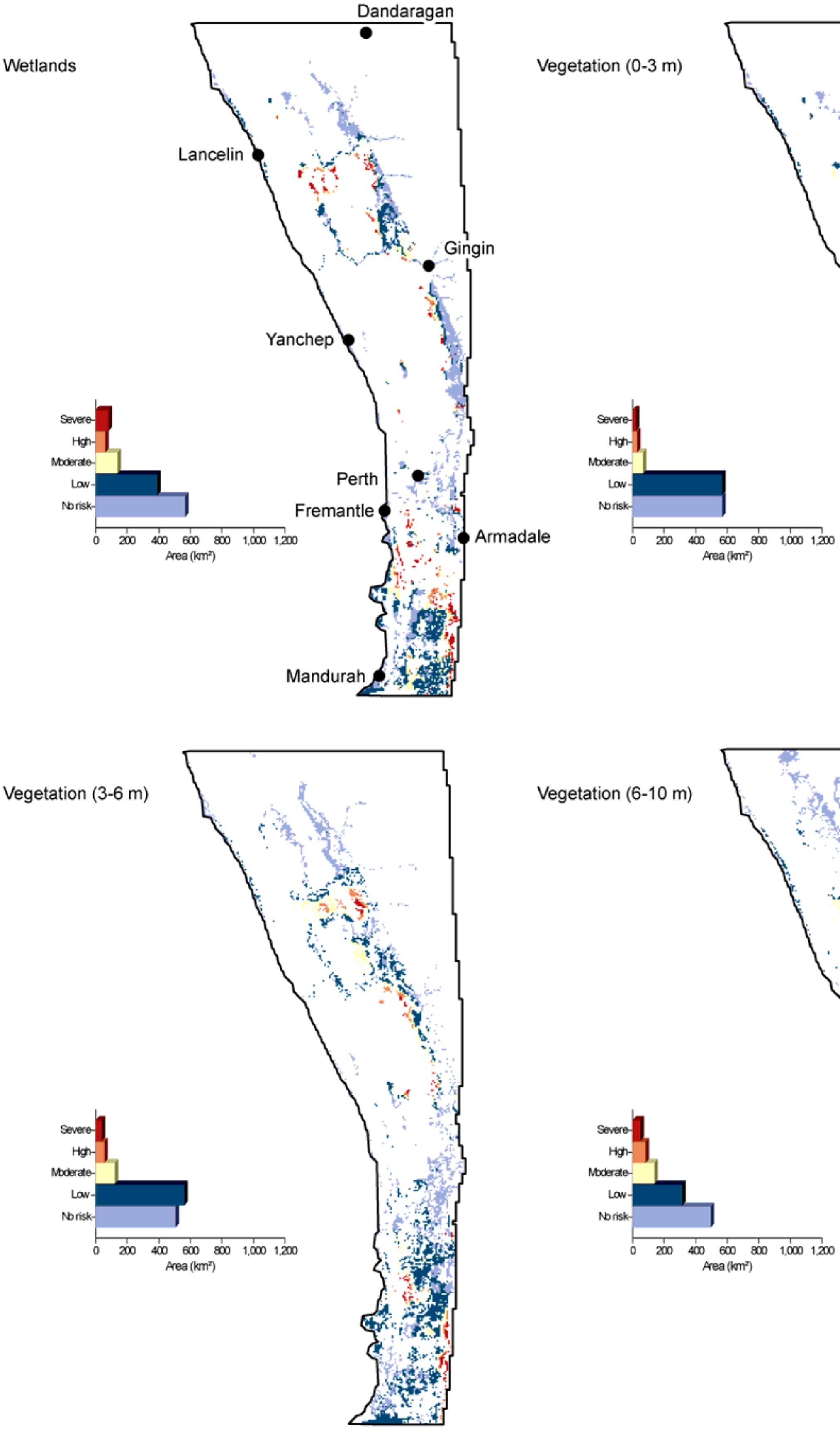


Figure D-4. The risk category associated with each type of groundwater dependent ecosystem in the Central Perth Basin under Scenario D

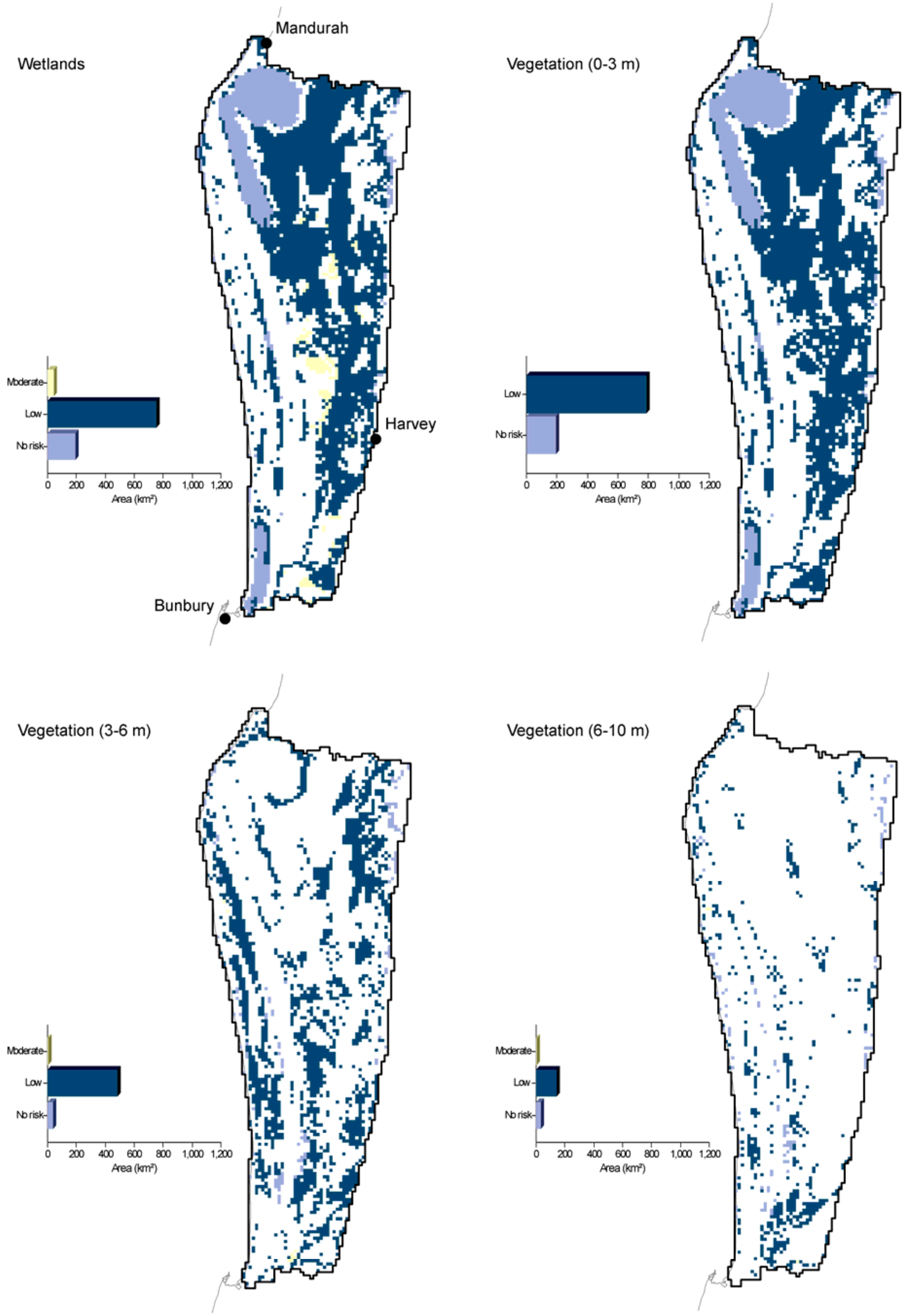


Figure D-5. The risk category associated with each type of groundwater dependent ecosystem in the Peel-Harvey area under Scenario A

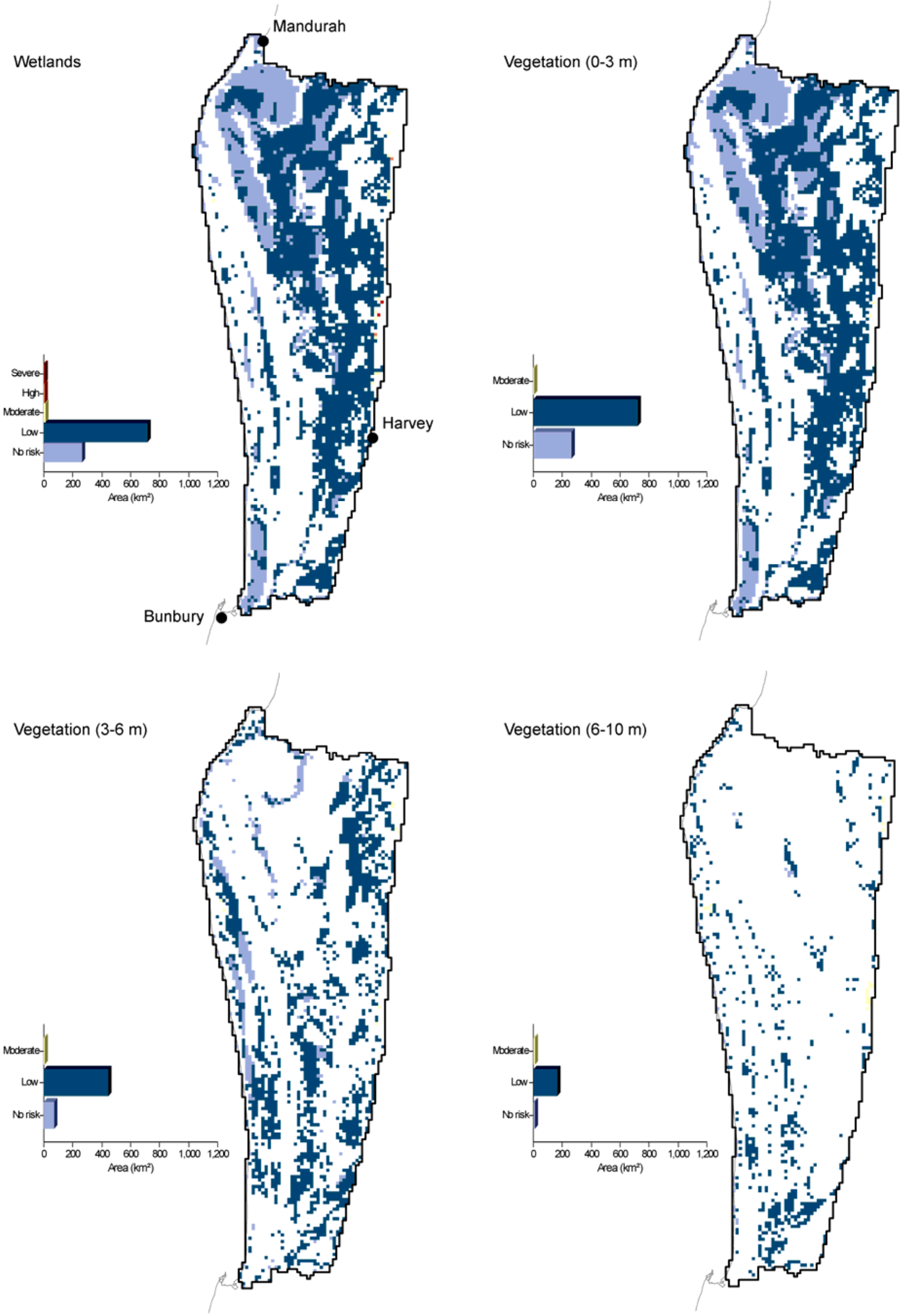


Figure D-6. The risk category associated with each type of groundwater dependent ecosystem in the Peel-Harvey area under Scenario B

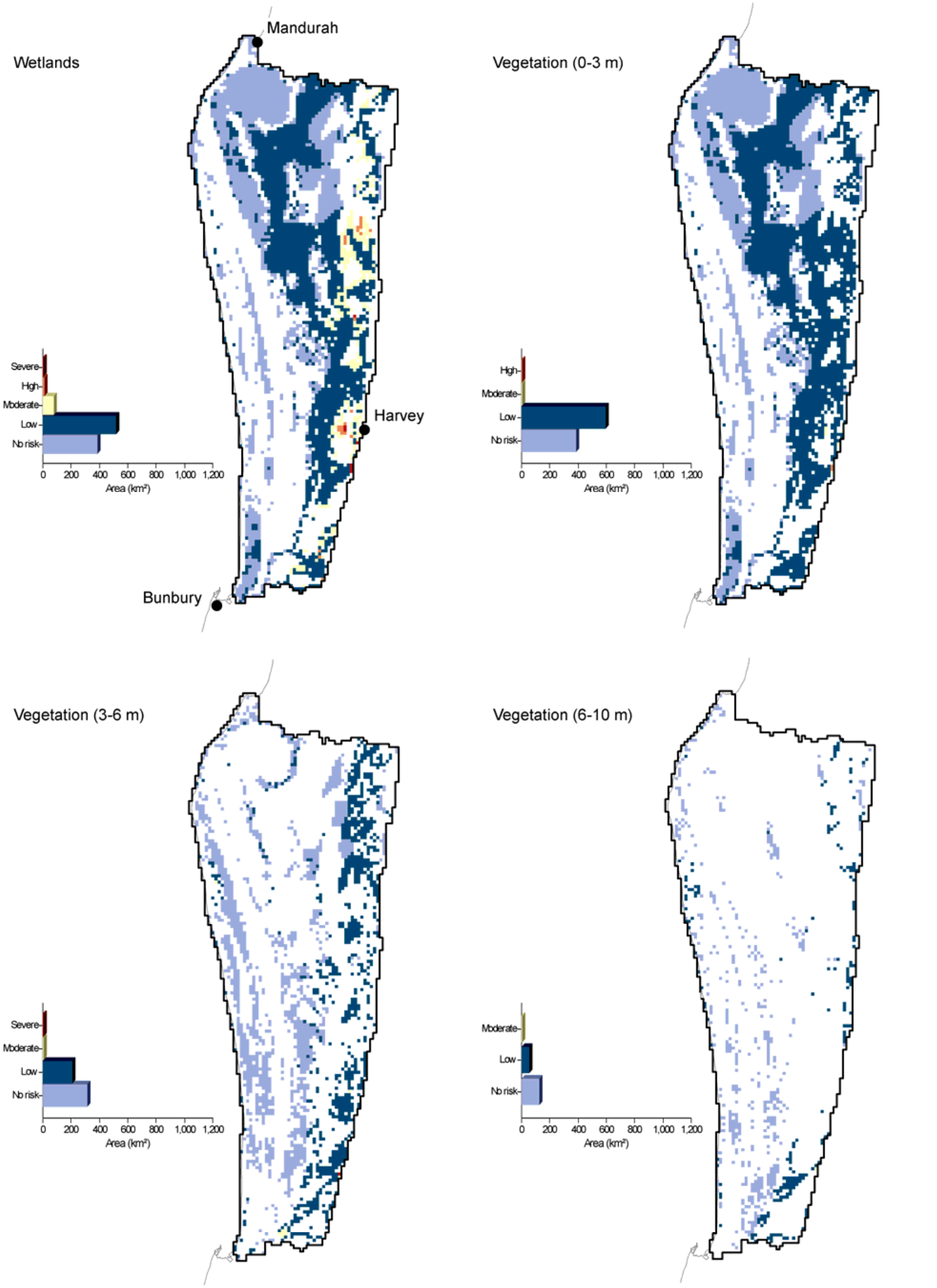


Figure D-7. The risk category associated with each type of groundwater dependent ecosystem in the Peel-Harvey area under Scenario Cwet

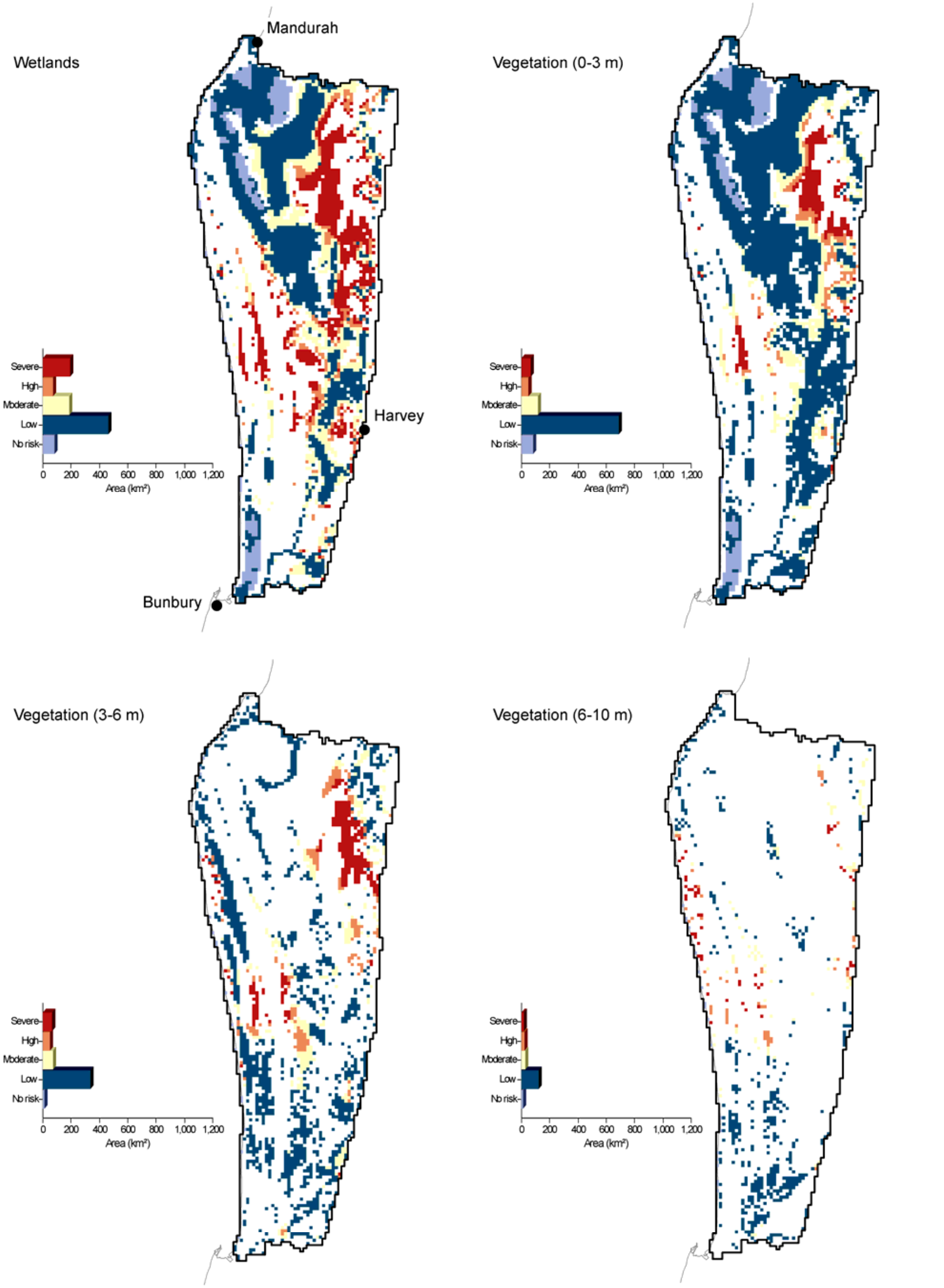


Figure D-8. The risk category associated with each type of groundwater dependent ecosystem in the Peel-Harvey area under Scenario D

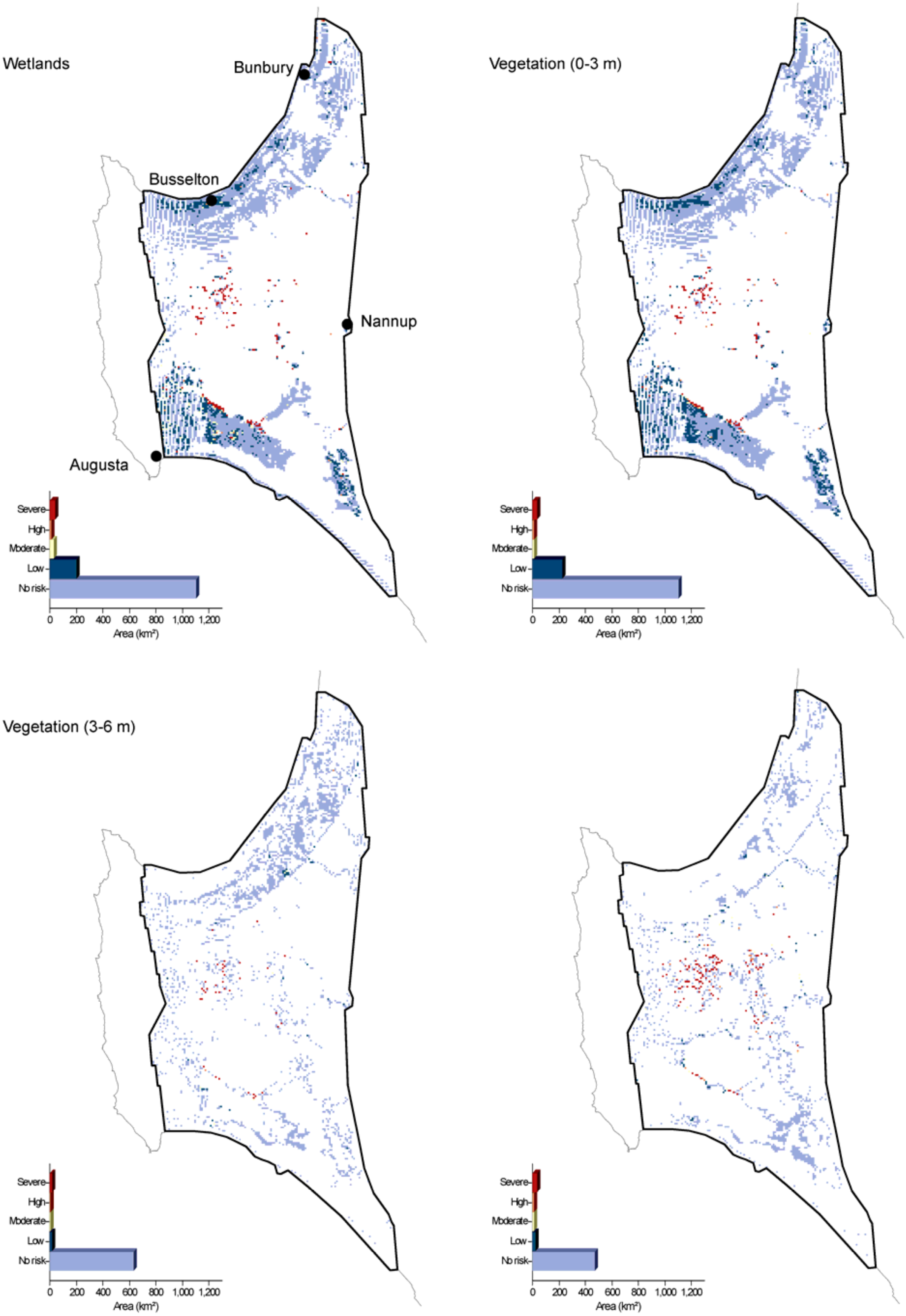


Figure D-9. The risk category associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario A

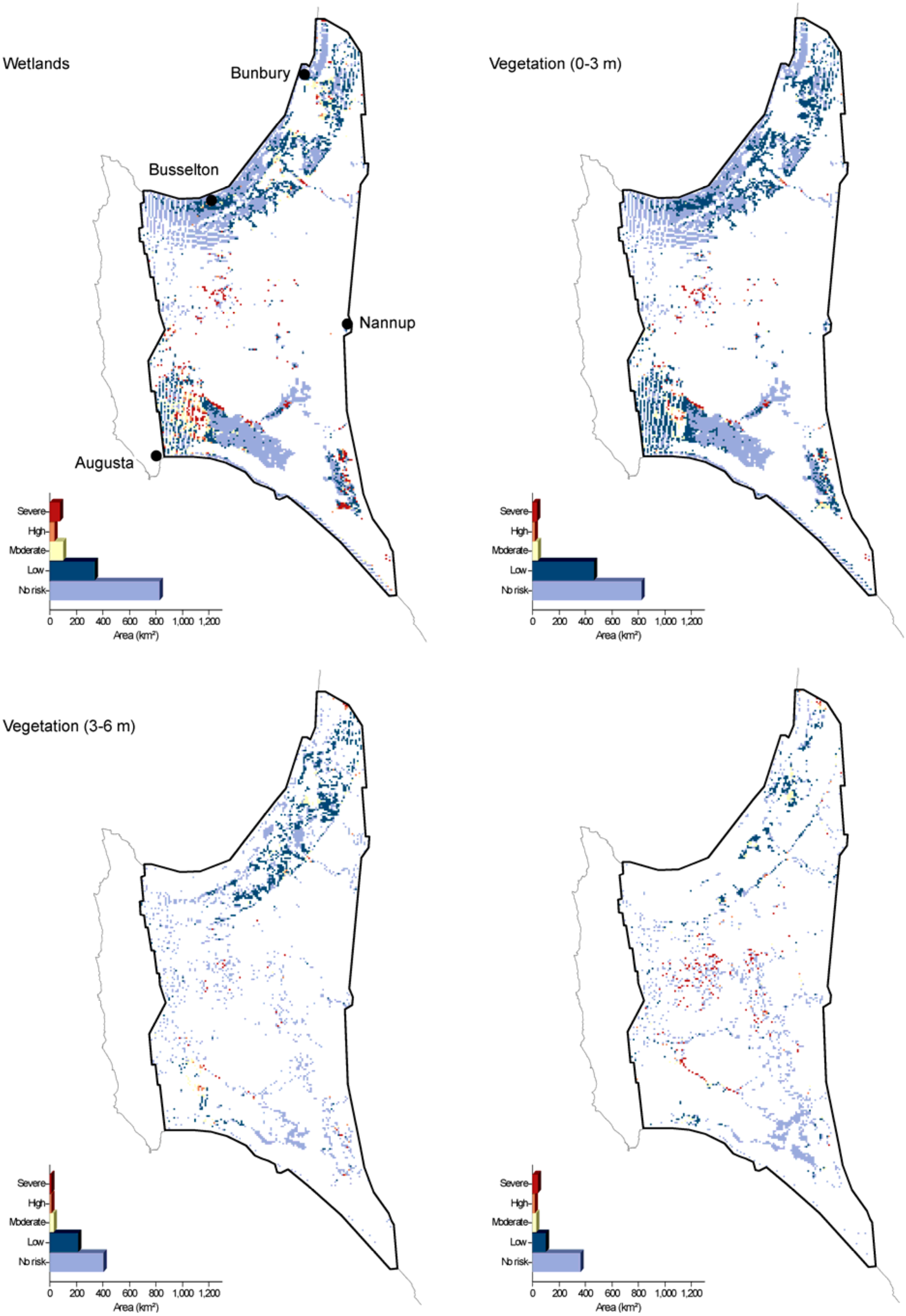


Figure D-10. The risk category associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario B

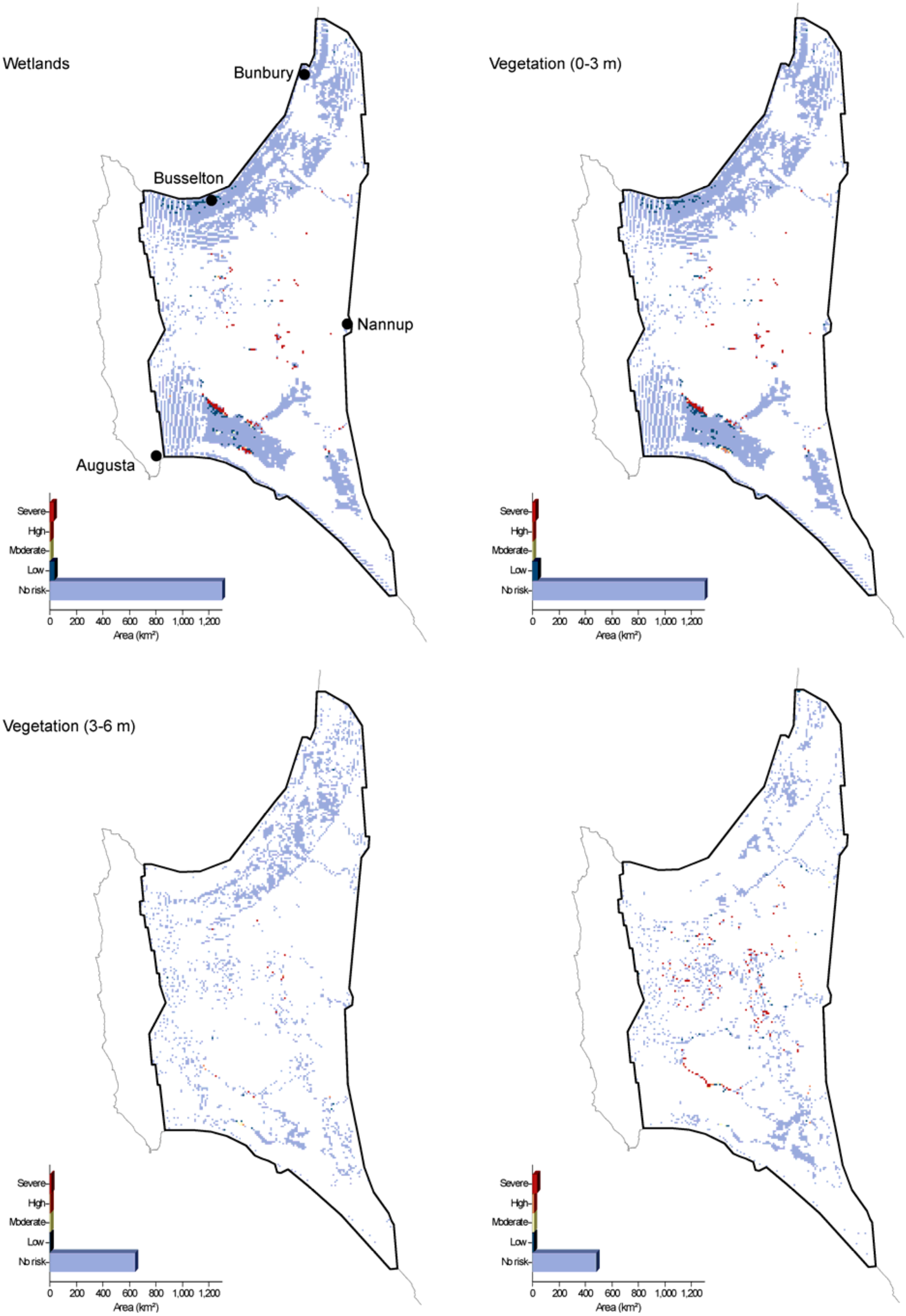


Figure D-11. The risk category associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario Cwet

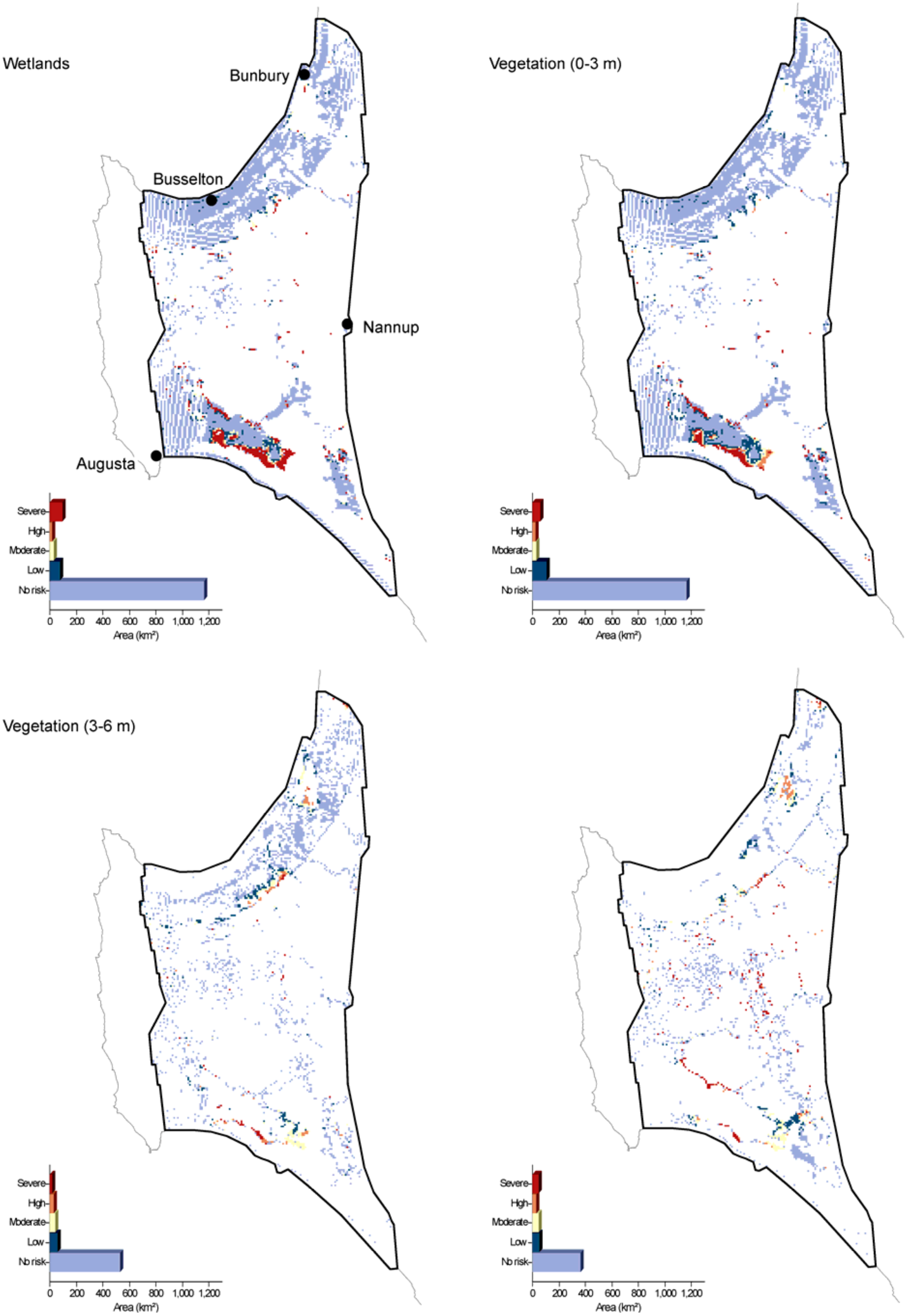


Figure D-12. The risk category associated with each type of groundwater dependent ecosystem in the Southern Perth Basin under Scenario D

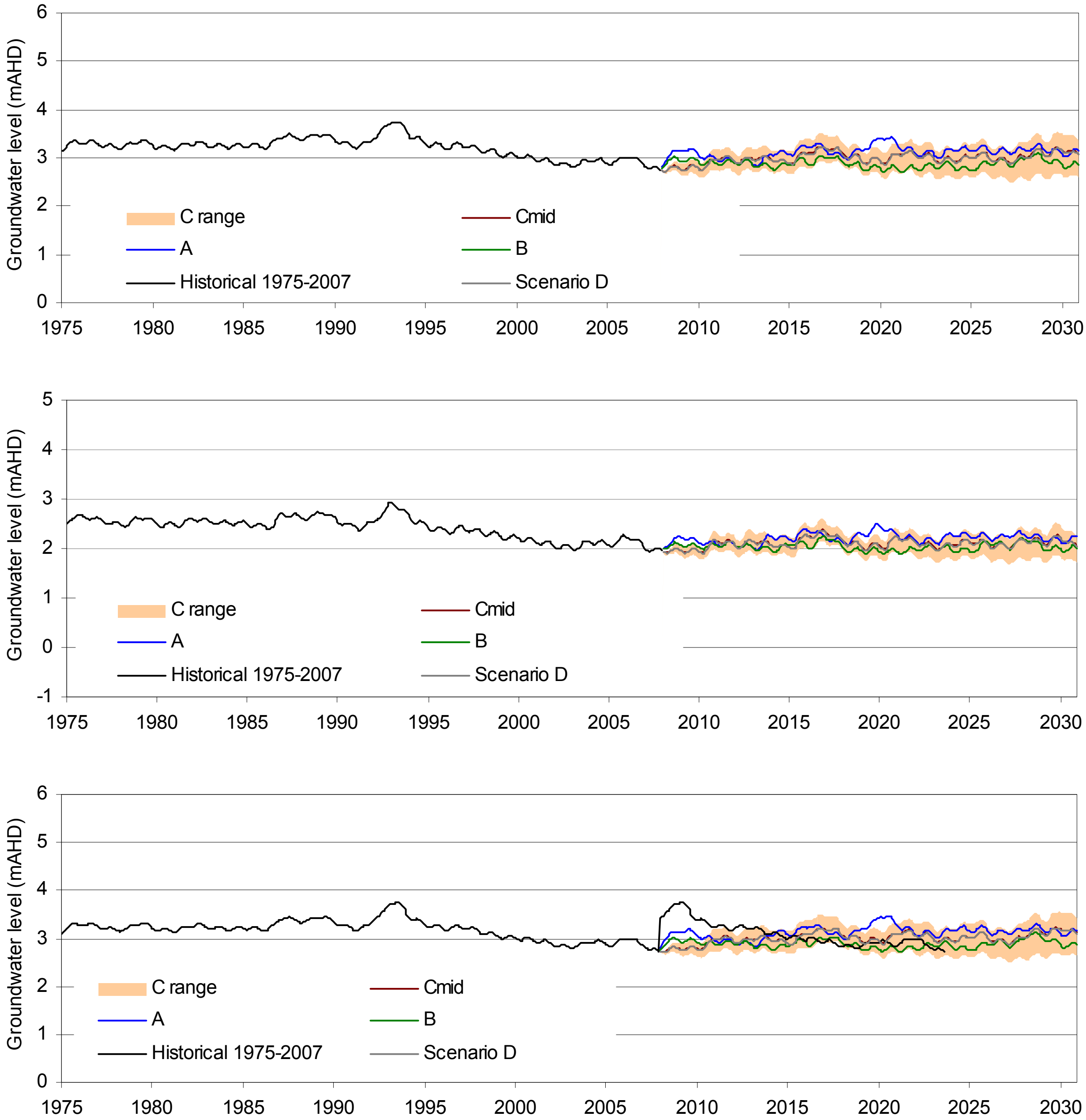


Figure D-13. Observed and modelled groundwater levels typical for Melaleuca Cave, Rose Cave and Minnie's Grotto

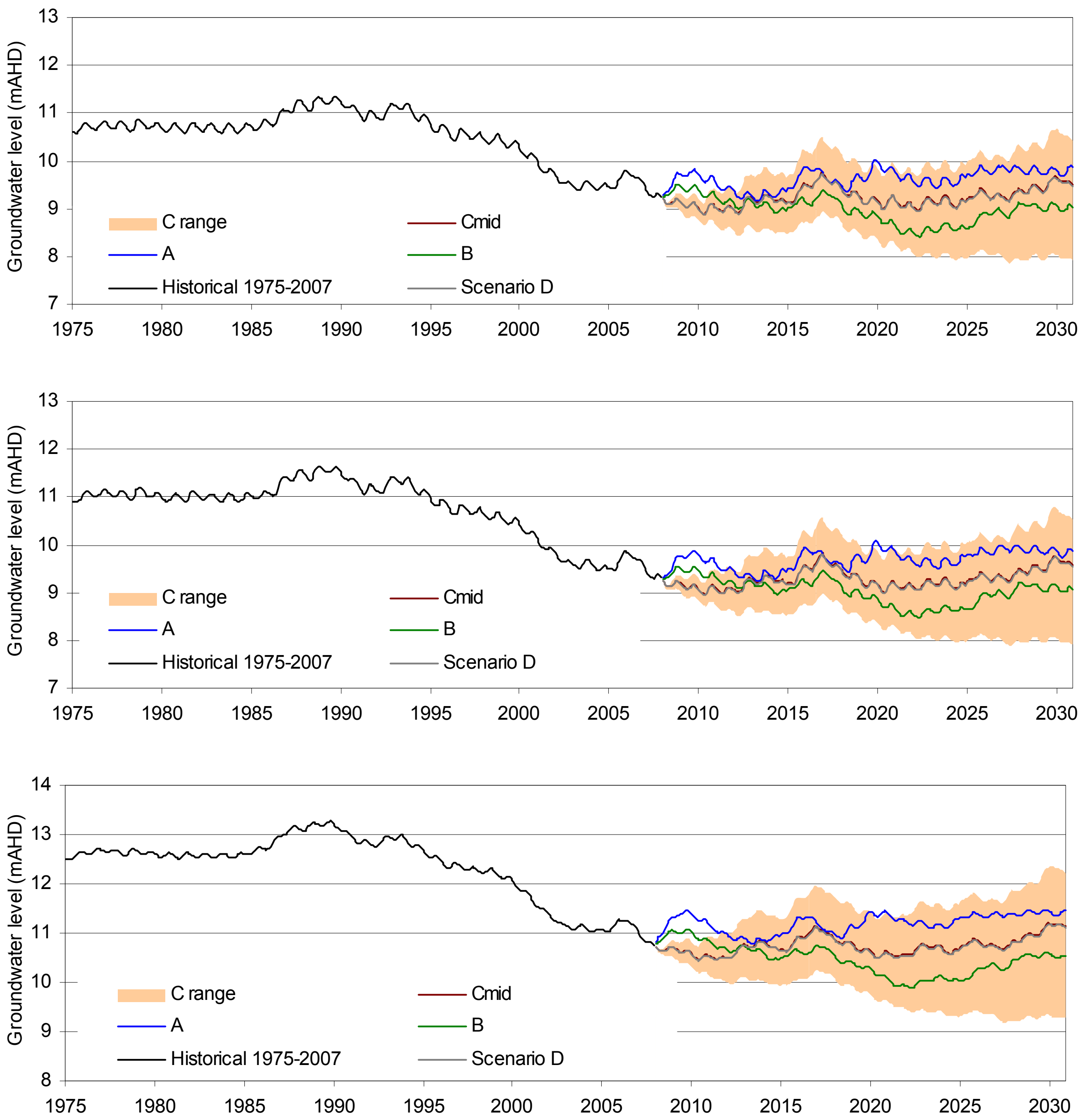
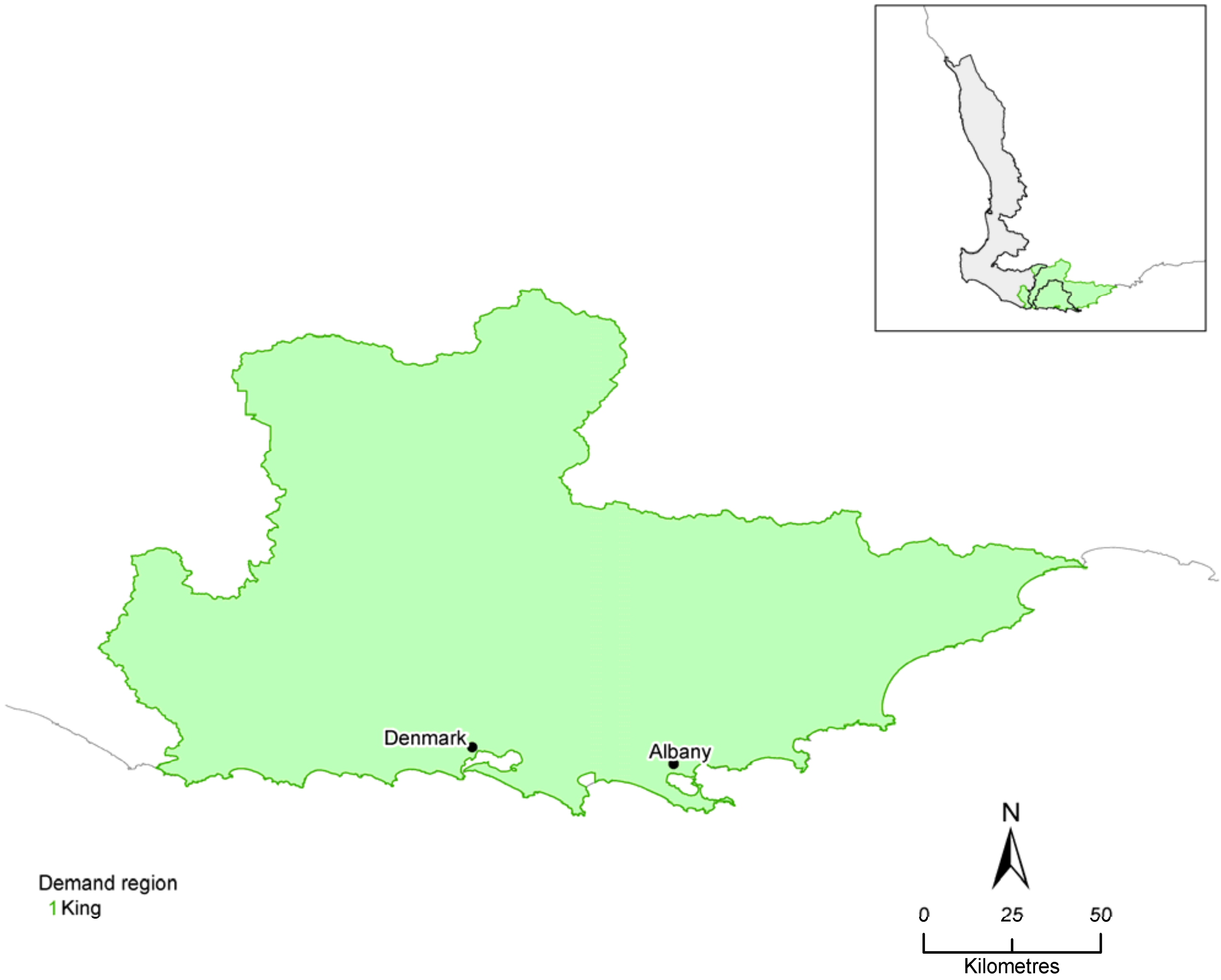


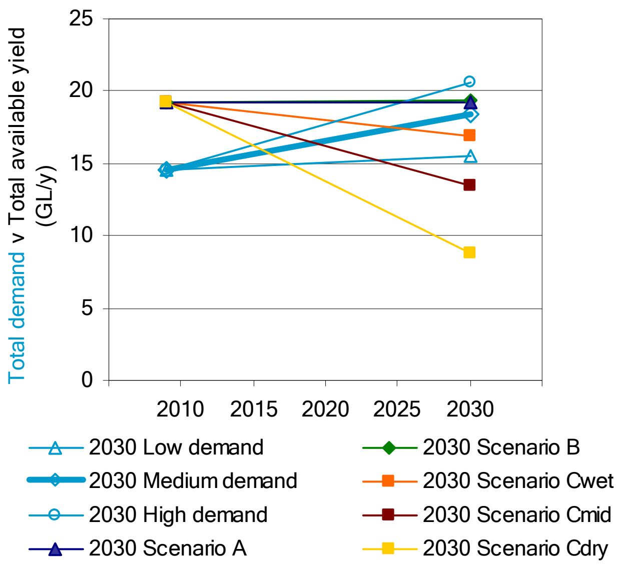
Figure D-14. Observed and modelled groundwater levels typical for Cauliflower Cave, Crystal Cave and Road Cave

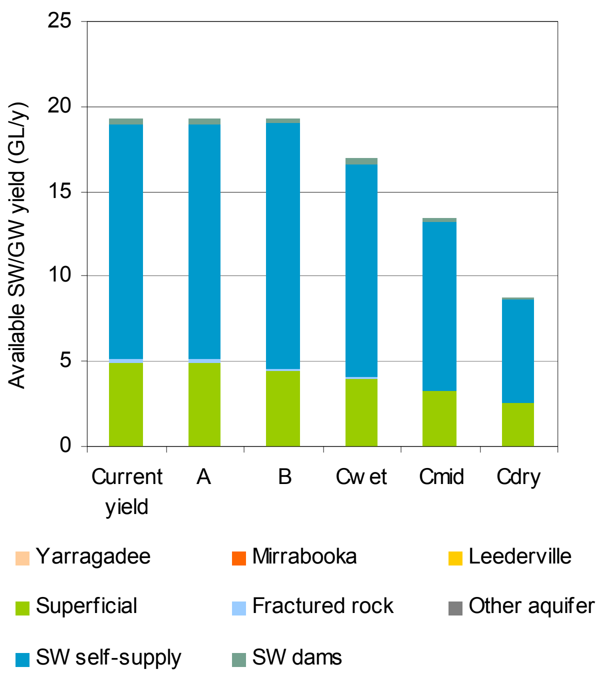
Appendix E Water yields and demands for demand regions and water management areas

This appendix provides information additional to Chapter 7 on water yields and demands for the eight demand regions and 45 water management areas (for both groundwater and surface water) in the South-West Western Australia Sustainable Yields Project area.

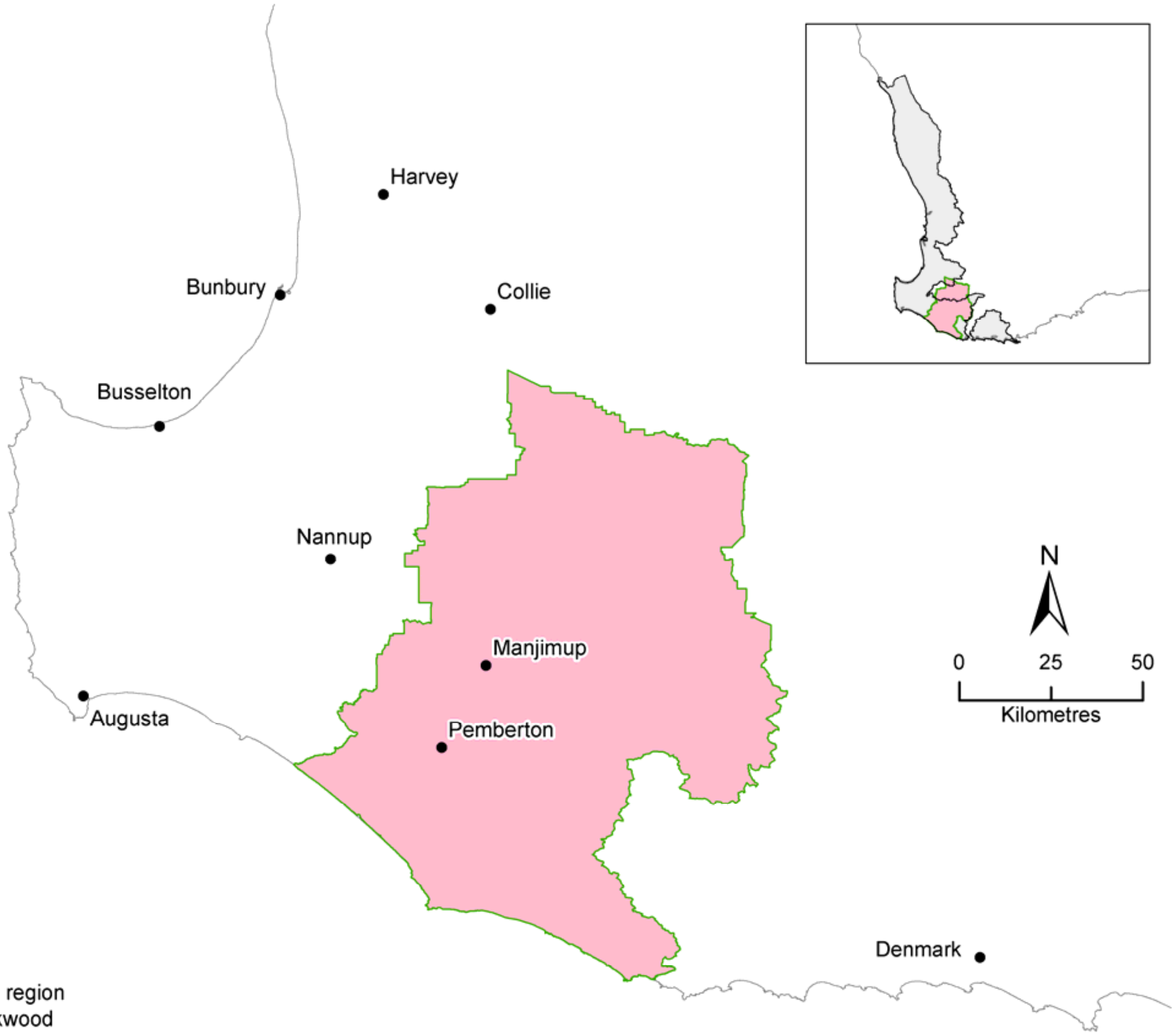
Water yields and demands in the King Demand Region

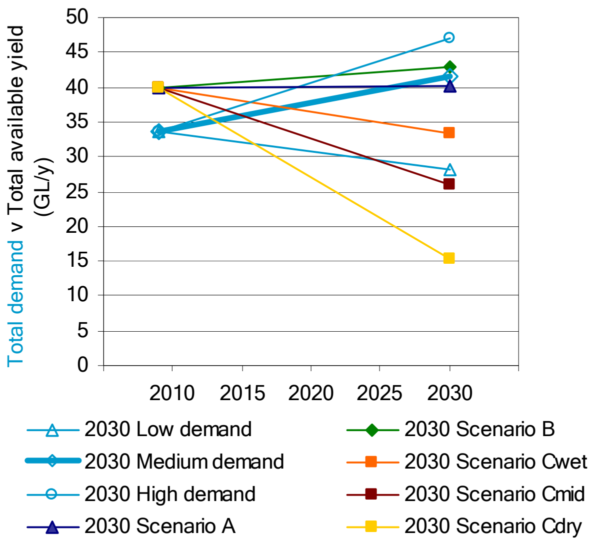


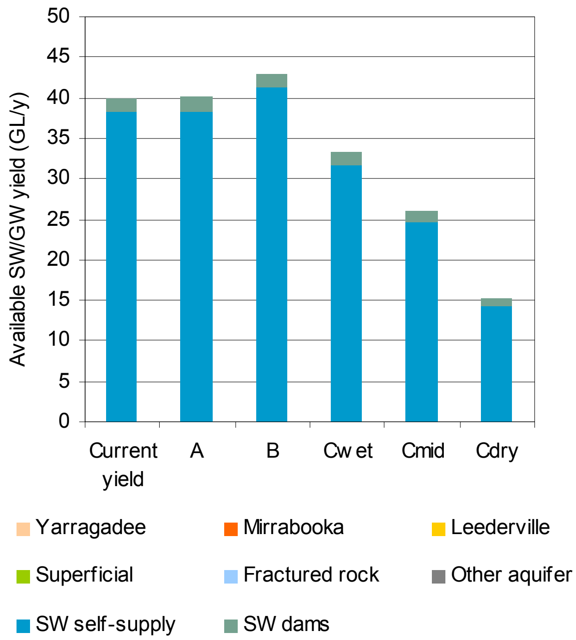




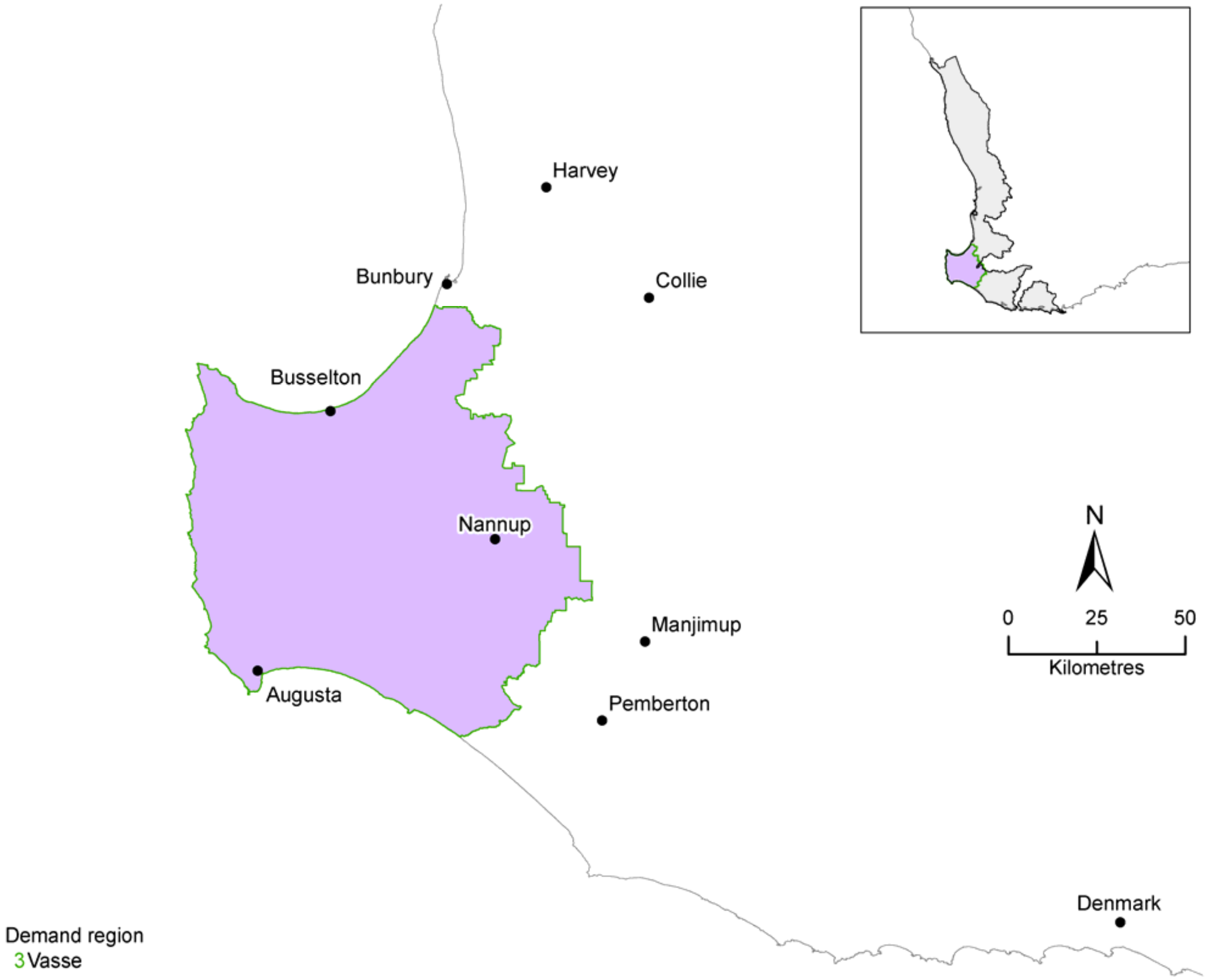
Water yields and demands in the Blackwood Demand Region

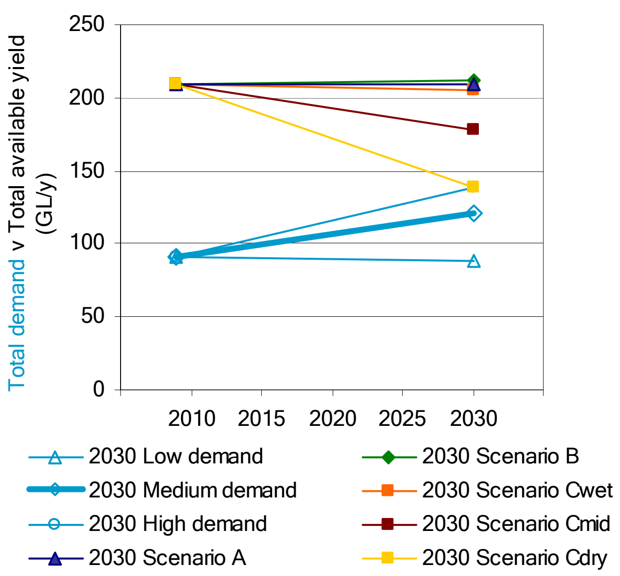


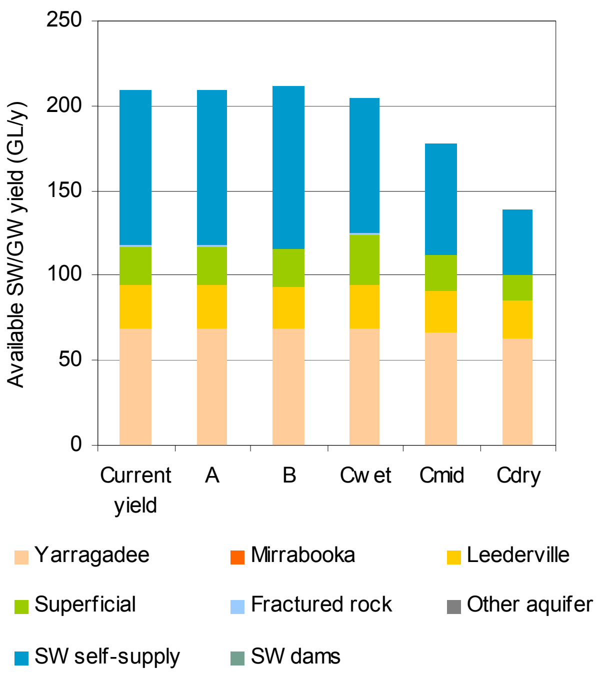




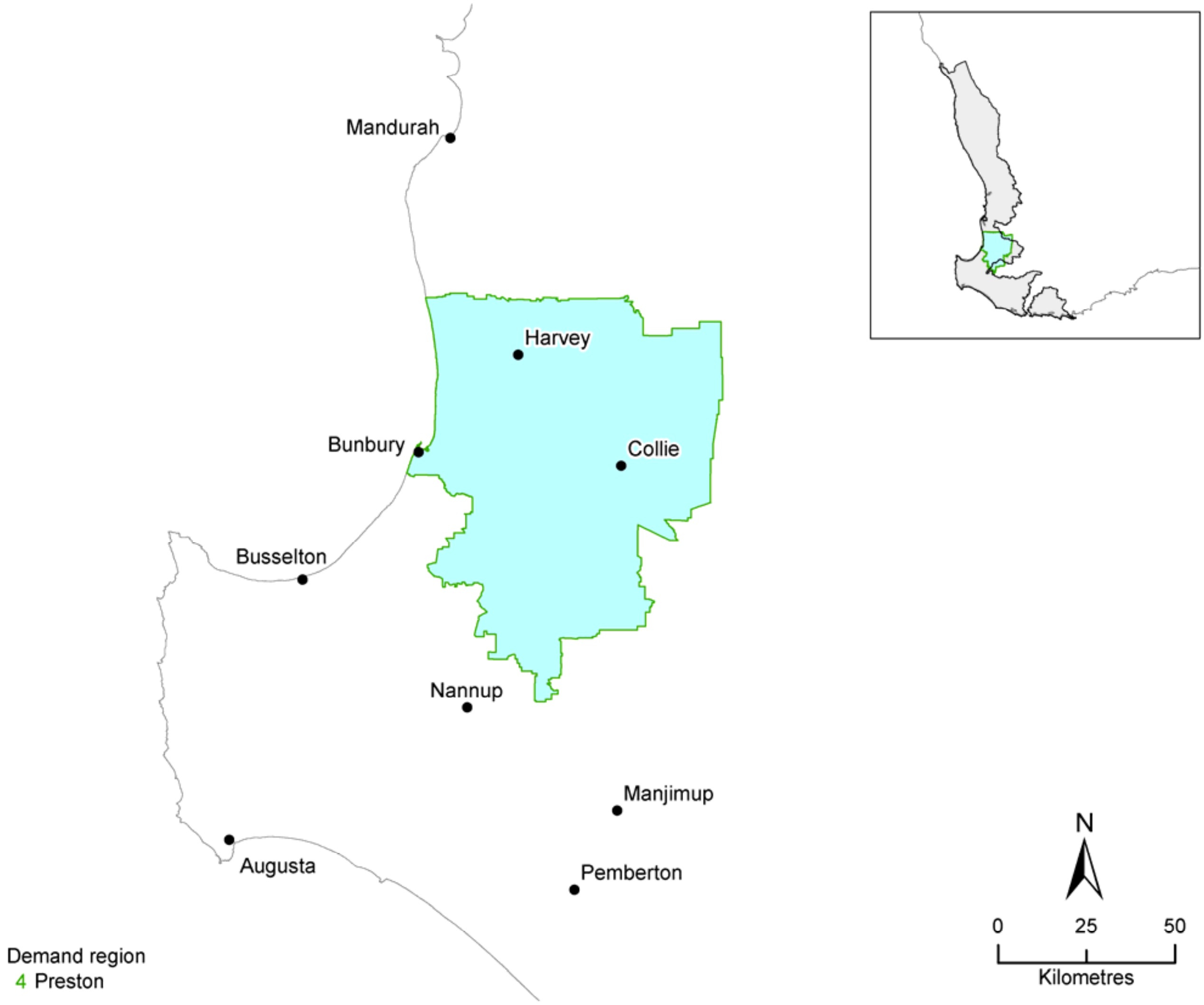
Water yields and demands in the Vasse Demand Region

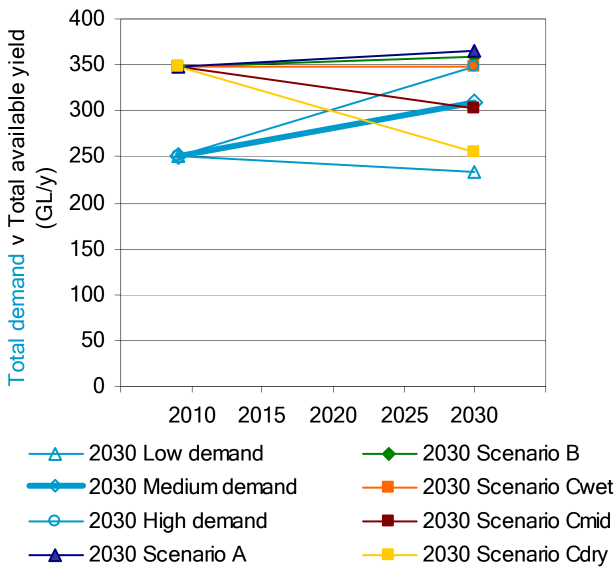


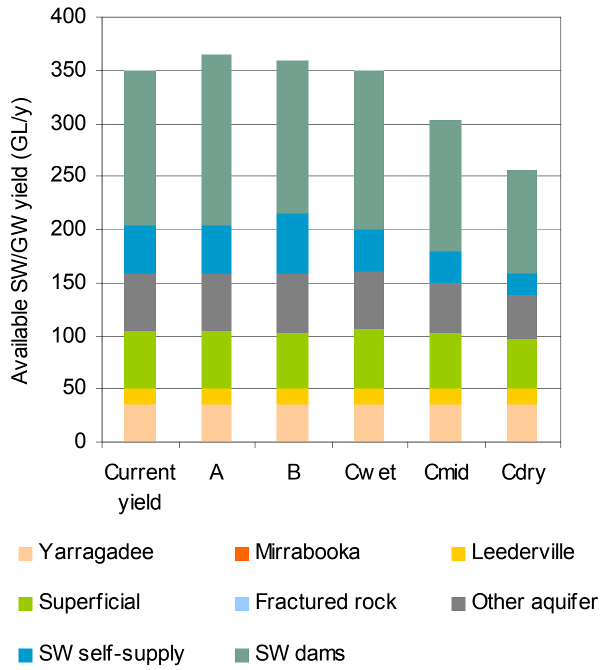




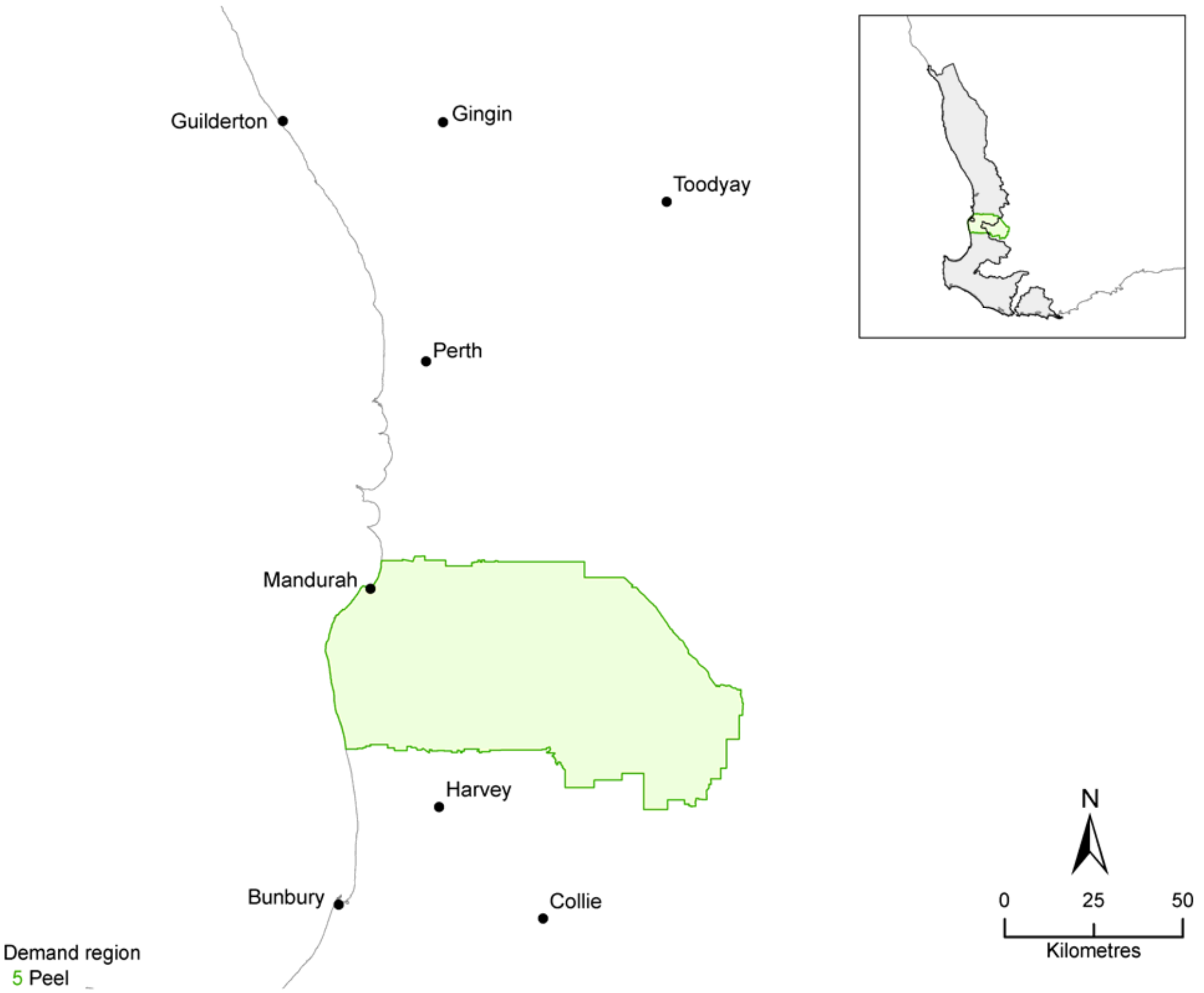
Water yields and demands in the Preston Demand Region

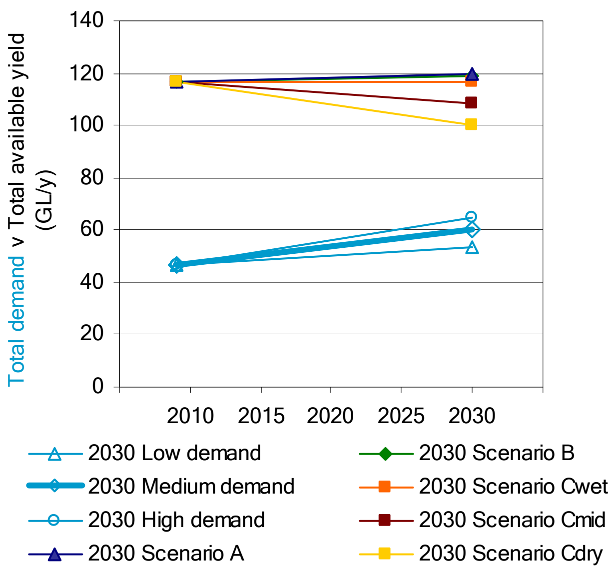


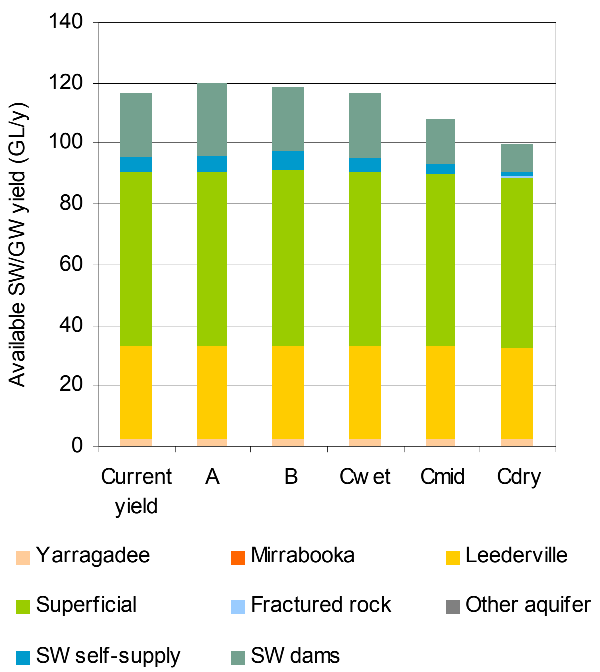




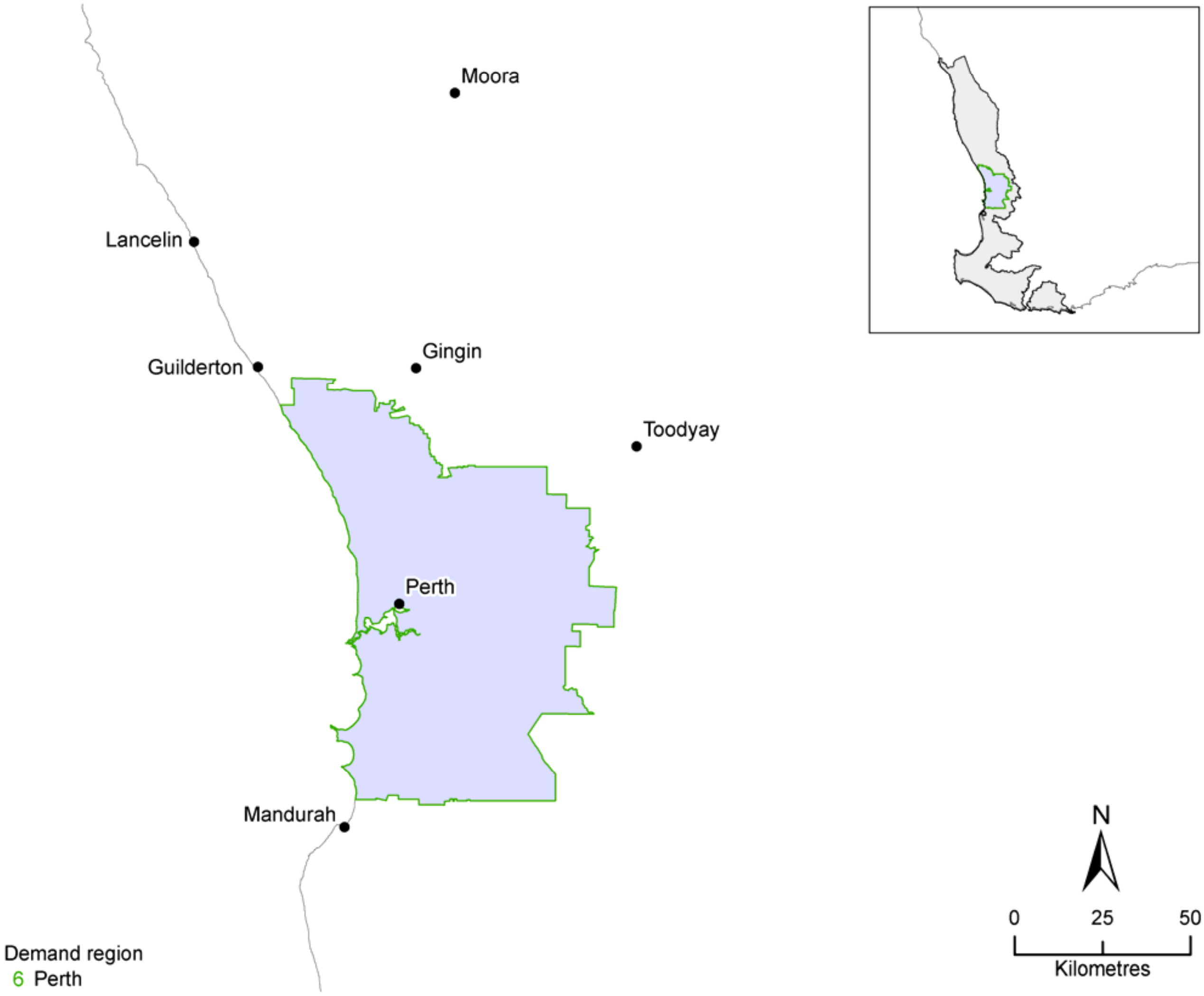
Water yields and demands in the Peel Demand Region

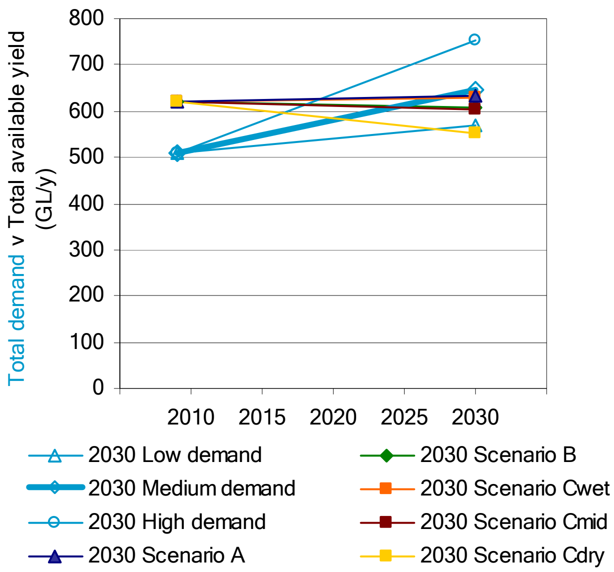


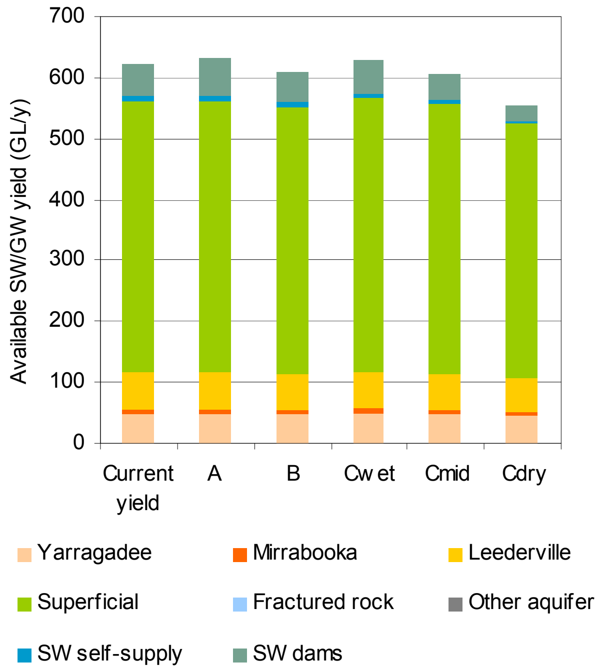




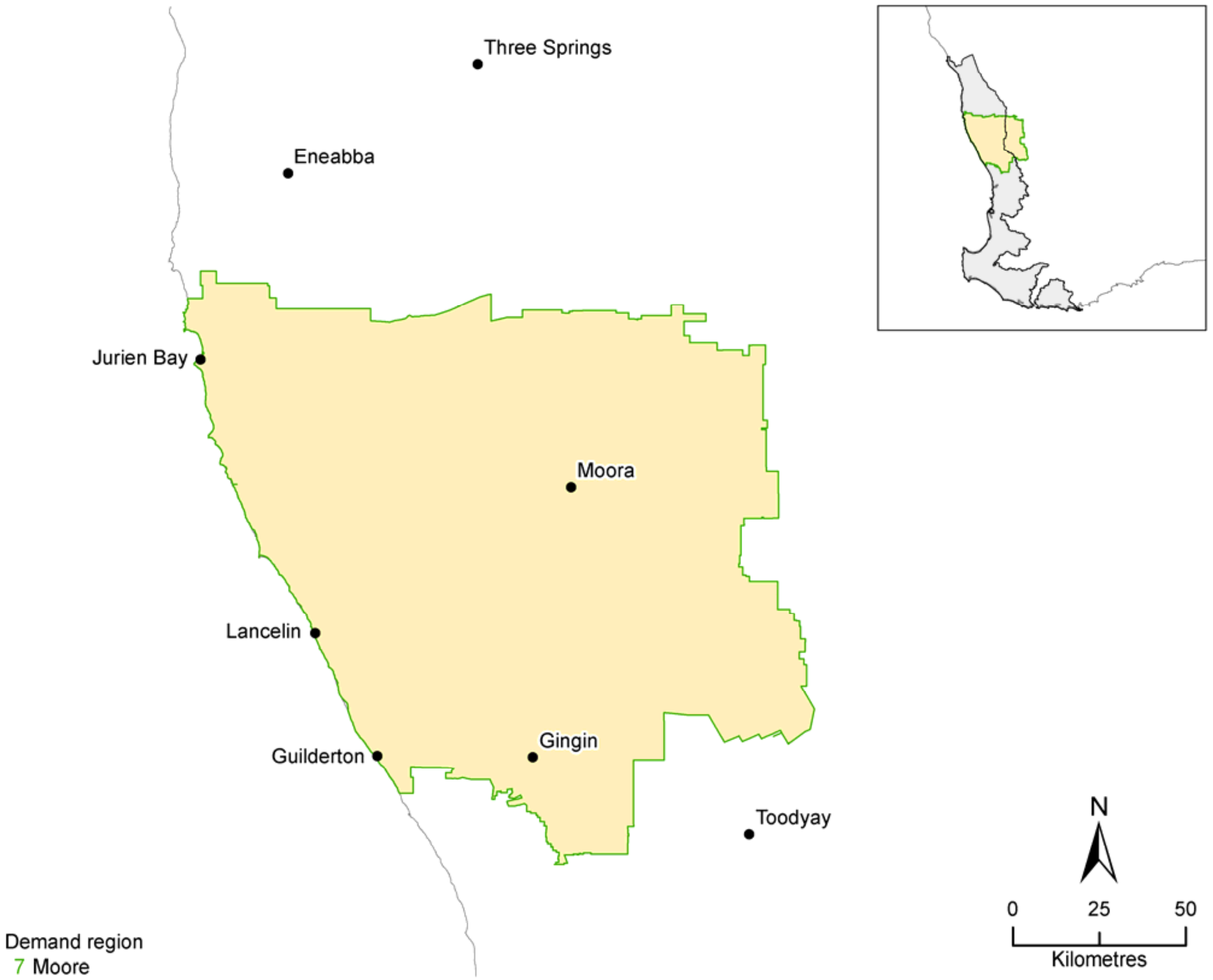
Water yields and demands in the Perth Demand Region

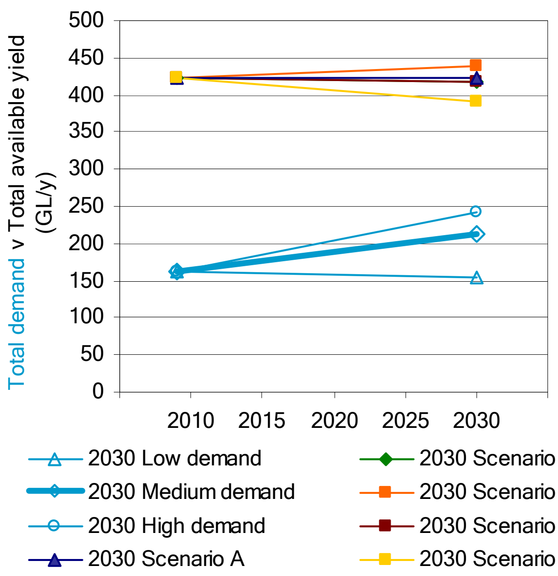


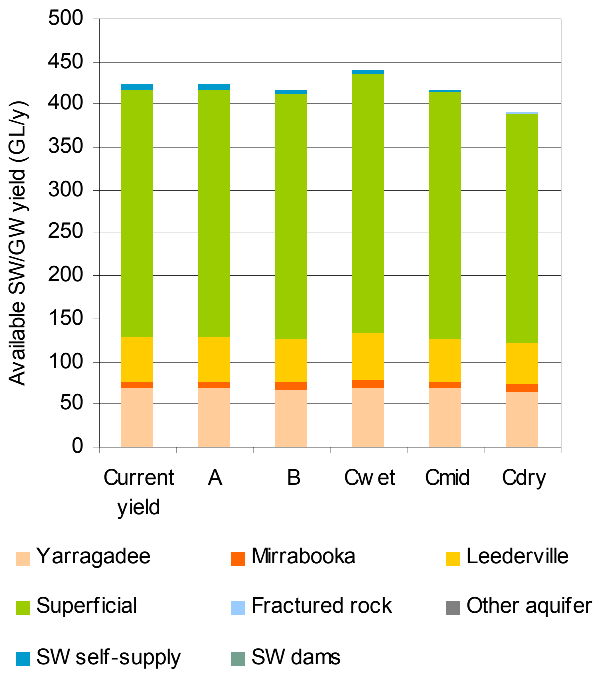




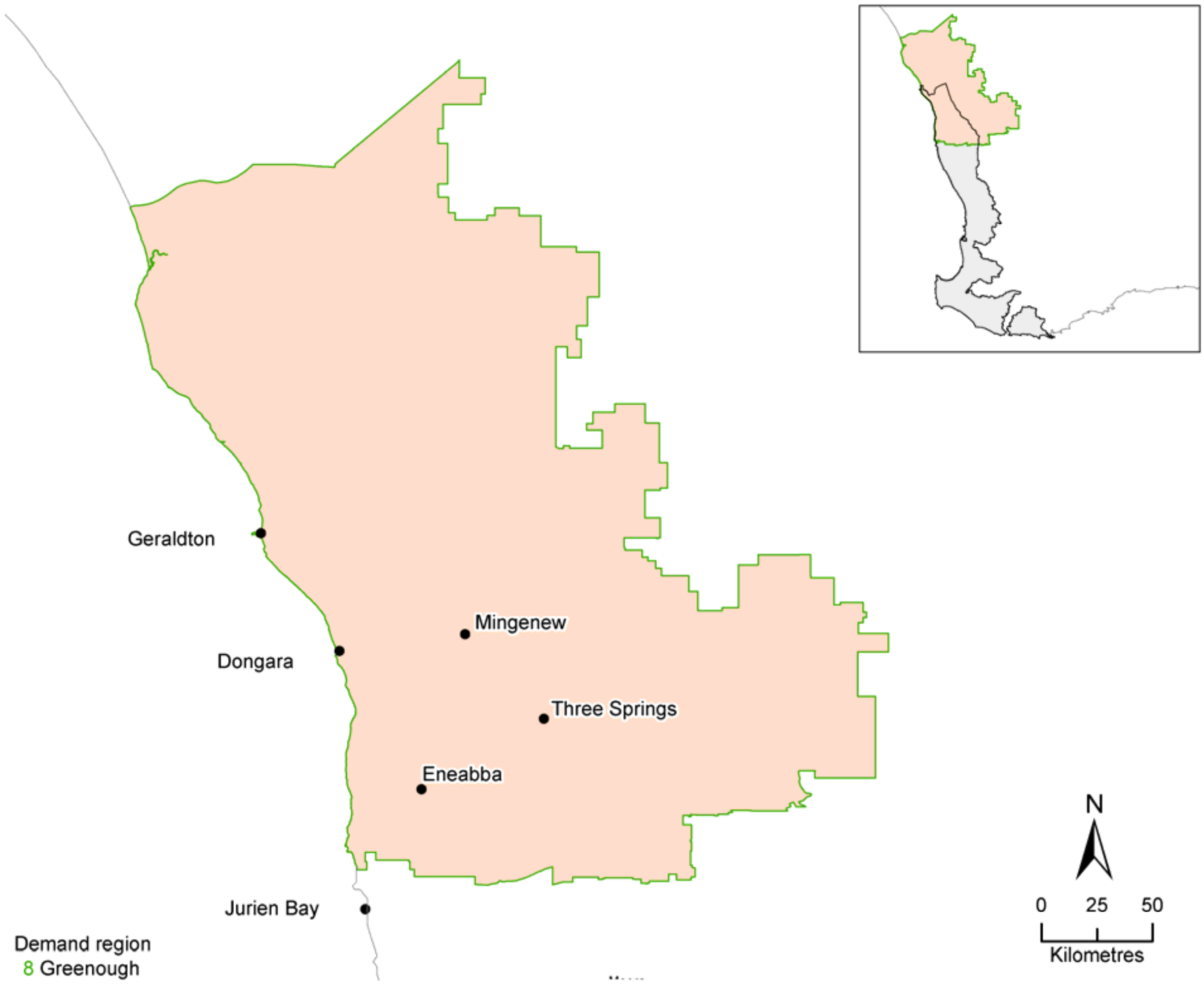
Water yields and demands in the Moore Demand Region

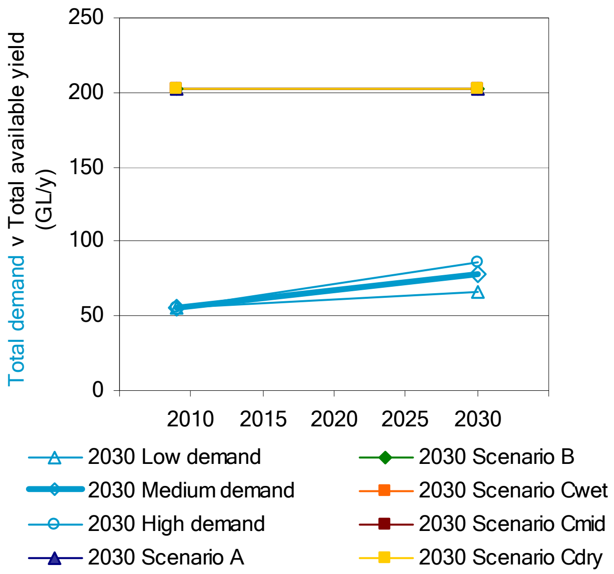


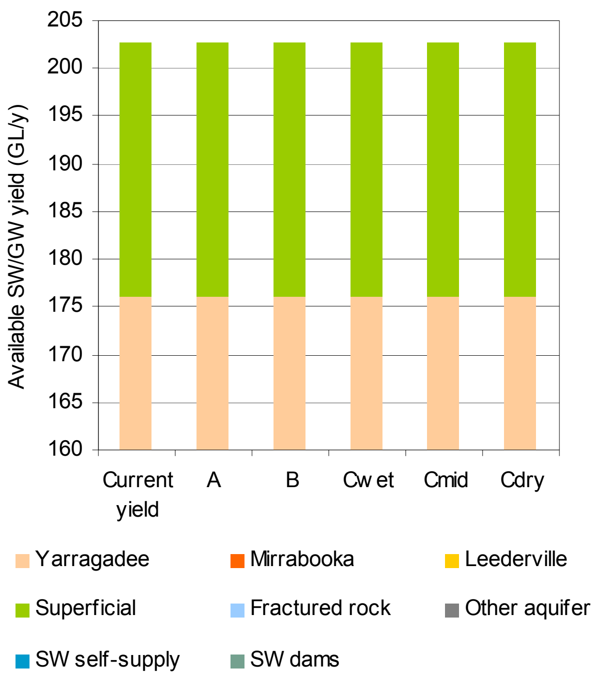




Water yields and demands in the Greenough Demand Region





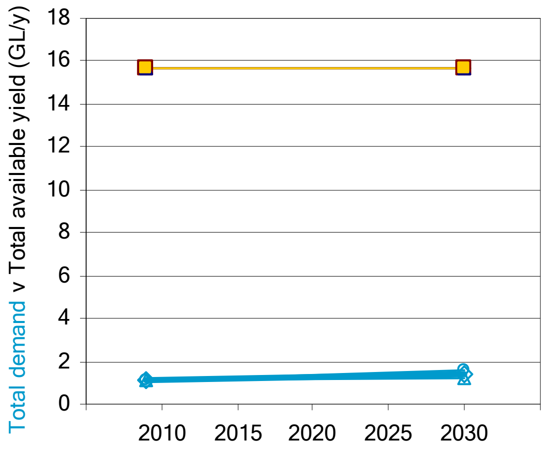


Water yields and demands in the Casuarina, Arrowsmith and Jurien groundwater management areas

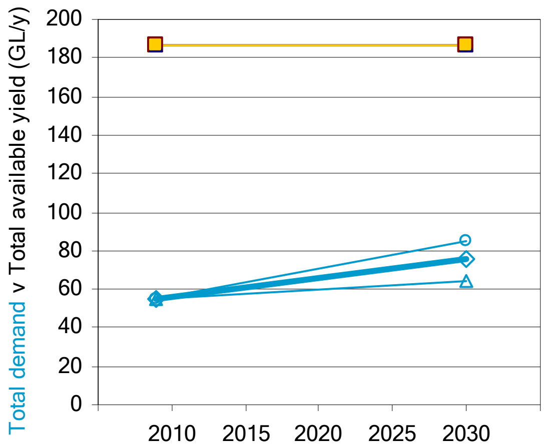
Gap analysis

Yield analysis

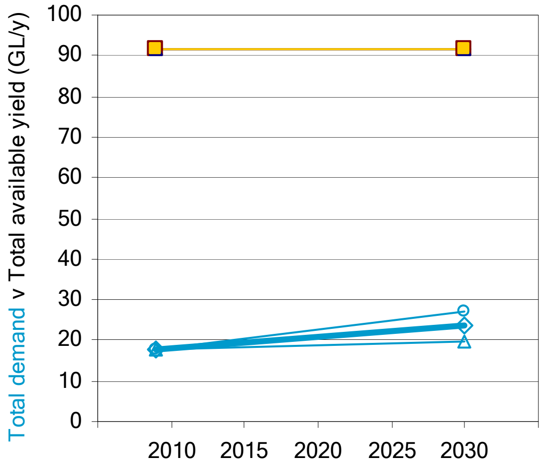
G1 Casuarina

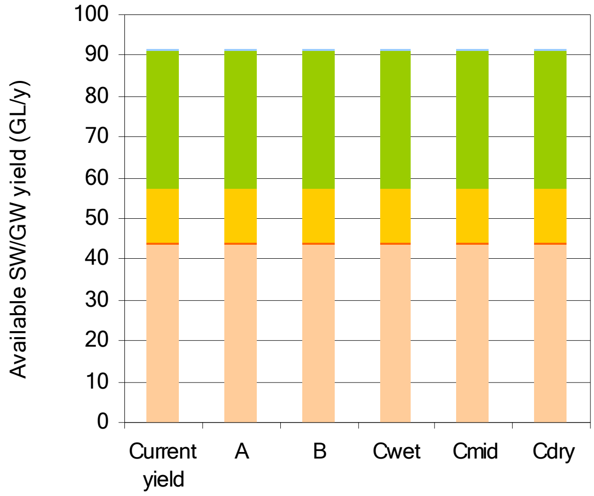


G2 Arrowsmith



G3 Jurien





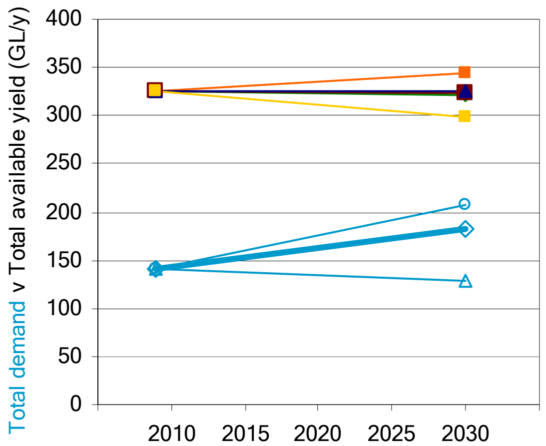
2030 Low demand
2030 Medium demand
2030 High demand
2030 Scenario A
2030 Scenario B
2030 Scenario Cwet
2030 Scenario Cmid
2030 Scenario Cdry

Yarragadee
Mirrabooka
Leederville
Superficial
Fractured rock
Other aquifer
SW self-supply
SW dams

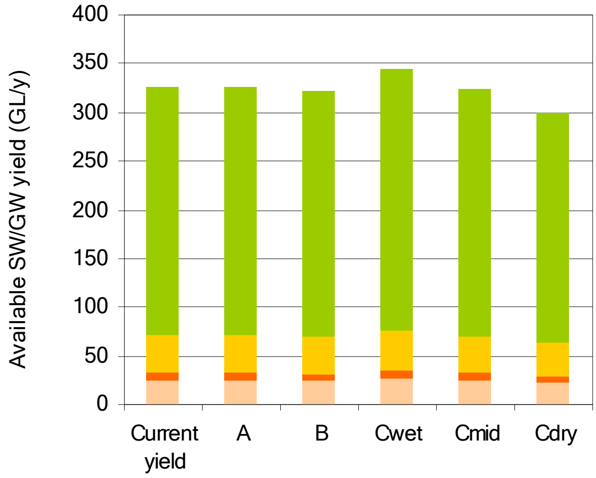
Water yields and demands in the Gingin, Gnangara and Yanchep groundwater management areas

Gap analysis

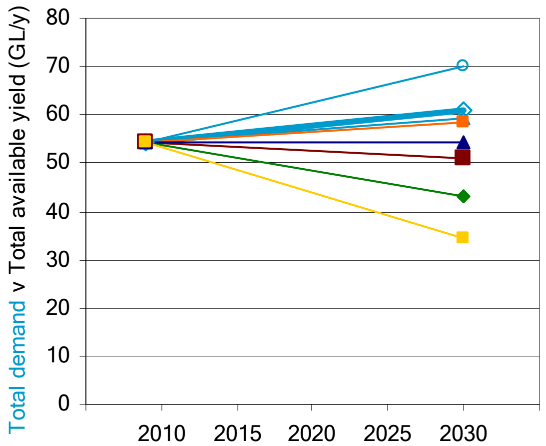
G4 Gingin



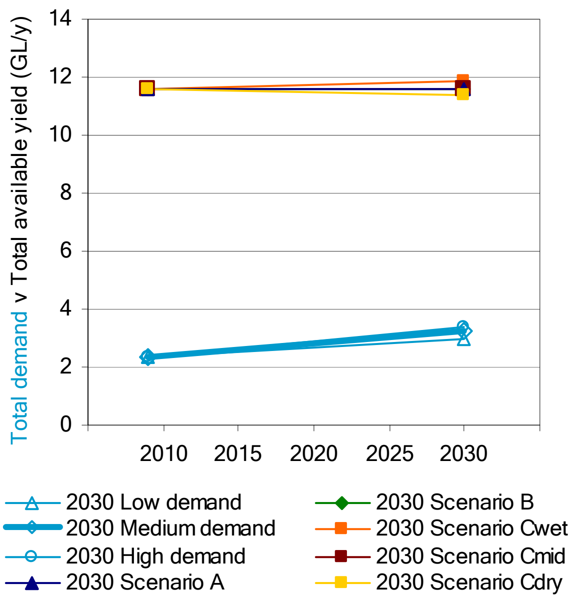
Yield analysis

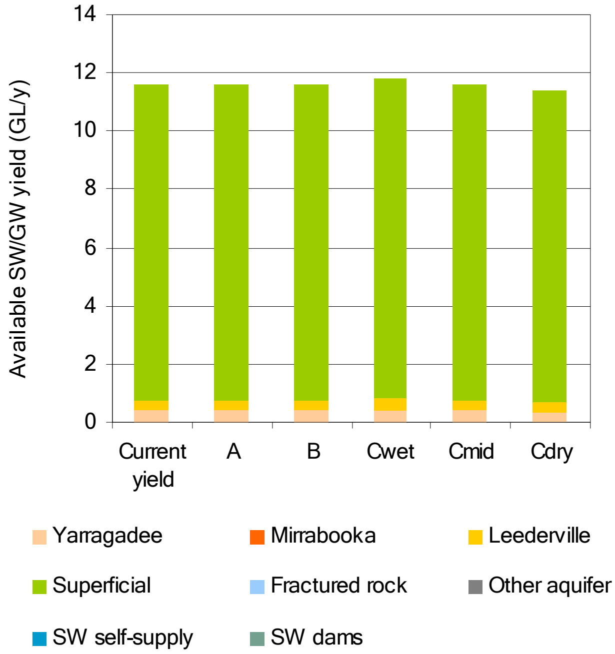


G5 Gnangara



G6 Yanchep

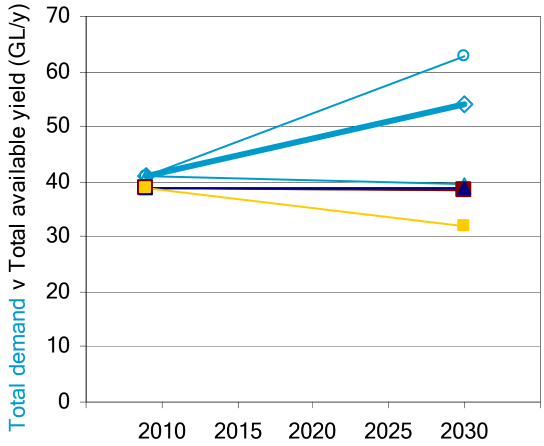




Water yields and demands in the Wanneroo, Swan and Mirrabooka groundwater management areas

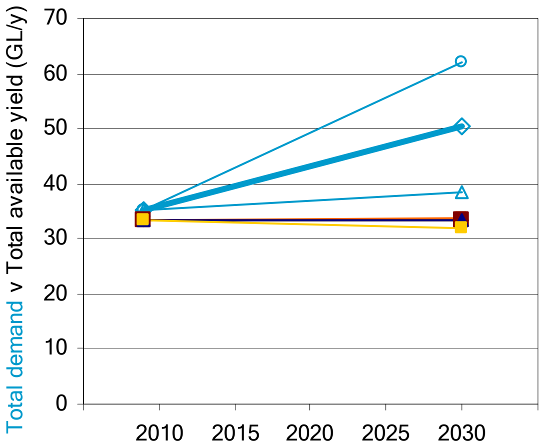
Gap analysis

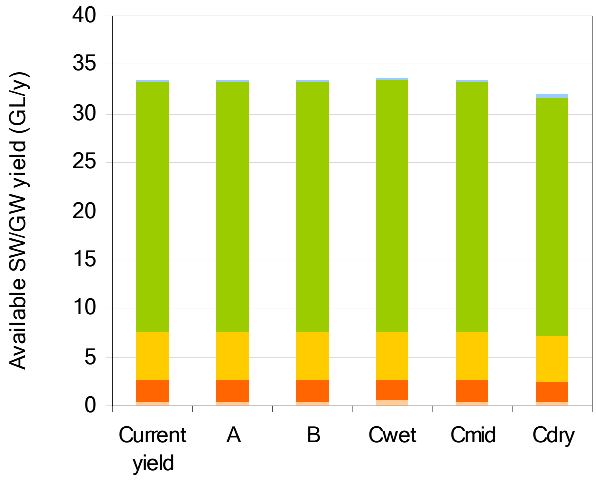
G7 Wanneroo



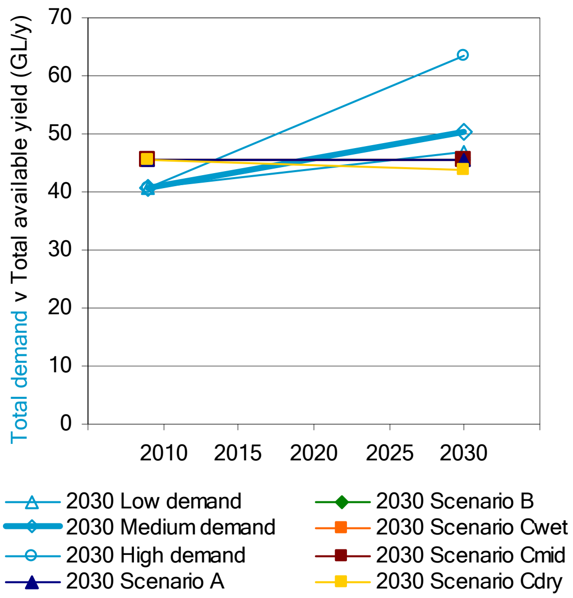
Yield analysis

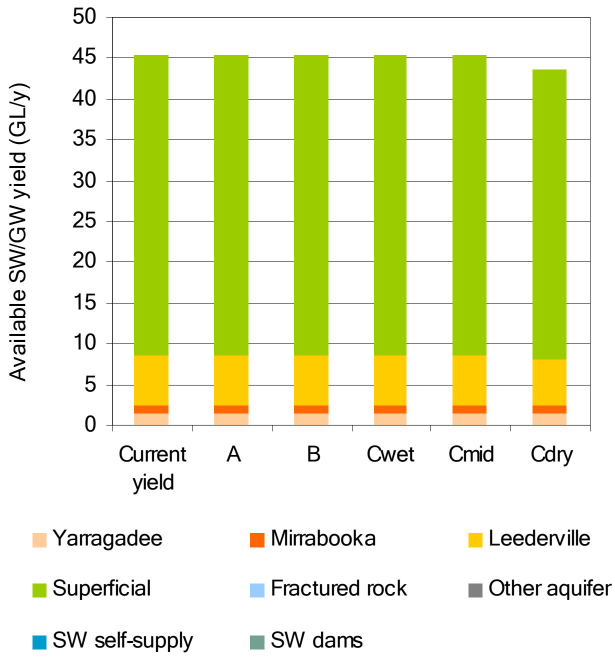
G8 Swan





G9 Mirrabooka

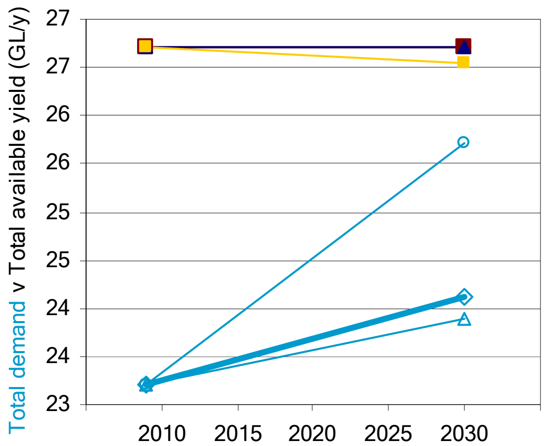




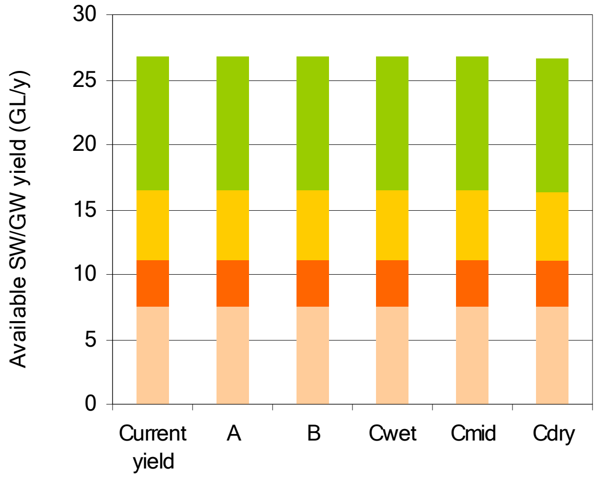
Water yields and demands in the Gwelup, Perth and Jandakot groundwater management areas

Gap analysis

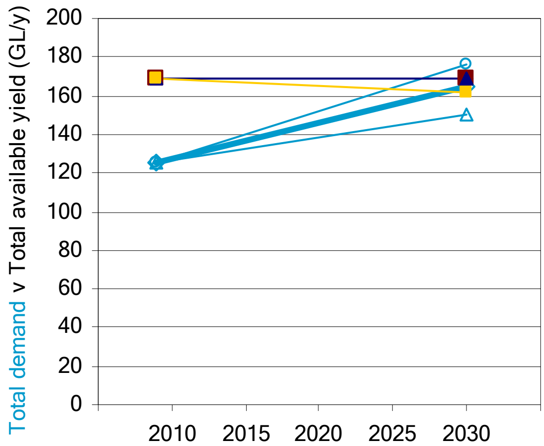
GW10 Gwelup

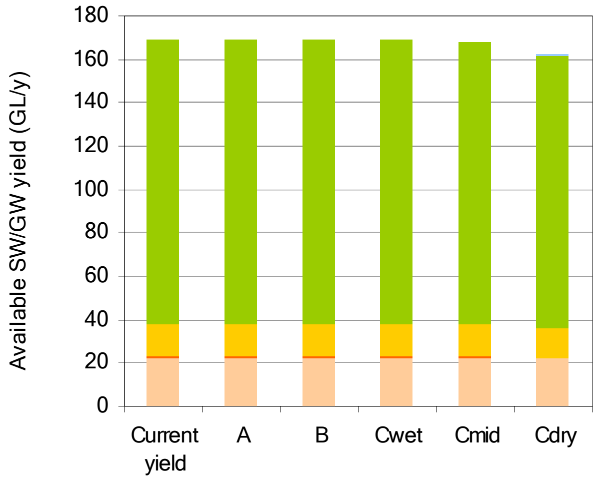


Yield analysis

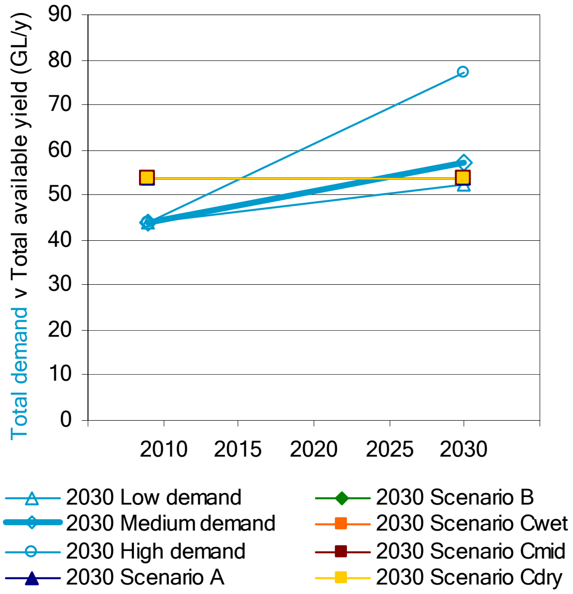


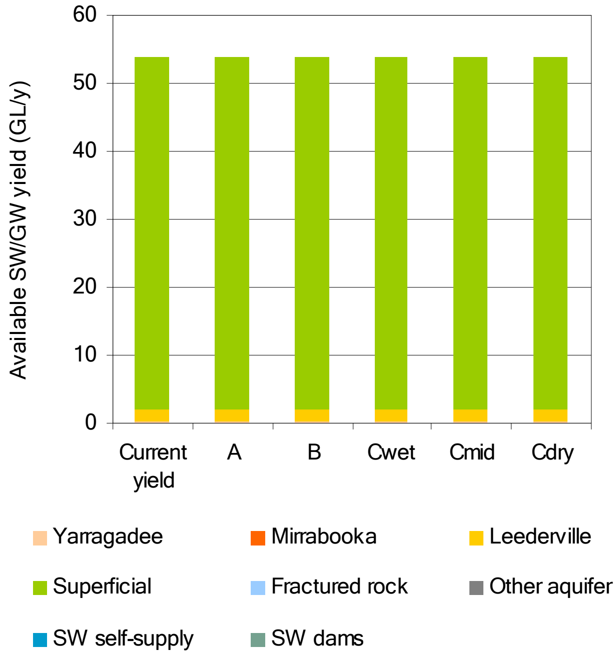
G11 Perth





G12 Jandakot



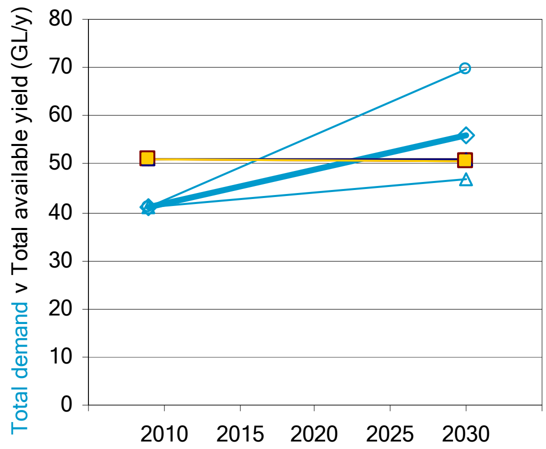


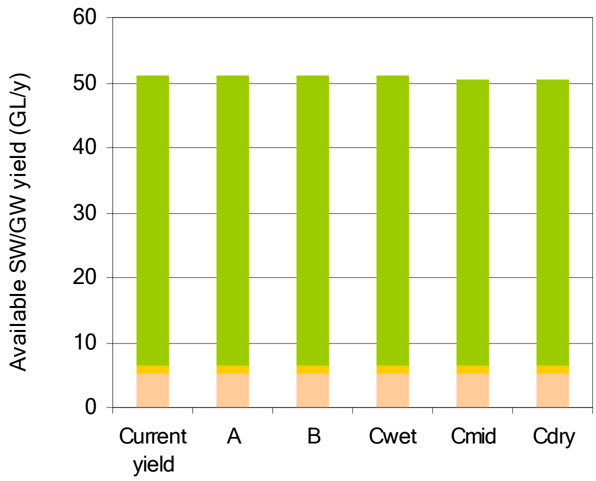
Water yields and demands in the Cockburn, Serpentine and Rockingham groundwater management areas

Gap analysis

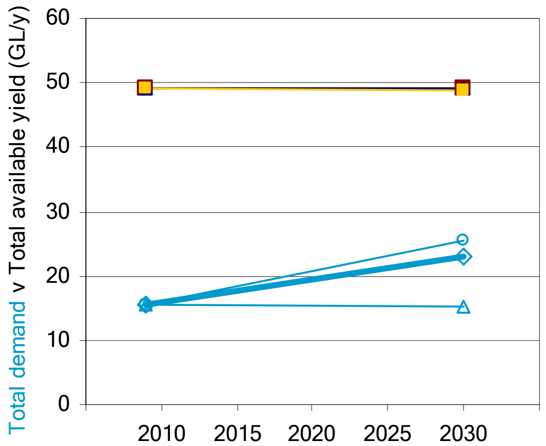
Yield analysis

G13 Cockburn

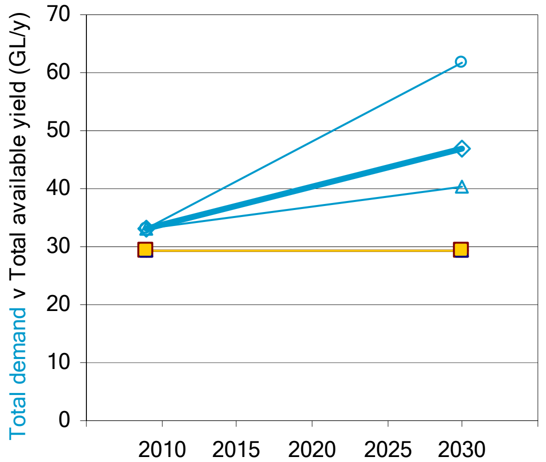


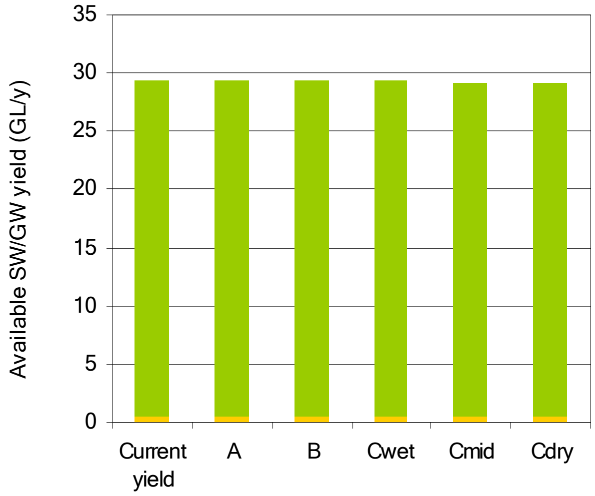


G14 Serpentine



G15 Rockingham





2030 Low demand
2030 Medium demand
2030 High demand
2030 Scenario A
2030 Scenario B
2030 Scenario Cwet
2030 Scenario Cmid
2030 Scenario Cdry

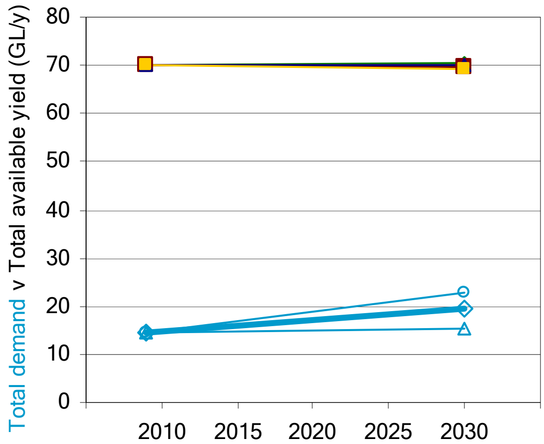
Yarragadee
Mirrabooka
Leederville
Superficial
Fractured rock
Other aquifer
SW self-supply
SW dams

Water yields and demands in the Murray, South West Coastal (Preston) and South West Coastal (Peel) groundwater management areas

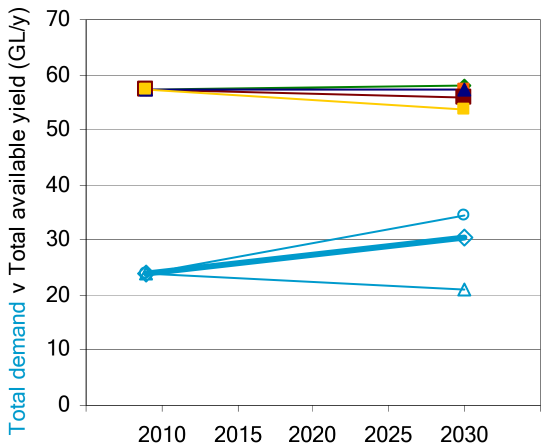
Gap analysis

Yield analysis

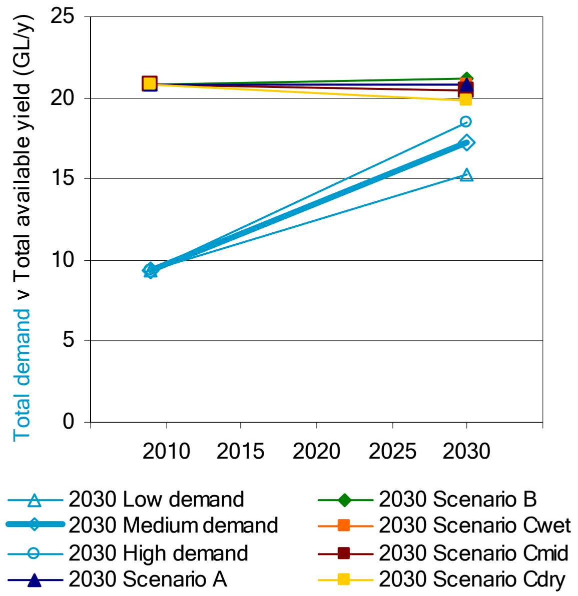
G16 Murray

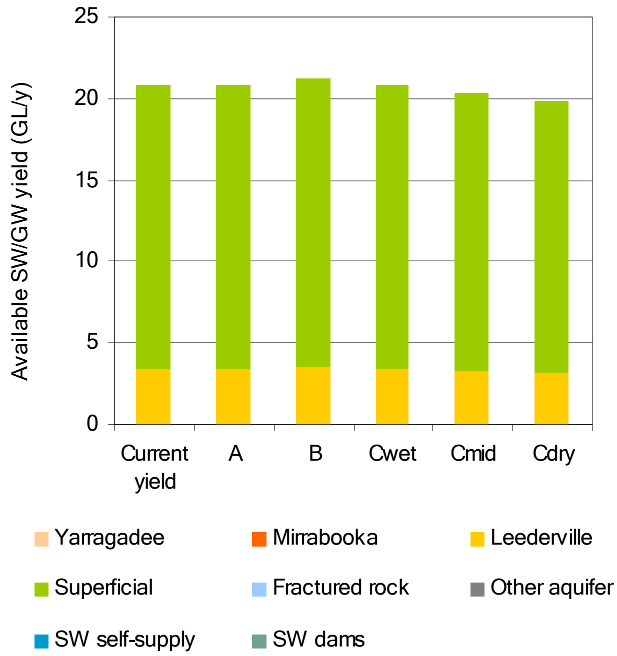


G17a South West Coastal (Preston)



G17b South West Coastal (Peel)



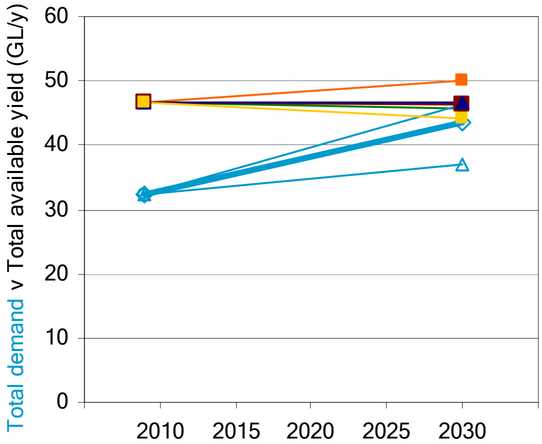


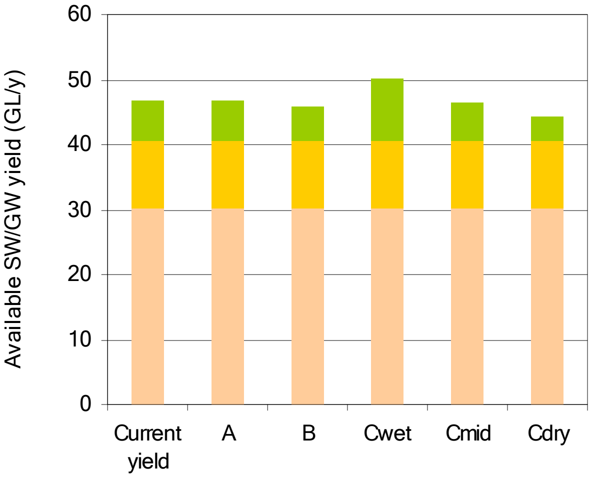
Water yields and demands in the Bunbury, Busselton-Capel and Blackwood groundwater management areas

Gap analysis

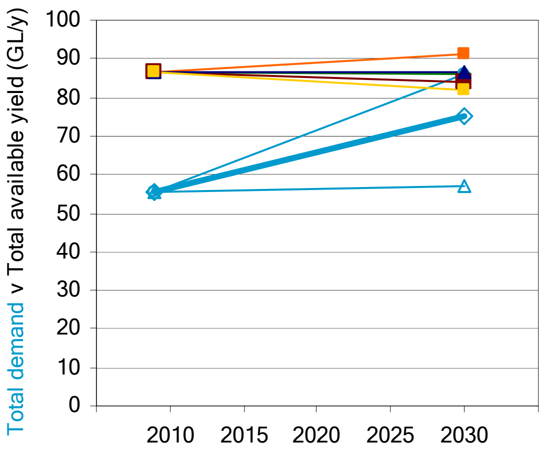
Yield analysis

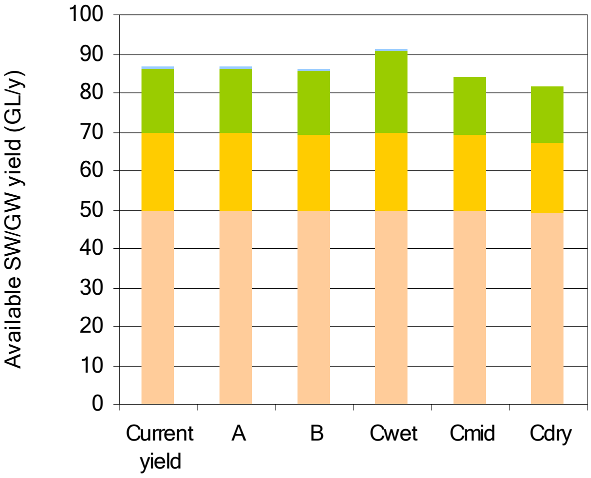
G19 Bunbury



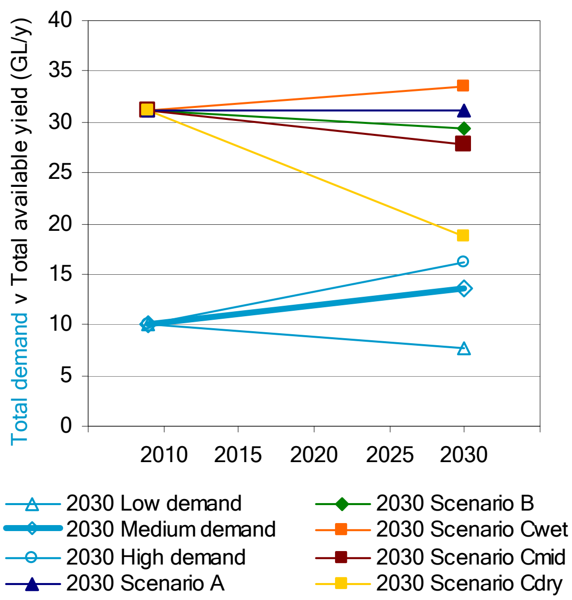


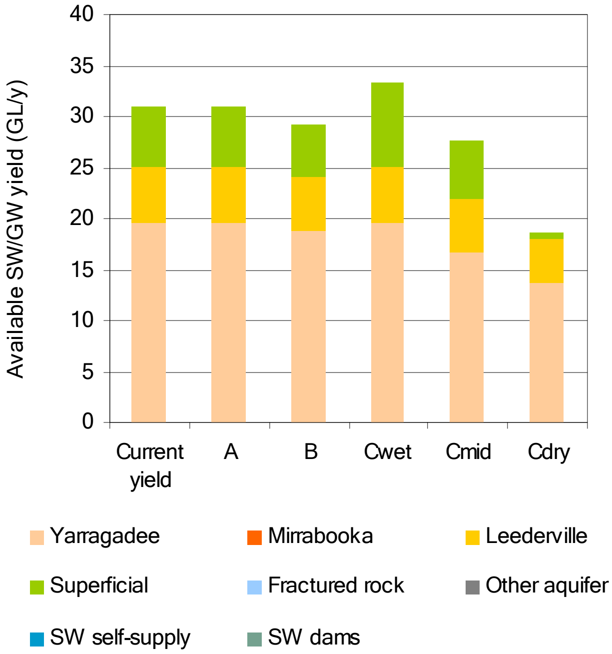
G20 Bussleton-Capel





G21 Blackwood

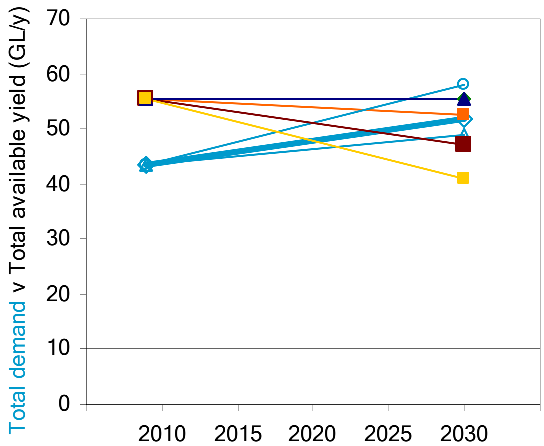




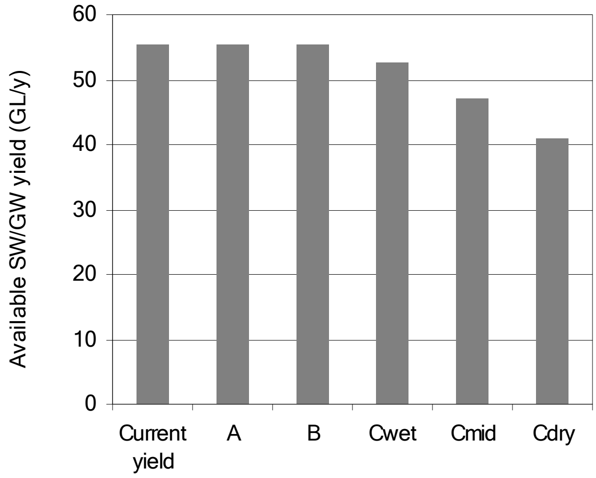
Water yields and demands in the Collie and Albany groundwater management areas

Gap analysis

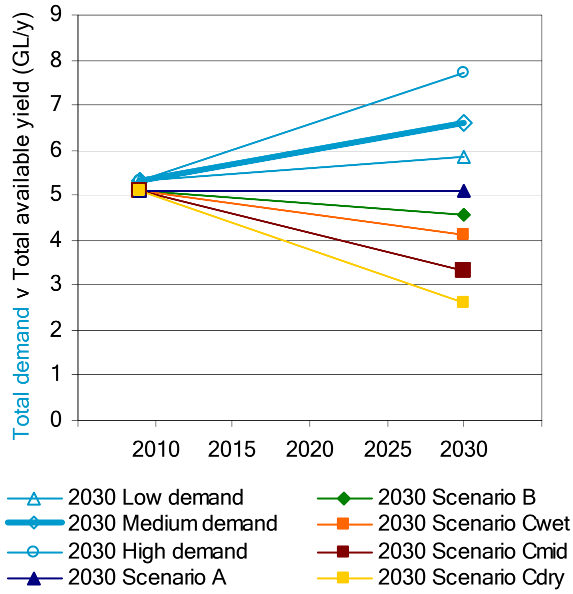
G22 Collie

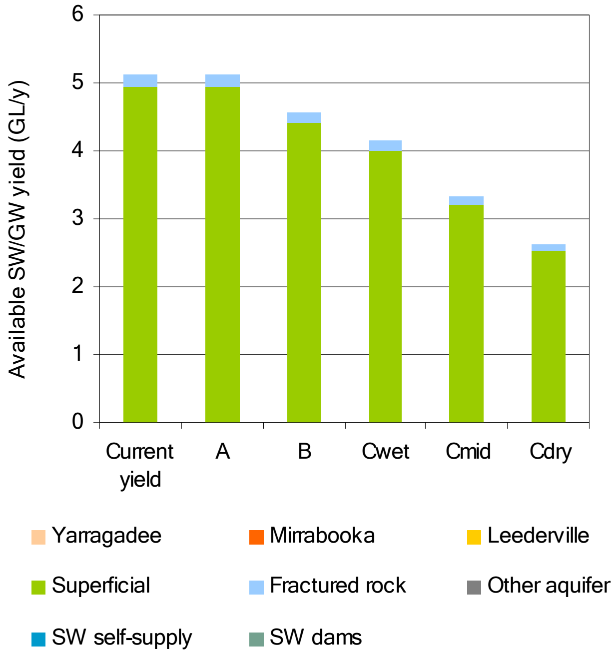


Yield analysis



G24 Albany

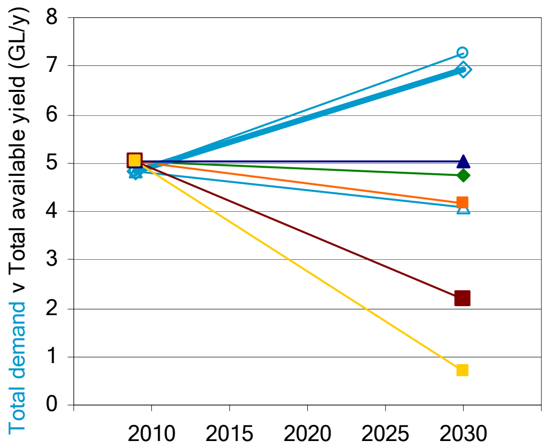




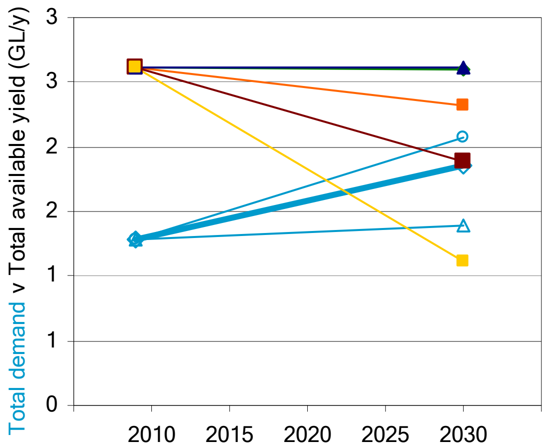
Water yields and demands in the Gingin Brook and tributaries, Swan River and tributaries, and Helena surface water management areas

Gap analysis

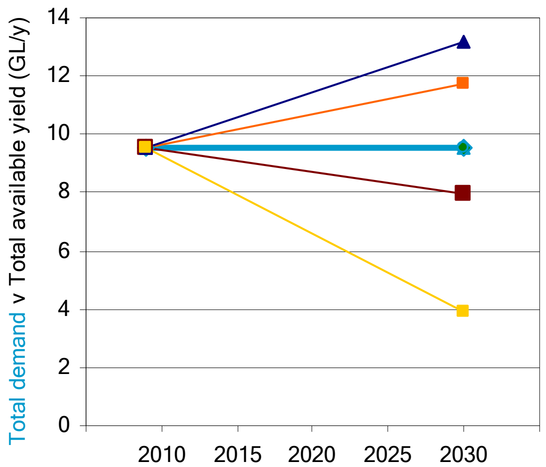
SW1 Gingin Brook and tributaries



SW2a Swan River and tributaries

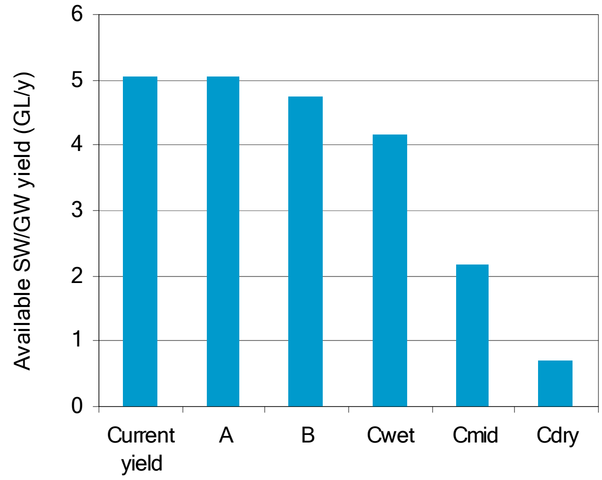


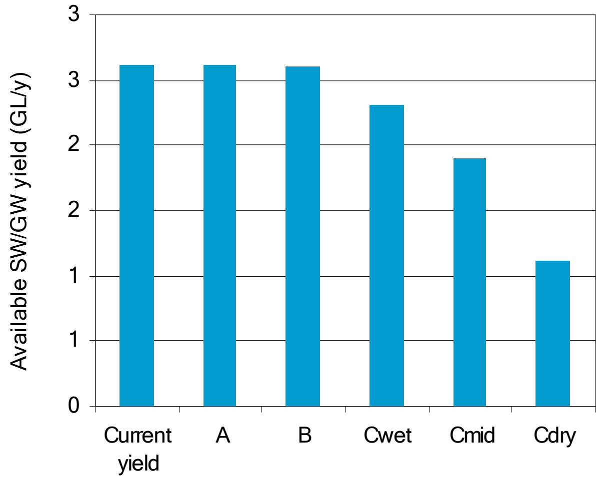
SW2b Helena

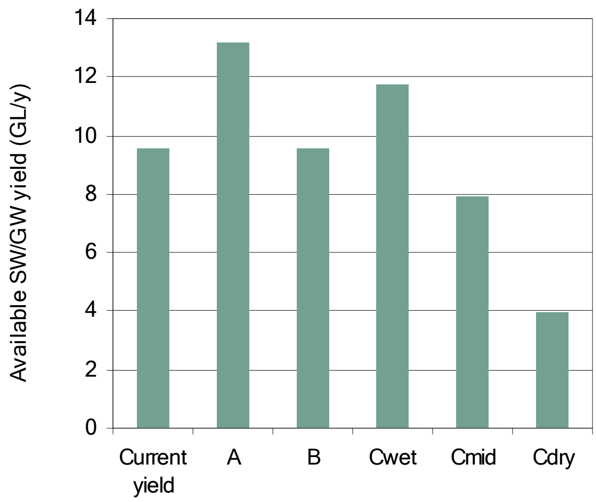


2030 Low demand
2030 Medium demand
2030 High demand
2030 Scenario A
2030 Scenario B
2030 Scenario Cwet
2030 Scenario Cmid
2030 Scenario Cdry

Yield analysis







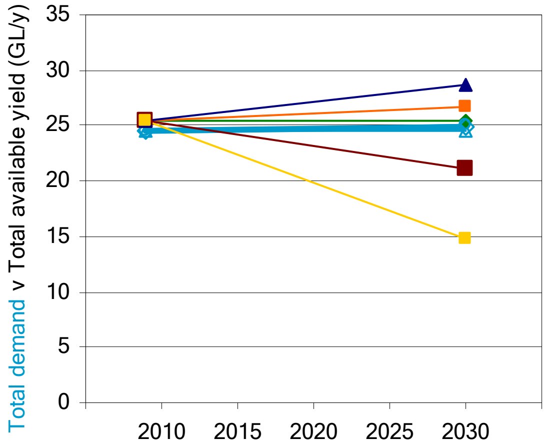
Yarragadee
Mirrabooka
Leederville
Superficial
Fractured rock
Other aquifer
SW self-supply
SW dams

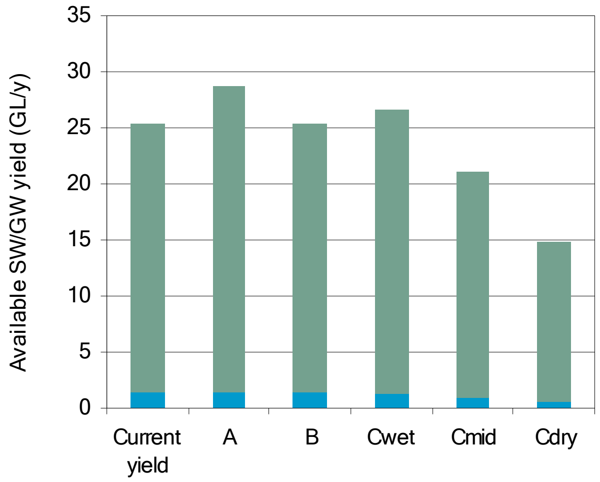
Water yields and demands in the Canning River, Cockburn-Kwinana Coastal and Serpentine River Catchment surface water management areas

Gap analysis

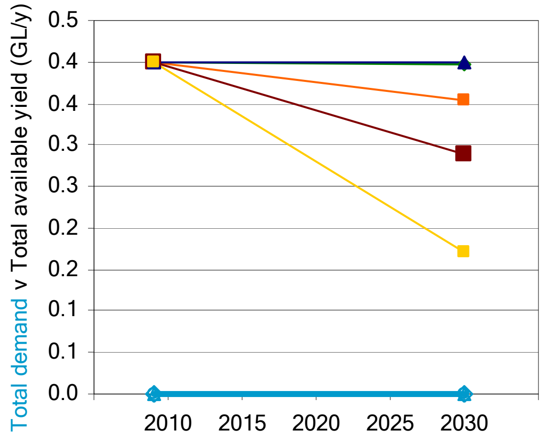
Yield analysis

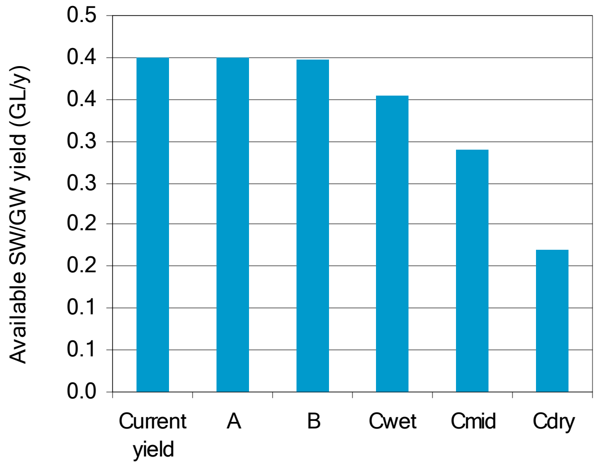
SW2c Canning River



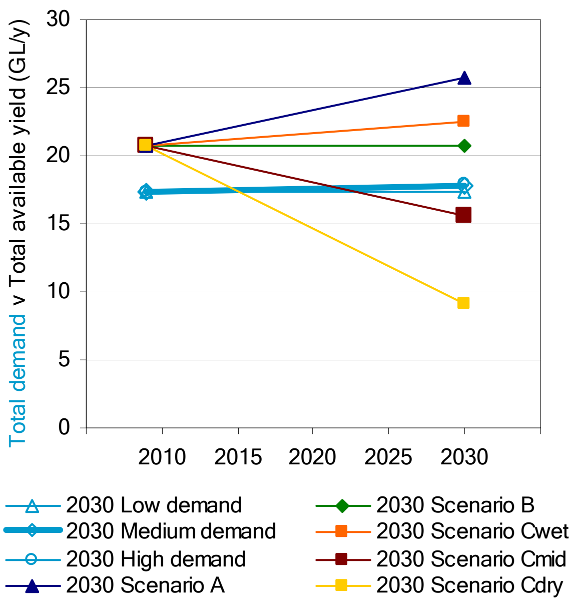


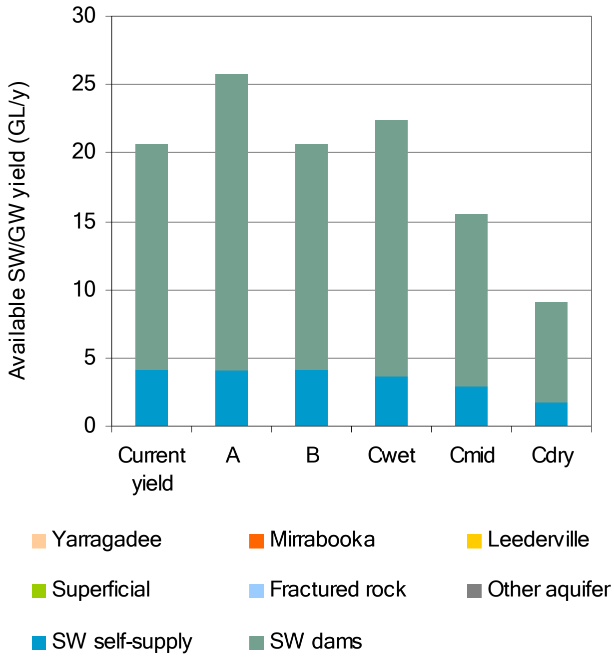
SW3a Cockburn-Kwinana Coastal





SW3b Serpentine River Catchment

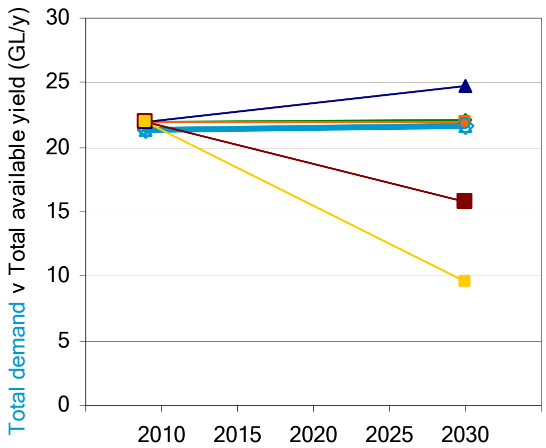




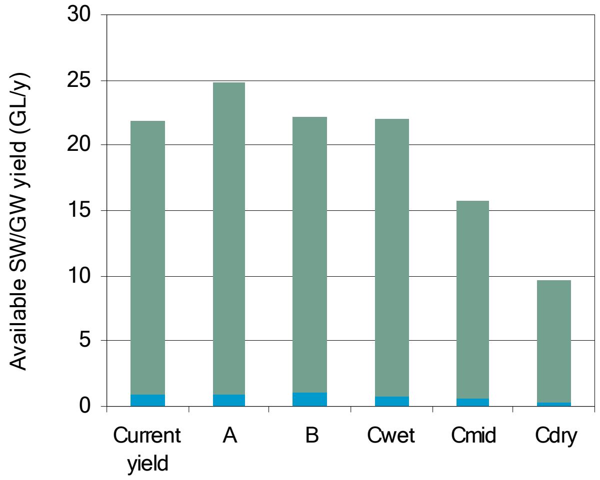
Water yields and demands in the Dardanup River System, Kwinana-Peel Coastal, and Murray River and tributaries surface water management areas

Gap analysis

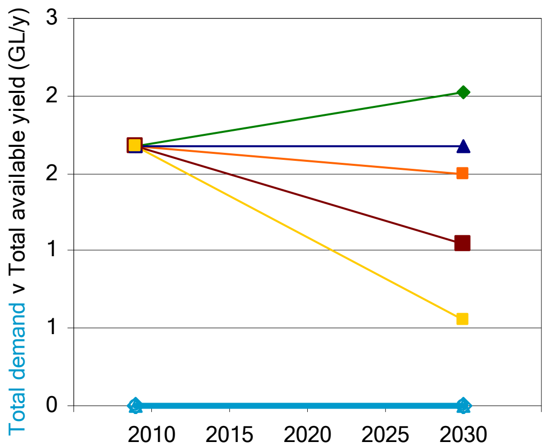
SW3c Dardanup River System

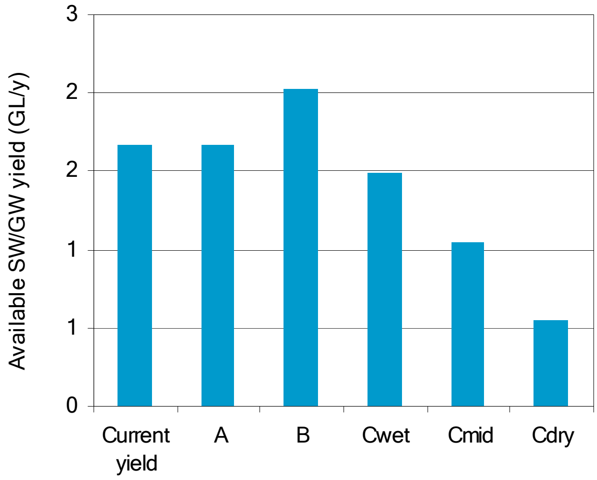


Yield analysis

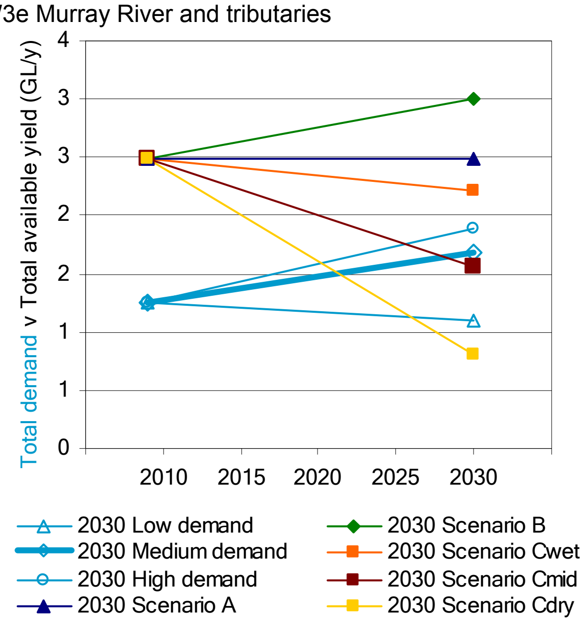


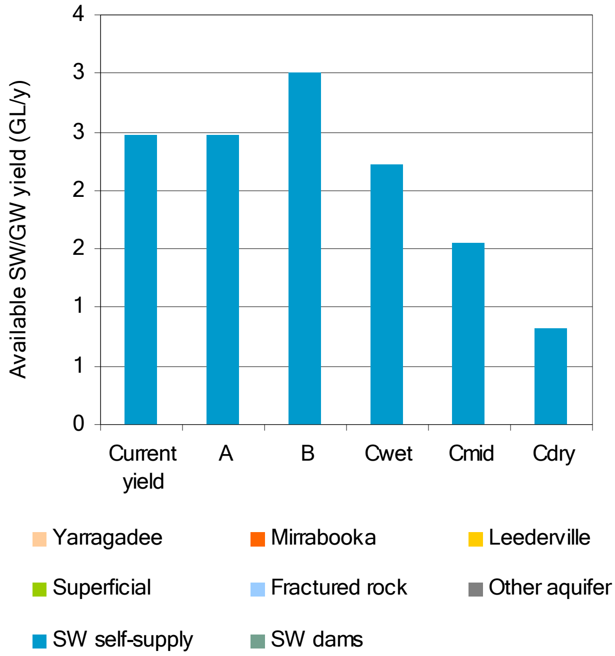
SW3d Kwinana-Peel Coastal





SW3e Murray River and tributaries

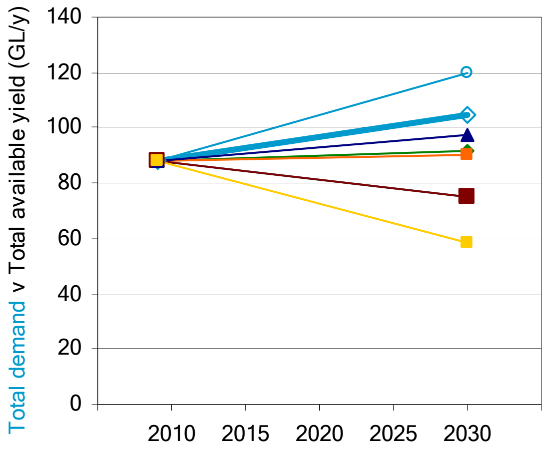




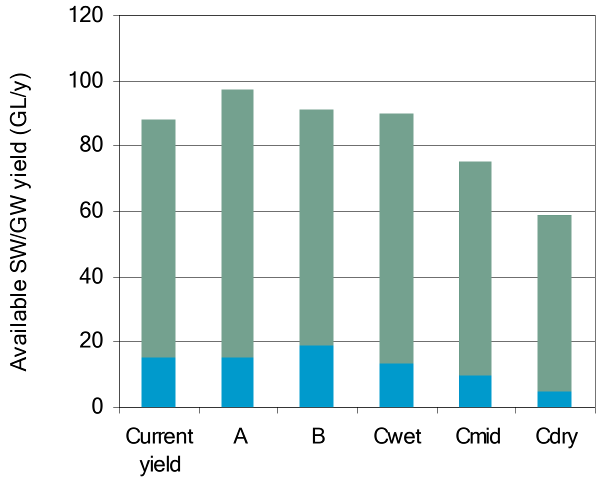
Water yields and demands in the Harvey, Collie and Preston surface water management areas

Gap analysis

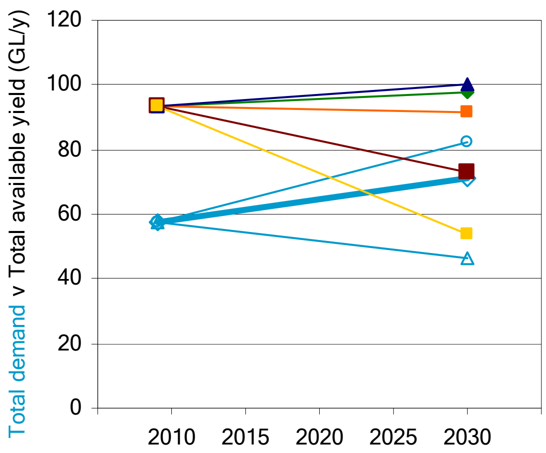
SW4 Harvey

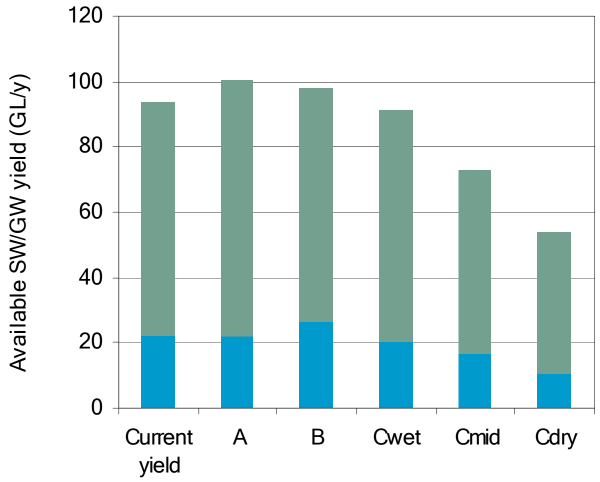


Yield analysis

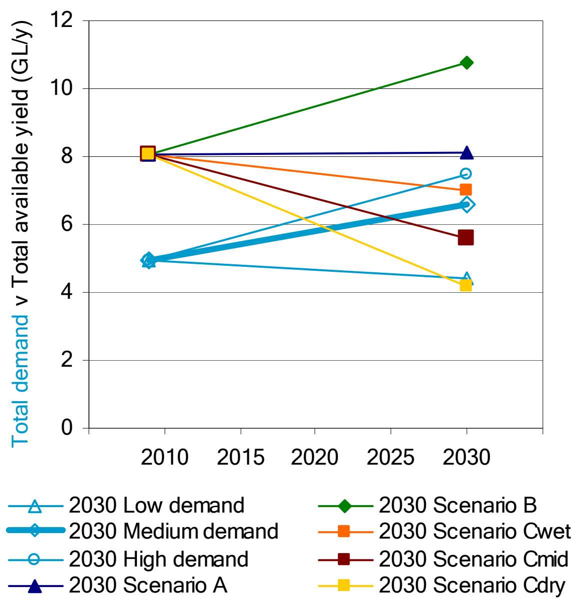


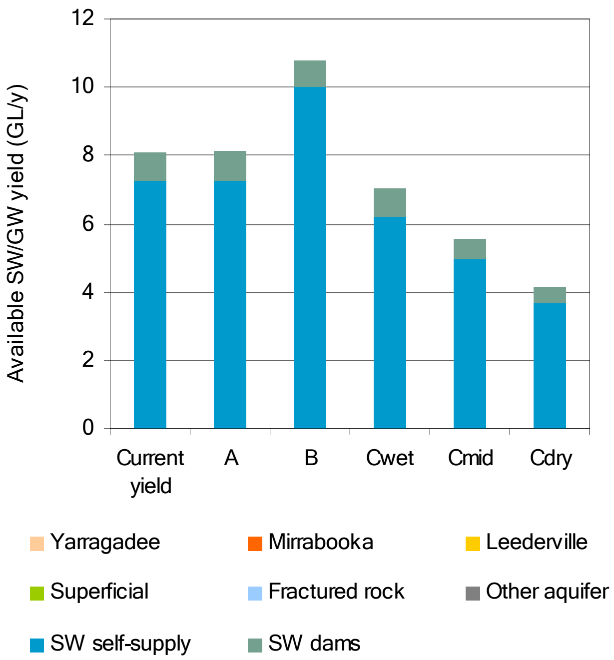
SW5 Collie





SW6 Preston



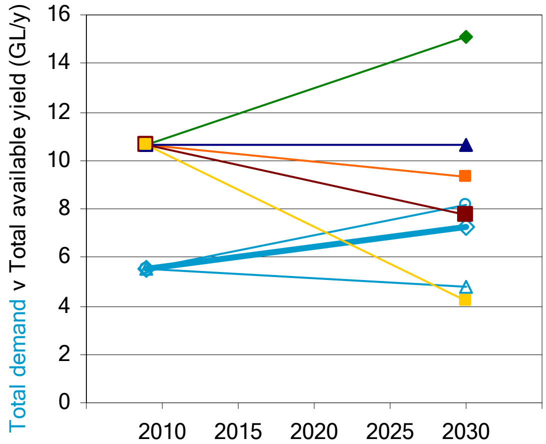


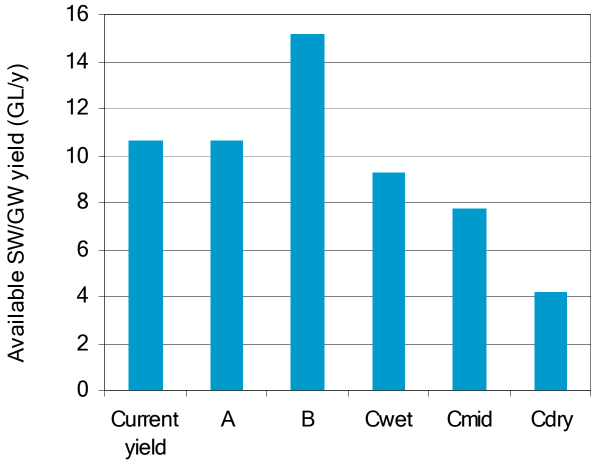
Water yields and demands in the Capel River, Busselton Coast and Lower Blackwood surface water management areas

Gap analysis

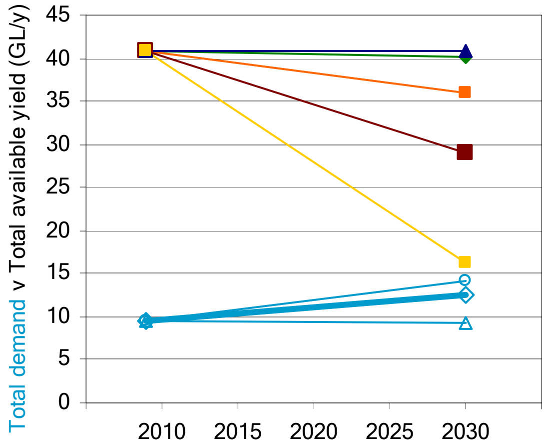
Yield analysis

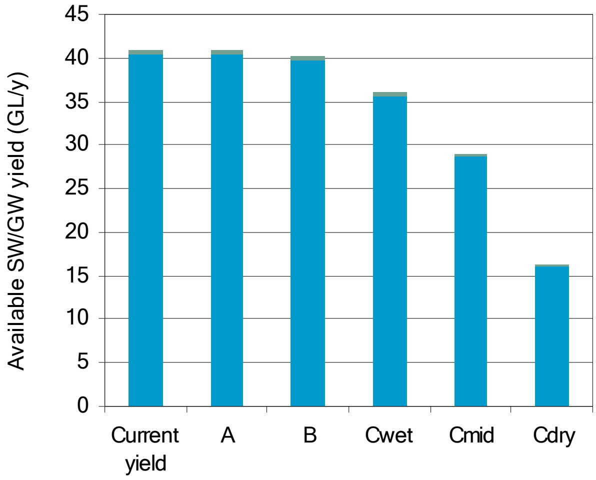
SW7a Capel River



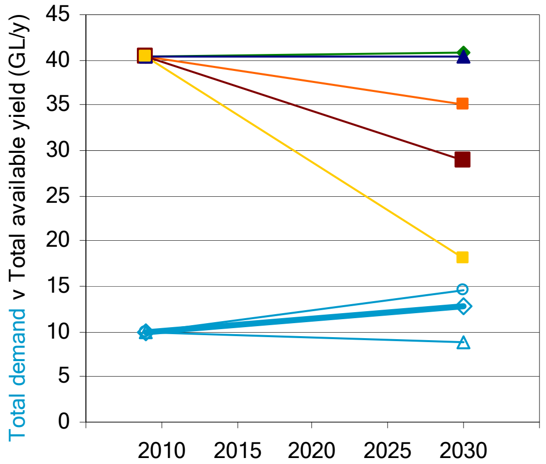


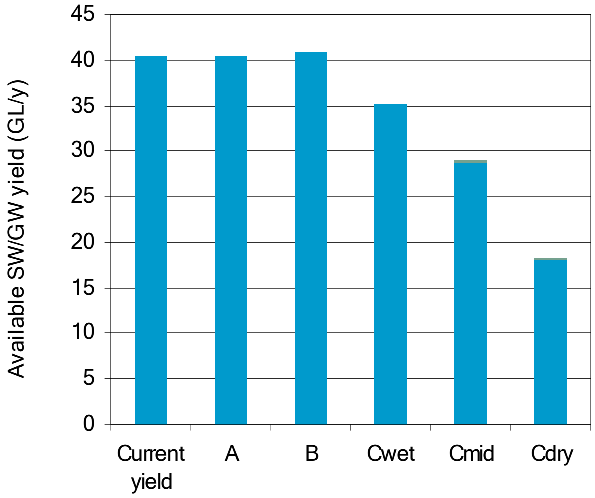
SW7b Busselton Coast





SW8 Lower Blackwood





2030 Low demand
2030 Medium demand
2030 High demand
2030 Scenario A
2030 Scenario B
2030 Scenario Cwet
2030 Scenario Cmid
2030 Scenario Cdry

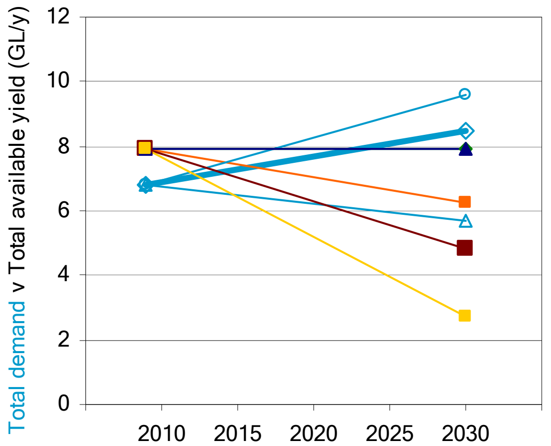
Yarragadee
Mirrabooka
Leederville
Superficial
Fractured rock
Other aquifer
SW self-supply
SW dams

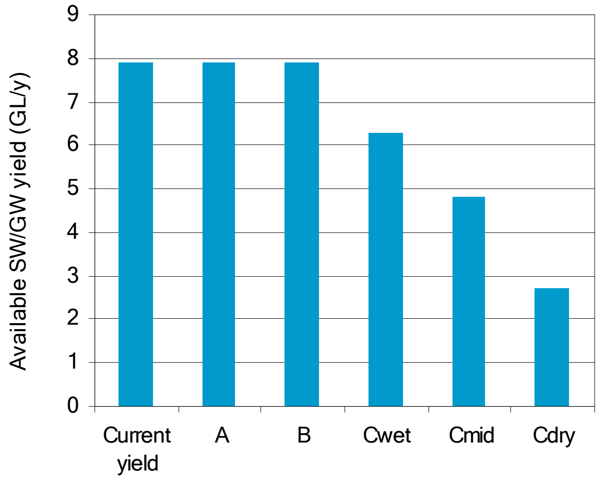
Water yields and demands in the Donnelly River and tributaries, Warren River and tributaries and Shannon-Gardner surface water management areas

Gap analysis

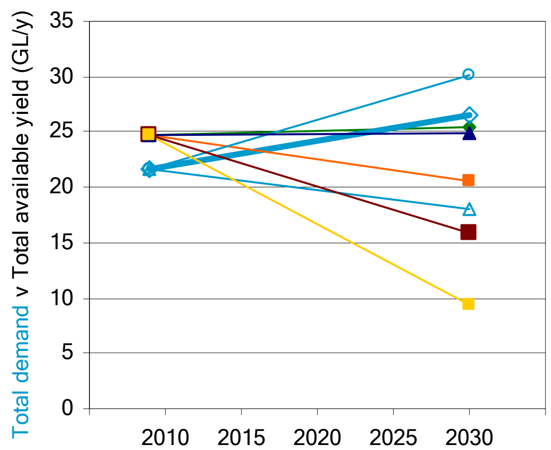
Yield analysis

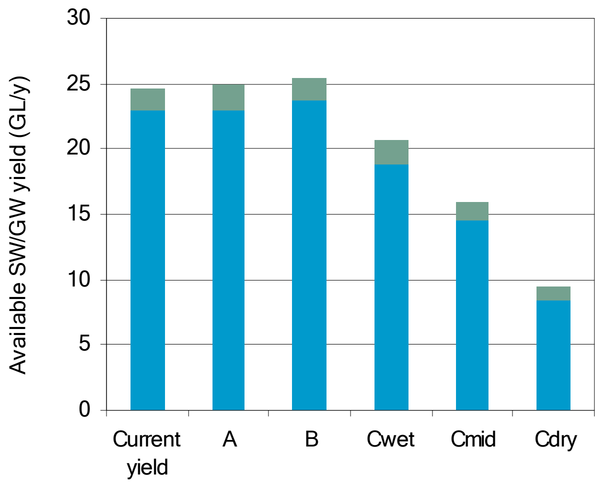
SW9 Donnelly River and tributaries



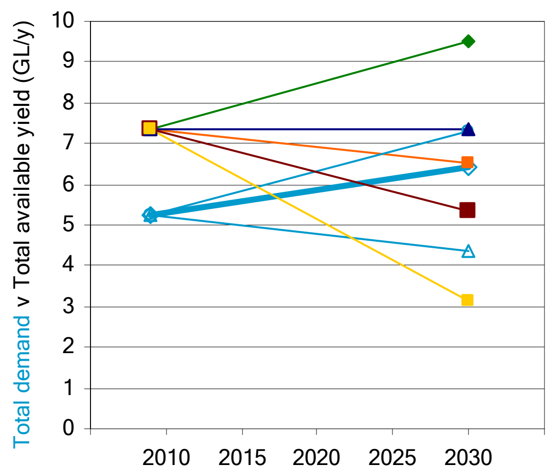


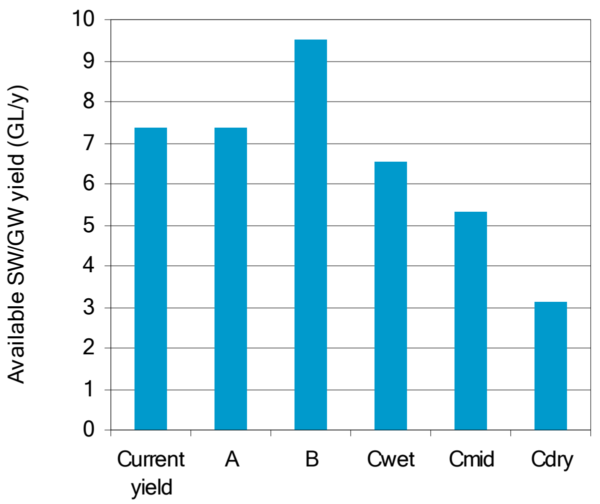
SW10 Warren River and tributaries





SW11a Shannon-Gardner





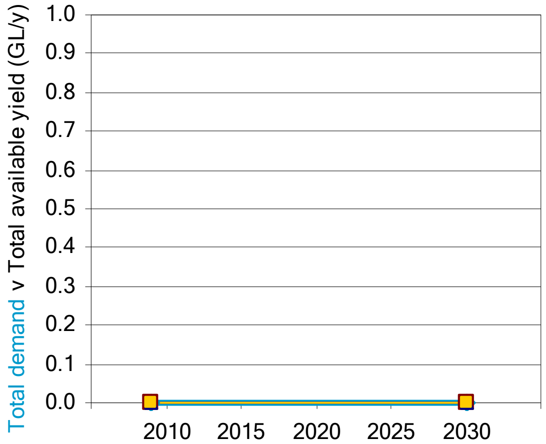
2030 Low demand
2030 Medium demand
2030 High demand
2030 Scenario A
2030 Scenario B
2030 Scenario Cwet
2030 Scenario Cmid
2030 Scenario Cdry

Yarragadee
Mirrabooka
Leederville
Superficial
Fractured rock
Other aquifer
SW self-supply
SW dams

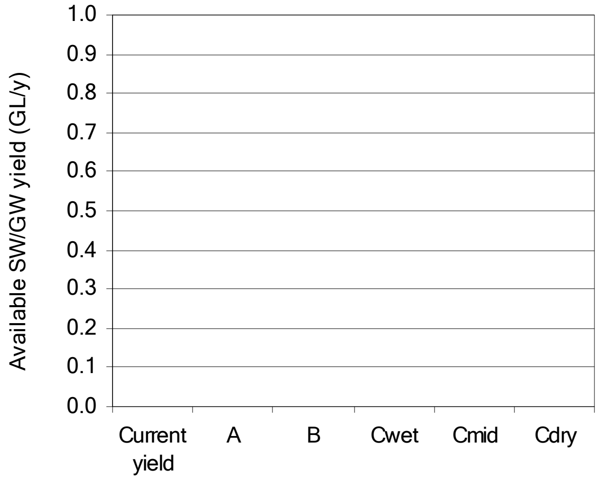
Water yields and demands in the Muir-Unicup, Kent and Denmark surface water management areas

Gap analysis

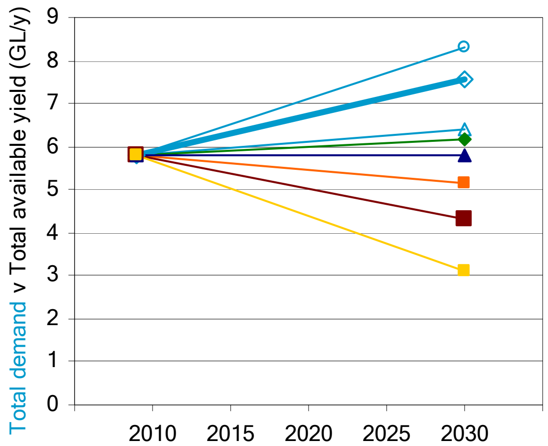
SW11b Muir-Unicup

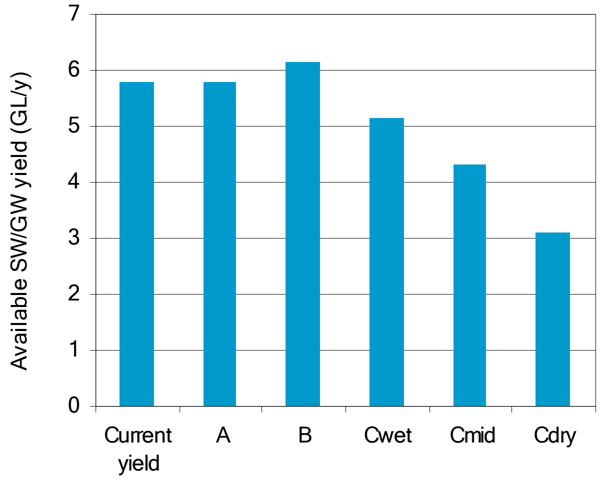


Yield analysis

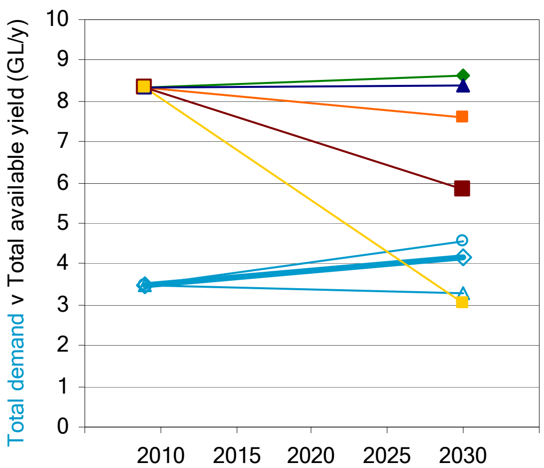


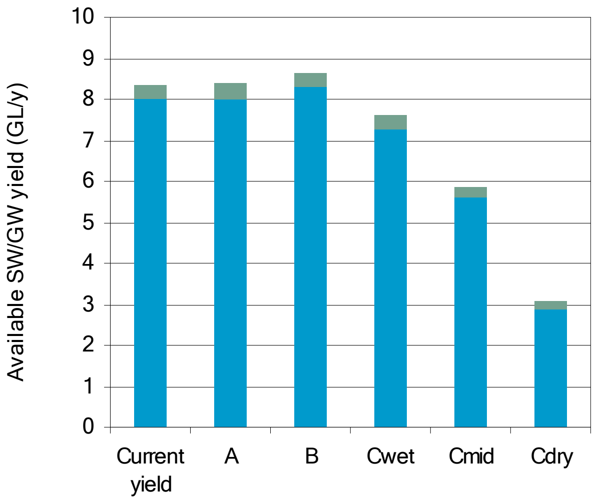
SW12 Kent





SW13 Denmark





2030 Low demand
2030 Medium demand
2030 High demand
2030 Scenario A
2030 Scenario B
2030 Scenario Cwet
2030 Scenario Cmid
2030 Scenario Cdry

Yarragadee
Mirrabooka
Leederville
Superficial
Fractured rock
Other aquifer
SW self-supply
SW dams

Erratum: Water yields and demands in south-west Western Australia

This is an erratum sheet, issued March 2010, for the following report:

CSIRO (2009) Water yields and demands in south-west Western Australia: A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO, Australia. 276pp

List of erratum

Erratum #	Chapter	Section	Page	Errata
1	Appendix C: Choice of post-1974 as the historical climate period		213	Sixth paragraph, third and fourth sentence clarification

1

The statement in Appendix C "*that the prolonged winter drying trend and reduction in storm intensity experienced since the mid-1970s was well outside the range of natural rainfall variability recorded in the isotopic record of the last 250 years*" was incorrectly attributed to Treble et al. (2005) and Fischer and Treble (2008). This statement was based on an interpretation of preliminary phosphorous isotope results (IOCI, 2004) that is not supported by subsequent research.

Subsequent research, investigating oxygen isotopes, suggests that whilst multidecadal variability can be detected in isotopic records it cannot yet be used to quantify rainfall variability with certainty due to ambiguities possibly caused by land use and moisture source changes (Fischer and Treble, 2008). Resolution of these ambiguities is the subject of on-going research (P. Treble, *pers. comm.*, 5th Feb 2010).

IOCI (2004). IOCI Stage 2 Bulletin Number 4, May 15 2004. 2pp. <http://www.ioci.org.au/pdf/IOCI_Bulletin4.pdf>

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