Government of Western Australia
Department of Water

Lower Gascoyne

water allocation plan methods report

Department of Water

October 2011

Lower Gascoyne water allocation plan methods report

Background information and description of methods used in preparing the Lower Gascoyne water allocation plan

Looking after all of our water needs

Department of Water

Water resource allocation planning series

October 2011

Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
National Relay Service 133 677
www.water.wa.gov.au

October 2011

ISBN 978-1-921907-80-7 (online)

Acknowledgements

The Department of Water would like to acknowledge the following for their contribution to this publication: Binh Anson, Michelle Antao, Sally Bowman, Katrina Burton, John Connolly, Brad Cox, Greg Davis, Clea Grant, Rob Hammond, Lazarus Leonhard, Adam Maskew, Kelly McKay, Neil Milligan, Chris O'Boy, Kelly Whitfield and Susan Worley.

For more information about this report, contact:

Mid West Gascoyne regional office
211 Robinson Street
Carnarvon Western Australia 6701
Telephone 08 9941 6100
Facsimile 08 9941 4931

Disclaimer

This publication is available at our website <www.water.wa.gov.au> or for those with special needs it can be made available in alternative formats such as audio, large print, or Braille.

Contents

Figures

Tables

Summary

What is this document?

This *Lower Gascoyne allocation methods report* is the main supporting document to the *Lower Gascoyne water allocation plan* (DoW 2011a). This supporting document details the information and process we used and the decisions taken in preparing the allocation plan.

Why we produced the Lower Gascoyne methods report

Transparency and consistency are two of the Department of Water's main principles in allocation planning. We have prepared this document to make the process we used to set the Gascoyne allocation limits transparent and publicly available to water users and other stakeholders in the Gascoyne area. This document explains the approach we used to reach the allocation and licensing decisions in the plan.

What this report includes

In this report, we describe how we set allocation limits in the Lower Gascoyne area. We also outline the data, detail our assumptions and describe the limitations associated with the methods we used to develop objectives, allocation limits and some of the specific, local licensing rules. We also describe the extensive hydrogeological, hydrological and water abstraction information for the Lower Gascoyne River area. We used this information to update the GASFAMS V1.1 numerical groundwater model and to inform our management decisions.

What were the outcomes?

As a result of this process the allocation limits below were set for each resource in the plan area along with complementary local licensing rules.

Resource	Yield range estimate	Allocation limit decision	Final allocation limit GL/yr
Lower Gascoyne alluvial subarea A	Based on predicted 5th and 95th percentile volumes of fresh water able to be abstracted from subarea A.	Allocation limit based on 80% reliability of supply.	6.1
Lower Gascoyne alluvial subarea B–L	Based on predicted 5th and 95th percentile volumes of fresh water able to be abstracted from subarea B–L.	Allocation limit based on 80% reliability of supply.	15.5
Lower Gascoyne surficial	Yield not able to be accurately estimated due to variability in system and predicted very low yields.	For management purposes a nominal allocation limit of 0.1 GL/yr has been set to allow for small, localised abstraction from this aquifer.	0.1
Carnarvon surface water irrigation district	Not able to be estimated due to variability of river flows.	Not applicable	Not set

1 Background to planning in the Lower Gascoyne

1.1 The Lower Gascoyne water allocation plan

Following extensive consultation, in November 2010 the Department of Water released the *Lower Gascoyne allocation plan – for public comment* for five months public comment (DoW 2010a). The final plan was released in October 2011 having been amended where appropriate to take into account formal comments and feedback from the community during the public comment period. The statement of response document, released with the final plan, details how individual comments were considered. This supporting document explains how we developed that plan in accordance with the department's allocation planning process.

1.2 The plan area

The Lower Gascoyne plan area covers 1187 km^2 and is located around 900 km north of Perth (Figure 1). Carnarvon is located within the plan area.

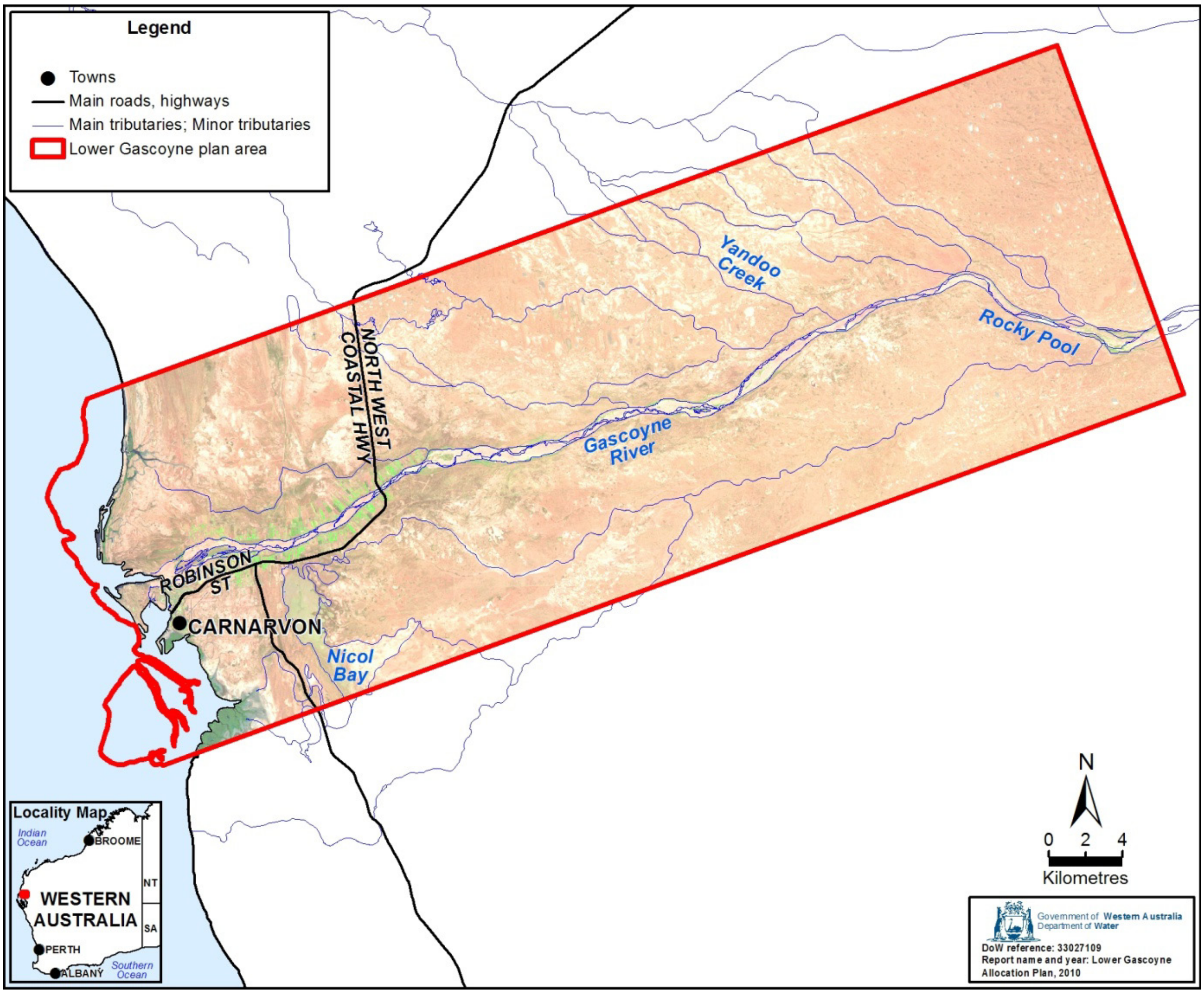


Figure 1 Lower Gascoyne allocation plan area

The plan boundary in the north, east and south was chosen to match the boundary of the GASFAMS[1] V1.1 groundwater model, as the model is the primary tool for informing management decisions in this plan. The western boundary aligns with the boundary of the proclaimed Gascoyne groundwater area.

1.3 Water resources managed under the plan

The Lower Gascoyne plan covers both groundwater and surface water resources.

Groundwater is the main water source in the plan area. Surface water is used opportunistically when the river is flowing.

All groundwater and surface water resources subject to this plan are proclaimed under the *Rights in Water and Irrigation Act 1914* as:

- Gascoyne groundwater area
- Gascoyne River and tributaries surface water area.

The Carnarvon groundwater irrigation district and the Carnarvon surface water irrigation district lie within the proclaimed groundwater and surface water areas listed above. Licences within the plan area will be issued against the Gascoyne groundwater area and the Gascoyne River and tributaries surface water areas. The proclaimed areas are shown in Figure 2.

The plan area also contains the area proclaimed as the Carnarvon water reserve to protect the water quality of the Carnarvon town water supply. Refer to the *Carnarvon water reserve drinking water source protection plan* (DoW 2010b) for further detail.

[1] Gascoyne River floodplain aquifers modelling system

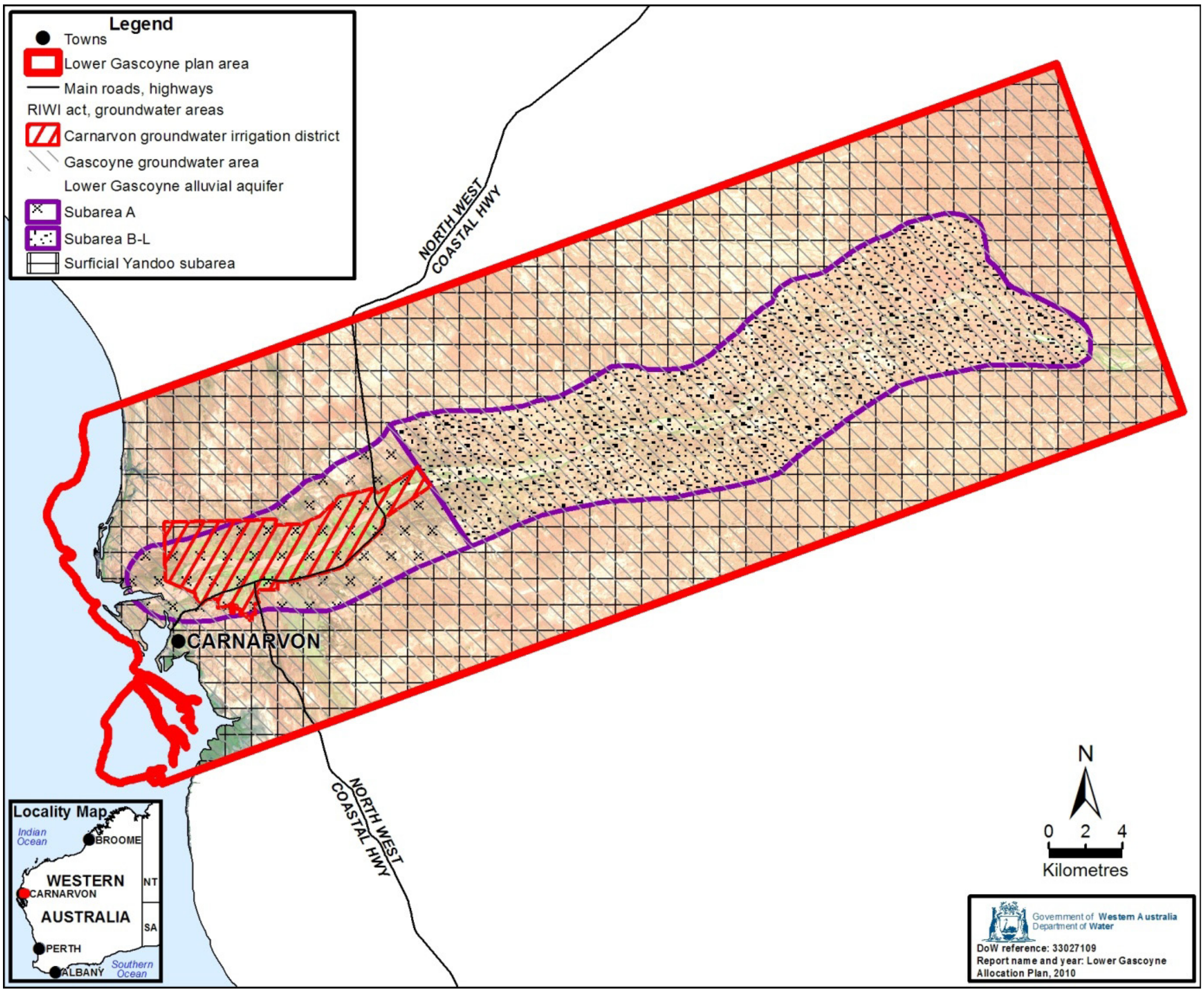


Figure 2 Groundwater resource boundaries

Three groundwater resources have been defined within the plan area in the Gascoyne groundwater area. These are shown in Figure 2. The department sets an allocation limit for each resource (see Section 3) and issues licences against the relevant resource.

Table 1 Groundwater resources

Groundwater resources		
Groundwater area	**Aquifer**	**Subarea**
Gascoyne groundwater area	Lower Gascoyne alluvial	Subarea A
Gascoyne groundwater area	Lower Gascoyne alluvial	Subarea B-L
Gascoyne groundwater area	Lower Gascoyne surficial	Yandoo subarea

One surface water resource has been defined within the plan area (Table 2). This is shown in Figure 3.

Table 2 Surface water resources

Surface water resource	
Surface water area	**Subarea**
Gascoyne River and tributaries surface water area	Carnarvon surface water irrigation district

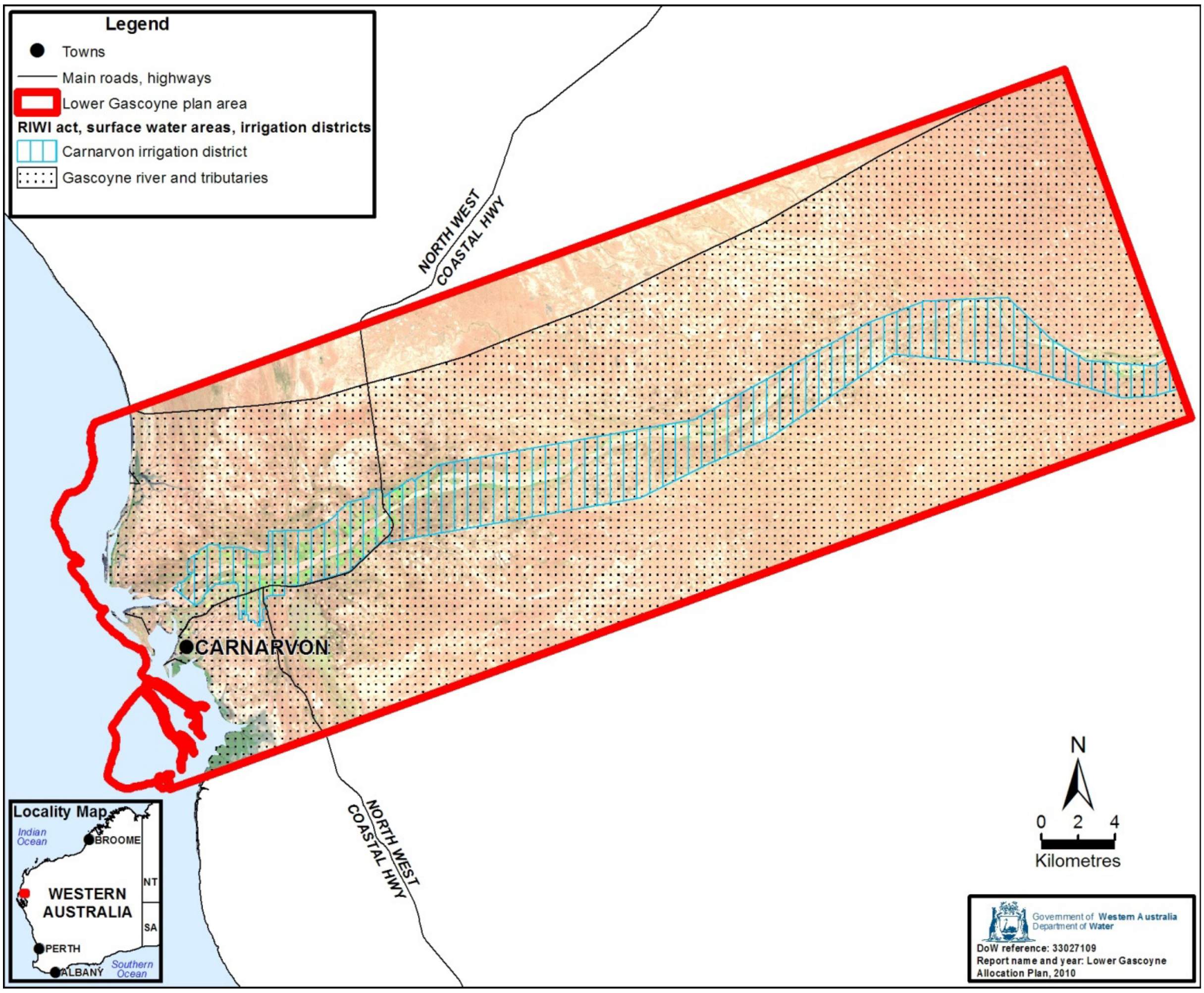


Figure 3 Surface water resource boundaries

1.4 The approach to setting allocation limits

Previous approach

The previous allocation limits were set by the department's predecessor, the Water and Rivers Commission, in 2004. The process used and the allocation limits chosen were published in *Managing the groundwater resources of the Lower Gascoyne River (Carnarvon) WA – groundwater management strategy* (WRC 2004).

To decide on the allocation limits, results from an earlier groundwater model (GRFAMOD, Dodson 2001) and the information gathered from the environmental water requirements assessments (SMEC 2001), was used. The GASFAMS groundwater model estimated the recharge, throughflow, discharge and storage characteristics of the flow system. The groundwater model simulated a number of recharge scenarios to determine how much water could be sustainably abstracted from the system.

Current approach

The department follows a standard planning process when developing an allocation plan. A component of this process is setting allocation limits and the management regime. For the Lower Gascoyne area we set allocation limits in accordance with this process (Figure 4).

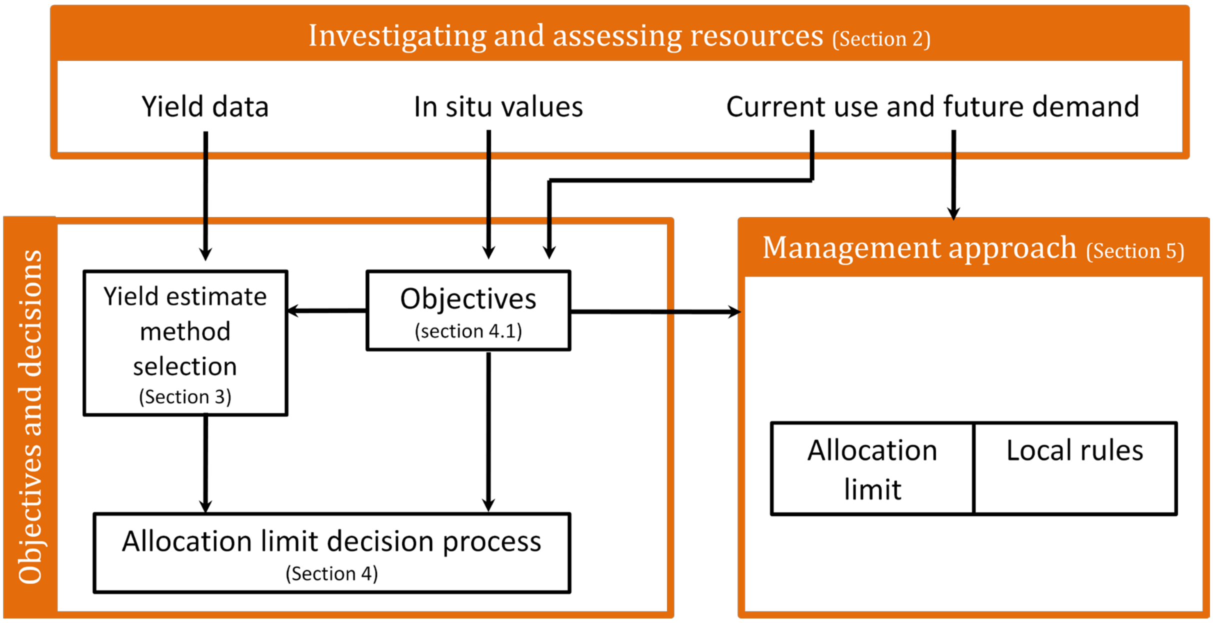


Figure 4 Process for setting allocation limits

The yield estimate tells us how much water can be taken from a resource for use and what volume or flow is needed to maintain the ecological and social values, within and downstream of the resource.

We also consider management considerations in our decision, such as reliability of supply, current use, future demand and the effects of water abstraction and use on water quality.

The department applied this process to the Lower Gascoyne alluvial aquifer to determine the allocation limits.

Definition of an allocation limit

An allocation limit is the annual volume of water set aside for consumptive use from a water resource. This includes the water available for licensing and the water set aside for uses exempt from licensing, such as stock and domestic.

For administrative purposes, the allocation limit is divided into three groups of components:

- licensable components (water available for licensing or currently licensed public water supply)
- reserves (including reserves for future public water supply)
- unlicensable components (including water for exempt use).

There was no exempt stock and domestic water use within the plan area when this plan was being prepared.

1.5 Working with water users and other stakeholders

Involving the community is an important part of the planning process. In the Lower Gascoyne area we consulted extensively to ensure we set the right management approach for the area. Particularly important was the need to build on the historical knowledge held by the community, particularly growers. We did this to ensure the decisions we made throughout the planning process were supported by the community, representative organisations and other regulatory agencies and would enable us to effectively manage the system.

Community involvement was twofold:

- The Carnarvon Water Allocation Advisory Committee played a major role in developing the earlier report, *Managing the groundwater resources of the Lower Gascoyne River (Carnarvon) WA – groundwater management strategy* (WRC 2004). We continued to use their input during the development of this plan.
- Broader ongoing consultation, including three workshops held in March, June and September of 2010.

We undertook three phases of consultation for plan development, prior to the standard period of public comment on the plan, which began on 30 November 2010.

Phase one was undertaken in March 2010. We invited the community to come to a series of meetings to discuss water allocation issues for the planning area, including any issues relating to the current management strategies.

Phase two was undertaken in June 2010. We made a series of presentations to the community on the hydrogeology of the Lower Gascoyne River, as technical background to the Lower Gascoyne River system was important to support the next phase.

Phase three was undertaken in September 2010. During this phase we invited the community to come to workshops to see the results of groundwater modelling and discuss options for how water could be managed into the future.

An estimated 30% of Carnarvon growers speak Vietnamese as their first language. To ensure all growers had the opportunity to participate, advertising for each phase of consultation, fact sheets and the verbal presentations were provided in Vietnamese.

2 Investigating and assessing the resources

This section describes the information we used to inform our management decisions. It includes the:

- interaction between surface water and groundwater
- surface water and groundwater systems in the plan area
- in situ values and risks to those values
- current and future water use and benefits.

2.1 Rainfall

Rainfall in the Gascoyne River catchment is highly variable and unpredictable. There are four major rain producing mechanisms in the Gascoyne River catchment that may contribute to river flow in the plan area (Dodson 2009). These are:

- Tropical lows and cyclones are the main source of heavy rainfall in the warmer months from November to March and are the main cause of significant river flows and flooding in the region (BoM 1998). From 1910 to 2000, 27 cyclones delivered significant rainfall to the catchment, approximately one every three and a half years.
- North-west Australian cloud bands form off the north-west coast of Australia and extend south-eastwards across the continent (BoM 1998). They produce rainfall in the cooler months from April to October and can combine with cold fronts to produce significant rainfall, as in 1980, when the area received the yearly average rainfall between May and June.
- Cold fronts mainly occur during the cooler months and sweep across Western Australia from west to east. Most fronts pass to the south of Carnarvon and rainfall declines as the front moves inland.
- Troughs and lows with easterly winds can generate significant rainfall in exceptional cases, producing either thunderstorms from troughs in warmer months, or mid-level lows in cooler months (BoM 1998). Thunderstorms generally affect inland catchment areas and may result in small river flows in the upper catchment, whereas mid-level lows generally affect the coastal area.

Predicted future rainfall trends

Local scale climate predictions have not been undertaken for the plan area. National scale climate predictions for the plan area do not consistently agree on what changes to rainfall and temperature are expected in the area. Model results are divided, with some predicting an increase in rainfall while others predict a decline (CSIRO & BoM 2007).

A best estimate (50th percentile) of the projected change in rainfall by 2030 for the Gascoyne region has been undertaken by CSIRO and the Bureau of Meteorology (CSIRO & BoM 2007).This estimate is presented as a percentage of 1961–1990 rainfall values for summer, autumn, winter, spring and annually (Table 3).

Table 3 Best estimate projected change in Gascoyne rainfall by 2030

Season	Projected change (50th percentile) in Gascoyne rainfall by 2030
Summer	–2.5% to –5.0%
Autumn	–2.5% to –5.0%
Winter	–7.5% to –10.0%
Spring	–10.0%
Annually	–5.0% to –7.5%

Source: CSIRO & BoM 2007

It is predicted that there could be an increase in the intensity of rainfall events (rain per rain day) but these events will be interspersed with longer periods of dry (no rainfall) days (CSIRO & BoM 2007).

A long-term shift to drier or wetter years may affect rainfall patterns that will in turn affect the river flow patterns and recharge characteristics and ultimately alter the availability of water.

2.2 Surface and groundwater interaction

The surface and groundwater systems in the plan area are closely linked. The high conductivity of the riverbed sands allows for rapid recharge of the aquifer during periods of surface water flow. As surface flows continue to recharge the riverbed sands, vertical leakage will occur into the underlying older alluvium. The degree of connection between the surface water and the older alluvium is primarily controlled by the hydraulic properties and distribution of the semi-confining clay lens.

The Gascoyne River generally loses water to the surrounding alluvial aquifers throughout flow events (Dodson 2009). The exception to this is when return flows from bank storage re-enter the river. This volume is considered to be small in comparison to the river recharge.

2.3 Surface water

The Lower Gascoyne plan area covers only a small portion of the Gascoyne River catchment, which is approximately 68 000 km^2 (Figure 5). The Gascoyne River flows west into the Indian Ocean. The Lyons River is the main tributary of the Gascoyne River and generally has saline flow. It joins the Gascoyne River near Gascoyne Junction, approximately 176 km upstream of the river mouth (Dodson 2009; DoW 2010b; SMEC 2001).

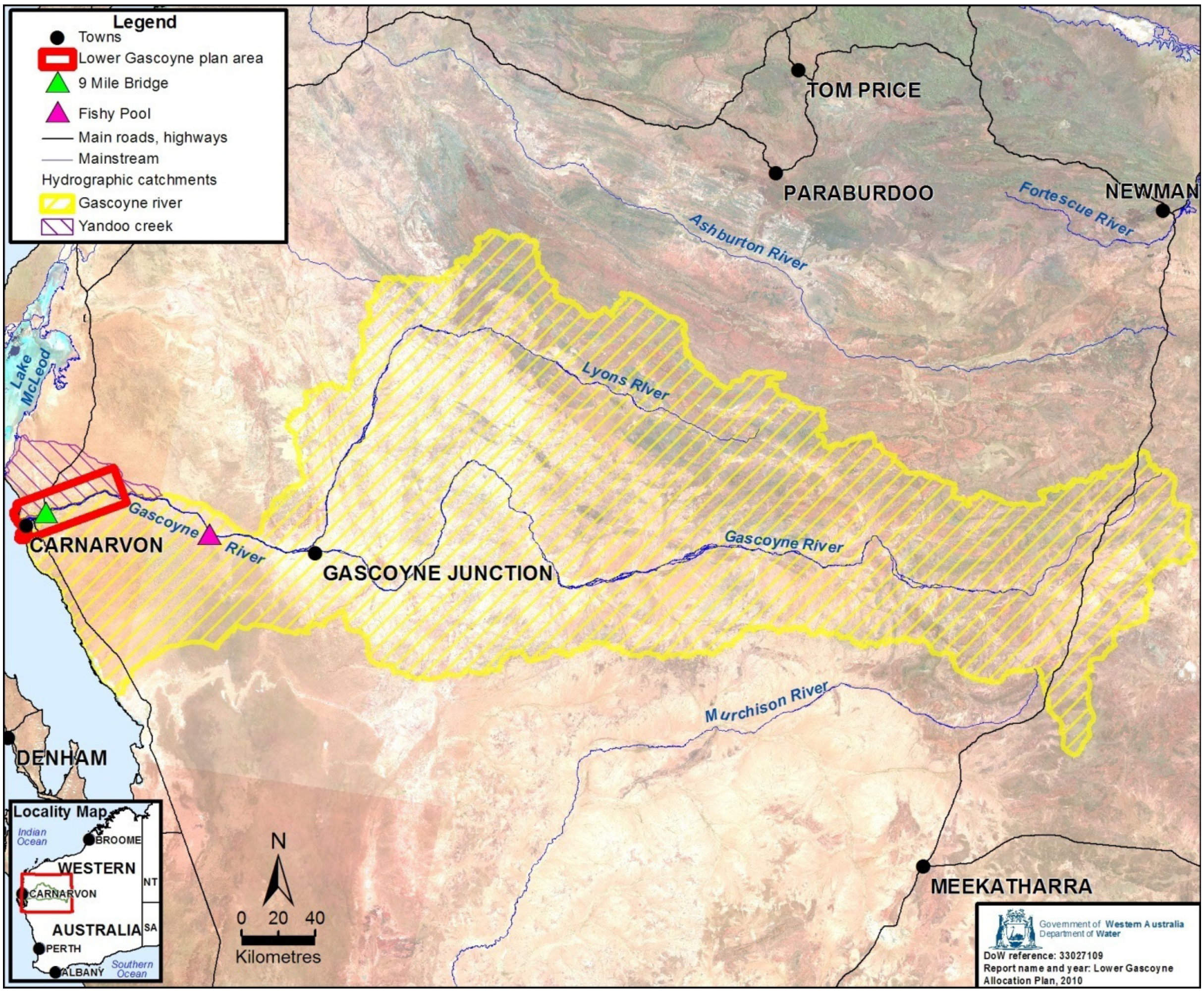


Figure 5   Gascoyne River catchment boundary

Measuring river water levels and flow

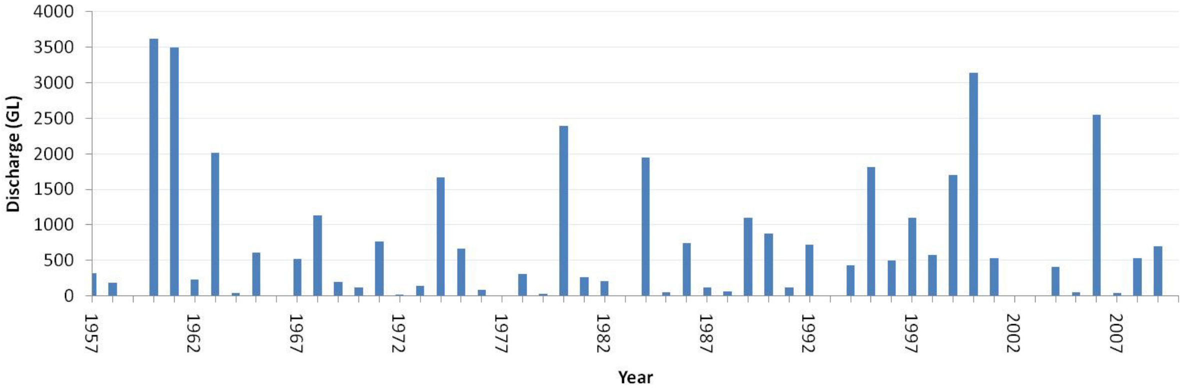
Sixty-three gauging stations have operated periodically within the extensive Gascoyne River catchment. However, Fishy Pool and Nine Mile Bridge provide the most consistent and long-term data series (Table 4). Nine Mile Bridge is the main gauging station we use to assess the duration and magnitude of river flows for the purposes of this plan. Water levels have been recorded at the Nine Mile Bridge gauging station continuously since 1957 and estimates of flow rate and discharge have been derived for this period.

Table 4   Streamflow gauges used in plan development

	River gauge ID	Number of readings	Data range
Fishy Pool	704193	16 253	1964 to present
Nine Mile Bridge	704139	18 855	1957 to present

Streamflow characteristics

The Gascoyne River is episodic with significant river flows resulting from heavy rainfall received inland. Water discharge at Nine Mile Bridge, as shown in Figure 6, shows years of significant river flow and gives an indication of the magnitude of river flow from 1957 to 2009. The three largest recorded stream discharges occurred after the cyclones of 1960, 1961 and 2000.



Source: Department of Water unpublished data

Figure 6 Total annual discharge at Nine Mile Bridge

Since 1958 the river has flowed on average approximately 108 days each year. The river is defined by long periods of no flow (Figure 6). The longest recorded period of no flow was 43 months (May 1910 – January 1914). Other no flow periods are shown in Table 5.

The frequency of long no flow periods is increasing as shown in Table 5, with three of the longest no flow periods in the last decade.

Table 5 Longest no flow periods for Lower Gascoyne River

No flow period	Months of no flow
April 2009 – ongoing (as at November 2010)	19
May 2005 to January 2006	8
May 2001 to January 2004	30
September 1992 to February 1994	18
July 1982 to March 1984	20
March 1976 to February 1978	22
February 1955 to February 1957	23
May 1937 to January 1940	31
May 1910 to January 1914	43

Source: Department of Water unpublished data

2.4 Groundwater

Aquifers

Within the plan area the geological formations support three aquifers:

- the Birdrong confined aquifer
- the Lower Gascoyne alluvial aquifer

- the surficial aquifer.

The department currently assigns all confined or artesian groundwater to the Birdrong groundwater resource. Due to the regional scale of this aquifer and the lack of interaction with any of the unconfined aquifers in the plan area the Birdrong aquifer is not dealt with further in this plan and is managed through the *Carnarvon Artesian Basin Water Management Plan* (DoW 2007).

Several detailed investigations into the hydrogeology in the plan area have been undertaken (Allen 1972; CyMod 2009, 2010; Dodson 2001, 2002; Martin 1990a, 1990b; Skidmore 1977).

Lower Gascoyne alluvial aquifer

The Lower Gascoyne alluvial aquifer consists of two distinct aquifers that are hydraulically connected (Figure 7) – the riverbed sands and the older alluvium. Due to the high degree of hydraulic connection and the difficulties in clearly distinguishing the boundary between the two aquifers they are collectively defined as the Lower Gascoyne alluvial aquifer.

The riverbed sands consist of the bed sediments of the Lower Gascoyne River. They form a single layered unconfined aquifer with a maximum thickness of approximately 12 m and an average thickness of approximately 5 m (CyMod 2009). The water quality is generally fresh, mirroring the water quality of the river. Hydraulic gradients are low within the riverbed sand resulting in low flow through the aquifer. During extended dry periods the water levels in this aquifer will fall and the riverbed sand formations may become locally dry (CyMod 2009).

The older alluvium aquifer is located directly below and adjacent to the riverbed sands. The older alluvium is multi-layered, with non-permeable clay layers interspersed with coarse gravel and sand. In places these clay layers result in the aquifer behaving as a semi-confined to confined system. Bore logs indicate a maximum thickness of 68 m. The thickness of the aquifer decreases in a westerly direction. The physical and hydraulic aquifer characteristics vary significantly. The water quality tends to be fresher close to the river and deteriorates with distance from the river. The older alluvium contains significant volumes of groundwater in comparison with the riverbed sand aquifer (Dodson 2009).

Hydrographs from the Lower Gascoyne alluvial aquifer show that the system is highly variable over short periods of time. The rates of change observed are not consistent across the plan area, with some bores showing less than 1 m change in groundwater levels in a year when others have in excess of 20 m change.

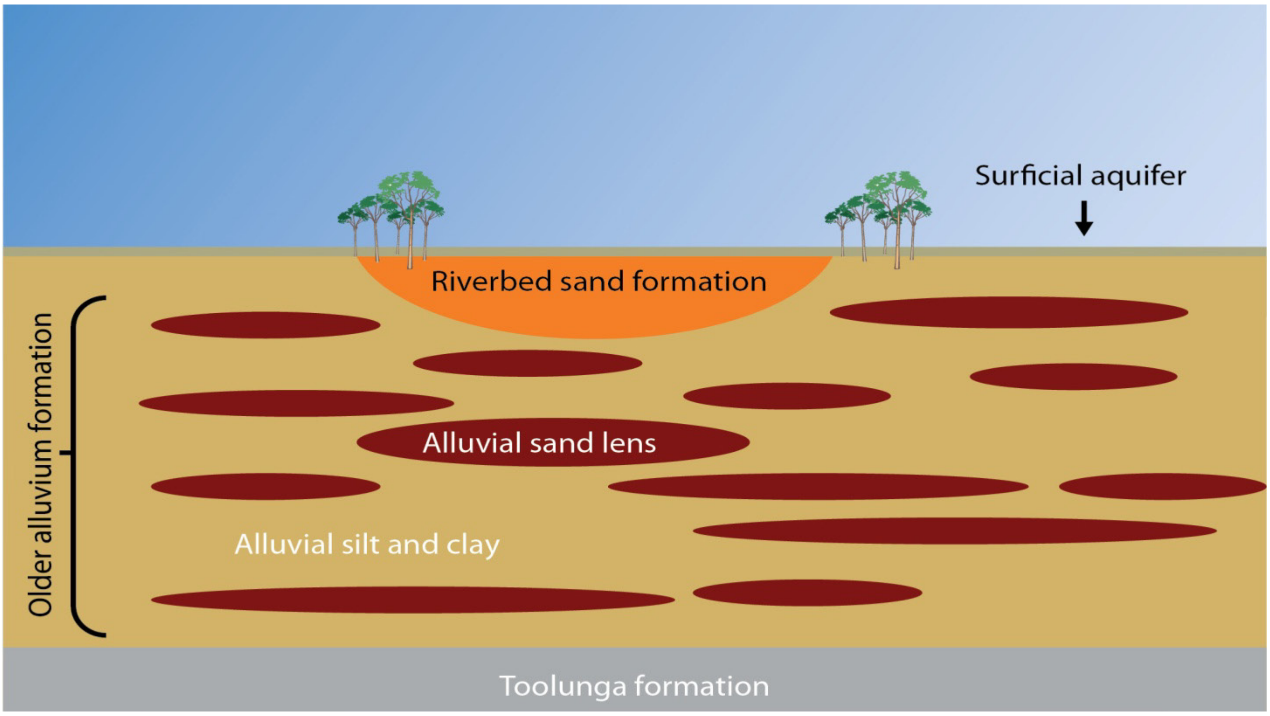


Figure 7 Aquifer cross-section

The department defined the boundary for the alluvial aquifer based on the zone of influence of the Gascoyne River. The zone of influence was based on information from Dodson (2009), Hydrosolutions (2009), Martin (1990b) and CyMod (2010*).* The method of net groundwater volume change was used to assess the flow envelope and extent of the aquifer boundary. An approximate distance of 3.6 km away from the river was derived as the zone of influence. This approach and the distance estimated is assumed to be a reasonable estimation, since Martin (1990) concluded that beyond 1.5 km, there was no discernible response to river flow within the older alluvium three months after a flow event. The eastern and western extent of the Lower Gascoyne alluvial aquifer is set by the saltwater interface of the Indian Ocean to the west and the Toolonga Calcilutite at Rocky Pool, approximately 54 km from the river mouth (DoW 2010b). Further data is required to accurately characterise the aquifer upstream of Rocky Pool.

The surficial aquifer consists of a thin layer of sediments which overlie the sedimentary rocks of the Carnarvon Basin. The surficial formations overlie Tertiary or Cretaceous rocks, with small palaeochannel deposits thought to be present in some areas. Groundwater levels are generally within 5 m to 10 m of the surface. Access to useable quantities of good quality water in this aquifer is highly variable.

Recharge

Groundwater recharge is the volume of water that infiltrates into the aquifer. The two possible sources of recharge in the Gascoyne alluvial aquifer are:

- river flow recharge
- rainfall recharge.

River flow recharge

Recharge derived from river flow is the largest contributor to recharge of the Lower Gascoyne alluvial aquifer. Water from river flows infiltrates the river bed sands and then vertically and horizontally migrates into the older alluvium. The movement of the water into the older alluvium is faster in areas where there is no confining clay lens and the hydraulic connection is good. River flow recharge was calculated using the SURFACT – MODFLOW package (CyMod 2010).

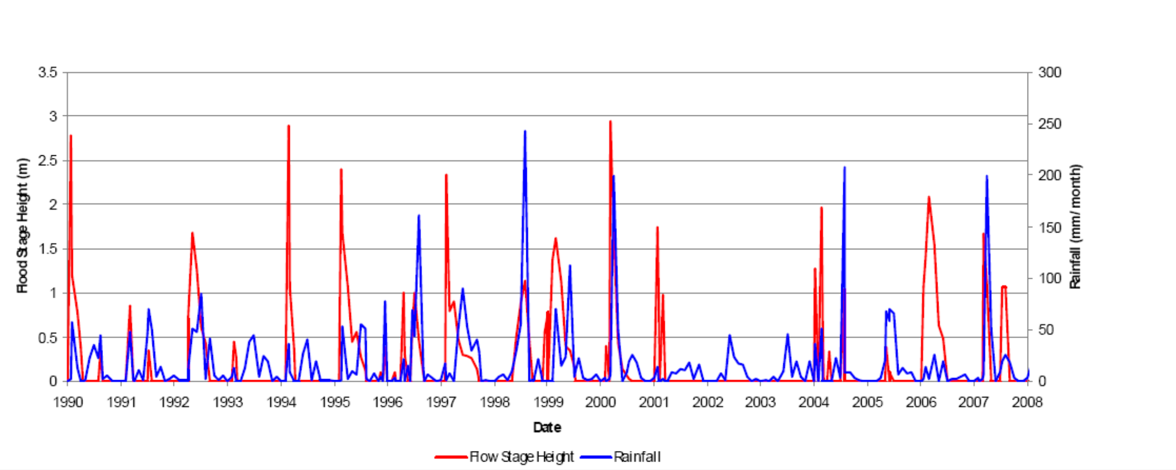
The amount of groundwater recharge from river flow depends on the flow volume and extent of the flow. River water levels and flow rates have been measured since 1957 at the Nine Mile Bridge and Fishy Pool gauging stations. This river water level and flow data and topography was used to generate continuous water levels for the Gascoyne River from the Indian Ocean to Rocky Pool and to map the spatial extent of the river flows. It was found that flows with corresponding water levels less than 2.0 m were contained within the Gascoyne River channel, while flows with water levels greater than 2.0 m extended beyond the river channel, inundating the surrounding land to some extent. Two typical flow extents, one for a flow contained within the channel and one which extended beyond the channel, were used to categorise flow events. This information was used to estimate groundwater recharge from river flows for varying sequences of river flow events.

The main source of recharge for the older alluvium is vertical and lateral leakage from the overlying riverbed sands during river flows. Recharge of the alluvial aquifer occurs predominantly as a result of significant river flow events generated from heavy rainfall received inland. This results in the formation of a freshwater lens within the aquifer system overlying saline 176mS/m EC at 25^{0}C–1146.5mS/m EC at 25^{0}C water (Dodson 2009).

In a highly variable system such as the Lower Gascoyne, the volume of groundwater recharge may change significantly each year. Groundwater recharge as a function of river flow was estimated for the Lower Gascoyne system using the GASFAMS V1.1 groundwater model.

Rainfall recharge

Recharge from direct rainfall only accounts for a small proportion of total recharge. Rainfall must be greater than 38 mm/month to produce any recharge to the Gascoyne alluvial aquifer, as evidenced by observed changes in water levels (Allen 1972). To estimate the amount of recharge as a result of direct rainfall, rainfall was plotted against river water levels to identify periods of rainfall which did not result in a river flow (Figure 8).



Source: CyMod 2010

Figure 8 Rainfall and flow stage height

From 1991 to 2008 there were only four rainfall events of greater than 38 mm/month without river flow. This indicates that most recharge is linked to river flow events rather than local rainfall. This is supported by Dodson (2002) who estimated that recharge as a result of direct rainfall is between 1% and 5% outside the river bed sands. Consequently, we did not consider recharge as a result of direct rainfall in the calculation of net recharge.

Groundwater modelling

Groundwater models for the unconfined aquifers within the plan area have existed since 1975.

The Gascoyne River floodplain aquifers modelling system (GASFAMS V1.1), a groundwater flow and solute transport model of the Lower Gascoyne River, was developed and is the model currently used by the Department of Water.

The original version of the model was based on the data contained in an earlier groundwater model of the region (GRFAMOD). GASFAMS V1.1 was updated to inform this planning process, using:

- Department of Water monitoring and abstraction data since 2001
- Department of Agriculture drilling in the Brickhouse Station area (Global Groundwater 2005)
- licensee monitoring and abstraction data since 2001.

Further detail on GASFAMS V1.1 is contained in CyMod (2009 and 2010).

2.5 In situ water requirements

We need to keep water in the system (in situ water) to maintain ecological, social, cultural values and the integrity of the aquifer.

Riverbank vegetation

The riverbank vegetation is an important ecological community in the region. It is significant to the river geomorphology (e.g. for stabilisation of banks, windbreak and stabilisation and enrichment of soils) and as habitat for other ecological species.

The dominant vegetation is river red gums *(Eucalyptus camaldulensis)* (SMEC 2001). No field investigations have been undertaken to accurately characterise the specific water sources and requirements of the river red gums in the Lower Gascoyne region. The characteristics of river red gums may vary between sites but we can use results from studies in other areas to help us understand how the river red gums might obtain their water and behave when stressed.

During sustained drought when soil water is not available, river red gums are reliant entirely on groundwater to meet their water requirements. The ability of river red gums to continue to draw water from groundwater when levels are declining depends on the:

- rate of decline
- absolute minimum groundwater levels in the system (including frequency and duration)
- average groundwater levels in the system
- resilience of the vegetation (vegetation condition) and morphological adaptations that reduce water use.

Historically, signs of stress have been evident in the vegetation along the river, initially as wilting and yellowing of leaves, followed by leaf drop (SMEC 2001).

River red gums in other locations are able to use saline water sources (3865mS/m EC at 25^{0}C to 11632mS/m EC at 25^{0}C) (Mensforth et al. 1994). This may provide the riparian vegetation in the Lower Gascoyne with a degree of resilience should salinity levels increase in the groundwater sources it depends on.

Gascoyne River pools

Chinaman’s Pool, Rocky Pool and the temporary pools along the river bed are important groundwater-dependent ecosystems (Figure 9). The pools are of high ecological value as they provide a refuge and maintain ecosystems during periods of no flow.

The location of the temporary pools and their extent vary considerably after each river flow event as the distribution of sand shifts during high flows.

Chinaman’s Pool is located in a marginal groundwater area where groundwater abstraction is limited by the 176mS/m EC at 25^{0}C ‘cease pumping’ threshold. At Rocky Pool, the riverbed sand is directly underlain by calcareous mudstone that outcrops either side of the river owing to an anticline. As a result of the low permeability of the mudstone, the surface water pool is likely to be supported by groundwater discharging from the aquifer upstream of Rocky Pool and disconnected from the downstream alluvial aquifer.

Wetlands

The McNeill claypan system is located within the plan area. It is also known as the Nichol Bay Flats. This claypan is listed in the *Directory of important wetlands Australia* (Environment Australia 2001). This system is an example of a freshwater claypan and shrub swamp system in the arid zone. The *Australian Natural Resource Atlas* (DEWHA 2007) indicates that McNeil claypan is in a 'fair condition', but rapidly declining, with recovery requiring 'significant intervention'. Although this system was thought to be dominated by surface water processes, some of the vegetation types that occur in this area are known to be groundwater dependent.

Salt water movement

Salt water may move into the freshwater Lower Gascoyne alluvial aquifer from areas of higher salinity along the coastal saltwater interface. Due to the influence of abstraction, high salinity water may also be drawn into the freshwater lens along the length of the Lower Gascoyne River. The salts are moved outwards and away from the river through the aquifer when a river flow recharges the system. The distance the salts are displaced depends on the size and duration of the recharge event.

Electrical conductivity (EC) or its equivalent total dissolved salts (TDS) were modelled in GASFAMS V1.1. When modelling the system, water with salinity greater than 176mS/m EC at 25^{0}C in subarea A and 146.5mS/m EC at 25^{0}C in subarea B–L was left in situ to protect the ongoing viability of the resource. Although these salinity thresholds protect the resource and reliability of supply of fresh water against major movement of the saltwater interface and saline intrusion, some movement is likely.

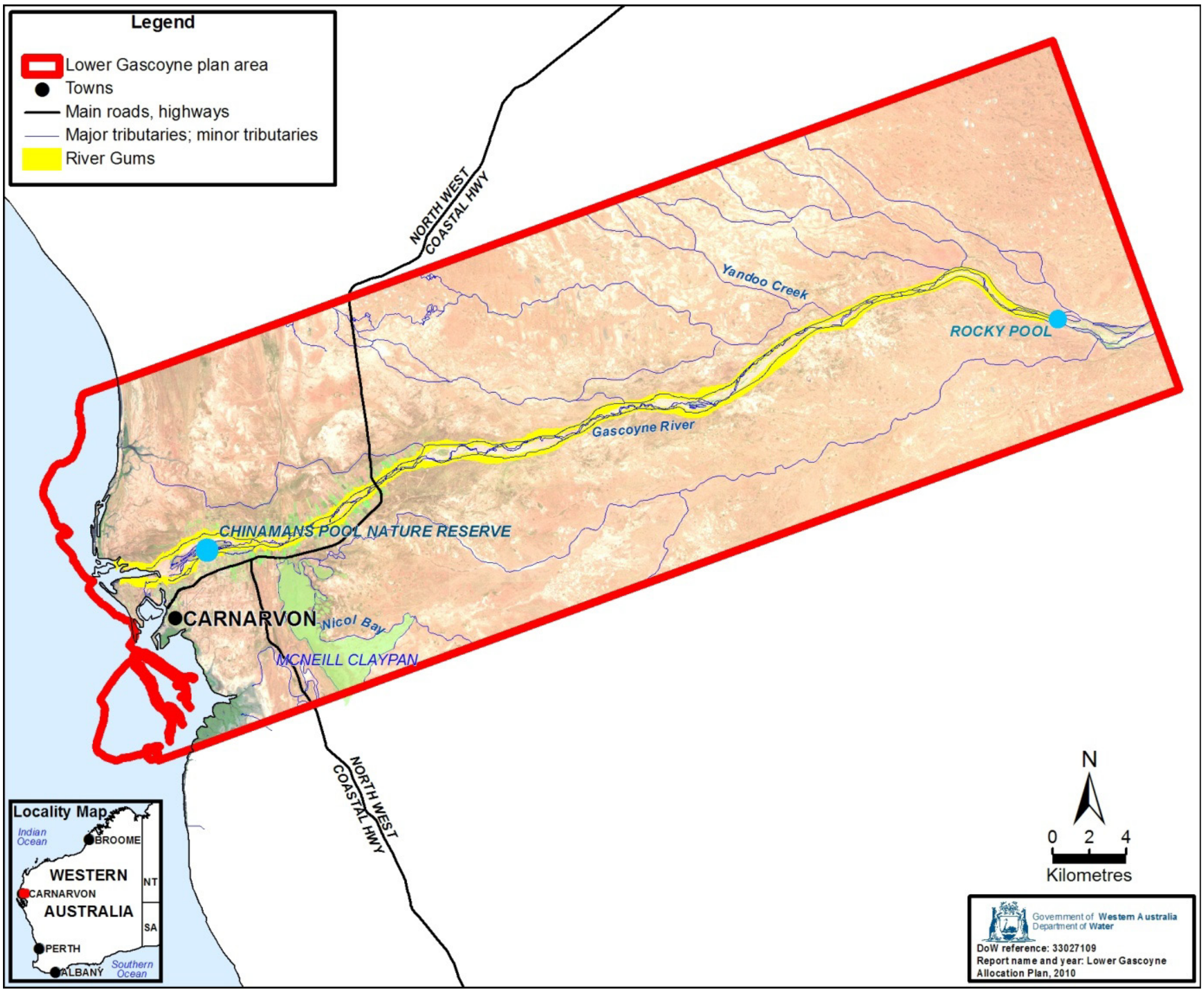


Figure 9 Pools and wetlands in plan area

Social and cultural values

The social and cultural values are mainly associated with the riverbank vegetation and pools as discussed above.

The riverbank vegetation and the pools have high social value due to their recreational and aesthetic importance to the Carnarvon community. No comprehensive studies have been undertaken into the specific services and amenity value they provide.

The Gascoyne River is of significance to the local traditional owners. Yamatji Marlpa Aboriginal Corporation (YMAC) is the native title representative body for the traditional owners in the plan area. The environment and the river specifically are important in Aboriginal culture. Sites of specific importance include:

- near the old Carnarvon reserve on the south bank of the Gascoyne River
- Lewer Road reserve
- McNeill claypan
- Chinaman's Pool (SMEC 2001).

2.6 Water use information

How water is abstracted and used (current demand)

Licensed abstraction

The taking of water (abstraction) in the plan area is licensed by the Department of Water's Gascoyne Licensing Group, based in Carnarvon. There is one licence for 60 000 kL/yr for surface water. There have been 158 licences issued in the plan area totalling approximately 15.5 GL/yr for groundwater, including 1.8 GL for public water supply (excluding temporary drought allocation in subarea B-L allowable under 2004 Lower Gascoyne management strategy). The main uses are irrigated horticulture and public water supply.

The total of licensed entitlements and actual abstraction is shown in Table 6.

Groundwater in subarea A is abstracted from privately owned wells or spear points for plantation irrigation under individual Department of Water licences. Growers who have access to river front prolongations are also licensed by the department to take water from private bores located within these. The current allocation limit for subarea A is 5.8 GL. Subarea A is currently over-allocated (10.7 GL) but not overused (4.9 GL abstracted in 2009 during restricted period).[2]

The borefield in subarea B–L is currently operated by the Water Corporation. Water is delivered to the plantations and other landholders by the Gascoyne Water Cooperative under a bulk water supply agreement. In 2010 irrigation water was delivered to approximately 170 cooperative members. The majority of these cooperative members also self-supply from subarea A.

In 2009 the total of licensed for abstraction in subarea B–L for irrigation purposes was 5.0 GL and 1.8 GL for town water supply. The current allocation limit for subarea B-L is 12.2 GL, which may be increased to 18.0 GL during drought. This system is currently approaching full allocation.

[2] 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 (NWC 2004)

.

Table 6 Licensed water entitlements and actual abstraction

Resource	Licensed entitlements kL	2009 actual use kL
Lower Gascoyne alluvial subarea A	10 700 000	10 970 000*
Lower Gascoyne alluvial subarea B–L	6 800 000	7 530 000
Carnarvon surface water irrigation district	70 000	6703

** 6 000 000 kL of abstraction occurred during unrestricted pumping period s and 4 970 000 kL of abstraction occurred during restricted pumping periods. Unrestricted pumping is declared at the department's discretion when continuous flow is measured at the department's Nine Mile Bridge gauging station. Water abstracted during a declared unrestricted pumping period does not count towards the licensee's annual entitlement and is not limited by monthly abstraction limits.*

Unlicensed abstraction

When allocation limits are set they need to include all use, not just licensed. This means we must account for water abstraction that is exempt from licensing. This includes water taken:

- for riparian rights or stock and domestic use only (such as water for household purposes and non-intensive stock watering)
- from springs and wetlands wholly within a property
- from streams arising on a property
- in unproclaimed areas.

For the resources covered by this plan, it is estimated that there is no unlicensed water abstraction.

Public water supply

In 2009 the Water Corporation abstracted 1.35 GL out of its 1.8 GL licensed volume for public water supply for the town of Carnarvon. Carnarvon is a single source scheme.

Future demands

Gascoyne Foodbowl Initiative

In 2008 a Ministerial Reference Group was established to help implement the Gascoyne Foodbowl Initiative. The Gascoyne Foodbowl Initiative has two main components:

- expansion of the Carnarvon horticultural district
- pastoral industry development using Carnarvon Basin artesian water sources.

The Department of Water is a technical advisor to the local consultative committee whose terms of reference are to explore the Carnarvon horticultural district expansion component. The department supports the expansion of the horticultural district by providing advice and direction for the project in relation to water availability and water management issues. The expansion of the Carnarvon horticultural district has implications for the future water demand in the plan area.

One of the main reasons for this plan review was to confirm if additional volumes of water are available to support the expansion of the area under irrigation. Exploratory drilling outside the public drinking water protection area on the northern side of the river was undertaken by the Department of Agriculture and Food in 2006. This data has been incorporated into the GASFAMS V1.1 model that we used set the allocation limits. Further exploratory drilling was undertaken closer to the river in 2010. We expect the results to provide improved understanding of the aquifer parameters in this area which will improve our estimate of the amount of available water. The allocation plan contains an implementation action to review allocation limits should new information indicate a significant change to the estimated yield range (See Section 6*, Lower Gascoyne allocation plan for public comment*).

Town water supply

The earlier report, *Managing groundwater resources of the Lower Gascoyne River (Carnarvon) WA – groundwater management strategy* (WRC 2004), sets aside 1.8 GL of water as a reserve for future public water supply, based on estimated town growth.

Sufficient water must be reserved for future growth. Population growth for the region has been approximately 1% per year (ABS 2010). The department will maintain an adequate reserve for future public water supply as regional centres such as Carnarvon may experience significant and rapid growth due to increased industrial or mining activity in the region.

3 Yield estimate

3.1 What is yield?

The yield is the volume of water that can be abstracted from a particular system that, if exceeded, would compromise environmental assets, or ecosystem functions and the long-term viability of the resource.

3.2 Selecting the method for determining the yield estimate

Using GASFAMS V1.1 there were two possible options for estimating the yield from the Lower Gascoyne alluvial aquifer (Table 7).

Table 7 Yield method options

Yield method option	Description	Assessment
Scenario modelling	Specific abstraction and management regime scenarios	• Gives a point yield with no indication of how often this is likely to be able to be drawn. • Highly dependent on recharge sequence selected for scenario.
Statistical reliability modelling	Generation of random recharge sequences to determine yield estimates with statistical probabilities	• Better reflects the natural variability of the system. • Allows reliability of supply to be quantified.

Due to the highly variable nature of this system, we have determined a yield range using statistical reliability modelling rather than a estimating a single value. We still used scenario modelling, however, to improve the reliability of the modelling and to test specific local licensing rule options.

3.3 How did we estimate the yield range?

The approach aims to determine the probability of being able to abstract a given volume of fresh water (less than 176mS/m EC at 25^0C) from each of the areas in the Lower Gascoyne system in any given year.

To achieve this, scenarios were run based on varying recharge events, abstraction, infrastructure and pump rate regimes. Assuming a normal probability, distribution statistical probability curves were generated for a given level of abstraction being exceeded (Figures 10 and 11). See CyMod (2010) for details of the scenarios and results.

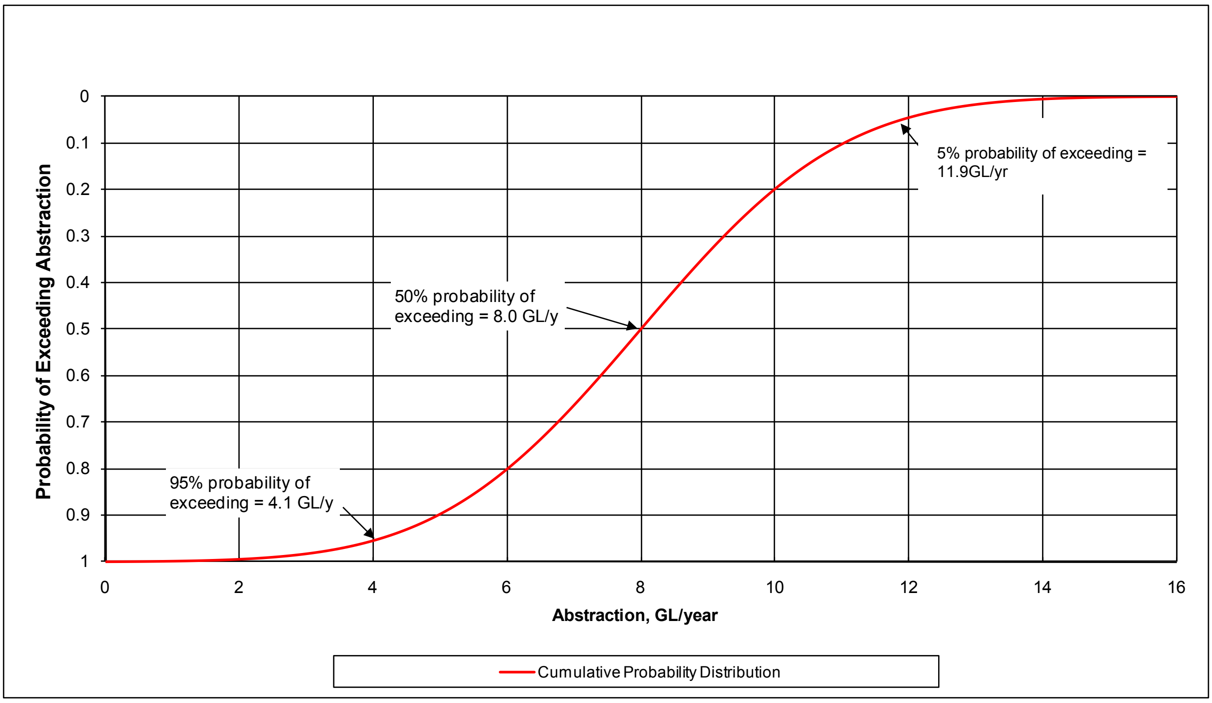


Figure 10 Subarea A probability curve for the yield range

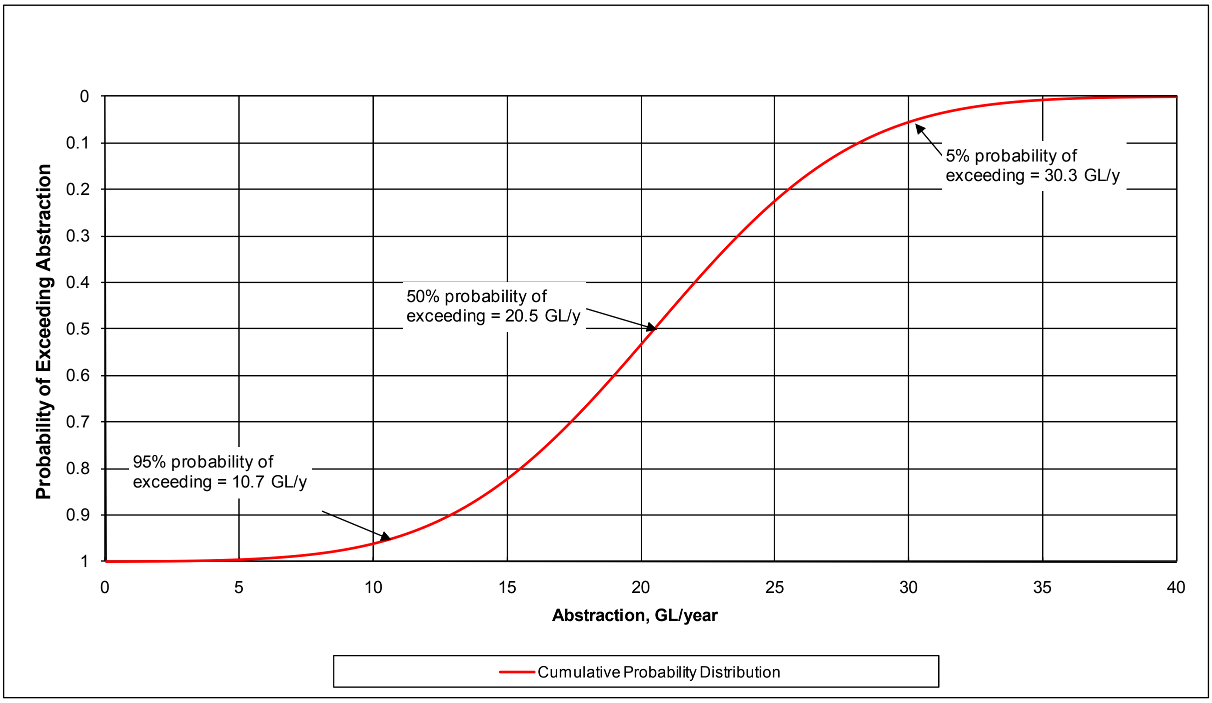


Figure 11 Subarea B–L probability curve for the yield range

Based on the probability distribution curves the yield ranges for the Lower Gascoyne plan area are:

- Subarea A 4.1 GL – 12.2 GL
- Subarea B–L 10.7 GL – 30.3 GL

There is a higher level of uncertainty in the probability predictions for subarea B–L due to a lower level of drilling and monitoring data. For the yield range to be refined, additional drilling and monitoring data would be needed to allow us to understand how the system responds to stress.

3.4 Climate scenario used to determine yield range

The yield range for the Lower Gascoyne alluvial aquifer was modelled on the basis of the historical climate conditions and groundwater recharge events (river flow). The GASFAMS V1.1 groundwater model was calibrated from 1991 to 1999 and the scenarios utilised recharge sequences based on climatic data since 1991. A long-term shift to drier or wetter years, and the occurrence of extreme rainfall events within the upper Gascoyne River catchment, could affect the river flow patterns and recharge characteristics that would ultimately alter the availability of groundwater to the Carnarvon horticultural district. Climate variability may affect the availability of water in the future and may result in an adjustment to the volume of water available for allocation in the Lower Gascoyne plan area.

3.5 How were in situ values considered when determining the yield range?

In situ values were not formally factored into the yield range.

Due to the nature of the in situ values and the information currently available, no volume of water has been set as a water requirement. In situ values will be dealt with through licensing rules.

We manage riverbank vegetation water needs through local licensing water level and water quality rules. This is due to:

- anecdotal evidence that indicates that no tree deaths have occurred historically during periods of low recharge
- thinning of crowns has been observed, indicating that vegetation has become stressed in the past (SMEC 2001).

River gums are moderately salt tolerant (Benyon et al. 1999). The 176mS/m EC at 25^0C salinity limit requires abstraction to cease during prolonged periods of no aquifer recharge, ensuring that sufficient groundwater remains in the system to sustain the moderately salt tolerant vegetation. Evapotranspiration was considered in the GASFAMS V1.1 groundwater model when determining the yield range.

3.6 Confidence in yield estimates

Due to calibration and assumptions inherent in the model, the yield estimates were assessed to be accurate to within +/– 0.5 GL.

4 Allocation limit decisions

4.1 Objectives

We set water resource and water management objectives in water allocation plans to guide us in determining the most appropriate management decisions when setting allocation limits.

Water resource objectives in this plan relate to maintaining surface water flow, groundwater levels and water quality. Detail of the objectives set for each resource may be found in the *Lower Gascoyne allocation plan for public comment* (DoW 2010).

The objectives were developed by a multi-disciplinary team based on the input received through community consultation.

4.2 How did we make the allocation limit decisions?

Surficial resources

It was not possible to accurately estimate a yield due to the variability in this aquifer. Similar surficial resources have very low yields and based on this a nominal allocation limit was set for the surficial aquifer. If further investigations reveal that more water is available from this aquifer the department may review the allocation limit.

Surface water resources

The availability of surface water is highly variable due to the interaction of the four major rain producing mechanisms in the Gascoyne River catchment which have the potential to produce river flows (refer to Section 2). The scale of the river flows means that when the river is flowing we generally encourage the unrestricted take of surface water in preference to using groundwater resources. Due to this variability and our desire to maximise the volume of water available for use we decided to not set an allocation limit for the surface water resource.

Lower Gascoyne alluvial resources

The allocation limits for the Lower Gascoyne alluvial resources were set using an approach consistent with the approach used for other areas of the state, adjusted to take into account the unique circumstances of the plan area (refer to Section 1.4).

A combination of allocation limits and local rules are used to manage abstraction. Water use in subarea A has historically been lower than the allocation limit because it is constrained by salinity. However, use of the salinity rule alone will not protect the resource if abstraction were to increase above the allocation limit.

If abstraction was to increase, local licensing rules such as the salinity threshold (176mS/m EC at 25^0C) would not provide sufficient long term protection for this system from increased salinity. Independent modelling results and historical experience shows that over the long term, abstraction from the system leads to increased salinity. This has already been seen in historical salinity readings which show a long term average increase in salinity. Any abstraction over 6.1GL/yr in subarea A increases the risk of permanent long term increases in salinity levels.

The allocation limit is set to ensure total abstraction is sustainable across the system as a whole, so if this is exceeded it would pose a serious threat to the resource and reliability of supply for horticultural users. Through the community consultation undertaken, there was a strong support for the need for an allocation limit to be set for the alluvial resource.

In making the allocation limit decision for the Lower Gascoyne area we considered the following factors:

- yield estimate
- current abstraction and future demand
- acceptable level of risk to reliability of water supply
- in situ values including risk to the resource
- confidence in yield estimates.

Based on the objectives for the plan area, feedback from consultation, the department's capacity to manage through local licensing rules we decided that the most significant factor to take into account when determining allocation limits was the risk to the reliability of water supply and the long-term risk to the resource (Figure 12).

	Confidence in yield estimate	**Current abstraction and future demand (reliability of supply)**	**In situ values**		
			Riparian vegetation including river red gums	**Saline intrusion and risk to aquifer**	**Pools**
	Best managed to achieve objectives through:				
Allocation limits	●	●		●	
Local licensing rules			●	●	●

Figure 12 Determining the primary factor influencing allocation limits

To decide on the allocation limit we asked the questions:

- What reliability of supply is the community willing to accept?
- If the allocation limit is set at a higher level of risk of increased salinity does the department or the water service provider have the capacity to manage the risks to users and the resource?

Managing to a clear reliability of supply helps inform on-farm water use decisions and assists to ensure the continued economic development of the Carnarvon horticultural industry. Farmers make long-term capital investments that are not easily altered from year to year. Investments in perennial crops, specialised farm machinery and irrigation systems are all examples. Studies have shown that an increase in the reliability of water deliveries can lead to an increase in expected farm profits (Sunding et al 2008).

Table 8 shows the implications of setting the allocation limit based on varying reliabilities of supply.

Table 8 Allocation limit options

Allocation limit option	Effect on licensees	Implications for management	Risk to resource
0 to 80% reliability of supply	Maximises water availability but provides very low level of certainty for business planning.	Very high level of management required.	Unacceptable risk to resource even with very high level of management.
80% reliability of supply	Moderate to high level of certainty for business planning.	Moderate to high level of management required.	Acceptable risk to resource if adequate management process is implemented.
80 to 100% reliability of supply	Does not maximise water availability but provides high level of certainty for business planning.	Low level of management required.	Acceptable risk to resource.

We set the allocation limit at the yield corresponding to an 80% reliability of supply. This is the lowest reliability of supply where the modelling indicates a manageable risk to the resource. This reliability is consistent with feedback received from Carnarvon horticultural district growers who have indicated that they would like a moderate level of certainty that they will be able to receive their full entitlement in most years. In other years their entitlement will still be partly met.

For subarea A, 80% reliability of supply when plotted on the probability curves used to generate the yield range, equates to a yield of 6.1 GL/yr (Figure 13). We set the allocation limit at this yield which is similar to the current allocation limit, so there will be no need for significant changes in the resources and rules needed to manage the system.

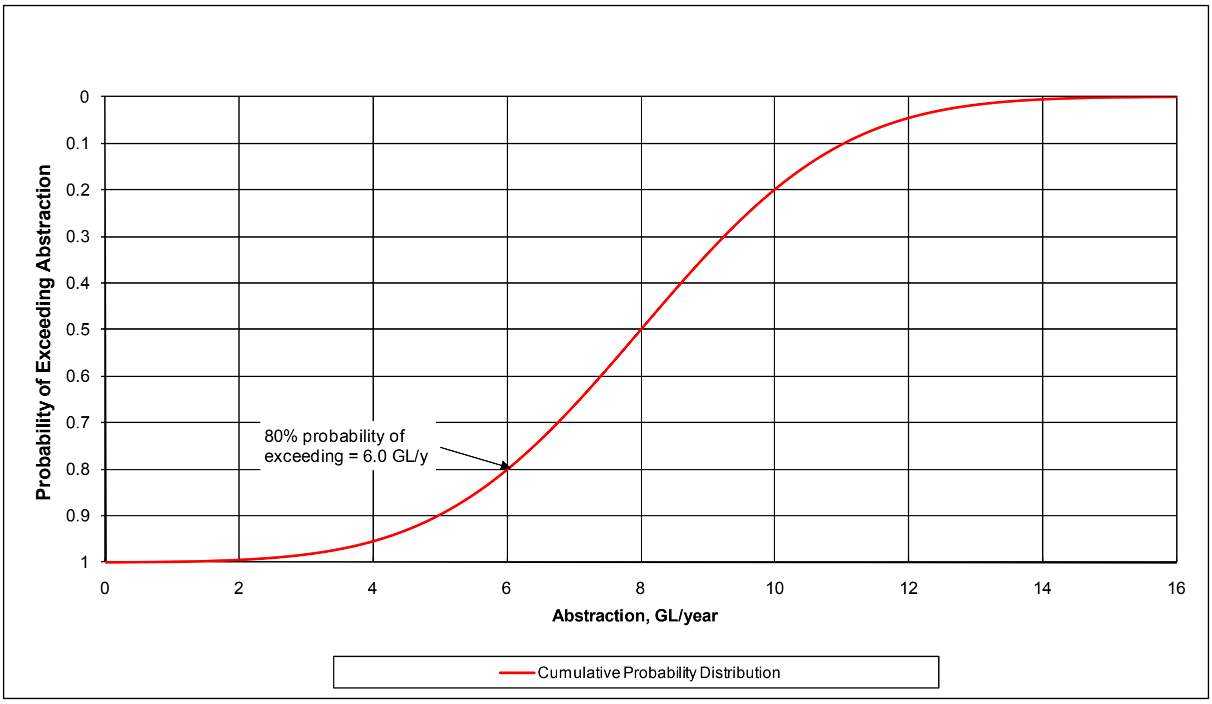


Figure 13 Subarea A allocation limit decision

For subarea B–L, 80% reliability of supply when plotted on the probability curves used to generate the yield range, equates to a yield of 15.5 GL/yr (Figure 14).

When deciding the allocation limit in subarea B–L we had to ensure that we had as close to 100% reliability as possible for the supply of the 3.6 GL/yr of water that is currently licensed and reserved for the town of Carnarvon public water supply. Maintaining reliability for public water supply was the main priority when determining the allocation limit for subarea B–L. There is a 99.8% probability that 3.6 GL/yr will be available in any year.

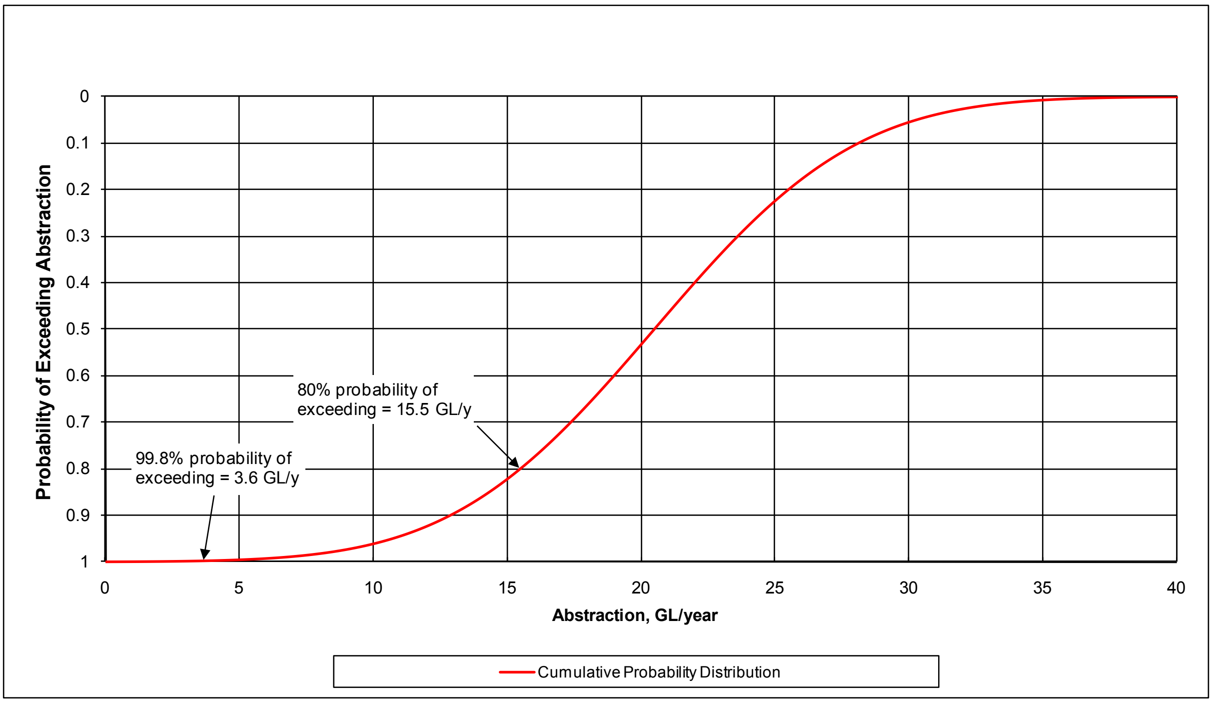


Figure 14 Subarea B–L allocation limit determination

4.3 Summary of allocation limit decisions

The allocation limits set for the Lower Gascoyne plan area are summarised below in Table 9. The yield and allocation limit decisions for each resource are summarised in Table 10

.

Table 9 Lower Gascoyne groundwater and surface water allocation limits

Resource	Allocation limit GL/yr	Allocation limit components GL/yr				
		Licensable		Unlicensable	Reserved water
		General licensing	Public water supply	Unlicensed use	Public water supply
Groundwater resources					
Lower Gascoyne alluvial subarea A	6.1	6.1	0.0	0.0	0.0
Lower Gascoyne alluvial subarea B–L	15.5	11.9	1.8	0.0	1.8
Yandoo surficial	0.1	0.1	0.0	0.0	0.0
Total	**21.7**	**18.1**	**1.8**	**0.0**	**1.8**
Surface water resources					
Carnarvon irrigation district	Not set	–	–	–	–

Table 10 Summary of Lower Gascoyne allocation decisions

Resource	Yield range estimate	Allocation limit decision	Final allocation limit GL/yr
Lower Gascoyne alluvial subarea A	Based on predicted 5th and 95th percentile volumes of fresh water able to be abstracted from subarea A.	Allocation limit based on 80% reliability of supply.	6.1
Lower Gascoyne alluvial subarea B–L	Based on predicted 5th and 95th percentile volumes of fresh water able to be abstracted from subarea B–L	Allocation limit based on 80% reliability of supply.	15.5
Lower Gascoyne surficial	Yield not able to be accurately estimated due to variability in system and predicted very low yields	For management purposes a nominal allocation limit of 0.1 GL/yr has been set to allow for small, localised abstraction from this aquifer.	0.1
Carnarvon surface water irrigation district	Not able to be estimated due to variability of river flows	Not applicable	Not set

5 Defining the management approach

5.1 How did we set the local licensing rules?

The department uses allocation limits to manage the water resources in the plan area at a resource scale to protect the resource. Due to the high variability in the system and the high level of use there is a need to manage some aspects at an individual licence scale through local licensing rules.

The horticultural industry and the department already have rules in place to manage water abstraction and use in the plan area. These were initially recorded in the minutes of the Carnarvon Irrigation District Allocation Committee (since the 1980s) and were first documented in 1998 in *Rules of the river* (CWAAC 1998). The department refined and formalised the local rules for managing the area in *Managing the groundwater resources of the Lower Gascoyne River (Carnarvon) WA – groundwater management strategy* (WRC 2004).

Community feedback and improved knowledge of the system has allowed us to build on these local rules. We also used the GASFAMS V1.1 groundwater model to explore possible effects on the resource if different local rules were implemented.

Local rules complement the department's state-wide strategic and operational policies. The local licensing rules in the *Lower Gascoyne water allocation plan (DoW 2011)* take precedence over state-wide policies in any instance.

Local licensing rules have been proposed to manage the following aspects:

- water accounting year
- metering
- maximum monthly draw limit
- unrestricted groundwater pumping periods
- 26D licence conditions on bore construction
- managing water quality
- water contamination
- groundwater-dependent ecosystems
- using the public water supply reserve for other purposes
- temporary increase to allocation limit in subarea B–L.

More detail can be found in Section 4.4 of the *Lower Gascoyne allocation plan* (DoW 2011).

Glossary

The terms that are used the most in reference to water resource management of the Lower Gascoyne are listed below.

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.
Allocation limit	Annual volume of water set aside for consumptive use from a water resource.
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.
Catchment	The area of land from which rainfall runoff contributes to a single watercourse, wetland or aquifer.
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.
Consumptive use	The use of water for consumptive purposes including public water supply, irrigation, industry, urban and stock and domestic use.
Ecological values	The natural ecological processes occurring within water-dependent ecosystems and the biodiversity of these systems.
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, for example a lake. It includes all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources.
Environment	Living things, their physical, biological and social surroundings, and interactions between all of these.
Evaporation	Loss of water from the water surface or from the soil surface by vaporisation due to solar radiation.
Flow	Streamflow. May also be referred to as discharge.
GASFAMS V1.1 model	Numerical groundwater model used to predict changes in water quality and quantity under varying conditions.

GRFAMOD	Model developed for the Lower Gascoyne River Floodplain by Dodson in 2002. It is a MODFLOW96 flow model and is the basis for the current modelling of the aquifer system.
Groundwater	Water which occupies the pores and crevices of rock or soil beneath the land surface.
Groundwater-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.
Groundwater recharge	Water that infiltrates into the soil to replenish an aquifer.
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.
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.
In situ values	The ecological, social, cultural and resource values supported by natural hydrological and hydrogeological processes.
Licence	A formal permit which entitles the abstraction of water from a watercourse, wetland or underground source.
Non-artesian well	A well, including all associated works, from which water does not flow, naturally to the surface but has to be raised, by pumping or other artificial means.
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 set level of abstraction for that system.
Recharge	*See* Groundwater recharge.
Reliability	The frequency with which water allocated under a water licence is able to be supplied in full. Referred to in some instances as security.
Self-supply	Water diverted from a source by a private individual, company or public body for their own individual requirements.

Salinity The measure of total soluble salt or mineral constituents in water. Water resources are classified based on salinity in terms of electrical conductivity (EC) or total dissolved salts (TDS).

Social value A particular in situ quality, attribute or use that is important for public benefit, welfare, state or health (physical and spiritual).

Social water requirement Elements of the water regime that are needed to maintain social and cultural values.

Subarea A subdivision within a surface or groundwater area, defined for the purpose of managing the allocation of groundwater or surface water resources. Subareas are not proclaimed and boundaries can therefore be amended without being gazetted.

Surface water allocation subarea Areas within a surface water allocation area defined by the Department of Water, used for water allocation planning and management that are generally hydrologic catchments.

SURFACT – MODFLOW A powerful three-dimensional finite-difference flow and transport program. It is designed to handle complex saturated and unsaturated subsurface flow and transport processes, and addresses the many limitations and short-comings of the standard MODFLOW code.

Sustainable yield See *Yield*

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.

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 any thing referred to in paragraph (a), (b) or (c).

From the *Rights in Water and Irrigation Act 1914*.

Water entitlement The quantity of water that a person is entitled to abstract annually in accordance with the *Rights in Water and Irrigation Act 1914* on a licence.

Water regime	A description of the variation of flow rate or water level over time. It may also include a description of water quality.
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.
Watertable	The saturated level of an unconfined groundwater. Wetlands in low-lying areas are often seasonal or permanent surface expressions of the watertable.
Wetland	Wetlands are areas that are permanently, seasonally or intermittently waterlogged or inundated with water that may be fresh, saline, flowing or static.
Yield	The yield is the level of water abstraction from a particular system that, if exceeded, would compromise in situ values.

Volumes of water

One litre	1 litre	1 litre	(L)
One thousand litres	1000 litres	1 kilolitre	(kL)
One million litres	1 000 000 litres	1 megalitre	(ML)
One billion litres	1 000 000 000 litres	1 gigalitre	(GL)

List of shortened forms

ABS	Australian Bureau of Statistics
BoM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEWHA	Department of Environment, Water, Heritage and the Arts
DoW	Department of Water
NWC	National Water Commission
WRC	Water and Rivers Commission

References

Australian Bureau of Statistics 2010, *Regional population growth, Australia, 2008-09*, Australian Bureau of Statistics, Canberra.

ALLEN, AD 1972, *Results of Investigation into groundwater resources along Lower Gascoyne River for Carnarvon irrigation and town water supplies*, record 1972/9, Geological Survey of Western Australia, Perth.

Benyon, RG, Marcar, NE, Crawford, DF & Nicholson, AT 1999, 'Growth and water use of *Eucalyptus camaldulensis* and *E. occidentalis* on a saline discharge site near Wellington, NSW, Australia', *Agricultural Water Management* 39, pp. 229–44.

Bureau of Meteorology 1998, *Gascoyne Murchison climate survey*, Bureau of Meteorology.

——2010, *Climate of Carnarvon*, Bureau of Meteorology, viewed 21 August 2010, <www.bom.gov.au/wa/carnarvon/climate.shtml>.

Carnarvon Water Allocation Advisory Committee (CWAAC) 1998, *Rules of the river,* Carnarvon Water allocation Advisory Committee. Draft.

Commonwealth Scientific and Industrial Research Organisation & BoM 2007, *Climate change in Australia: technical report 2007,* CSIRO.

CyMod Systems Pty Ltd 2009, *The development of the Gascoyne River floodplain aquifers modelling system GASFAMS V1 Volume 1*, prepared by CyMod Systems Pty Ltd for the Department of Water, Perth.

——2010, *The assessment of groundwater resources of the Gascoyne aquifer system using GASFAMS V1.1,* prepared by CyMod Systems Pty Ltd for the Department of Water, Perth.

Department of Environment, Water, Heritage and the Arts 2007, Australian Natural Resource Atlas *Biodiversity Assessment – Carnarvon: Wetlands,* Department of Environment, Water, Heritage and the Arts, <www.anra.gov.au/topics/vegetation/assessment/wa/ibracarimpwetlands>. November 2010.

Dodson, WJ 2001, *Basin A water quality review, Lower Gascoyne River*, Hydrogeological report 192, Water and Rivers Commission, Perth.

Dodson, WJ 2002, *Groundwater recharge from the Gascoyne River, Western Australia*, Hydrogeological report 204, Water and Rivers Commission, Perth.

Dodson, WJ 2009, *Groundwater recharge from the Gascoyne River, Western Australia*, Hydrogeological record series, report no. 32, Department of Water, Perth.

Department of Water 2007, *Carnarvon Artesian Basin water management plan*, Water Resource Allocation and Planning Series Report no. WRAP 24.

——2010a, *Lower Gascoyne groundwater and surface water allocation plan – draft for public comment*, Water resource allocation planning series, Department of Water, Perth.

——2010b, *Carnarvon water reserve drinking water source protection plan: Carnarvon town water supply,* Water resource protection series, report no. 119, Department of Water, Perth.

——2011a, *Lower Gascoyne water allocation plan*, Department of Water, Perth.

——2011b, (in prep) *Lower Gascoyne River monitoring program*, Department of Water, Perth.

Environment Australia 2001, *A directory of important wetlands in Australia*, 3rd edn, Environment Australia, Canberra.

Global Groundwater 2005, *Brickhouse drilling bore completion report*, Department of Agriculture, Perth.

Hydrosolutions 2009, *Conceptual hydrogeology – Gascoyne River floodplain aquifer modelling system*, Report prepared for Cymod Systems, Perth.

Martin MW 1990a, *Carnarvon irrigation scheme recharge and salinity investigation well completion report*, Hydrogeology report no. 1990/10 (unpublished), Geological Survey of Western Australia, Perth.

—— 1990b, *Groundwater resources of the older alluvium, Gascoyne River, Carnarvon, Western Australia*, Hydrogeology report no. 1990/21 (unpublished), Geological Survey of Western Australia, Perth.

Mensforth, LJ, Thorburn, PJ, Tyerman, SD & Walker, GR 1994, 'Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater, *Oecologia* 100, pp. 21–8.

National Water Commission 2004, *Intergovernmental agreement on a National Water Initiative*, National Water Commission, Canberra.

Skidmore, DJP 1997, *Carnarvon irrigation scheme, review of monitoring requirements*, Hydrogeology report no. 91 (unpublished), Water and Rivers Commission, Perth.

SMEC 2001, *Ecological water requirements for the Lower Gascoyne River final report*, prepared for the Waters and Rivers Commission, SMEC Australia Pty Ltd.

Sunding, D, Zilberman, D, Moreno, G & Osgood, D 2008, *Valuing investments in water supply reliability*, viewed 13 November 2010, <http://are.berkeley.edu/~sunding/Valuing_Investments.pdf>.

Water and Rivers Commission 2004, *Managing the groundwater resources of the Lower Gascoyne River (Carnarvon) WA – groundwater management strategy*, Water and Rivers Commission, Perth.

RECYCLED CONTENT

Department of **Water**
168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842
Phone: 08 6364 7600
Fax: 08 6364 7601
www.water.wa.gov.au