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A report on the Gascoyne River catchment following the 2010/11 flood events

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Department of Agriculture and Food

CARING FOR OUR COUNTRY

Cover picture: *Gascoyne River mouth sediment plume – 10.00 am, 22 December 2010*. Image processed and enhanced by Landgate, Satellite Remote Sensing Services; *Erosion cell.* Photo: P Waddell; *Flooding through Carnarvon horticultural district.* Source: Unknown.

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All photographs are of the Gascoyne River catchment. Photographs were taken by the authors principally during field work in June and August 2011; where there are exceptions the photographer is acknowledged in the caption. Aerial photography provided by and with the permission of the Western Australian Land Information Authority trading as Landgate.

Finally, the authors appreciate the hospitality extended by pastoralists of the area. Without this logistical support the project would have been all the more challenging.

Executive summary

Context and scope

The Gascoyne River catchment is located in the mid north-west of Western Australia. The catchment covers an area of about 80 400 km^2. The native vegetation primarily consists of scattered perennial shrubs of various genera amongst a very scattered acacia overstorey, and supports an extensive pastoral industry. Near the town of Carnarvon on the river levee and floodplain delta there are about 1000 ha of irrigated horticulture.

In December 2010 an extreme tropical storm resulted in widespread flooding at Carnarvon and across the catchment. Another two flood events followed during the summer of 2010–11. At the time of the floods the catchment was considered to have been in poor condition with low vegetative groundcover following an extended period of dry seasons, in combination with a legacy of historic overgrazing and continuous stocking despite seasonal conditions. The flooding resulted in significant soil erosion and damage to infrastructure in the towns of Carnarvon and Gascoyne Junction, as well as the horticulture area. The damage bill was estimated at $90 million.

The rationale for this assessment is to provide illustrative evidence on the role that perennial vegetation groundcover management has in influencing the risk of flooding and soil loss in the catchment. It may be possible that the impact of flooding associated with extreme storm events can be reduced. This report focuses on catchment condition and is not a review of the pastoral industry's economic viability.

Definition of groundcover and catchment condition

In the context of this report groundcover refers to the presence of perennial vegetation. Annual vegetation was not assessed as it is spatially and seasonally variable, and typically does not persist in summer when most flooding is known to occur. Other non-woody cover (cryptogams, dead vegetation and litter) was assessed at the Western Australian Rangeland Monitoring System (WARMS) sites, though this is a relatively small component of groundcover within the Gascoyne River catchment.

Rangeland condition categories (good, fair, poor) are defined in Payne et al. (1987) and Appendix 3.1. Poor condition rangeland in the Gascoyne River catchment typically has low to nil perennial vegetation groundcover and some degree of soil loss, as shown in examples below, and in Section 3.

Poor condition stripped sand sheet

Poor condition duplex surface stripped by sheet flow

Objectives

This project, which was jointly funded through the Department of Agriculture and Food, Western Australia (DAFWA) and the Australian Government's Caring for Our Country has three objectives:

I. Assessment of the influence of catchment condition or perennial vegetation groundcover on downstream flooding in the Gascoyne River catchment

II. Assessment of the influence catchment condition or perennial vegetation groundcover has on soil erosion in the Gascoyne River catchment

III. Provision of illustrative evidence on the role perennial vegetation groundcover has in reducing the risk of soil loss for different rangeland landscapes.

Methods

To context the flooding and erosion events, descriptions of weather events and rainfall records were sourced from the Bureau of Meteorology (BoM). The magnitude and characteristics of the December 2010 flood, along with previous flood events, were compared using hydrographs obtained from the Department of Water (DoW). A qualitative assessment of soil loss was based on plume areal extent at the mouth of the Gascoyne River using MODIS satellite data and estimates of the plume sediment load.

Prior to undertaking field work, DAFWA conducted an analysis of existing information and data sets relevant to the catchment. Landsat and NOAA NDVI satellite imagery was used to assess trends in perennial vegetation cover and pastoral lease inspection traverse information to review past vegetation condition assessments. Between June and August 2011 officers from DAFWA undertook an assessment of the present condition of the mid to upper Gascoyne River catchment, primarily east of Gascoyne Junction. Survey teams collected data at 96 long-term monitoring sites (WARMS) on perennial plant numbers and landscape function. In addition soil infiltration rates were measured at 50 sites, and were used to assess the relative importance of perennial vegetation cover and soil texture on infiltration rates.

Whilst on route to WARMS sites and areas of interest, predetermined using aerial photography, traverse notes and photographs were compiled to formulate an overall perspective of catchment condition and to assess and describe erosional features. Experienced rangeland advisers based the assessment of catchment condition on subjective visual assessments in accordance with condition categories defined in Payne et al. (1987).

Key findings and issues

- *A record storm and flood resulting in high sediment loss*

  The tropical storm that crossed over the Gascoyne River catchment between 16 and 19 December 2010 resulted in falls in excess of 250–300 mm over a 24-hour period, the highest on record. The record rainfall brought record flooding with the peak at 7.77 metres at Nine Mile Bridge, near Carnarvon. The previous high was 7.63 metres in 1960, followed by 7.6 metres in 2000 (BoM, DoW).

  Soil erosion estimates indicate that the soil loss was substantial; the total mass of suspended solids in the December flood could have been at least 5 625 000 tonnes. The sediment plume for the December 2010 flood was two to seven times larger than other recent flood events. Examples of erosion described in Section 3 of the report, coupled with data from long-term monitoring sites and earlier published reports indicate that accelerated erosion has been occurring in the catchment at least since the 1960s.

- *The Gascoyne River catchment is in poor condition with reduced groundcover (perennial vegetation)*

  The Gascoyne River catchment is in poor condition (characterised by loss of cover, few perennial plants and ongoing soil loss) and has been in poor condition at least since the 1960s and possibly the 1930s (Wilcox & McKinnon 1972; Jennings et al. 1979; Williams, Suijdendorp & Wilcox 1980; House et al. 1991; Hopkins, Pringle & Tinley 2006); many areas are continuing to decline.

  Over 3.6 million hectares were assessed as being in poor condition for the years 2002 to 2009, with a 15% decline in perennial shrubs in the last five years. This was characterised by a 39% decline in the perennial plant numbers recorded in the above average seasons of 1995 to 2000, reduced resource capture (13% decline overall and 22% decline in mulga groves/run-on sites) and an increase in erosion features. Generally the overall trend in vegetation cover (1989 to 2010) was stable, thus areas that were assessed as poor condition since 1989 are still in poor condition. However, large contiguous areas are declining in cover between the central Gascoyne and Lyons rivers with plant numbers in 2011 declining to 1995 levels.

Poor condition, eroded interpatch

Poor condition fragmented sand bank surrounded by eroded and scalded surfaces

- *A series of poor seasons were coupled with continuous stocking*

  Satellite images and rainfall records (BoM) indicate that the seasonal conditions had been poor for four or more years prior to the December 2010 flood. A low greenness index at the time of the flood indicates that the groundcover was also low. Nevertheless, the sequence of poor seasons coupled with the practice of continuous stocking through consecutive dry years (Annual Return of Livestock and Improvement forms, Pastoral Lands Board of Western Australia), in excess of the carrying capacity of the resource (Wilcox & McKinnon 1972; Payne, Curry & Spencer 1987), has contributed to the poor condition of the catchment.

- *Catchment condition (and perennial groundcover) may impact flooding*

  Vegetation, groundcover and obstructions are fundamental to reducing sheet flow and erosion (Coles & Moore 1968; Tongway & Ludwig 1996, 1997). However, it is difficult to determine to what degree groundcover and catchment condition contributed to the Gascoyne River 2010–11 summer floods.

  Analysis shows that several major floods, with similar characteristics to the December 2010 flood, have been associated with substantial rainfall events since 1960. This suggests the catchment has not changed substantially since the 1960s. As discussed above, the catchment was in poor condition at the time of the December 2010 flood, and it is likely to have been since at least the 1960s. Such is the poor state of the catchment that despite the decline in plant numbers over the last five years it is probable that this decline would have only a minor influence on major flood events.

The catchment is naturally a high water shedding catchment. Infrequent vegetated zones, 'patches', which capture water and nutrients and moderate run-off are sparse and interspersed between sparsely vegetated areas, 'interpatches'. The ratio of interpatch to patch density is estimated at 88:12. The soil infiltration rates in the patches were about fourfold higher than the interpatches. The presence of vegetation had a greater impact on infiltration rates than soil texture alone. Increasing the number of patches through plant abundance and litter obstructions would likely increase infiltration capacity over time, reduce run-off and therefore the likelihood of flooding.

However, irrespective of infiltration rates, the magnitude of the December rainfall event was such that the subsurface and surface storage capacities of the soil would have been exceeded on the interpatches. The soils are generally shallow, frequently less than 30 cm deep, often consist of a sandy loam over clay, hardpan or weathered rock. Assuming a total soil water storage of 60 mm, the December rainfall event exceeded this amount by at least three to five times.

Nevertheless, it is likely that a catchment in better condition (more perennial groundcover) will likely reduce the severity of flooding from minor and moderate storms.

- *Erosion is associated with loss of perennial groundcover in different landscapes*

  Hills and ranges, despite their relief, have a lower susceptibility to accelerated erosion due to the protection offered by their abundant stony mantle. However, they do shed a significant volume of water from their surfaces, and thereby still contribute to erosion problems within adjacent landscapes. In comparison, the slopes of mesas and breakaways generally lack a stony armouring and are typically severely degraded. This is due to overgrazing of smaller areas of highly attractive forage within larger less palatable pasture units. This results in these features also contributing to erosion problems in the catchment.

  Within the upland areas the drainage flats provide the most valued pastures, occurring as inclusions within less attractive pasture types. Chenopod communities formerly occupied sites of restricted drainage; however, excessive grazing pressure has largely reduced these areas to unpalatable shrubs and seasonally dependent ephemeral species. Along the valley floors and in the drainage foci, where vegetation loss has been considerable, channelisation as rill and gully erosion encourages water shedding. From these drainage areas increased discharge is affecting downstream landforms.

  Downslope of the upland areas the landscape is dominated by extensive sheet wash plains. Here, especially during dry periods, it is the vegetation groves and bush clumps that provide sources of browse. Over-utilisation has increased run-off from upper slopes, causing soil instability and disrupting water flow and nutrient cycles. Overgrazing of wanderrie bank communities has reduced the perennial grass component to such an extent that the low strata of many sandy banks now only supports annual grasses such as wind grass (*Aristida contorta*) and annual wanderrie grass (*Eriachne aristidea*).

  A significant problem within the catchment is the disruption to surface hydrology by infrastructure (e.g. roads, tracks, fence lines). Where vegetation cover is drastically reduced infrastructure initiated erosion problems have a considerable impact on general rangeland condition.

Riparian pasture productivity is highly variable. Initial settlement of the Gascoyne River catchment was along the river, with stock reliant on river pools and natural springs. Consequently, many riparian pastures are overgrazed and degraded. Where buffel grass has become established, it has a significant role in stabilising surfaces and preventing further erosion. In addition, buffel grass colonisation has increased the productivity of some riparian pastures in favourable seasons. However, stock numbers in favourable seasons are often above that which the surrounding native vegetation can support in the absence of buffel grass (Wilcox & McKinnon 1972; Payne, Curry & Spencer 1987). With the onset of dry conditions the protein content of buffel grass declines and livestock seek supplementary forage. Stock migrate upslope and fertile patches become the primary browse source. Without appropriate stocking rates fertile patches are over-utilised, leading not only to their deterioration as a forage source but also their capacity to retain water. This reduces their resource capture role and contributes to escalating erosion downslope.

The reduction in vegetation cover (Section 2.2.2.2) has reduced the landscape's capacity to retain water (Section 2.2.3). Run-off and erosion potential have increased, resulting in erosion cell development. Consequently, the Gascoyne River catchment is locked in the feed-back loop of an erosion cycle. The loss in capacity to retain water drives the desiccation process, reducing vegetation cover. The cycle will continue until new base levels are reached in equilibrium with erosive processes.

Conclusions

Large areas of the catchment are water shedding with very shallow soils with limited storage capacity. However, a major flood would likely have occurred regardless of the catchment condition, perennial vegetation groundcover or infiltration rates as these landscapes would have been overwhelmed by the December 2010 rainfall event.

Erosional features are widespread throughout the Gascoyne River catchment and have increased over the monitoring period but cannot necessarily be attributed to the December flood. It is almost certain that these features have developed as a result of loss of groundcover since European settlement. It is known that vegetative groundcover reduces erosion, and it is clear that erosion would be much less if the catchment was in better condition.

While catchment condition may not have had a significant impact on the December 2010 flooding resulting from a record rainfall event, improving catchment condition (perennial groundcover) is an important aim that will likely reduce the impact of minor and moderate flood events, in particular soil erosion.

If the arid shrublands of the Gascoyne River catchment are to improve significantly in productive value, and be able to sustain ongoing pastoralism, then land surfaces in such an active catchment will need to be restored before landscape systems can efficiently conserve and use rainfall and run-on. This will require long periods with greatly reduced grazing pressure and interventions at critical control points in the landscapes.

Based on the historical and recent review of the Gascoyne River catchment it is likely that future high rainfall events will continue to result in localised flooding, soil loss and damage to infrastructure unless catchment condition is improved.

Gascoyne River catchment assessment

1 Introduction

1.1 Purpose

The rationale for this assessment of the Gascoyne River catchment is to provide evidence on the role that perennial vegetation groundcover management has in influencing the risk of flooding and soil loss for different landscapes in the catchment, and supports the Caring for Our Country theme of Sustainable Farming Practices.

Specifically, the desired outcome of this report is to contribute to a better understanding of rangeland landscapes and thereby improve land management practices. By understanding how rangelands function to regulate scarce resources (water and nutrients) through the maintenance of groundcover and reducing soil loss, catchment resilience may be reinstated and the impact of extreme storm events can be reduced.

This report is directed specifically at the Gascoyne River catchment where record flooding during the summer of 2010 and 2011 resulted in damage to infrastructure and soil loss in both the rangelands and the Carnarvon horticulture area. A period of dry seasons with relatively high stock numbers preceded the flood events. Catchment condition may have contributed to the record flooding and the subsequent damage to infrastructure and soil.

1.2 Objectives

This report has three objectives:

I. Assessment of the influence of catchment condition or perennial vegetation groundcover on downstream flooding in the Gascoyne River Catchment

II. Assessment of the influence catchment condition or perennial vegetation groundcover has on soil erosion in the Gascoyne River Catchment

III. Provision of illustrative evidence on the role perennial vegetation cover has in reducing the risk of soil loss for different rangeland landscapes.

1.3 Background

The Gascoyne River catchment is located in the mid north-west of Western Australia (Figure 1). The catchment covers an area of about 80 400 km^2 (Department of Water, 2007). The catchment is drained by numerous ephemeral rivers. The largest river in the catchment is the Gascoyne River, which extends ~760 kilometres and flows westward into the Indian Ocean. The Gascoyne River has three branches: Gascoyne River North, Middle and South. Its most prominent tributary is the Lyons River, which drains the northern part of the catchment, joining the Gascoyne River just east of the Kennedy Range. Other notable tributaries of the Gascoyne River include the Thirty One, Thirty Three and Thomas rivers, Dalgety Brook and Bush, Daurie, Durlacher, Nanular, Pells and Turner creeks.

A delta has formed at the mouth of the Gascoyne River. The town of Carnarvon and the horticultural area, with about 1000 ha under irrigation, are located on the river levee and floodplain of the delta. The December 2010 flood and subsequent flooding in January and February 2011 caused significant damage to the Carnarvon and Gascoyne Junction town-sites and the Carnarvon horticultural area, as well as soil loss and infrastructure damage within the catchment.

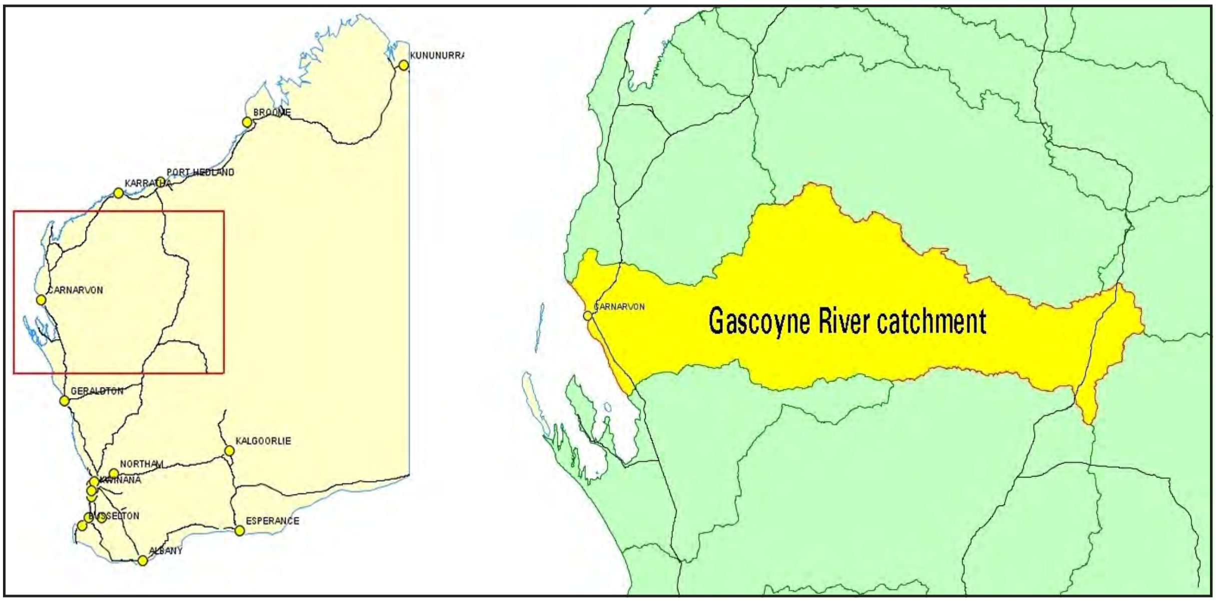

Figure 1 **Gascoyne River catchment in Western Australia**

The December 2010 flood resulted in the Western Australian Government declaring Carnarvon a natural disaster zone (Figure 2a, b). Direct damage associated with the December flood was estimated at nearly $70 million. Additional costs associated with indirect damage increased the total damage estimate to approximately $90 million (Department of Water pers. com.). These events resulted in significant government investment, approximately $3 million, to assist in repairing the damage in the Carnarvon horticultural area. Damage from the following two floods in 2011, which were considered to be less severe than the December flood, is unquantified as flooding affected areas previously impacted (Figure 2c, d).

Figure 2a **Flooding through the Carnarvon horticultural area (December 2010).**
Photograph: Source unknown

Figure 2b **Flood damage at Gascoyne Junction townsite (December 2010).** Photograph: J Stretch

Figure 2c (above), d (right) **Flooding through the Carnarvon horticultural area (January 2011)**

There is a history of repeated review of the Gascoyne River catchment centred on catchment condition (Wilcox & McKinnon 1972; Jennings et al. 1979; Williams, Suijdendorp & Wilcox 1980; House et al. 1991; Watson 2002; Hopkins, Pringle & Tinley 2006). The fundamental management issue in the region has been the mismatching of animal (livestock, feral and native) grazing pressure to land capability (in the medium to long-term) and feed availability (in the short to medium-term) (Watson 2003).

Flooding and erosion processes are directly or indirectly affected by a number of factors (Coles & Moore 1998). Rainfall, infiltration, vegetation and surface cover, soil conditions, such as soil porosity and soil water content, may change with time. During December 2010, the amount and intensity of rainfall was substantial. Catchment condition, in particular perennial vegetation cover and soil condition, were said to be poor as a result of the dry season and relatively high grazing pressure. Therefore, it is possible that the flooding and erosion associated with the December 2010 event may have been exacerbated by the rangeland condition. In the future if rainfall and catchment conditions are similar to 2010–2011 are the downstream consequences likely to reoccur?

Factors in addition to those discussed above, such as catchment shape, topography and soil distribution usually remain constant between events (Coles & Moore 1998). During the summer of 2010–11 the three storm events were centred over different parts of the catchment. As a result catchment shape, topography and soils types would have influenced each of the three flood events differently. Nevertheless, significant flooding still occurred after each event. These key catchment features do not seem to have had a major impact on the degree of flooding during December 2010 relative to other flood events and therefore are not examined in this report.

Economic conditions, technology and management practice have changed significantly since European settlement. In addition rangeland science has developed, providing an opportunity to reassess the impact of catchment condition on flooding and erosion. If the significant social and economic costs of the 2010–2011 flood events in the lower Gascoyne can be avoided by an improved understanding of the record December 2010 flood, a review of the present condition of the catchment is warranted.

In Section 2 below, we describe the record December 2010 rainfall and flood event. An estimate of the severity of erosion is provided and we present the results from an assessment of catchment condition and perennial vegetative cover. In Section 3, we present illustrative evidence of the relationship between catchment condition (as defined by DAFWA, Appendix 3.1) and erosion. In Section 4 we explore the link between the factors contributing to the record December 2010 flood and subsequent soil erosion, in particular, the rainfall event and potential role of catchment condition and perennial vegetative cover. In concluding (Section 5) we provide some observations concerning the catchment condition and the December 2010 flood.

2 Impact of catchment condition on flooding and erosion

2.1 Methodology

Information and data to support the analysis of the flood events were obtained using a variety of sources and methods. Information was obtained from government agencies, previously published reports, existing Department of Agriculture and Food (DAFWA)[1] databases, and satellite data (Appendix 2). These data were supported with field investigations.

Between June and August 2011 officers from DAFWA undertook an assessment survey of the present condition of the mid to upper Gascoyne River catchment, primarily east of Gascoyne Junction. Field assessment was based on a methodology established from the DAFWA rangeland survey project and from previous reviews of flood events (Wilcox & McKinnon 1972; Payne, Curry & Spencer 1987; Curry et al. 1994; Mitchell & Leighton 1997).

Pastoralists were notified in advance by mail that an assessment of the catchment was occurring, as well as verbally on arrival at their property. During the survey, on-ground inspections specifically targeted rangeland monitoring sites to provide quantifiable data as well as visiting areas of interest predetermined by aerial photography interpretation. Navigators followed predetermined routes on ortho-rectified aerial photographs and satellite imagery using computer software, which allowed real time GPS-tracking. Predetermined routes had been chosen through desktop analysis of rangeland condition and monitoring data, aerial photography, review of various satellite imagery and other historical data sets.

Whilst on route to areas of interest or Western Australian Rangeland Monitoring System (WARMS) sites, traverse notes and photographs were compiled to formulate an overall perspective of catchment condition. The assessment of catchment condition is based on subjective visual assessments by experienced rangeland advisers and ecologists. These opinions are based on the assessor knowing what type of vegetation is supported on the particular landform/soil association being assessed, and an understanding of the natural range of attributes such as species composition, density and cover and the effect unnatural and natural disturbances have on the landscape. The findings of traverse notes and aerial photographic interpretation form the basis of Section 3.

2.1.1 Rainfall, flooding and erosion

Climatic data, rainfall records and map products of rainfall distribution and a description of the summer of 2010–2011 weather events were obtained from the Bureau of Meteorology (BoM). Details of the method used to collect and compile climatic and weather records can be obtained from BoM.

The magnitude of the flood was assessed from hydrographs generated from an automatic gauging station at Nine Mile Bridge operated by the Department of Water (DoW). The 2010 flood was compared with the hydrographs of flooding dating back to 1960. Four other gauging stations at Fishy Pool, Jimba, Yinnietharra Crossing and Lyons River Crossing provide extra information on the magnitude of the December 2010 flood. Details of the gauging stations can be obtained from DoW. Map products generated from satellites such as MODIS did not indicate the full extent of the flood because of cloud cover at the time.

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[1] Refer to Appendix 1 for a list of acronyms used in this report.

Erosion, as a result of the December 2010 flood, was assessed in terms of the areal extent of the sediment plume obtained by digitising MODIS imagery (NASA/GSFC, Rapid Response). An indication of the relative magnitude of the erosion to similar events was obtained by comparing the December 2010 sediment plume with sediment plumes from the January and February 2011 flood events. Sediment load data is not recorded along Gascoyne River gauging stations.

MODIS imagery was used to obtain estimates of the Total Suspended Solids (TSS) based on calibrations obtained from other studies. These values were used to estimate total sediment load within a defined area for a specified image. The total sediment load was estimated by assuming each pixel is 250 m and the sediment is evenly mixed in the first 1.5 m of water, which is likely to be fresh and therefore float on the sea water (Dr Peter Fearns and Mark Broomhall, Curtin University, pers. com.). Each pixel sediment mass is determined by multiplying the concentration (TSS) by the litres of water per pixel (i.e. 250 x 250 x 1.5 x 1000 = 375 000 x TSS = mass [kg]). Other methods such as remote sensing for measuring erosion are not sufficiently well developed or fall outside the scope of this study.

In addition, photographs of erosion and deposition along the Gascoyne River taken during field investigation coupled with verbal accounts of erosion by pastoralists provide qualitative evidence of the scale and severity of erosion. Visual assessment of the type and severity of erosion in the catchment not directly attributable to the December 2010 flood was considered as part of catchment condition assessment (see below) and provides an overview of erosion and catchment condition. Photographs of erosion features, some of which are likely to be a product of past events, which illustrate the relationship between vegetation cover and erosion are presented in Section 3.

2.1.2 Catchment condition

2.1.2.1 Condition (Traverse data)

As part of the formal DAFWA pastoral lease inspection process, during the period 2002 to 2009, traverse ratings of vegetation and soil condition were collected at 1 km intervals, based on criteria used to assign traverse condition ratings (Payne et al. 1987) (Appendix Table 3.1). Traversing was limited to existing tracks and fencelines. Previously the Gascoyne River catchment was surveyed in 1969–70 (Wilcox & McKinnon 1972).

2.1.2.2 Trends and condition over time (WARMS)

WARMS sites were established to assess the grazing impact at the broad scale (regional, state, vegetation type) by monitoring relatively long-lived perennial species. Site selection and stratification was based on pasture productivity, areal extent and ‘fragility’ (Watson, Novelly & Thomas 2007). Site installation and selection was at the Land Conservation District (LCD) level. Sites were selected in uniform, representative areas of the LCD or region and not in actively eroding areas. The network of WARMS sites within the Gascoyne River catchment may not represent all landscapes or processes.

At the WARMS sites assessed in 2011 data were recorded on:

- perennial plant counts by species within the permanent photographic area (Watson, Thomas & Fletcher in prep.)
- two components of landscape function analysis (LFA):
  - (i) the landscape organisation (log of resource capture zones) on permanent transects (Tongway 1994), and
  - (ii) soil surface assessment of 11 attributes (including two non-woody groundcover attributes) within twenty 1 m^2 quadrats along permanent transects (Tongway 1994).

To avoid areas of stock concentration, sites are generally located at least 1.5 km from permanent water. The majority of sites (83%) are within 3.5 km from permanent water (Figure 3).

WARMS shrubland sites consist of a permanently marked trapezoid shaped photographic area (121.5 m^2) with three permanent transect belts of variable length at the rear of the trapezoid (Figure 4). Transect length is dependent on the density of perennial plants. Sites are typically aligned downslope so that the LFA transect is perpendicular to the contour.

Landscape function refers to processes involved in transporting and regulating resources such as water, nutrients and organic matter across the landscape at a localised scale (Tongway & Ludwig 1997). WARMS sites, whilst very small in comparison to the local catchment, provide a quantitative assessment point within a patch/interpatch sequence that is linked through hydrological processes, which commonly reflect higher order, broader scale patterns and processes occurring across the landscape.

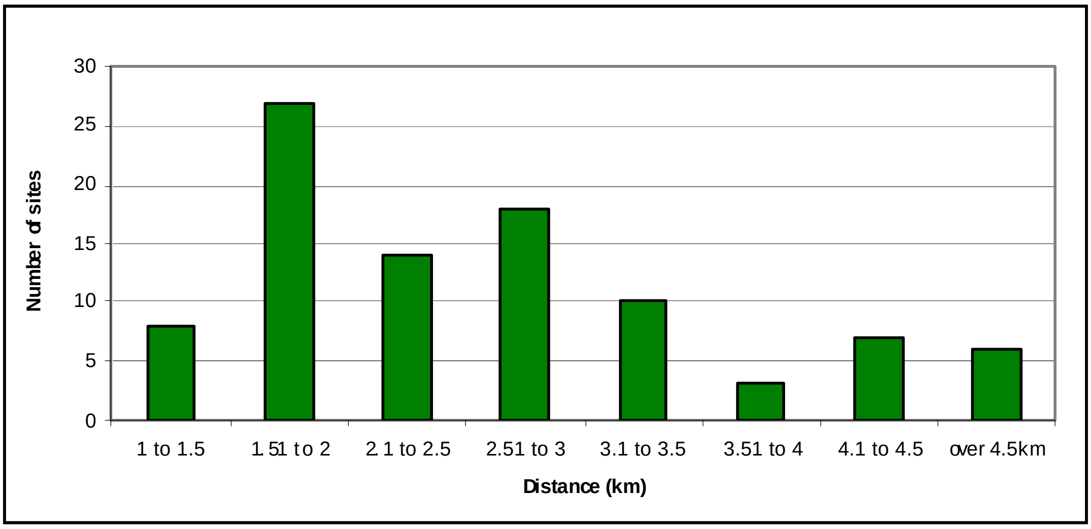


Figure 3 **Distance from water of WARMS sites assessed within the Gascoyne River catchment**

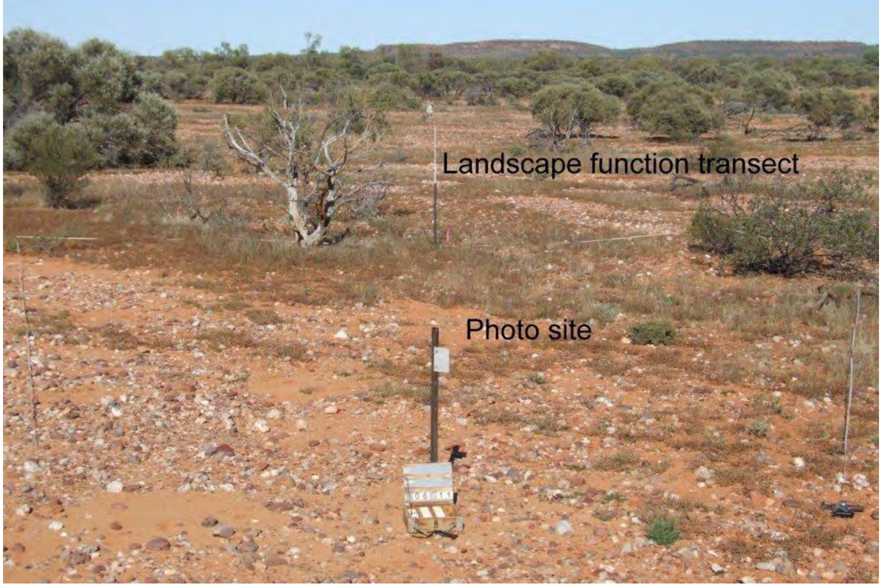


Figure 4 **WARMS data collected within demarcated photographic site area and central Landscape Function Analysis (LFA) transect at rear of site**

2.1.2.3 Vegetation cover (Remote sensed data)

Vegetation cover was assessed using two methods:

- trend in perennial cover (Landsat Cover Change Analysis), and
- the greenness (approximating vegetation cover) in 2010 and preceding seasons.

Landsat TM data was acquired from the AGO NCAS archive for 1989, 1992, 1995, 2000, 2002, 2004, 2006 and 2010. A simple perennial cover index was derived for each year. Landsat MSS imagery pre-1989 was not incorporated due to numerical differences between Landsat MSS and Landsat TM data. The greenness for 2010 preceding the flood was derived from NOAA NDVI and the seasonal quality (1992 to 2010) was assessed using NOAA NDVI based on methodology in Cridland et al*.* (1998).

Using the derived perennial cover index, the trend in perennial vegetation groundcover for the period 1989 to 2010 was calculated based on Wallace & Thomas (1998).

2.1.3 Soil infiltration measurements

At 49 WARMS sites and one other site, soil infiltration measurements and soil profile descriptions were collected (Appendix Table 4.1). Four soil profiles were described at WARMS sites where no successful infiltration measurements were completed. An attempt was made to obtain at least one soil infiltration measurement and an accompanying profile description at each WARMS site visited. However, owing to time constraints and technical difficulties such as stony surfaces, this was not always possible. Land systems where soil infiltration measurements and soil profile descriptions were recorded are shown in Appendix Table 4.2.

Soil textures for the surface (0–5 cm) and the subsurface (5–10 cm) were obtained from soil profile descriptions (see below). These depths were chosen because it was considered they would have the greatest influence on infiltration measurements when using the single ring infiltrometer method. Soil textures were classified based on texture groups outlined in Northcote (1979).

The infiltration measurements and soil profile descriptions were usually located within 10 to 30 m of the side of the WARMS site. The location was chosen to be representative of the WARMS site but not too close so as to interfere with the long-term monitoring. An additional 14 infiltration measurements were undertaken to provide comparison measurements between adjacent landscape features of contrasting patch-interpatch surfaces, such as grove–intergrove, wanderrie bank–hardpan interpatch, remnant sand sheet–stripped duplex surface (Appendix Table 4.3). The distance between these paired sites was generally in the 7–25 metre range.

Soil water infiltration rates were measured using the ‘single ring falling head infiltrometer method’ modified from Minasny and McBratney (2010). The use of the infiltration ring is shown in Figure 5 with details provided in Appendix 4.

Figure 5 **Infiltration ring, steel rule and plastic sheet**

The cumulative infiltration **I** (mm) is plotted over time. The steady portion of the graphed infiltration data was visually determined and a linear regression fitted (Snedecor & Cochran 1989) (Equation 1).

Equation 1: $$I = Q\,t + c$$

The gradient of the regression equation is the steady-state infiltration rate **Q** (mm/hr) and is a surrogate for hydraulic conductivity of the wetted zone or the saturated hydraulic conductivity often used in the literature (Bouwer 1978); **t** (hr) is time elapsed and **c** is a constant of the regression.

The infiltration rate was assessed in relation to the vegetation associations (i.e. interpatch or patch) and the soil textures of the surface and subsurface. At 36 sites infiltration measurements were undertaken in either the interpatch or patch (Appendix Table 4.1). At 14 sites interpatch and patch infiltration measurements were paired. Three readings were replicated on either the interpatch or patch.

A two-sample student t-test assuming unequal variances was used on all the data to determine whether infiltration rates for interpatch and patch are likely to have similar means (Welch 1947). At sites where infiltration measurements are paired, a paired two-sample student t-test was used to test for equality of the population means of the estimates of **Q** (Snedecor & Cochran 1989).

Other soil and land properties were obtained from descriptions of the soil profiles and associated landforms using the criteria in the *Australian Soil and Land Survey Field Handbook* (McDonald et al. 1990). Soil profile descriptions involved exposure of the upper-most soil layers to the main subsoil layers, usually by hand auger borings or shallow pits down to a depth of about half a metre where possible. The detail of the profile descriptions varied from a brief description of surface textures to comprehensive descriptions including texture, colour, depth, consistency, structure, fabric, pH and stone or gravel content for each soil layer (horizon), porosity and nature of underlying materials.

2.2 Results and analysis

2.2.1 Rainfall, flooding and erosion

2.2.1.1 Summer 2010-2011 weather events

During the summer of 2010–2011 three weather systems (December 2010, January 2011 and February 2011) produced heavy and widespread rainfall, which subsequently resulted in flooding of the Gascoyne River and erosion of the catchment and Carnarvon horticultural area (Figure 6).

(i) December 2010

Following a prolonged drought, heavy rainfall from a monsoonal low began in the Gascoyne River catchment during Thursday 16 and continued until Saturday 18. From 19 December the low pressure system started to move to the south-west, away from the Gascoyne coast (Bureau of Meteorology 2011a). Through western parts of the Gascoyne River catchment significant rainfall was recorded, with some sites recording over 300 mm, whilst a large proportion of the region recorded over 150 mm (Figure 7).

In the 24 hours to 9.00 am on 17 December 205 mm of rainfall was recorded. The rainfall intensity had been consistent between 8 and 15 mm per hour over the previous 21 hours (Figure 8). It is likely rainfall intensity in areas east of Carnarvon that received 250–300 mm were in excess of this.

The Gascoyne River began rising from late Friday night (17 December) to early Saturday morning (18 December). From Saturday 18 to Monday 20 along the Gascoyne River three of the five river gauging stations recorded the highest flood levels on record (Bureau of Meteorology 2011a):

- Nine Mile Bridge gauging station, in the town of Carnarvon, recorded a flood peak height of 7.77 m at 04:00 WST on Monday 20 December. The previous high was 7.63 m in 1960, followed by 7.6 m in 2000 (Figure 9).
- Fishy Pool gauging station, located 110 km upstream of Carnarvon and 60 km downstream of Gascoyne Junction, recorded a peak height of 15.53 m at 09:00 WST on 19 December 2010. The previous record high was 12.23 m during the 1980 flood.
- Jimba gauging station, located near the town of Gascoyne Junction, recorded its highest peak on record of 10.76 m at 19:00 WST on 18 December 2010 prior to instrument failure. The previous record high was 9.5 m during the 2000 flood (Bureau of Meteorology 2011a).

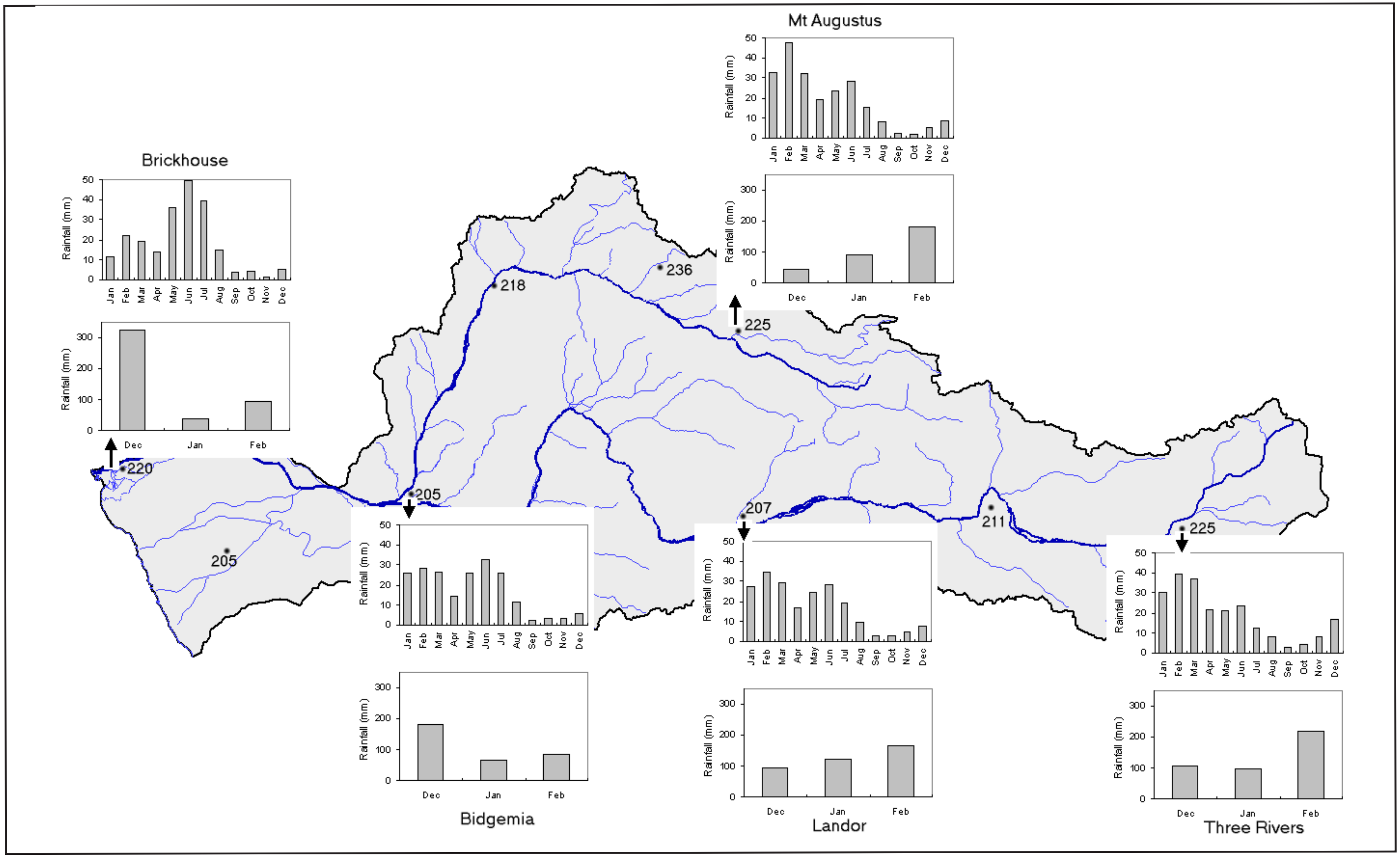


Figure 6 **Monthly rainfall across the Gascoyne River catchment. For each pair of graphs, the top graph represents average monthly rainfall (mm) and the bottom graph represents monthly rainfall for December 2010, January and February 2011. Integers represent the annual average rainfall (mm).**

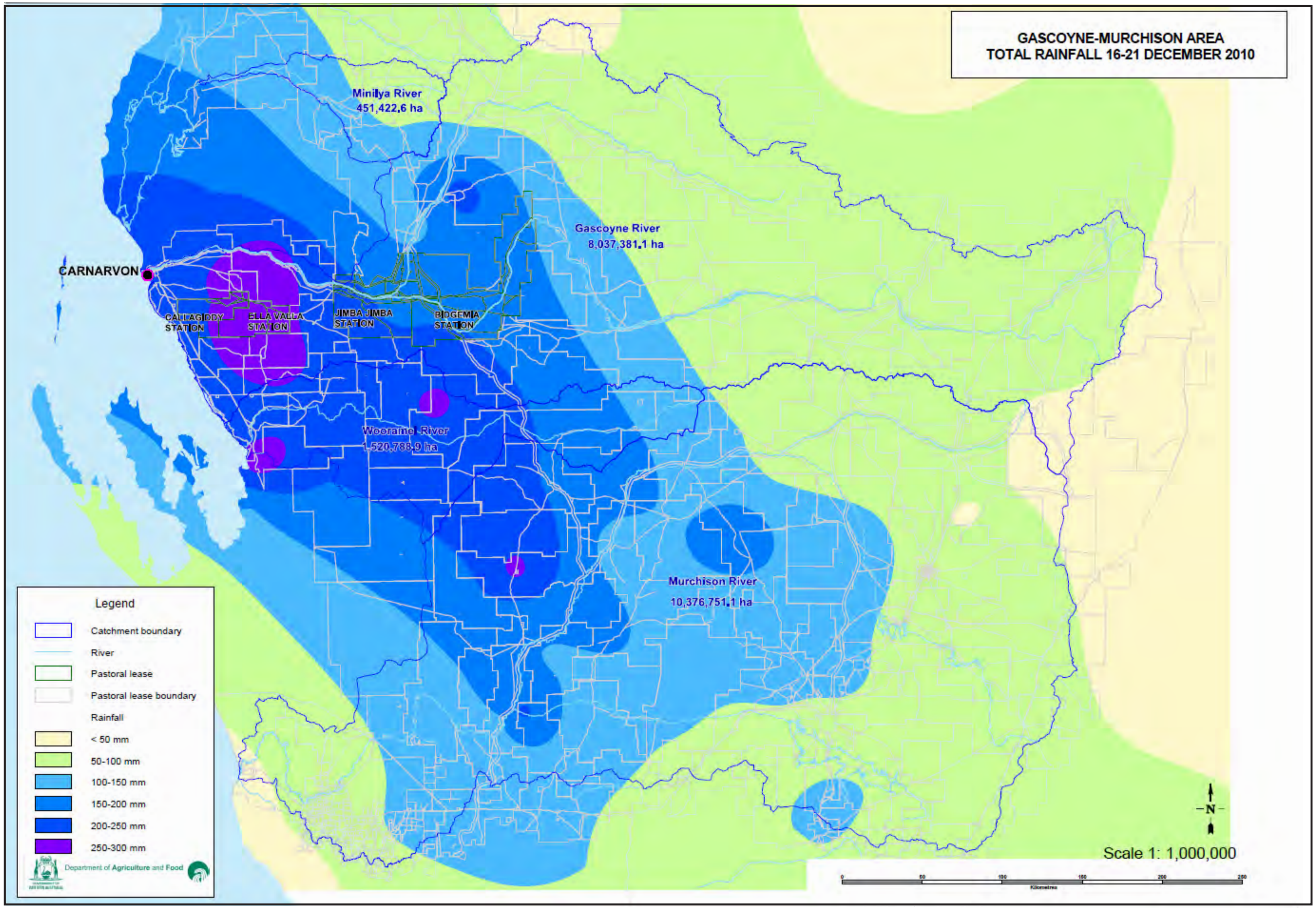


Figure 7 **Total rainfall in the Gascoyne-Murchison area from 16 to 21 December 2010**

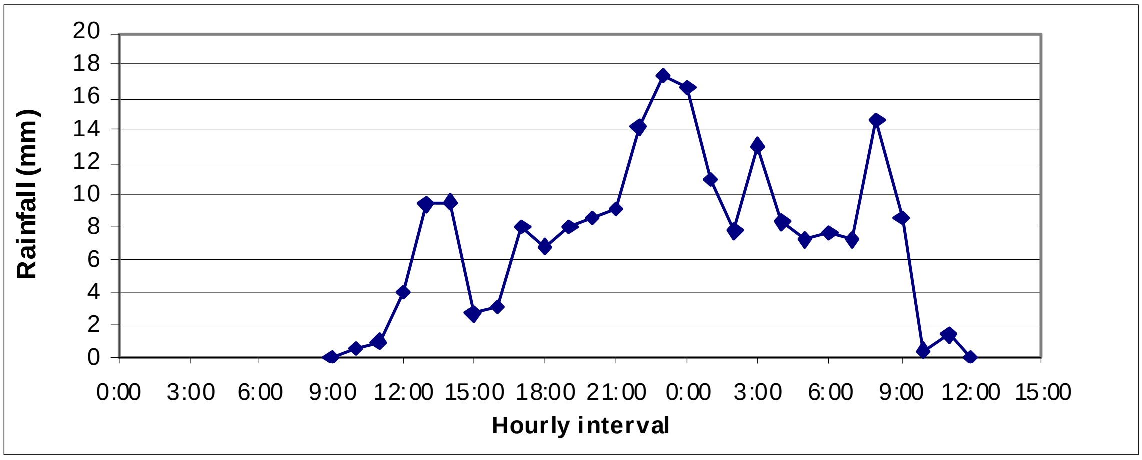


Figure 8 **Hourly rainfall for Carnarvon, 16 and 17 December 2010**

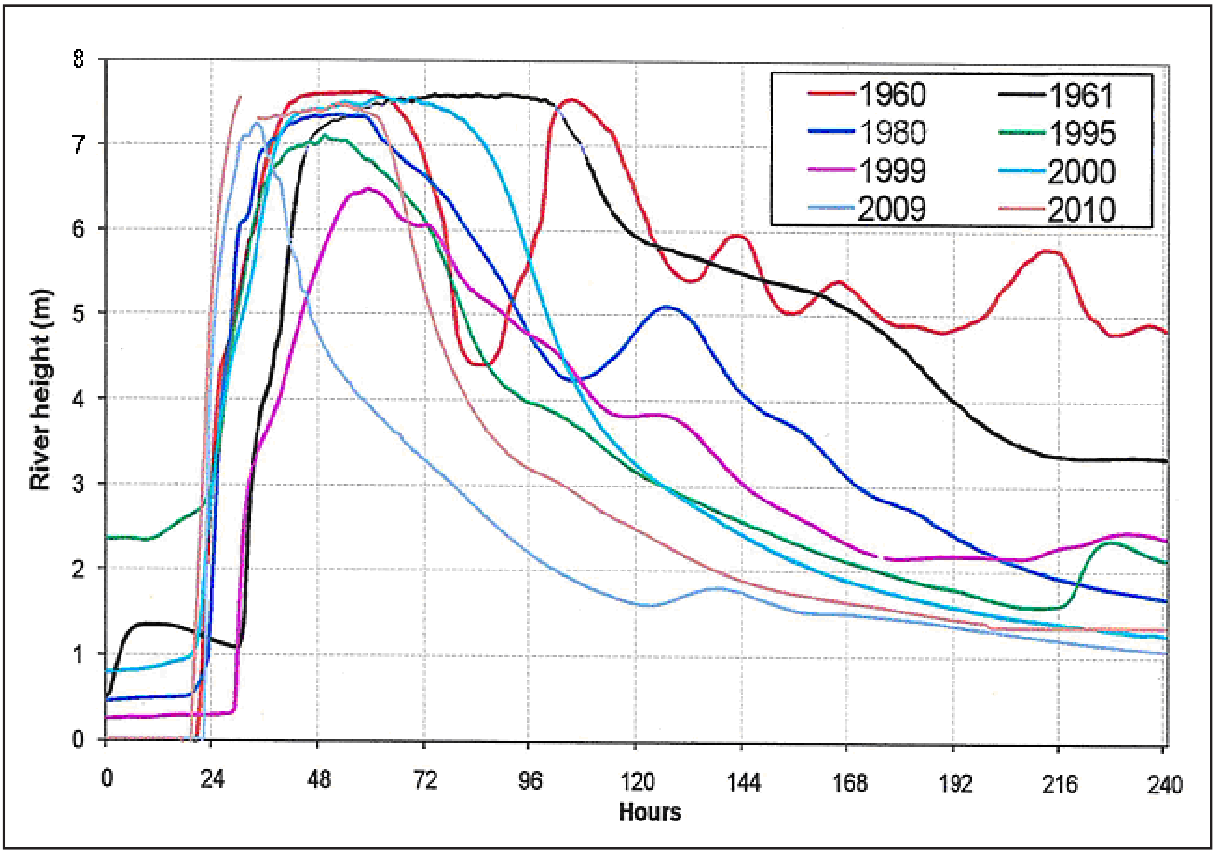


Figure 9 **Gascoyne River hydrographs recorded from Nine Mile Bridge** (courtesy DoW)

(ii) January 2011

On 5 January 2011 severe thunderstorm activity caused by a front interacting with tropical moisture resulted in severe wind gusts and heavy rainfall in the southern Gascoyne region (Bureau of Meteorology 2011b).

On 6 January at Nine Mile Bridge the Gascoyne River peaked at 6.5 m (Figure 10). The Carnarvon townsite and horticultural area again suffered significant inundation, though not to the same level as experienced in the December 2010 flood.

(iii) February 2011

A cloudband associated with Tropical Cyclone *Dianne* off the north-west coast extended into central and south-east parts of Western Australia from 16 to 19 February, developing into a severe Category 3 system, causing widespread and heavy rainfall of over 50 mm, with isolated falls of over 100 mm, in the inland Gascoyne. Following rainfall events from 17 and 18 February associated with the development of Tropical Cyclone *Dianne* the Gascoyne River again suffered several minor flooding events (Bureau of Meteorology 2011c).

Figure 10 **Gascoyne River flood waters at Nine Mile Bridge, near Carnarvon**

2.2.1.2 Rainfall and flooding

Rainfall data for the three flood events indicates three different patterns. The December flood was predominantly over the western end of the catchment from the Carnarvon area to Gascoyne Junction. The January flood was characterised by widespread falls across the catchment of 50 to 100 mm over three days. The February flood was largely generated from rain in the eastern end of the catchment, where 150 mm of rain fell over five days. The December flood had the biggest impact on Carnarvon and the horticultural area.

The December 2010 flood hydrograph at Nine Mile Bridge (Figure 9), although indicating a record level, is of similar magnitude and shape to other major floods since 1960. There are also similarities between the rainfall and peak flood heights of the 1960, 1961, 1999 and 2000 floods (Appendix 5). It is relevant to note that substantially larger rainfall events will result in only a marginal increase in river height. The similarity of flood hydrographs suggests that climatic and catchment conditions that existed at the time of the December 2010 flood were likely to be similar to those of earlier events.

In addition, an examination of rainfall data and flood peak gauge height from 1960 to 2011 indicates that relatively small falls can result in flooding. However, it should be recognised that rainfall stations may not capture the extent and magnitude of all rainfall events. For example, falls associated with the January 2009 flood peak at Nine Mile Bridge are atypical in comparison with other flood events (Appendix 5).

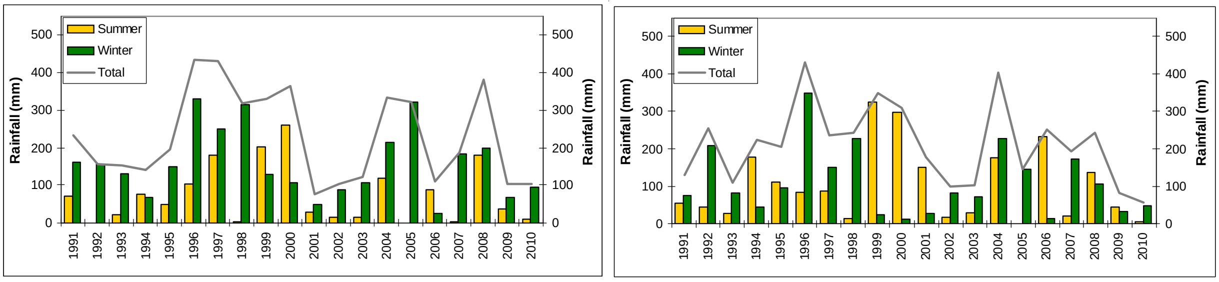
Climatic events surrounding the December 2010 flood, namely consecutive dry seasons and heavy falls in summer are not unusual. However, the magnitude of the December 2010 rainfall event was unusual.

The Gascoyne River catchment has a semi-arid to arid transitional climate affected by winter (May to July) and summer rainfall (January to March). Inland climatic conditions are more extreme than those experienced near the coast. However, rainfall is unreliable from year to year and extremely variable and successive years with below average rainfall occur frequently (Bureau of Meteorology 1998).

The seasonal rainfall for four stations across the catchment shows the transition from winter rainfall pattern (on the west coast) to a summer rainfall pattern in the eastern and north-east part of the catchment (Figure 11). Of the two seasons, summer rainfall is generally much less reliable. However, during this period intense rainfall events can result from the development of low-pressure troughs and the southern movement of monsoonal lows that may develop into tropical cyclones.

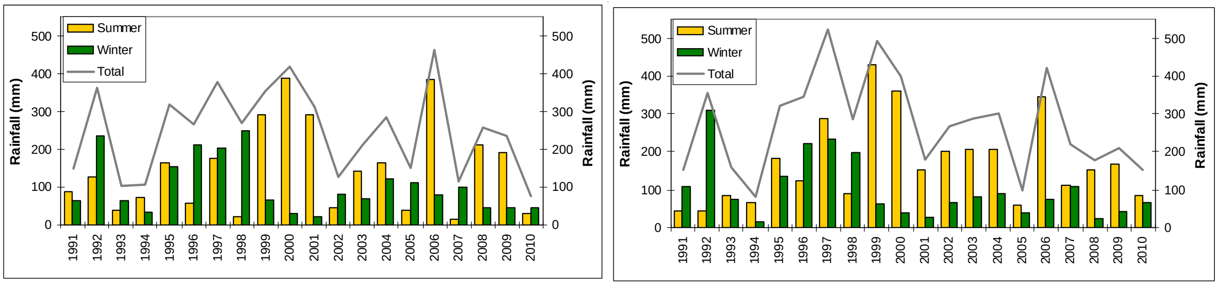
The average annual rainfall ranges from 290–270 mm on the south-west coastal margins to 250–200 mm in inland areas (Bureau of Meteorology 1998). In comparison, the December 2010 rainfall over two days (> 250 mm) over parts of the catchment, equalled or exceeded the annual average rainfall, and for some gauging stations rainfalls were the highest on record in over 100 years. Previously the largest rainfall totals at Gascoyne Junction were 286.5 mm in March 1943 (120.7 mm, March 95th percentile) and 226.6 mm during January 1927 (85.5 mm, January 95th percentile) (Bureau of Meteorology 2012). The previous highest monthly total for December at Gascoyne Junction was 73.6 mm in 1932 (16.5 mm, December 95th percentile). Clearly, the December 2010 rainfall event greatly exceeds previous December recorded events.

In all three events during the summer of 2010–11, the total rainfall and period of time in which it fell over the catchment was likely to be a major driver of downstream flooding and erosion in the catchment.



(a) Brickhouse station (west) – winter 157 mm, summer 62 mm

(b) Bidgemia station (central west) – winter 114 mm, summer 95 mm



(c) Landor station (central west) – winter 105 mm, summer 108 mm

(d) Three Rivers station (east) – winter 93 mm, summer 138 mm

Figure 11 **Seasonal rainfall 1991 to 2010 and average long-term annual rainfall** (see Figure 6 for station locations within the Gascoyne River catchment)

2.2.1.3 Erosion

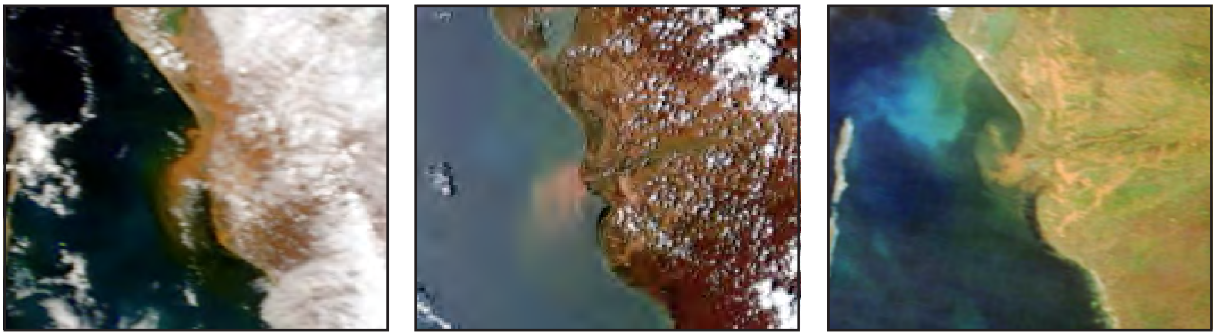
The size of the sediment plume off Carnarvon provided an indication of the level of soil erosion. The sediment plume sizes for the three flood events December 2010, January and February 2011 (Figure 12), along with the January 2009 flood are given in Table 1. Dates shown are for cloud-free imagery and may not represent the maximum plume dimensions.

The plume from the December 2010 flood is nearly twice that of the January 2011 flood (25 330 ha c.f. 13 740 ha) and over three times that of the February 2011 flood (25 330 ha c.f. 5265 ha). The January 2009 flood peak was larger at 6.8 m but the plume area was much smaller than either of the 2011 floods and was 1/7th the area of the December 2010 plume. The January 2009 flood hydrograph was very different; it rose quickly and within 12 hours had fallen.

The different plume characteristics suggest that the erosion from the catchment in December 2010 was much higher than from the later 2011 flood events. In addition, the characteristics of the December rainfall event, sustained over several days and covering a wider area, are likely to have resulted in greater erosion.

Table 1 **Sediment plume size for the three flood events during the summer of 2010–11 and the January 2009 flood. Some days are not presented as cloud cover obscured the plume. (MODIS imagery reference source: 'NASA/GSFC, Rapid Response')**

Date	River height (m) at Nine Mile Bridge	Maximum length (km) at Gascoyne River mouth	Area (ha)
January 2009			
30	6.99	5.1	3 800
December 2010			
20	7.77	29.8	25 330
21	na	18.4	18 640
22	na	6.2	3 450
January 2011			
6	6.52	12.5	9 440
7	6.30	15.5	13 740
8	na	11.8	10 120
9	na	6.5	3 420
February 2011			
21	5.85 (20th)	6.0	3 435
22	6.37 (23rd)	9.5	5 265
25	na	6.2	2 215
27	4.36 (28th)	2.2	1 305



20 December 2010 7 January 2011 22 February 2011

Figure 12 **MODIS images of peak plumes from which the plume characteristics were measured** (see Table 1. Note not all images are shown. MODIS imagery reference source: 'NASA/GSFC, Rapid Response')

The total mass of sediment in the plume from the January flood was estimated at 2 250 000 tonnes in the 'boxed' area (approximately 20 km^2) in Figure 13. This value represents a minimum soil loss from the catchment for the period to 8 January. The area of the plume on 8 January was about 40% of the 20 December 2010 plume. Assuming similar sediment load to the plume on 8 January, the total mass of suspended solids in the December flood could have been at least 5 625 000 tonnes. Restoration of damaged land in the Carnarvon area after the three floods required 140 000 tonnes of topsoil (Andrew Watson DAFWA, pers. com.).

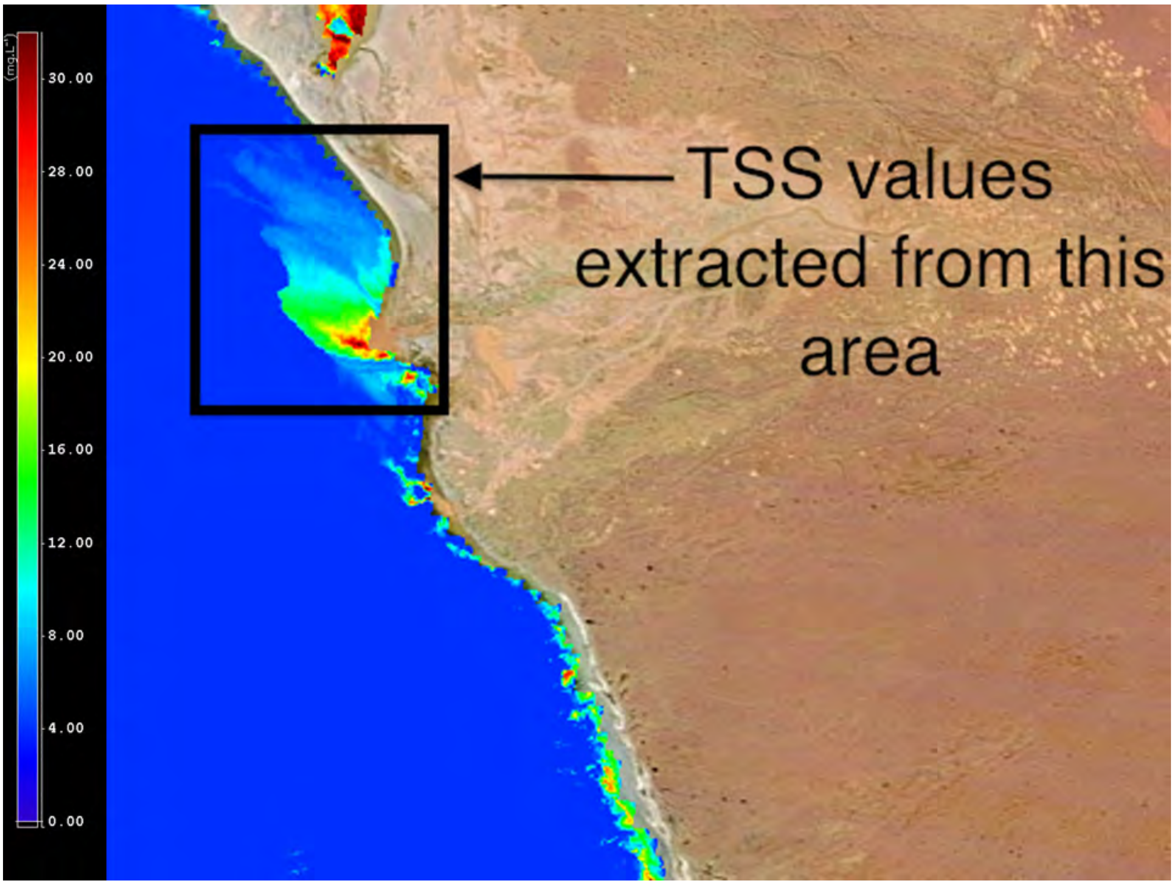


Figure 13 **MODIS satellite image showing the sediment plume exiting the Gascoyne River during the January 2011 flood (TSS: Total Suspended Solids, measured in mg.L^{-1}).** Total mass of suspended solid was estimated for the box area (see text). Some sediments along Shark Bay coastline are shallow sand banks not erosion products. *(Image Ashburton for the 2.30UTC Terra overpass on the 8 Jan. 2011, supplied by Dr P Fearns and M Broomhall, RSSRG, Curtin University)*

The estimate of total mass of suspended solids does not give a complete picture of the nature of the erosion event and total soil loss as a result of the December flood event. In major floods large sections of the main river channels are eroded and the material is deposited in sandbars further downstream. Pastoralists near Gascoyne Junction reported an area covering about 1 square kilometre of mature trees being washed away. Erosion features, predominantly as a result of the December 2010 flood, were evident during field investigations in June and August 2011 (Figure 14a, b). Evidence for ongoing erosion in the catchment is presented in Section 2.2.2.2.3 and examples are discussed in Section 3.

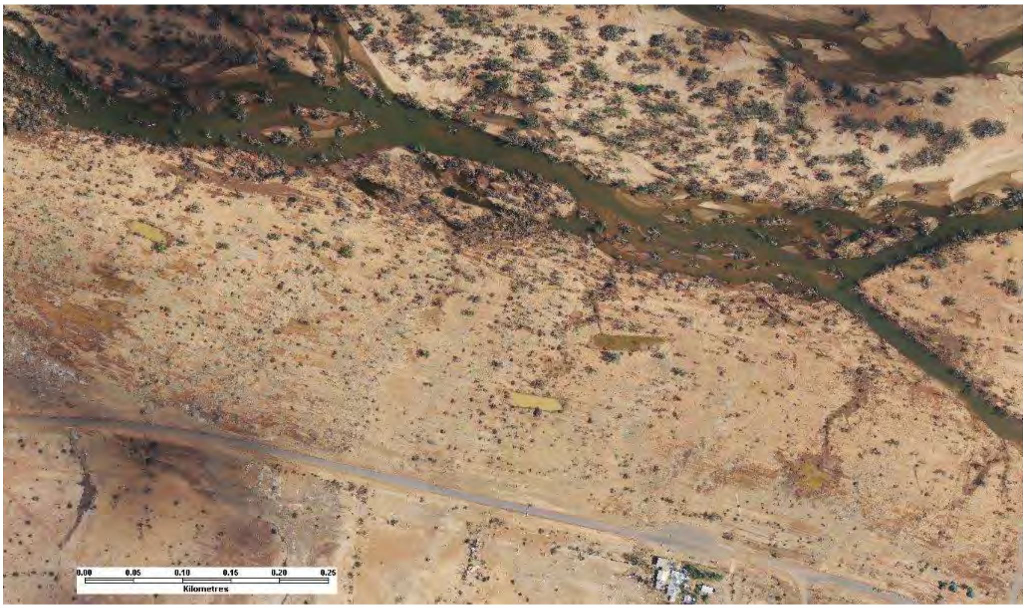


Figure 14a **Erosion at Gascoyne Junction resulting from December 2010 flood. (a) The area between the main river channel, the Carnarvon–Mullewa Road and the roadhouse was a recreational area prior to December 2010**

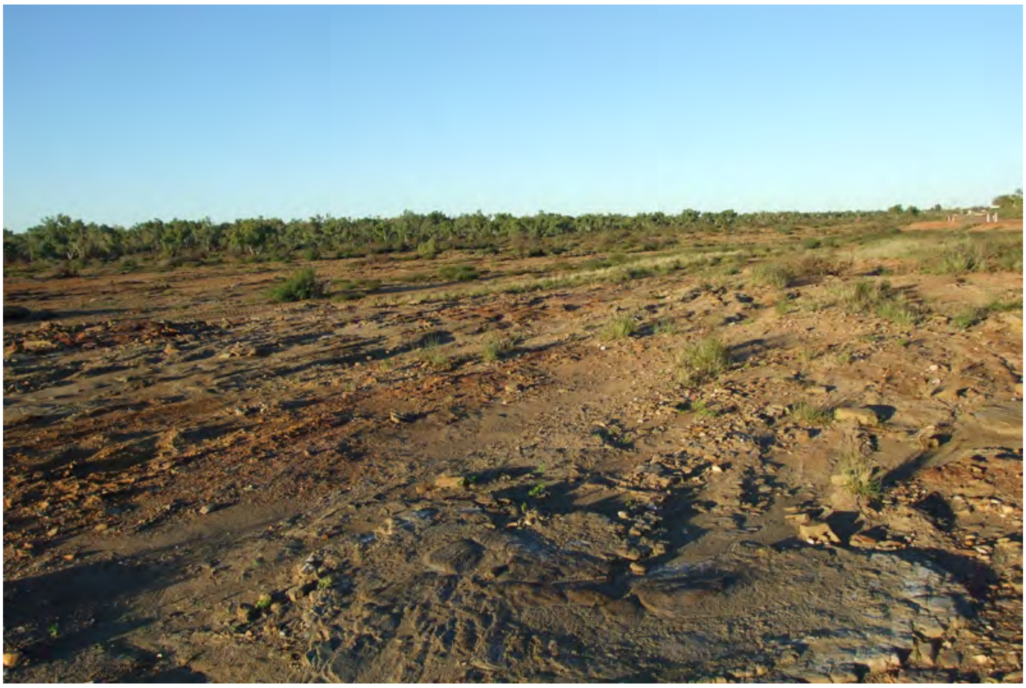


Figure 14b **Looking east towards Gascoyne Junction roadhouse, June 2011**

2.2.2 Catchment condition

2.2.2.1 Condition (Traverse data)

The perennial vegetation condition on 27 pastoral stations (fully or partly) within the Gascoyne River catchment was assessed as 15% good, 42% fair and 43% poor based on the latest traverse data (3703 traverse points assessed between 2002 and 2009). Land systems with more than 20 traverse points in the recent assessment (2002 to 2009) are summarised in Appendix Table 3.2. No traverse assessment of vegetation condition was made during the 2011 Gascoyne River catchment assessment; however traverse notes were taken and are reported on in Section 3.

Based on the traverse data from traverse points assessed between 2002 and 2009 the land systems in better condition are: Sable (54% good), Yalbalgo (32% good), Collier (30% good) and Ella (23% good). Those in the poorest condition are: Three Rivers (80% poor), Warri (76% poor), James (78% poor) and Bryah (71% poor).

When aggregated into land type (Figure 15), the *Alluvial plains with halophytic shrublands* (land type 36) have the highest percentage of good condition. This land type includes Sable and Delta land systems, and is primarily in the lower part of the catchment.

The *Stony plains with acacia shrublands and halophytic shrublands* (land type 17), accounts for 16% of the catchment and is one of the poorest condition (68% poor) land types. Based on traverse assessment 759 637 ha was assessed in poor condition (Appendix Table 3.2). This land type includes Bryah, Durlacher, Kurubuka, Mantle, Nadarra and Yinnietharra land systems. Land types, such as land type 1 with a high percentage of natural shedding land units, although in fair condition will contribute more to stream flow than other 'depositional or sink' land types.

Apart from the *Alluvial plains with halophytic shrublands* (and equal percentages in *Hills and ranges with acacia shrublands*), the land types in the Gascoyne River catchment have a higher percentage of poor condition vegetation compared with the shrublands overall (Figure 15).

The recent traverse data (2002 to 2009) indicate the catchment is in poor condition, with over 3.6 million ha rated as poor (Appendix Table 3.2). The large proportion of the catchment in poor condition (43%) and the observed altered landscape processes (Section 3) suggest there is a reduced capacity for water and resources to be retained or slowed within the landscape.

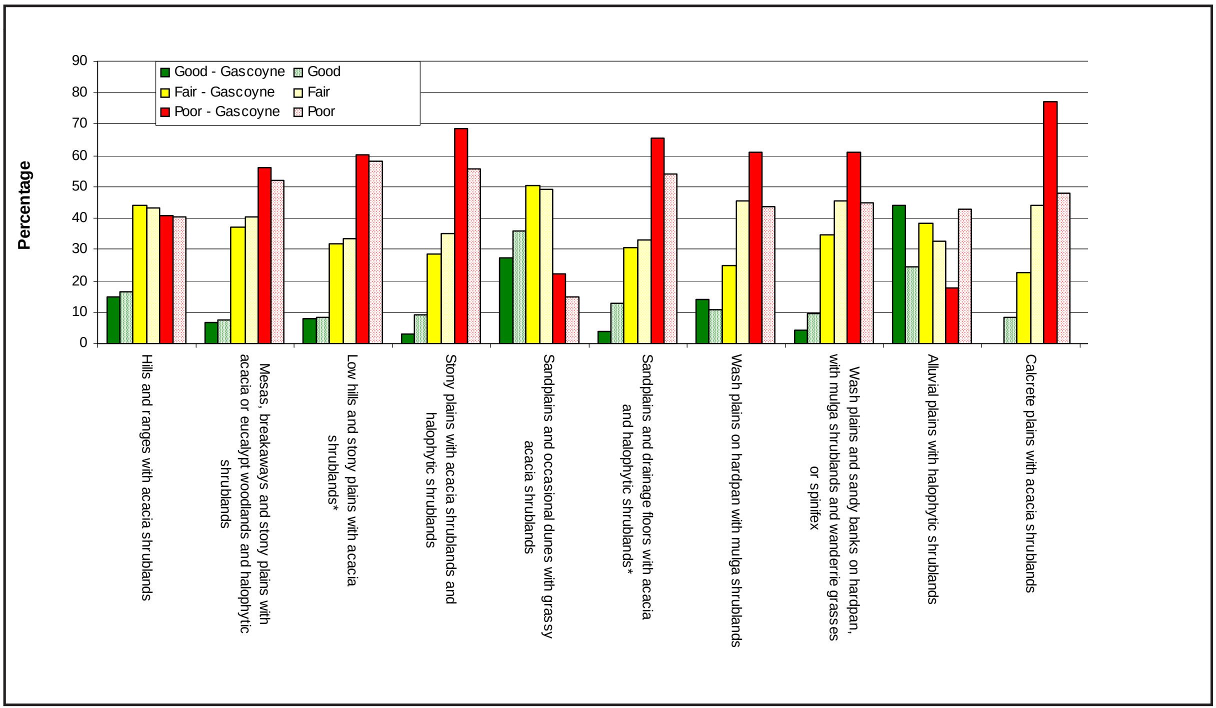


Figure 15 **Percentage of good, fair and poor condition by land type for the Gascoyne River catchment in comparison to shrublands** (Source: DAFWA Inspection traverse data 2002 to 2009)

2.2.2.2 Trends and condition over time (WARMS data)

In 2011, 96 WARMS sites within the Gascoyne River catchment were assessed (Figure 16). These WARMS sites were installed in 1995–1996 and have been reassessed in 2000, 2006 and 2011. The number of WARMS sites assessed in 2011 within each land type is shown in Table 2. As an attribute of the WARMS site stratification was pasture productivity, the low production land type of *Hills and ranges with acacia shrublands* (land type 1) is under-represented when compared to the proportion of catchment area.

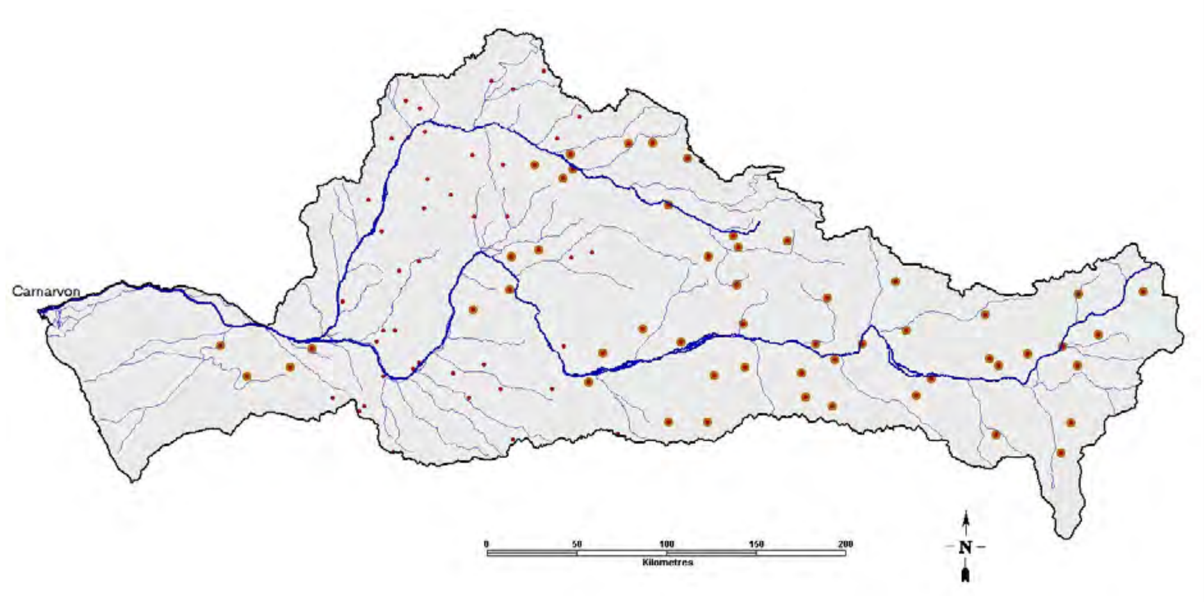


Figure 16 **Distribution of 96 WARMS sites assessed in Gascoyne River catchment** (*53 sites shown with a larger dot also have soil infiltration assessment and/or soil profile – Section 2.2.3*)

Table 2 **Number of WARMS sites by land type and percentage of catchment**

Land type number	Land type	Number of sites (% in brackets)	Percentage of catchment
1	Hills and ranges with acacia shrublands	8 (8%)	18.0
5	Mesas, breakaways and stony plains with acacia or eucalypt woodlands and halophytic shrublands	6 (6%)	5.5
10	Low hills and stony plains with acacia shrublands	16 (17%)	15.2
16	Stony plains with acacia shrublands	2 (2%)	2.0
17	Stony plains with acacia shrublands and halophytic shrublands	28 (29%)	16.0
25	Sandplains and occasional dunes with grassy acacia shrublands	2 (2%)	5.8
27	Sandplains and drainage floors with acacia and halophytic shrublands	3 (3%)	1.3
28	Sandplains and occasional dunes with spinifex grasslands	-	2.3
29	Sandy plains with acacia shrublands and wanderrie grasses	-	0.4
31	Wash plains on hardpan with mulga shrublands	14 (15%)	10.0
32	Wash plains and sandy banks on hardpan, with mulga shrublands and wanderrie grasses or spinifex	12 (13%)	11.5
34	Alluvial plains with acacia shrublands	-	0.2
36	Alluvial plains with halophytic shrublands	-*	6.7
40	Calcrete plains with acacia shrublands	4 (4%)	1.9
42	River plains with grassy woodlands and tussock grasslands	1 (1%)	3.1
44	Coastal plains, cliffs, dunes, mudflats and beaches; various vegetation	-	0.1

* Seven WARMS sites in alluvial plains with halophytic shrublands land type were not assessed in 2011 as they are in the lower catchment.

2.2.2.2.1 Perennial plants

Perennial plant numbers can be viewed in a perennial vegetation groundcover (total plants) or pastoral management (number of desirable plants) perspective. Each plant species is classified as desirable, undesirable or intermediate depending on the pastoral utilisation. Desirable species are preferred by stock and decrease under grazing. Undesirable species increase under grazing and in some cases are classed as woody weeds.

For the 96 WARMS sites assessed in 2011, perennial plant numbers are generally low, with the mean density across all WARMS sites of 2410 perennial plants per hectare (2250 shrubs), and a range of 100 to 13 200 perennial plants per hectare (13 000 shrubs). The diversity of perennial species ranges from 1 to 12 species per site, with a mean of 6 species. The most numerous species were *Ptilotus obovatus*, *Ptilotus polakii*, *Senna artemisioides* subsp. x *sturtii*, *Eremophila forrestii*, *Acacia victoriae* and *Eremophila cuneifolia*. In 2011, the mean density of desirable plants was 980 plants per hectare (ranging from 0 to 6500 desirable plants per hectare) per site.

Overall, since WARMS sites were established in the Gascoyne River catchment in 1995–1996, the total number of perennial plants (i.e. perennial vegetation groundcover) has generally remained stable (0.5% increase). However, there was an increase in plant numbers in cycle 1 (1995 to 2000) in response to the run of above average seasons (87% of sites experienced an above average season), 'perhaps a once in a lifetime sequence of events' (Watson 2001) but declined in successive assessments with seasons more in line with average conditions. In the most recent cycle (2006 to 2011) plant numbers (thereby perennial vegetation groundcover) have declined 15% (Table 3; Figure 17).

In terms of desirable plant numbers (pastoral management perspective) desirables have decreased by 4%, intermediates decreased 7% and the undesirables have increased by 24% between 1995 and 2011. In the most recent assessment (2006 to 2011) the desirable plant numbers decreased by 17%, intermediate plant numbers decreased by 18% and undesirable plant numbers decreased by 6% (Table 3; Figure 17).

The decline in the total number of perennial plants in recent years reduces landscape function, whilst the decline in desirable plants has implications for management in respect to setting appropriate stocking rates to manage the decline in the number of desirable plants. Although there was a 'seasonal pulse' in response to the sequence of above average seasons (1995 to 2000), plant numbers have declined from this level.

Table 3 **Change in plant numbers (total and by desirability class) and seasonal quality for WARMS sites within the Gascoyne River catchment**

Cycle		Change in total plant numbers	Desirability			Seasonal quality		
			Desirable	Intermediate	Undesirable	Above average	Average	Below average
1	Epoch 1 to Epoch 2 (1995 to 2000)	64%	82%	53%	46%	87%	10%	3%
2	Epoch 2 to Epoch 3 (2000 to 2006)	-28%	-37%	-25%	-10%	3%	39%	58%
3	Epoch 3 to Epoch 4 (2006 to 2011)	-15%	-17%	-18%	-6%	20%	51%	29%

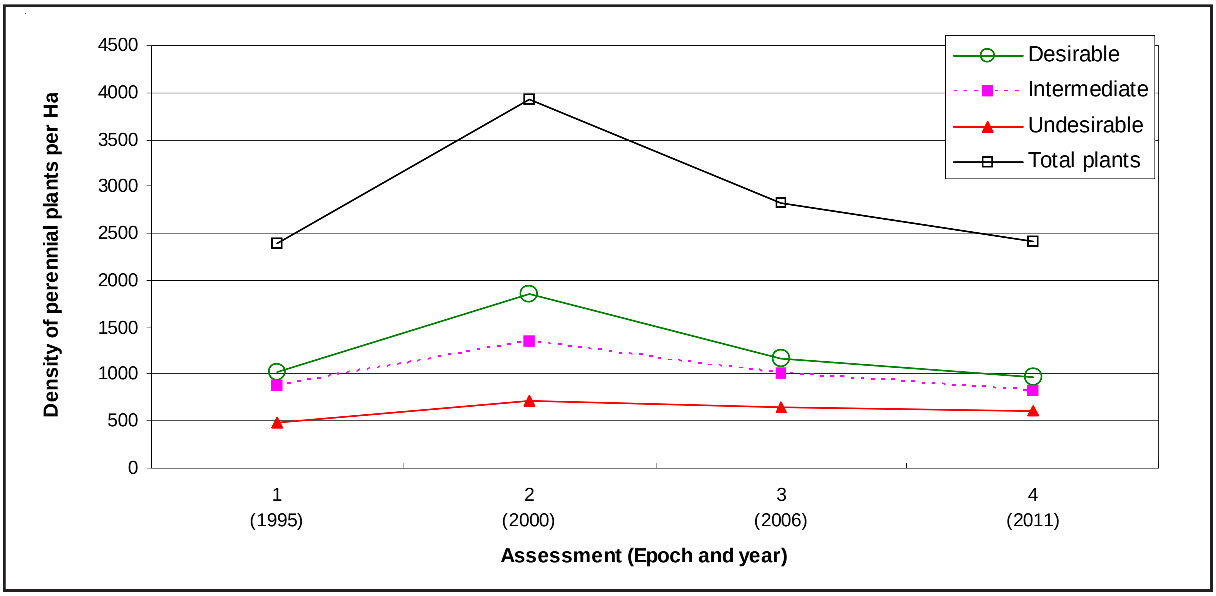


Figure 17 **Density (per ha) of total perennial plants and by desirability class on WARMS sites within Gascoyne River catchment**

2.2.2.2.2 Resource capture

The resource capture index (RCI) is a measure of how many capture zones or patches (typically accumulation under shrubs, chenopod mounds or fallen timber) exist throughout the landscape to capture and retain resources (water, soil and nutrient). Capture zones (patches) have higher infiltration rates than interpatch (shedding) zones (Section 2.2.3). The average RCI for the WARMS sites assessed in 2011 was 0.116. This was a decline of 13% from the previous sampling and is consistent with the 15% decline in shrub populations, as described above, as accumulation zones and chenopod bush mounds reduce in size or became remnant patches.

Based on WARMS sites assessed in 2011, on average 11.6% of the landscape is defined as capture zones. However this varies from 0% capture zone on some stony plains to 72% capture zone on a run-on unit. The change in RCI between 2006 and 2011 was most noticeable in grove/run-on sites, where RCI declined 22% (0.421 to 0.327), although these sites were only 7.5% of the sites assessed in the catchment. Plains and stony plains (71.2% of sites) declined 12%, and shrubby plains–sandy banks declined by 8% (21.3% of sites).

The average interpatch (shedding zone) length across all WARMS sites was 686 cm, ranging from 5 cm to 4950 cm. The average patch length for the dominant capture zone types and the interpatch are shown in Table 4.

On average there were only five capture zones per 50 m, ranging from 0.5 to 12 patches per 50 m. The grove/run-on sites have the most and largest capture zones (8.6 capture zones per 50 m and 700 cm long). However these sites only account for 7.5% of sites throughout the catchment. The potential for retaining resources on shrubby plains (6.4 capture zones per 50 m and 184 cm long) and stony plains (4.9 capture zones per 50 m and 185 cm long) is much reduced with both fewer and smaller obstructions than the grove communities. In the stony plain and shrubby plain landscapes, the low number of capture zones and long interpatch (shedding) lengths allow water to build energy and increase erosion processes.

The reduction in RCI between 2006 and 2011 indicates fewer resources are being retained in the landscape and the zones of higher infiltration are being reduced in size and number.

Table 4 **Average patch length (cm) and number of obstructions per 50 m (in brackets)**

Patch type	Overall	Stony plain	Shrubby plain	Grove
Accumulation under shrub or trees (capture)	125 (4.2)	112 (3.8)	127 (4.6)	294 (3.3)
Grove (capture)	320 (3.3)			320 (3.3)
Fallen timber (capture)	72 (1.5)	73 (1.1)	57 (1.8)	86 (2)
Interpatch (shedding)	686	796	586	503

2.2.2.2.3 Soil surface assessment

In general the WARMS sites show the soil surface to have few rainfall and surface flow intercepts (about 2 to 5% cover); the crust is intact; litter cover is around 10 to 25%; and micro topography is flat (3 to 8 mm).

For the soil surface attributes of soil cover rain intercept, soil cover overland flow and litter cover the average values were better in capture zones than on interpatch (shedding) zones. This highlights the importance of capture zones to protect the soil surface and provide obstructions for litter accumulation, thereby increasing nutrient and infiltration characteristics. There is little difference between other soil surface attributes (Appendix 6).

The assessment of soil surface erosion at the WARMS site (in a 1 m^2 quadrat) is at the fine scale and does not account for larger erosion processes (discussed in Section 3) that may be occurring around the site. However it provides a precursor to developing erosion. The type and severity of erosion recorded in 2011 on individual quadrats is summarised in Table 5.

In 2011 there was no erosion recorded on 43% of interpatch (shedding) zone quadrats. Of the quadrats showing erosion, slight sheet erosion (89%) was the most prevalent erosion type, rather than rill and terracette erosion. On the capture zones there was no erosion recorded on 56% of quadrats.

There was an increase in assessed erosion between 2006 and 2011 in both capture and interpatch (shedding) zones (Table 6). In 2011, 57% of the interpatch (shedding) had an erosion feature (previously 44%) and 44% of the important less frequent capture zones have an erosion feature, previously only 28%. The influence of the 2010–11 floods on this increase is unknown.

Large areas of the Gascoyne catchment are characterised by a stony mantle and high watershedding surface (Appendix Table 3.2). Based on estimations at each WARMS site, on average there was 32% stony mantle cover across all WARMS sites. By broad landscape type, stony mantle was estimated to average 53% on the stony plains, 18% stony mantle on the shrubby plains, and 7% stony mantle on the grove sites.

Based on WARMS sites the number of obstructions in 2011 has declined to an average of only 11.6% of the assessed landscape, with the remaining 88.4% interpatches. Soil surface erosion increased in both shedding and capture zones.

Table 5 **Percentage of erosion types by resource capture zone (2011)**

(a) Shedding zones (Interpatch)

	Nil	Slight	Moderate	Extensive
Overall	***43***	***33***	***17***	***7***
Sheeting		89	81	76
Pedestalling		1		
Rill			1	2
Scald		8	16	22
Terracettes		2	2	

(b) Capture zones (Patch)

	Nil	Slight	Moderate	Extensive
Overall	***56***	***33***	***8***	***3***
Sheeting		79	84	80
Pedestalling		4		
Rill		2	8	10
Scald		11		
Terracettes		4	8	10

Table 6 **Change in assessed erosion by resource capture zone between 2006 and 2011**

(a) Shedding zones (Interpatch)

	Nil	Slight	Moderate	Extensive
2006	56%	25%	13%	6%
2011	43%	33%	18%	7%

(b) Capture zones (Patch)

	Nil	Slight	Moderate	Extensive
2006	72%	21%	6%	1%
2011	56%	33%	8%	3%

2.2.2.3 Vegetation cover

2.2.2.3.1 Cover change analysis using Landsat

At the catchment scale the average perennial vegetation groundcover in the Gascoyne River catchment over the period 1989 to 2010 generally remained stable, with only a small decline. Cover declined in 2004 (Figure 18) in response to the consecutive dry seasons and total grazing levels. Whilst the 2010 season was poor, cover levels were marginally higher than in 2004. There were also changes in cover levels across the catchment during 1989 to 2010; Figure 19 shows cover increased (green) in the south-west and eastern parts of the catchment and declined in the central catchment (red) over this period.

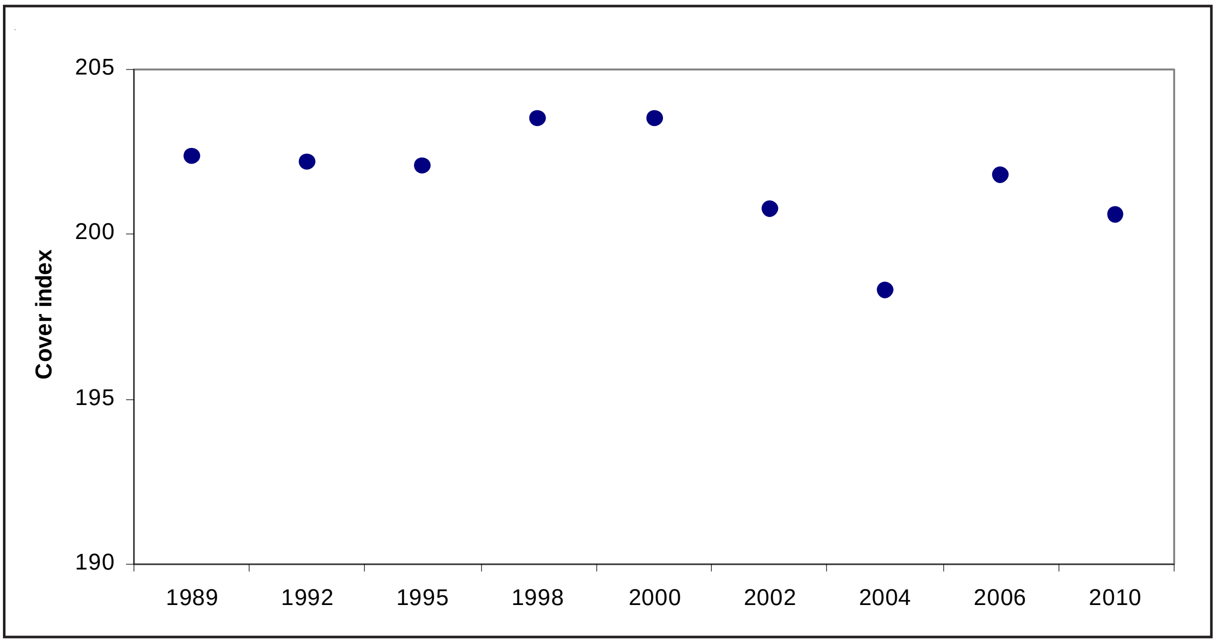


Figure 18 **Average Cover Index for Gascoyne River catchment (1989 to 2010)**

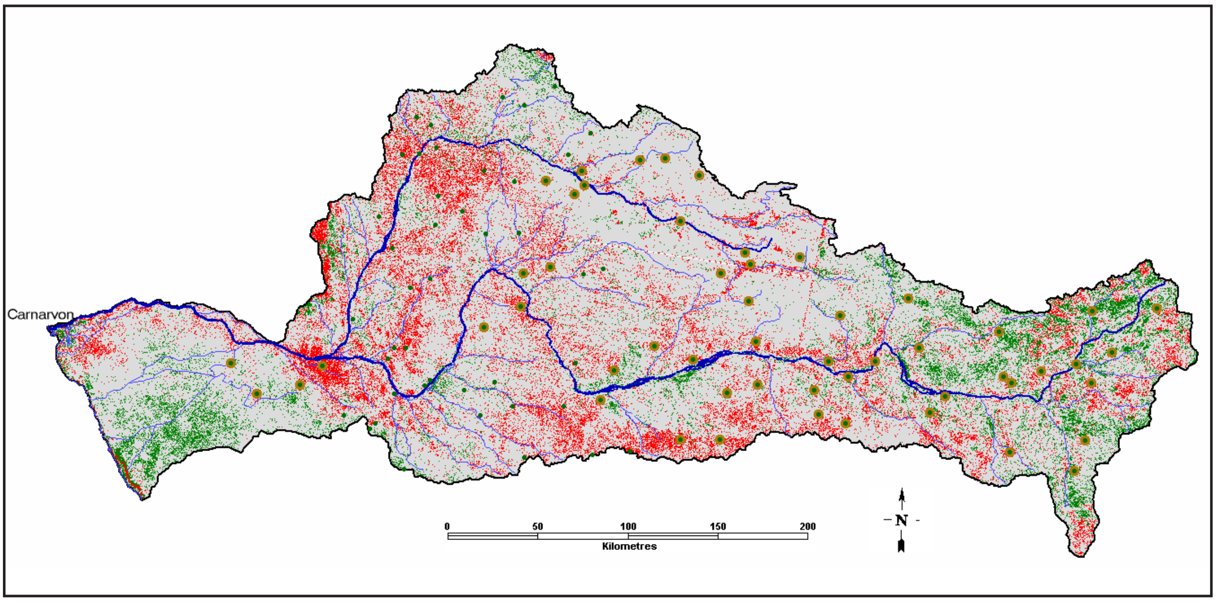


Figure19 **Trend in cover index (1989 to 2010)** *(red – cover decreased; green – cover increased; grey – no change)*

At a land system scale the long-term cover trend from 1989 to 2010 indicates that 41 land systems had stable cover, while in 33 land systems cover declined. Perennial cover is variable between land systems of the same land type depending on the condition and vegetation of the land system. Time traces for the land systems within the dominant four land types are shown in Figures 20a, b, c and d.

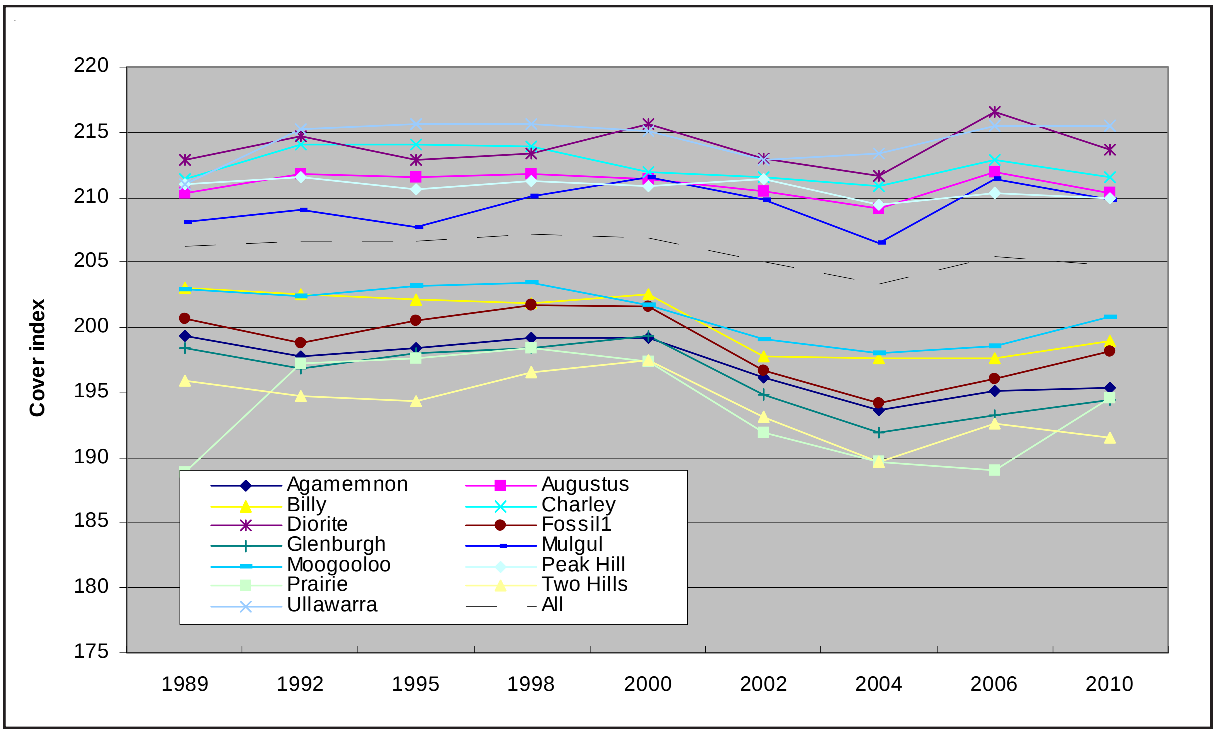


Figure 20(a) **Hills and ranges with acacia shrublands (18% of catchment)**

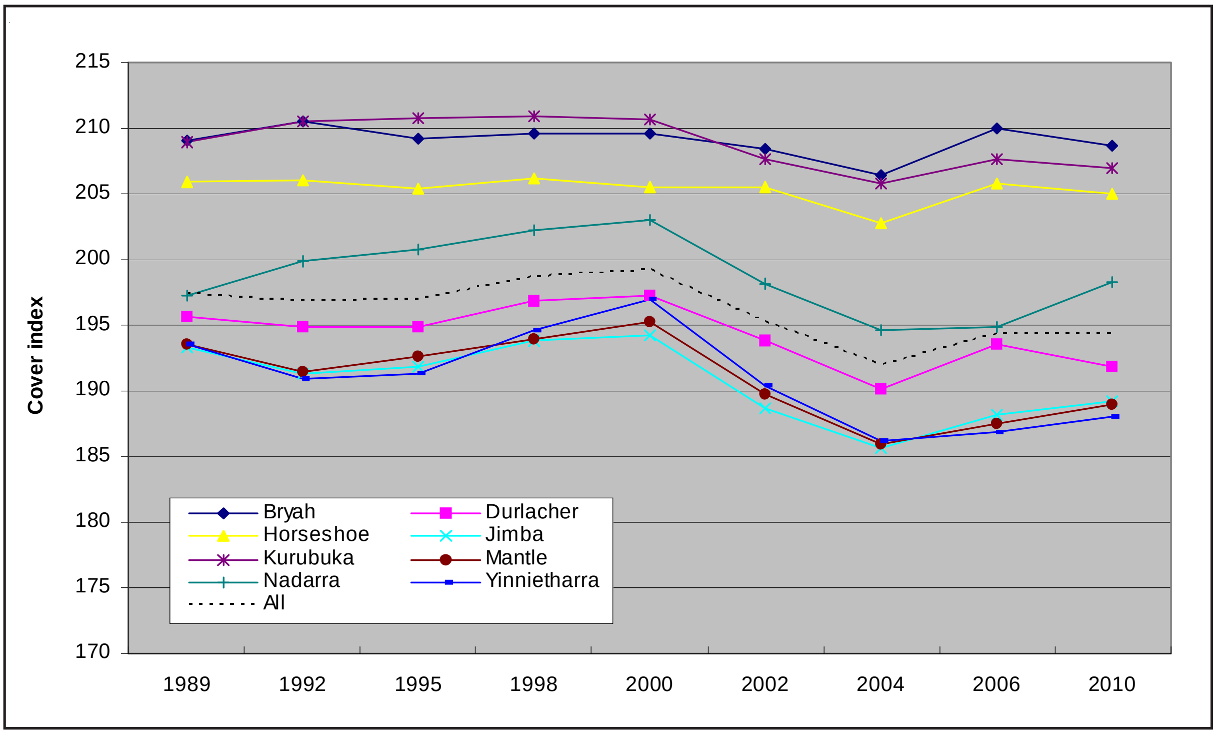


Figure 20(b) **Stony plains with acacia shrublands and halophytic (16% of catchment)**

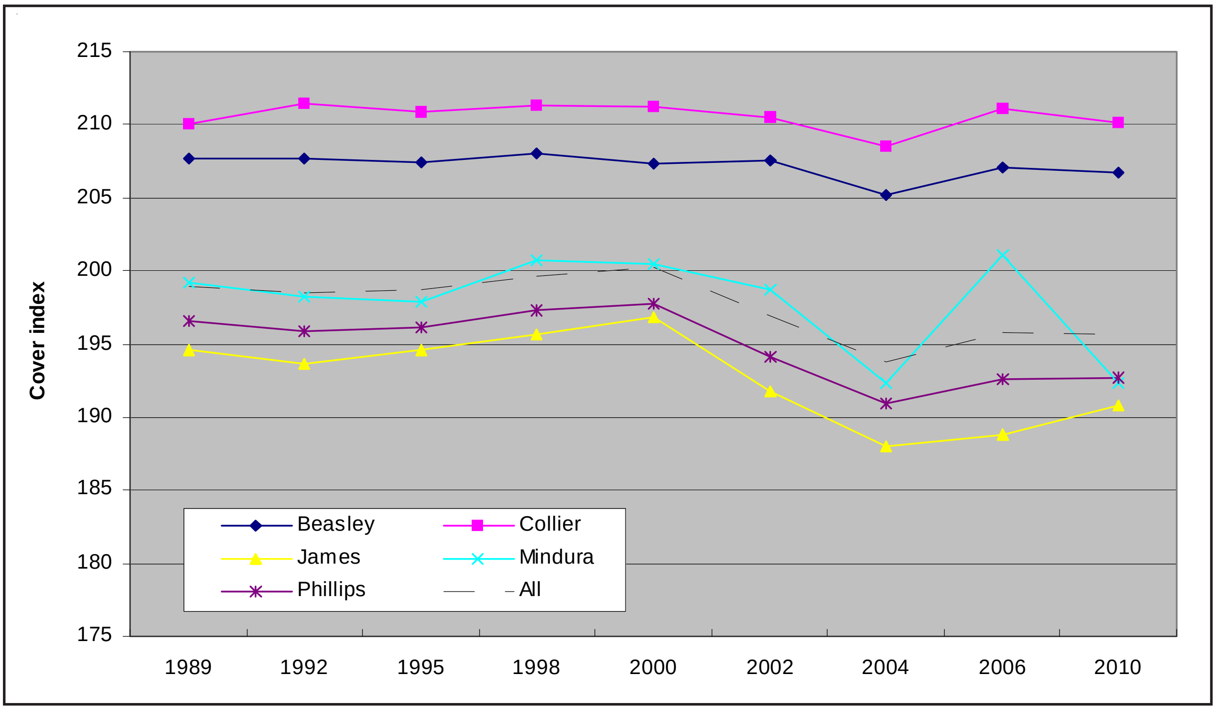


Figure 20(c) **Low hills and stony plains with acacia shrublands (16% of catchment)**

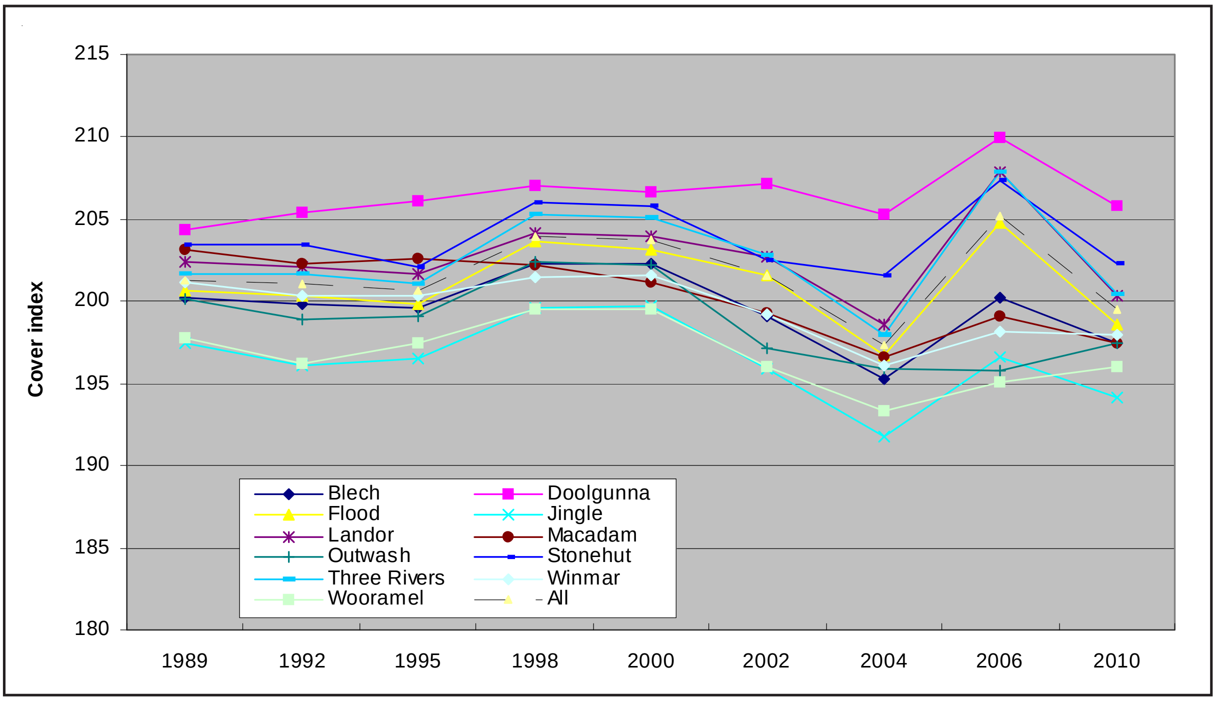


Figure 20(d) **Wash plains and sandy banks on hardpan, with mulga (12% of catchment)**

2.2.2.3.2 Seasonal analysis using NOAA NDVI – The 2010 season

As seen in Figure 21, areas of the central Gascoyne and Lyons rivers with low NDVI (116, with some areas as low as 110), coincident with the areas of high rainfall in December 2010 (Figure 7), highlight the susceptibility to erosion and higher run-off in this part of the catchment. The average NDVI in December 2010 and January 2011 is little different to the 10-year average for these months suggesting that any summer rainfall of significance will have little groundcover to influence water flow.

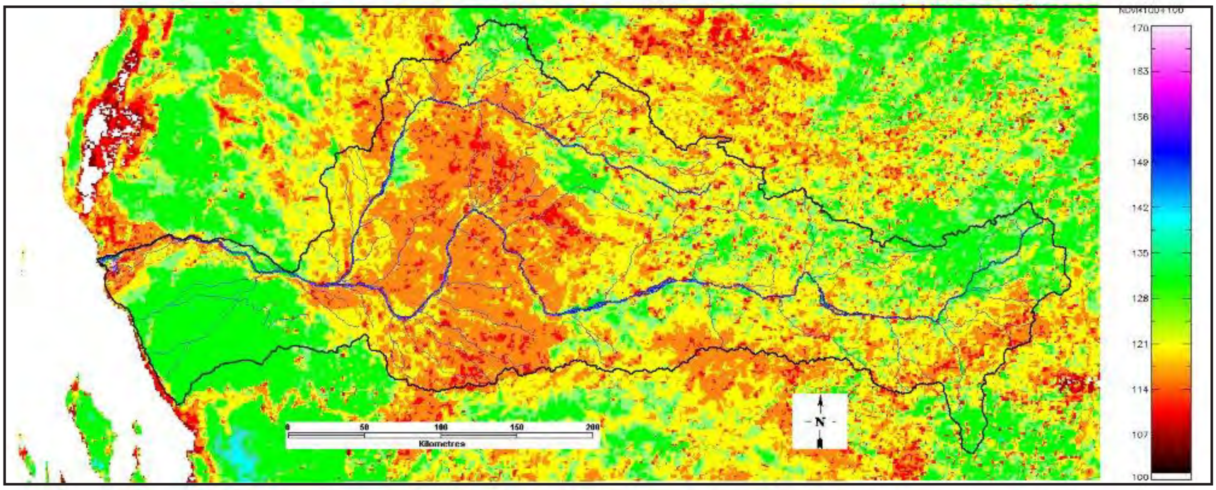


Figure 21 **Minimum NDVI July to December 2010**

Analysis of NDVI data from 1992 to 2010 shows that for 40% of the catchment, the year of last reasonable season was in or prior to 2006 (Figure 22). For the subsequent 4 years (2007 to 2010), much of the catchment experienced variable seasonal conditions, with only 27% of the catchment recording a reasonable season in 2010. The percentage of the catchment by year of last reasonable season is shown in Table 7. The high December 2010 rainfall was too late to affect the 2010 season.

The low perennial vegetation groundcover levels are indicative of the condition within the Gascoyne River catchment (Section 2.2.2.1) and have shown no broadscale improvement for the period analysed. There are some management units that have increased cover. However, the loss of perennial vegetation groundcover in the central Gascoyne and Lyons rivers from 1989 to 2010 coupled with the low NDVI (greenness cover) in December 2010, and 40% of the catchment not having a reasonable season for over 4 years, suggest a potential for increased run-off and erosion in 2010–11.

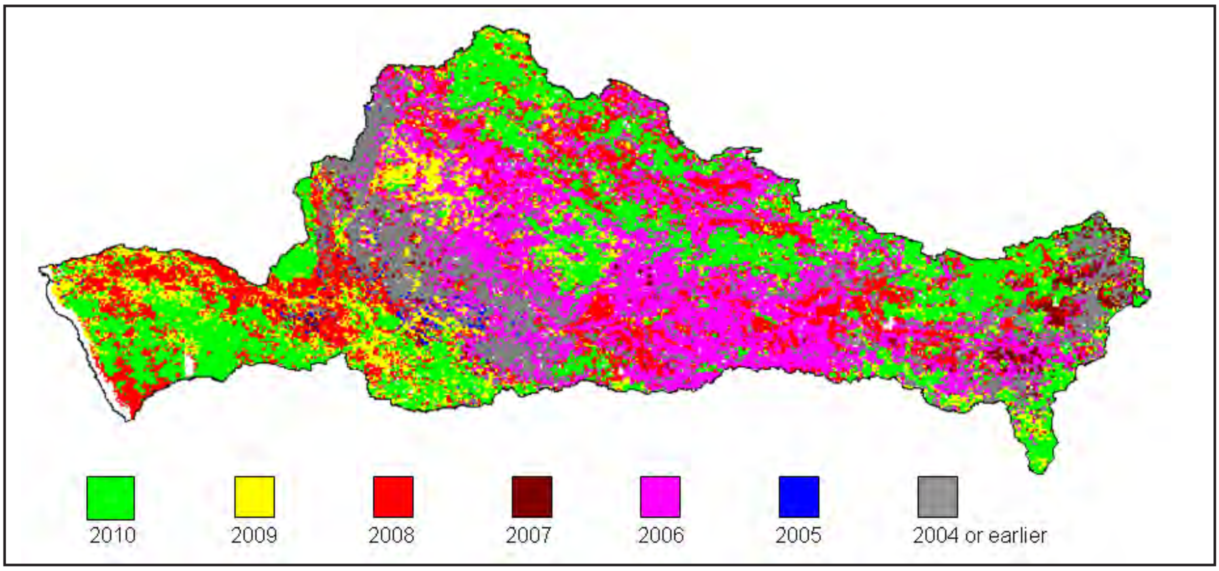


Figure 22 **Year of last reasonable season**

Table 7 **Percentage of catchment – year of last reasonable season**

	2010	2009	2008	2007	2006	2005 or before
Percentage of catchment	27	11	20	3	26	14

2.2.3 Soil infiltration measurements

2.2.3.1 Soil and site data

Surface (0–5 cm) textures tended to be lighter across both patch classes (Table 8), with 77% in texture groups: sand, sandy loam and loam compared with the subsurface (5–10 cm), with 66% in the same texture groups (Table 9). Similarly, the patches tend to have lighter textures than the interpatches. For example, sandy textures dominated surface of the patches (44%), while sandy loams dominated the subsurface of the interpatches (44%). This suggests that there is a change in texture down the profile, more evident in the interpatches than the patches. The difference in texture between the resource capture zones reflects the accumulation of sand and resources in the patches and the stripping of the surface in the interpatch.

Table 8 **Comparison of number and percentage of infiltration measurements for each patch class and texture group at soil depth 0–5 cm (surface)**

	Number			**Percentage**		
	Interpatch	**Patch**	**Total**	**Interpatch**	**Patch**	**Combined**
Sand	8	10	18	18	44	28
Sandy loam	19	3	22	42	14	33
Loam	8	3	11	18	14	16
Clay loam	7	3	10	16	14	15
Light clay	2	3	5	4	14	7
Clay	1	0	1	2	0	1
Total	45	22	67	100	100	100

Table 9 **Comparison of number and percentage of infiltration measurements for each patch class and texture group at soil depth 5–10 cm (subsurface)**

	Number			**Percentage**		
	Interpatch	**Patch**	**Total**	**Interpatch**	**Patch**	**Combined**
Sand	4	7	11	9	32	17
Sandy loam	20	4	24	44	18	36
Loam	6	3	9	13	14	13
Clay loam	8	5	13	18	23	19
Light clay	5	3	8	11	13	12
Clay	2	0	2	5	0	3
Total	45	22	67	100	100	100

2.2.3.2 Analysis of Infiltration measurements

Equation 1 (Section 2.1.3) was applied to the 67 sets of infiltration measurements collected in the field. The mean value for steady-state infiltration rate Q, was 151 mm/h with values ranging from 9 mm/h to 1000 mm/h, with the average standard error of 5 mm/h. The average R2 for the regression equations was 0.992 ranging from 0.913 to 0.999 with the standard error of the regression ranging from 0.1 mm to 4 mm with an average of 1 mm.

The photographs in Figure 23 show the difference in soil surface conditions between the patch and interpatches. This difference is reflected in the infiltration rates in Figure 24, which shows a comparison between three sets of data collected at one WARMS site. In the Figure 24 example, there is a twofold difference between the infiltration rates in the patch, illustrating the large variability within the patch class at one site (Figure 24: line A verses line B). However, this example also shows a substantial four to ninefold difference in infiltration rates between the patch and interpatch.

Figure 23 **Examples of different resource capture zones where comparison infiltration site measurements were undertaken on interpatch and patch surfaces**

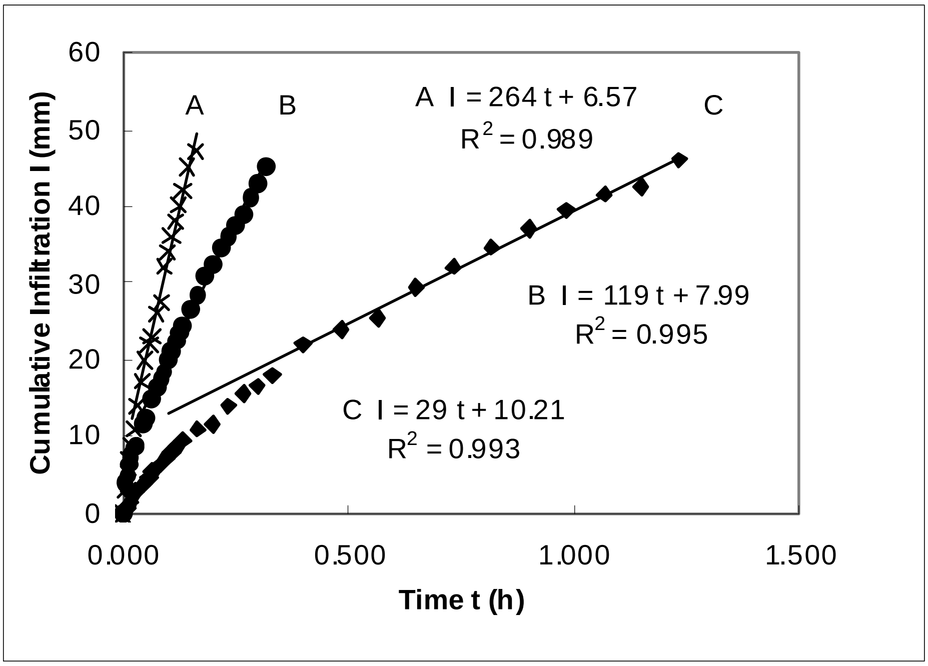


Figure 24 **Three infiltration measurements taken at the one WARMS site. A and B are infiltration replicates in the patch while C is the infiltration in the interpatch**

The differences in infiltration rates (Q) observed in Figure 24 are seen across the soil infiltration measurements as a whole. The average steady-state infiltration for the patches was four times higher than the interpatches (Table 10). For all the sites, patch infiltration rate was 305 mm/hr compared to 75 mm/hr for the interpatch infiltration rate. With the 14 paired infiltration measurements, Q was 73 mm/hr and 326 mm/hr for the interpatch and patch respectively (P0.05; Two tail Paired t-Test), thus supporting the whole data set.

With all the measurements, there were more than twice the number of infiltration measurements made in the interpatch compared with the patches—a reflection of the proportion of interpatch and patch at WARMS sites (Appendix Table 4.3). There are observable differences in soil texture with patches tending to have lighter soil textures than interpatches (Section 2.2.3.1). Light textured soils are often associated with high infiltration rates. Here however, Tables 10 and 11 indicate infiltration rates for all texture groups are higher in the patches than in interpatches, and importantly, average steady-state infiltration rates are of similar magnitude for a range of texture classes within a patch class at either depth. In addition there is only a weak relationship between infiltration rate and soil texture, with infiltration rates slower for heavier textures.

Differences in infiltration due to vegetation have been observed by others. Tongway and Ludwig (1996) demonstrated that infiltration under a simple mulga branch stack (in effect fallen timber) improved tenfold, from 11.6 mm/hr to 118 mm/hr. Dunkerley (2000, 2002) showed in the interpatches between mulga groves infiltration was a function of distance from the stems of shrubs, with infiltration rates near the stem up to 20 times greater than those measured 6 m away. These differences are similar to those observed here.

The results suggest that in the Gascoyne River catchment vegetation may determine infiltration rate across the catchment and not soil texture. Therefore, it is reasonable to expect soil infiltration rates are more likely to change with changes in vegetative cover from season to season and in the longer term as a result of droughts and land management practices.

Table 10 **Comparison of average steady-state infiltration rates (mm/h) for each patch class and texture group at soil depths 0 to 5 cm**

	Soil depth 0–5 cm		
	Interpatch	**Patch**	**Average**
Sand	74	333	218
Sandy loam	76	424	124
Loam	89	133	101
Clay loam	73	435	182
Light clay	39	134	96
Clay	22	N/A	22
Overall average	75	305	151

Table 11 **Comparison of average steady-state infiltration rates (mm/h) for each patch class and texture group at soil depths and 5–10 cm**

	Soil depth 5–10 cm		
	Interpatch	**Patch**	**Average**
Sand	130	366	280
Sandy loam	73	448	136
Loam	85	133	101
Clay loam	86	312	173
Light clay	29	134	68
Clay	26	N/A	26
Overall average	75	305	151

3 Effect of soil and vegetation condition on landscape stability

This section describes the mechanisms and processes within the Gascoyne River catchment associated with landscape function using photographic evidence to demonstrate the role perennial vegetation groundcover has in maintaining landscape stability and in reducing the risk of soil loss for different rangeland landscapes.

The information presented in this section is based on field work in the Gascoyne River catchment between June and August 2011. All photographs used in this section are of the Gascoyne River catchment. Aerial photography has been provided by and with the permission of the Western Australian Land Information Authority trading as Landgate.

Evaluations of catchment condition that form the basis of this section are based on the methodology established from the DAFWA rangeland survey project and from previous flood reviews (Section 2.1). Landforms and landscape patterns of interest, predetermined through aerial photograph interpretation, were visited whilst on route to WARMS sites. To formulate an overall perspective of catchment condition, traverse notes and photographs were collected throughout the field work period.

To explain the landscape processes responsible for influencing soil and vegetation condition in the catchment it is first necessary to present the landscapes of the catchment in a broad geological and geomorphic context. This is provided in ‘Physiographic regions of the Gascoyne River catchment’ (Section 3.1). A soil-landscape mapping hierarchical framework is used to describe the different landscapes. Landscapes with similar topographic features, soils, vegetation and drainage patterns are grouped at a systems level. The spatial organisation of the catchment’s landscapes are explained through descriptions of landforms, geomorphology and vegetation.

Prior to summarising the condition of the catchment’s landscapes it is also necessary to describe how rangeland ecosystems function, and how the present condition of the soil and vegetation is affecting landscape stability. Landscape processes operating within, but not unique to, the Gascoyne River catchment are briefly described in ‘Landscape organisation and function’ (Section 3.2). Whilst focusing on the Gascoyne River catchment much of the information presented on landscape organisation and function is relevant to many of the southern rangeland environments of Western Australia.

The findings from traverse notes and aerial photograph interpretation form the basis of the ‘Gascoyne River catchment condition summary’ (Section 3.3). Degradation and erosion processes common to the various land types are discussed to explain how catchment function is being impaired and therefore affecting landscape stability. This section concludes with a brief summation of the catchment.

3.1 Physiographic regions of the Gascoyne River catchment

The area of the Gascoyne River catchment is 80 400 km^2 (Department of Water 2007). Physiographically, approximately two-thirds of the catchment is located within the southern portion of the Ashburton Province of Tille (2006), based on the Capricorn Orogen tectonic unit of Tyler and Hocking (2001).

The western portion of the catchment extends into the Carnarvon Province of Tille (2006), formerly the northern portion of the Western Coastlands Province of Jennings and Mabbutt (1977). This corresponds with the Southern Carnarvon Basin tectonic unit of Tyler and

Hocking (2001). A small portion along the central southern margin of the catchment comprises the Murchison Province of Tille (2006), based on the Murchison Province of Bettenay (1983). This boundary is based on the northern half of the Yilgarn Craton tectonic unit of Tyler and Hocking (2001).

The Department of Agriculture and Food uses a soil–landscape mapping hierarchy based on a scheme where each level is a subdivision of the preceding level. **Regions** are the highest level and are subdivided into **provinces**. Provinces are subdivided into **zones**. Zones are in turn, further subdivided into **systems** (*land types*), **subsystems** (*land systems*) and **phases**.

The provinces of the Gascoyne River catchment are subdivided into the following zones based on geomorphologic or geological criteria, as described by Tille (2006). Refer to Figure 25 below and Appendix Table 7.1.

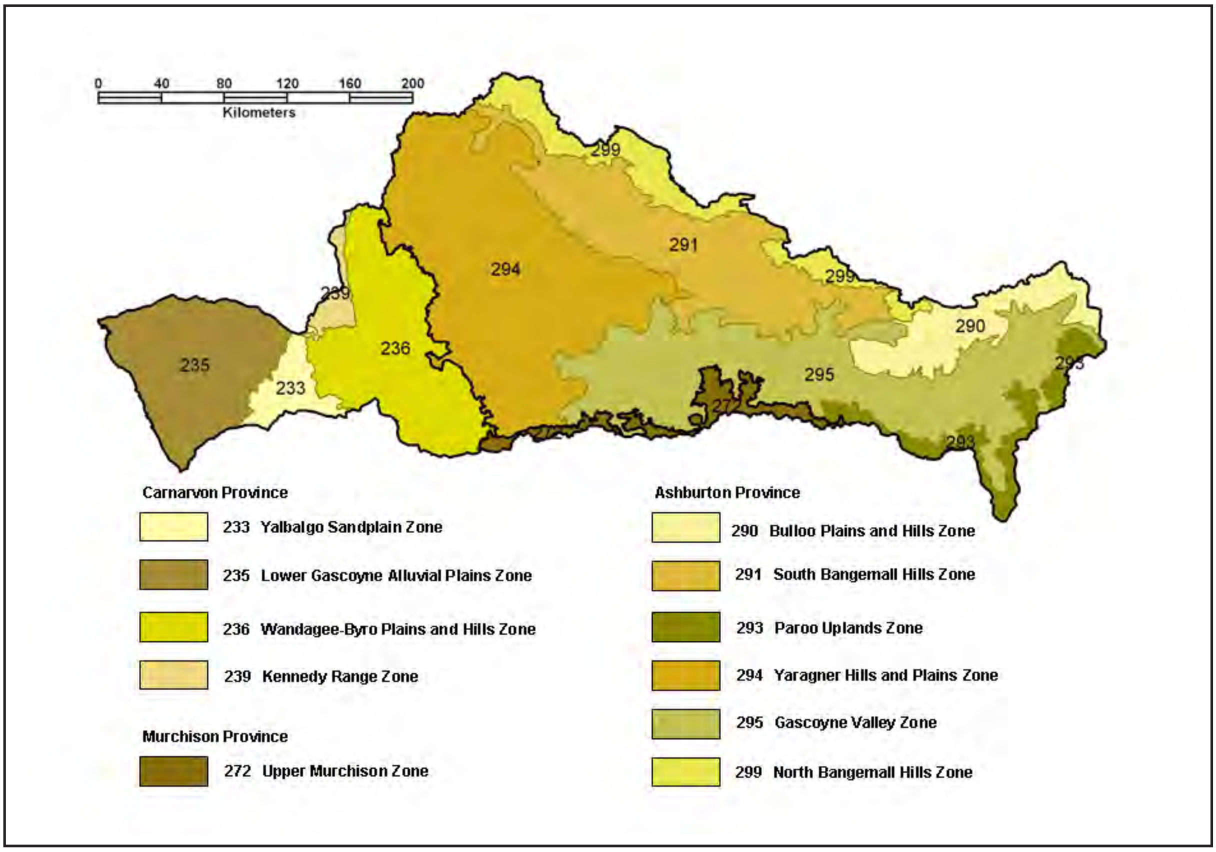


Figure 25 **Provinces and soil–landscape zones of the Gascoyne River catchment**

Wilcox and McKinnon (1972) used a land system mapping approach to logically and sequentially study all parts of the catchment within their 1969–1970 survey area. A 'land system' is described as an area or group of areas throughout which there is a recurring pattern of topography, soils and vegetation. Land systems commonly consist of smaller land units or elements, each of which has a distinctive photographic pattern. The relative proportion of the component units and their relationship gives the broader photographic pattern that characterises the particular land system.

Land systems are grouped into land types according to a combination of landforms, soils, vegetation and drainage patterns. Land types provide a method of referral to similar landscapes within a specific topographic position or landscape catena sequence. Within the Gascoyne River catchment there are 77 land systems which have been combined into

16 land types (Table 2, Section 2.2.2.2). Appendix Table 7.2 shows the land types and their component land systems. In this section, to provide information at a level more appropriate for considering catchment characteristics and processes, land types have been amalgamated into broad topographic positions based on their spatial organisation.

3.1.1 Spatial organisation

Landscapes within a catena profile are functionally linked through their relationship between upland source areas, transfer or wash zones and bottomland deposition areas. Within a catchment or watershed these sequences are linked as a network. Table 12 summarises the topographic sequence of the land types within the Gascoyne River catchment. The catena sequence presented below, and the land types within, is typical of southern rangeland environments with external (exoreic) drainage systems (Payne, Curry & Spencer 1987; Curry et al. 1994; Van Vreeswyk et al. 2004).

Table 12 **Land type position within the topographic sequence of the Gascoyne River catchment**

Topographic position	Land type
Upland source areas	Hills and ranges
	Mesas and breakaways
	Stony plains
Transfer zones (Sheet wash plains)	Wash plains on hardpan
	Sandy plains or sandy banks on hardpan
Bottomland deposition areas	Alluvial plains
	Calcrete platforms
	River plains
	Sandplains and occasional dunes
	*Coastal plains, cliffs, dunes, mudflats and beaches

* Coastal plains comprise only a small proportion of the catchment (0.1%) and are restricted to coastal areas in the west. They contribute little to condition of the central and upper catchment and are not considered in any detail in this report.

The upland source areas are hills and ranges or indurated remnant plateau surfaces of ferruginised or silicified duricrust. Downslope relief is more subdued, being composed of low rises and undulating stony plains. Where internal drainage is restricted or sluggish, drainage foci and gilgai can develop within level stony plains.

Down the topographic sequence, undulating plains give way to gently sloped to near-level hardpan wash plains. These surfaces are differentiated by the presence and extent of grove organisation, typically mulga (*Acacia aneura*). Across the lower slopes gradational sand deposition forms sandy banks, which in good condition support dense stands of perennial wanderrie grasses under scattered mulga or other acacia species, commonly referred to as ‘wanderrie banks’.

The erosional processes operating through the upland source and transfer zones change to deposition in bottomland deposition areas. Alluvial surfaces develop in association with deposition on floodplains and river frontages, playas, claypans, swamps and lake country. Calcrete formation in much of the catchment is attributed to cementation of alluvial units and is considered a weathering/pedogenic product. The western portion of the catchment occurring in the Carnarvon province is of low relief and dominated by widespread alluvial and aeolian deposition with extensive sandplains and dune fields.

3.1.2 Upland source areas

Hills and ranges comprise some of the highest features in the landscape (relief > 30 m), with gentle inclined to precipitous slopes. Abundant outcrop and stony mantles of cobbles, pebbles and gravels are typical, and provide some resistance to erosion (Figure 26). Extending below hill crests and ridges are lower slopes and interfluves sloping to level drainage plains confined between undulating low rises (Figure 27). Drainage tracts in undulating sections are generally incised and shallow, restricted by bedrock. Where gradient is reduced drainage may slow, spread and become braided.

Mesas and breakaways are characterised by indurated remnant plateau surfaces on granites and gneisses above lower plains, and rounded rocky hills. They are also amongst the highest landforms in the catchment, and are commonly dissected by incised drainage tracts. On the lower footslopes and associated stony plains, saline, duplex soils are common. On alluvial fans extending away from breakaways halophytic pastures should exist. Despite a moderate mantle of cobbles and pebbles overgrazed lower slopes are frequently rilled and gullied.

Stony plains commonly surround upland areas of higher relief and occupy a greater proportion of the landscape. They are dominated by extensive interfluves sparsely dissected by drainage tracts. As slope gradients lessen and drainage becomes sluggish drainage foci, gilgai-flats and broad drainage tracts or marginal flood plains adjacent to major tributaries develop. Acacia and halophytic shrublands tend to occur where drainage becomes restricted and weak depositional habitats form.

Figure 26 **Low hills of Phillips land system with an abundant surface mantle of cobbles, pebbles and gravels**

Figure 27 **Sparsely vegetated interfluve of Phillips land system**

3.1.3 Transfer zones (Sheet wash plains)

Sheet wash plains occur where there is minimal gradient and drainage is not clearly defined. They are typically distal slope deposits composed of colluvium and alluvium, which form tributary plains between upland and bottomland areas. Wash plains on hardpan are one of the most extensive catchment land types.

Extending downslope from areas of relief, gently rounded interfluves form the upper gradients of these extensive plains. Interfluve convexities are separated by level drainage tracts supporting closely spaced mulga groves. With lessening gradient interfluves flatten, and extensive gravel-covered loamy plains dominate.

These sparsely vegetated plains are dominated by interpatches, except where tree-based clumps, vegetated drainage foci and pronounced narrow vegetation bands occur. Vegetation bands are generally arranged transverse to flow (Figures 28 & 29a, b, c) and are commonly dominated by mulga or gidgee (*Acacia pruinocarpa*). The interpatches shed sheet flow which is restricted and absorbed by groves, when in good condition, facilitating resource retention. Across interpatches evaporation rates are high and water infiltration is poor. Consequently large areas of these plains are unsuitable for prolific plant growth and are unproductive.

Sandy banks occur on the lower reaches of hardpan wash plains, deposited by water and wind. Their height and shape are dependent on their location. As drainage slows, in response to the reduced gradients, sand deposits accumulate. Interbank sections often occupy a greater proportion of area than the sand banks. However, having a similar function to vegetation patches, the importance of sandy banks in impeding sheet flow across the plains, promoting water infiltration and nutrient capture, is critical.

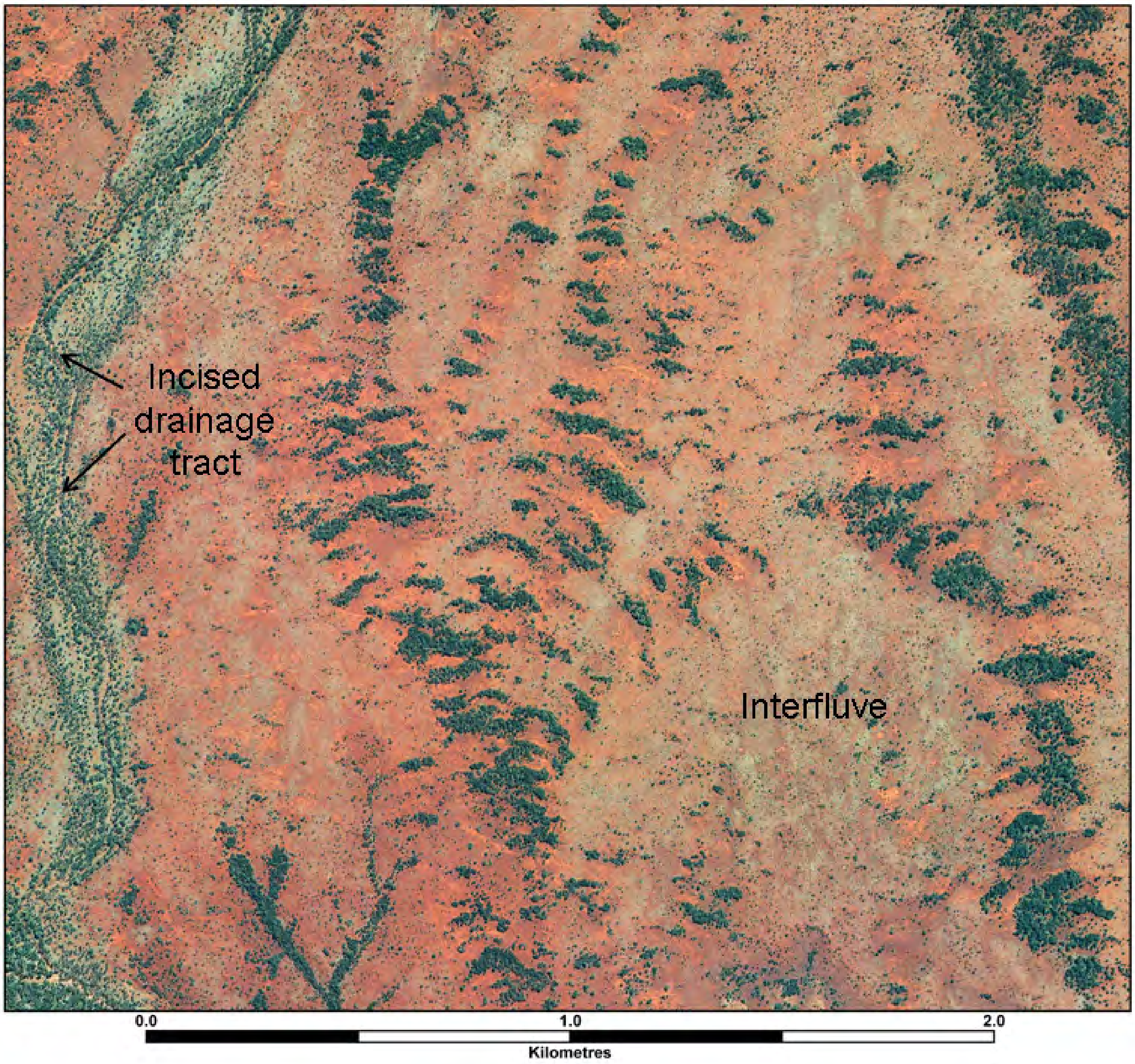


Figure 28 **Aerial photograph of remnant mulga groves aligned transverse to flow, Jamindie land system; Gascoyne River catchment** (2007 aerial photograph provided by Landgate)

Figure 29a **Mulga grove banding, foreground is upslope interpatch, Frederick land system**

Figure 29b **Mulga grove banding, Jamindie land system**

Figure 29c **Mulga grove banding, Three Rivers land system**

Figure 29a–c **Examples of vegetation banding formed by mulga groves with typical spatial arrangement of interpatch-patch (grove) – interpatch-patch**

3.1.4 Bottomland deposition areas

Alluvial plains marginal to and including major drainage channels are the dominant features of bottomland areas. They are areas of active surface redistribution through sheet erosion due to overbank discharge.

Streamlines may be single, deeply incised waterways or braided channels, with reduced but still considerable incision. Major drainage channels are generally wide with coarse sand or cobble strewn beds. Lesser channels and lateral gutters are often bare, having cut into hardpan surfaces, with deposits only present in scour pools and as point bar banks.

The vegetation of the riparian zone is typically dense and dominated by river gum (*Eucalyptus camaldulensis*), with mulga, curara (*Acacia tetragonophylla*) and creekline miniritchie (*Acacia cyperophylla*). Despite the density of riparian vegetation during peak flows considerable destruction can occur (Figure 30). Buffel grass (*Cenchrus ciliaris*) has colonised the understorey of many islands, river banks and margins, though it rarely dominates beyond a watercourse's inundation zone.

Figure 30 **Vegetation destruction along river channel; Gascoyne River Middle Branch**

Where slope gradients are drastically reduced drainage systems become sluggish, with swamps and drainage foci forming on restricted, level areas. Swamps support *Chenopodium auricomum* and lignum (*Muehlenbeckia florulenta*), whilst other drainage foci should support claypan grass (*Eriachne flaccida*) and neverfail (*Eragrostis setifolia*). Sandy banks support various species of acacia and eremophila, though overgrazing has eliminated perennial grasses and needlebush (*Hakea preissii*) is increasing.

Large sections of calcrete may outcrop within river plain land types. Calcrete platforms support scattered to moderately closed acacia shrubland dominated by mulga, limestone wattle, curara, snakewood (*A. xiphophylla*) or bardi bush (*A. victoriae*) over mixed shrubs.

With proximity to the coast, sand quantity increases and its availability facilitates dune development which characterises sandplains. Restricted to the western portion of the catchment, different dune formations are primarily shaped and modified by wind; land systems are differentiated based on dune pattern (i.e. reticulated, linear). Sand dunes range from sparsely vegetated to moderately closed tall shrubland. The second predominant sandplain type occurs as aeolian deposits on residual (old plateau) surfaces. Composed of deep sands, surfaces are dominated by vegetated, low linear or reticulate dunes with broad sandy swales. Predominantly supporting spinifex grassland beneath variable scattered mid to tall overstorey, they offer limited forage value. Sandplain pastures are generally stable although wind erosion can occur where vegetation is reduced through disturbance.

3.2 Landscape organisation and function

3.2.1 Rangeland ecosystem function and soil moisture balance

Slope and topography influence water and material movement, which in turn affects soil development, its drainage characteristics and its mineral composition. Rangeland ecosystems are structured to conserve scarce water and nutrients by mechanisms regulating limited resources through the landscape (Tongway 1994; Ludwig et al. 1997). It is often only a few key landscape factors that are critical for maintaining an ecosystem as a viable dynamic system. A system can be irreversibly altered or totally replaced as patterns and processes become disrupted by changes to any of these key factors.

In arid and semi-arid environments, soil moisture drives terrestrial productivity. Rainfall is important, geomorphically and ecologically, because it is highly variable temporally and spatially, in amount and intensity (and the severity and duration of dry periods). However, it is not rainfall amount, but the moisture within the soil profile that is directly important.

In regulating scarce resources, arid landscapes commonly consist of fertile patches within greater resource-poor areas or ‘interpatches’ (Tongway 1994). Being zones of water and soil accumulation these often support greater species density and diversity. Such patches are critical as ecological refugia from which plant re-establishment can occur after extended dry periods or disturbance. Similarly, they are important in drought buffering arid landscapes, providing forage during dry periods. Arid landscapes with many fertile patches are extremely efficient at capturing, recycling and utilising scarce resources (water and nutrients), and therefore lose few resources from the local system. Vegetation banding organisation has the critical function of retaining resources within vegetated patches.

Rangeland landscapes in good functional condition conserve resources which are cycled within the system. They are generally stable, capable of responding positively to disturbance and resist accelerated erosion. The soils have a degree of fertility with good water-holding capacity. In comparison, dysfunctional rangeland landscapes are poor at water and nutrient conservation. They have a reduced capacity to maintain existing nutrients, utilise incident rainfall or capture replacement materials. Figures 31a, b, c and 32a, b show the different states of a fertile patch.

Figure 31a **Intact mulga grove**

Figure 31b **Poor condition mulga grove with understorey removed**

Figure 31c **Remnant mulga grove degraded through overgrazing and water starvation**

Tree groves, bush clumps and wanderrie banks act as fertile patches, and are important in patch-interpatch water and nutrient capture processes. Consequently, greater floristic diversity generally occurs within groved habitats or under tree-based clumps (Figure 32a). Canopy shelter and the microhabitat below the sub-canopy are an advantage compared with establishment in exposed interpatches (Tester et al. 1987). Within groves branch and leaf litter accrete around their bases and obstruct ground surface winds and water flow. Wind and water dispersed material, (i.e. leaf litter, seeds, animal scats, general debris) accumulate within and immediately upslope of the grove or clump. This enriches soil with nutrients, particularly nitrogen, increases microbial activity and contributes to greater soil moisture (Garner & Steinberger 1988), and creates improved conditions for germination and establishment.

The continual grazing of groves and bush clumps during dry periods results in deterioration of the structure and composition of these habitats. Their fragmentation and decline reduces the system's capacity to retain scarce resources and continues to impair catchment function.

Exposed landscapes, eroded landscapes, dysfunctional groves, reduced spatial organisation or patterning characterise dysfunctional landscapes (Tongway & Ludwig 1997). The Gascoyne River catchment has all these features. In all phases of the catena sequence throughout the catchment the landscape has lost or has a much reduced capacity to regulate resources through retention of water and nutrients (Sections 2.2.2.2 and 2.2.3).

Figure 32a **Tree-based clump in good condition with good density and diversity of perennial plant species below the canopy**

Figure 32b **Tree-based clump in poor condition with a browse-line and limited understorey, primarily annual grasses**

3.2.2 Landscape incision and the desiccation process

A legacy from early pastoral settlement has been the construction of infrastructure that concentrated animal activity in critical catchment control points. Prior to reticulated piping pastoralists sought water where it could most readily be obtained in good quality and quantity. Frequently this occurred in drainage tracts. In combination with overgrazing, drainage systems became canalised and base levels lowered. Instead of intensified flows in natural creeklines slowing, fanning and spreading, sheet wash now mostly remains restricted in increasingly linear channels or concentrated washes. This leaves the plains to their sides perched, desiccated and more prone to sheet erosion. Increasingly greater rainfall events are now required to flood incised drainage tracts and return water to perched, water-starved surfaces (Figures 33a, b).

Figure 33a **Incised drainage line cut into hardpan**

Figure 33b **Increasingly greater rainfall events are required to fill these channels and get water back onto the adjacent plains**

3.2.2.1 Headward erosion

Breaching of base levels can significantly alter drainage patterns and soil moisture balance (Pringle & Tinley 2003). When an influential base level is cut, erosion progresses upslope; stripping topsoil, fragmenting and desiccating grasslands, chenopod shrublands and wooded groves, breaching ephemeral wetlands and draining floodplains as incisions leave them perched (Tinley 1982). Once erosion is initiated, it will probably continue until a new equilibrium has developed (Pickup 1985; Pringle, Watson & Tinley 2006). Figures 34a–e show the development of a typical erosion cell.

Figure 34a **Typical erosion cell sequence displaying the escalating stages of erosion from vegetation fragmentation through to sheeting, microterracing and rilling**

Figure 34b **Reduced ground coverage leads to surface stripping and vegetation fragmentation**

Figure 34c **Loss of groundcover results in sheet erosion, fine particles are removed and coarser material forms lag piles**

Figure 34d **Increased sheet flow amplifies the erosive potential facilitating the development of microterracing, and eventually gully heads**

Figure 34e **Gully heads concentrate water flow which increases water velocity and therefore erosive potential. Incision results and rills develop**

The desiccation process is driven by accelerated erosional processes, a consequence of increased run-off due to decreased groundcover, local landscape incisions and straightening of drainage tracts. High intensity rainfall events, typically associated with summer thunderstorm or cyclonic activity, exacerbate erosion. Accelerated water flows operate with increased erosive power where the landscape is incised (Pringle, Watson & Tinley 2006). Such locations may vary from a minor incision caused by an animal pad or track across a gentle drainage line to a breached rock bar across a major river.

3.2.2.2 Lateral erosion

The process of erosion cutting deeper within drainage tracts tends to slow as the incision nears harder substrates such as rocky pediments or cemented soil horizons, typical of the region. At this phase stream energy can no longer be minimised through vertical incision, and lateral microterracing becomes the predominant erosion process etching away from the primary gullies and channels. As lateral microterracing progresses upslope from concentrated drainage tracts, the stripped surfaces concentrate sheet wash into the main drainage system. Fertile patches and areas that remain functionally intact begin to contract as lateral stripping erodes into them. This results in increased water loss from the landscape through accelerated surface flow and reduced infiltration time, leaving a desiccated, perched land surface with a reduced capacity to capture and maintain soil moisture (Figures 35a, b).

Figure 35a **Perched interfluve. Sheet flow is channelled into incised drainage tract (on left), leaving interfluve water-starved except for during heavy rainfall events when water may fill and flood out of the channel**

Figure 35b **Water-starved vegetation on a perched interfluve**

3.2.2.3 Erosion exacerbated by infrastructure

Infrastructure (roads, tracks and fencelines) further disrupts the mechanisms that regulate resources through the landscape, primarily sheet flow. Road or track placement perpendicular to flow can capture sheet flow and channel it away from the downslope side, effectively water starving that slope, causing widespread plant death (Figures 36 & 37a–c). This can occur where a road is built up above the land surface or a graded windrow restricts water from flowing across the track. Likewise, if a track is cut below the land surface then water flows into and along it until it encounters an outlet. Another problem of tracks cut below the land surface is that the very process of water flowing onto the track causes back cutting upslope. This can initiate the migration of an erosion front upslope from the track, further disrupting resource capture processes. Similarly, if a track occurs parallel to sheet flow then water is rapidly channelled downslope, comparable to a drainage line. In this instance the greater the volume and velocity of water the more likelihood for track erosion.

The effect of infrastructure initiated erosion problems is intensified where overgrazing has reduced vegetation communities. This issue is not unique to the Gascoyne River catchment; it occurs in most rangeland environments and contributes significantly to catchment dysfunction.

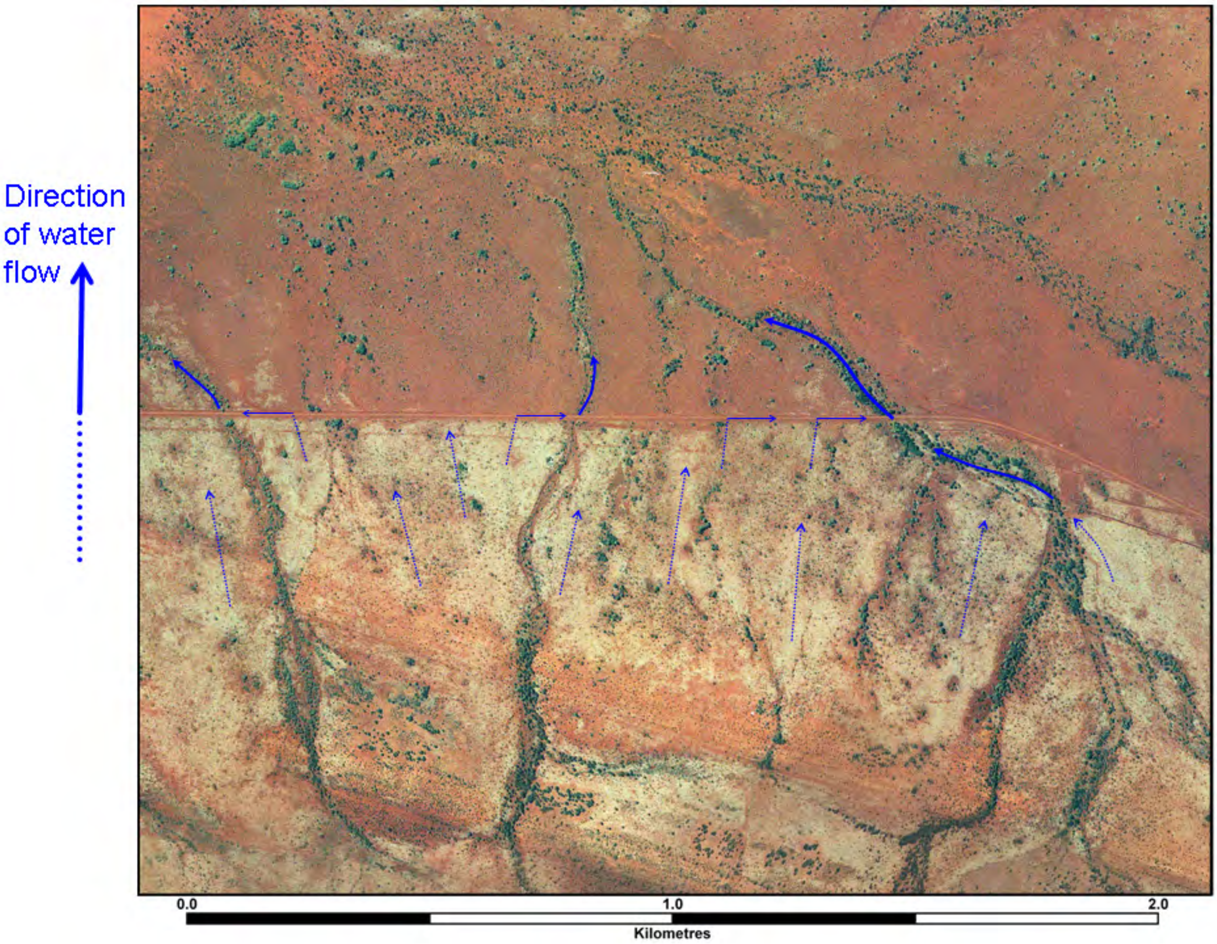


Figure 36 **The effects of water starvation can be seen in this aerial photograph. The lower half of the image shows the upslope areas, which in good seasons has a coverage of annual wind grass (*Aristida contorta*); this appears yellow in the image. In contrast, the top half of the image can not support any groundcovering of significance because it is water-starved by the road. Water from upslope areas is being directed down the road to exit into drainage tracts, rather than continuing as sheet flow across downslope areas; Gascoyne River catchment** (2007 aerial photograph provided by Landgate)

Figure 37a **Ground view of the road shown in Figure 36 showing the variation of groundcover on the upslope (Figure 37b) and downslope (Figure 37c) sides of the road**

Figure 37b **Healthy shrubs and an abundance of annual wind grass upslope of road**

Figure 37c **Downslope of road showing water-starved, sparsely vegetated shrubland**

3.3 Gascoyne River catchment condition summary

A reduction in vegetation cover (Section 2.2.2.2) has reduced the landscape's capacity to retain water (Section 2.2.3). Run-off and erosion potential have increased, resulting in erosion cell development. Consequently, the Gascoyne River catchment is locked in the feed-back loop of an erosion cycle. The loss in capacity to retain water drives the desiccation process, reducing vegetation cover. The cycle will continue until new base levels are reached in equilibrium with erosive processes.

With the exceptions of sandplain habitats and coastal plains, which are relatively resistant to alluvial erosion processes, there is an escalating trend in erosion severity in each land type progressing down through the Gascoyne River catchment catena sequence.

3.3.1 Upland source areas

These are naturally watershedding and erosional surfaces. Continual erosion by wash, creep and, in some cases, landslide is gradually modifying their surfaces. However, some areas, in particular breakaways and undulating stony plains show evidence of accelerated erosion. On fragile footslopes preferential grazing has reduced vegetation cover and run-off has increased. The unstable duplex soils associated with breakaways and saline stony plains are commonly scalded, with all stages of erosion from microterracing to gullying present.

In the drainage foci and valley floors between the interfluves of upland stony plains run-off is rapid where vegetation reduction is significant. Extensive gully systems are draining interfluves, leaving them perched and desiccated.

Watershed from upland areas is exacerbating erosion problems within degraded drainage tracts. Formerly slow-moving areas of drainage, these tracts are now increasingly channelised and desiccated (Figure 38). Subsequently, landscape condition down the catchment is deteriorating as erosive processes become increasingly aggravated and excess water is shed into incised creeklines and more run-off flows through lower slopes.

Figure 38 **Drainage flat that once supported chenopod shrubland and has been largely stripped of the upper surface of a duplex soil profile, Durlacher land system**

3.3.2 Transfer zones (Sheet wash plains)

Hardpan wash plains consist of undulating plains giving way to gentle slopes and near-level surfaces. The structured organisation of vegetation (groves and wanderrie banks) is a distinctive feature through the plains. Overgrazing and deterioration of vegetation patches has reduced the plain's capacity to retain water and drainage areas are regularly incised, draining readily.

In some locations hardpan is covered by broad sandy tracts or sand sheets (Figure 39a). Where water volume and velocity has increased, due to in-situ and upslope vegetation loss, sand sheets fragment and decline (Figures 39b, c). Braided water channels give way to linear gullies and sandy tracts become dissected.

Figure 39a **Intact sand sheet**

Figure 39b **Deteriorating sand sheet**

Figure 39c **Stripped sand sheet in poor condition**

With a reduction in stabilising perennial groundcover and increased exposure, wanderrie banks deteriorate. Sheet flow erodes bank edges or washes through breaches caused by stock padding. Banks reduced to annual pastures and exposed during dry periods are also wind eroded. In severely degraded areas wanderrie banks can become isolated hummocks subject to sand drift and surface redistribution (Figures 40a, b). In many areas, widespread soil stripping has exposed hardpan and rendered these tributary plains incapable of producing significant pasture (Figures 41a, b).

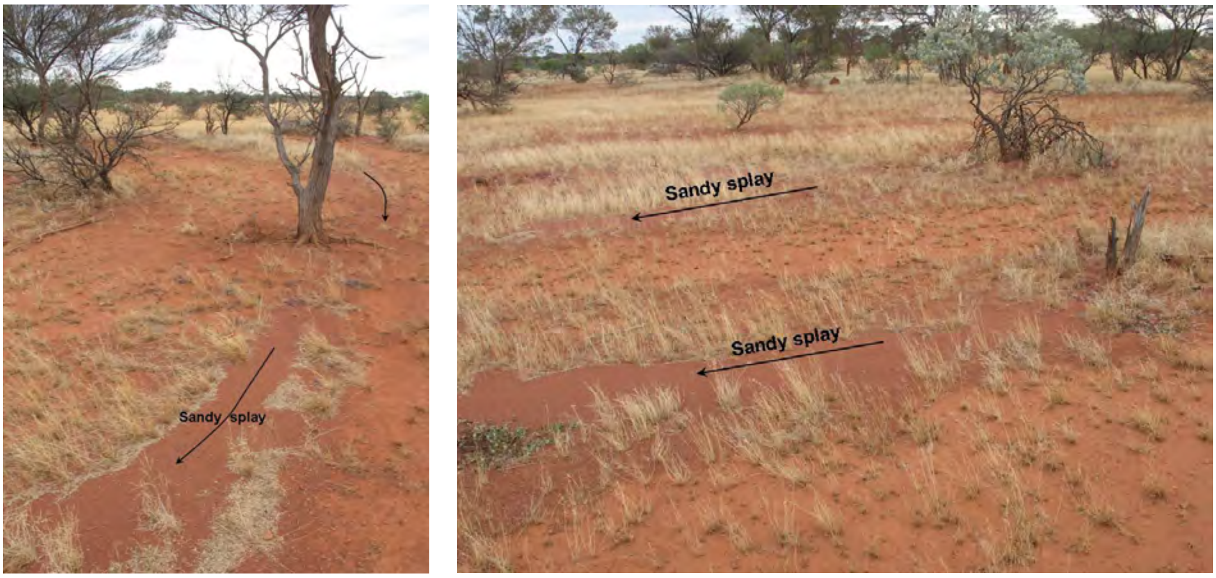


Figure 40a, b **Wanderrie bank erosion with sandy splays extending downslope of degrading sand bank**

Figure 41a **Remnant wanderrie bank on upper tributary plain**

Figure 41b **Remnant wanderrie bank on lower tributary plain, now isolated by coalescing interbank sections**

As sandy banks contract through fragmentation interbank sections coalesce and increasing sheet flow escalates scalding and sheet erosion. Both processes can strip the soil surface on wide fronts, leading to terrace erosion (Figures 42a, b). Once terrace, rill and gully erosion commences, reduction in capacity to restrict sheet flow facilitates erosion development upslope, impacting on grove health (Figures 43 & 44a, b, c). Figure 43, taken in 2007 shows widespread sheet and gully erosion progressing upslope through a wash plain. Figures 42a, b and 44a, b, c are ground level photographs taken in August 2011 at the same location.

Figure 42a **Stripped surface of an interpatch in poor condition**

Figure 42b **Bare interpatch in poor condition with micro-terrace erosion progressing upslope**

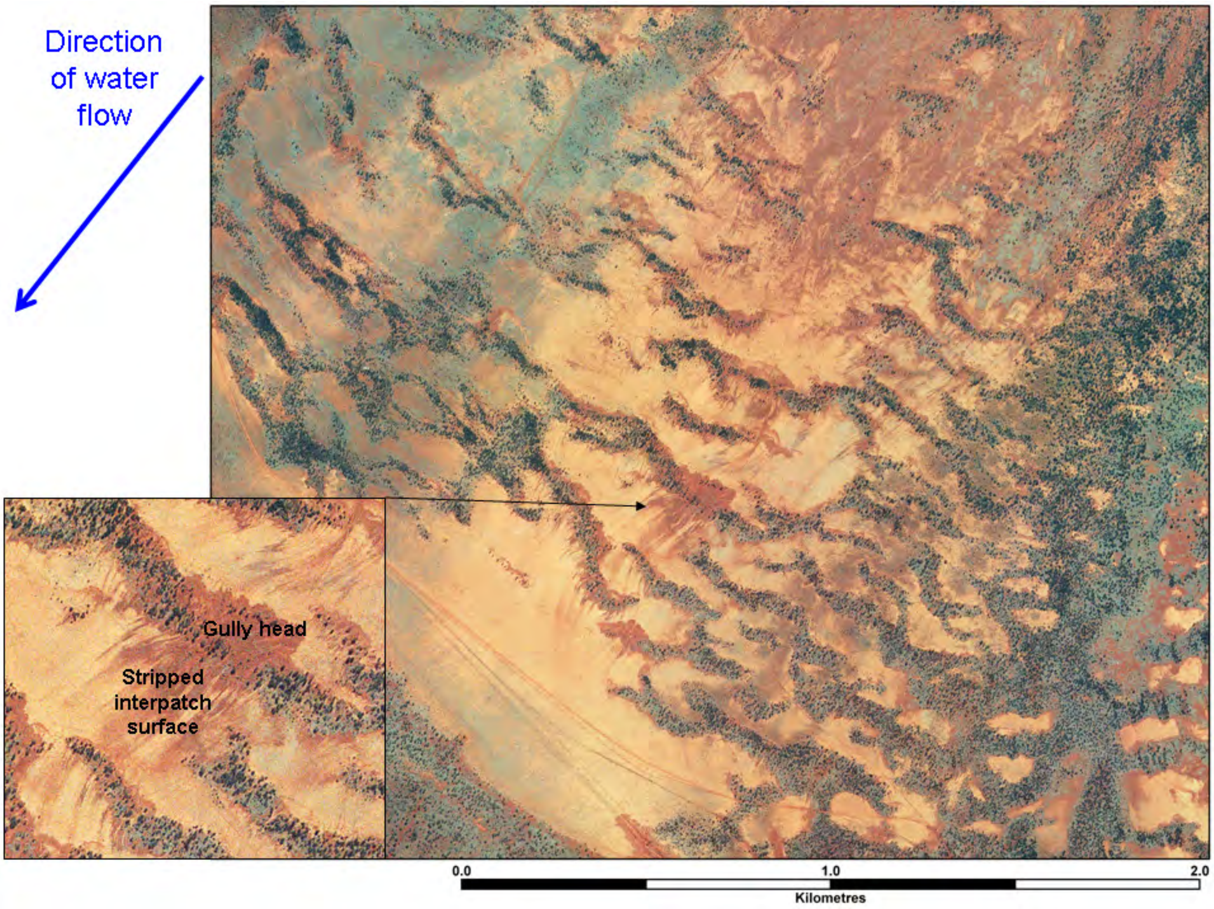


Figure 43 **Sheet and gully erosion causing fragmenting of mulga groves, Three Rivers land system; Gascoyne River catchment** (2007 aerial photograph provided by Landgate). **Aerial view corresponds with ground level photographs of Figures 42a, b and 44a, b, c**

Figure 44a **Dissected grove where stock pads have reduced the soil surface, resulting in unrestricted water flow which further fragments the grove**

Figures 44b (above), c (right) **Gully heads eroding through grove and upslope across interpatch**

Wilcox and McKinnon (1972) observed that erosion was removing the sandy banks and obliterating the patterns that differentiated the component land systems. This process continues, and is still common in degraded lower hardpan plains (Figures 45 & 46a, b, c). Drainage through the lower plains marginal to major tributary channels should be sluggish and restricted. However, with overuse these plains are frequently incised and drain readily.

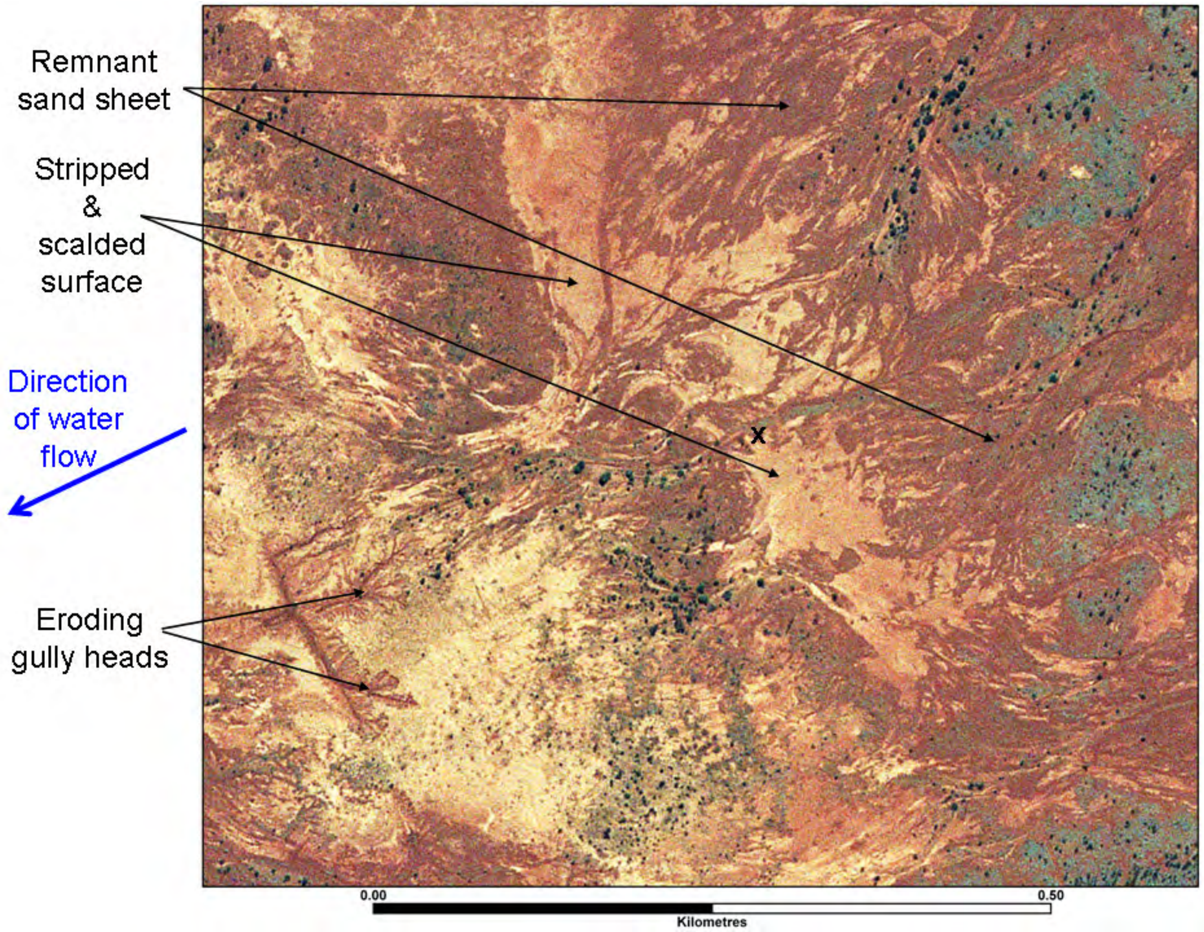


Figure 45 **Aerial photograph of eroding alluvial plain, Flood land system; Gascoyne River catchment. Point X relates to ground photographs (Figures 46a–c)** (2007 aerial photograph provided by Landgate)

Figure 46a **Edge of a fragmented remnant sandy bank in poor condition, which is surrounded by stripped and scalded surfaces, Flood land system**

Figure 46b **Perished water-starved plants on a former sandy bank, now surrounded by scalded surfaces, Flood land system**

Figure 46c **Ripple patterns on redistributed sands eroded from sand banks indicate the velocity with which sheet flow moves across the plain, poor condition Flood land system**

3.3.3 Bottomland deposition areas

Within bottomland deposition areas, erosional processes operating through the upland source and transfer zones change to deposition, and surfaces derived from alluvium develop, such as floodplains, playas, claypans, swamps and lake country. Being overgrazed, most of the alluvial plains are degraded and shed large volumes of water.

Some severely eroded areas are entirely stripped of their sand sheet, leaving a bare and unproductive exposed surface. Figures 47a–e show a degradation sequence through a tributary alluvial plain. On the sandy interfluves, between zones of sheet flow, overgrazing and drying soil profiles have reduced perennial vegetation to unpalatable shrubs such as curara, turpentine bush (*Eremophila fraseri*), sandbank poverty bush (*E. margarethae*), variable cassia (*Senna artemisioides* subsp. *x sturtii*) and bloodbush (*S. artemisioides* subsp. *oligophylla*) (Figure 48). In some areas these shrubs obstruct sheet flow, but increasingly they become isolated as the interfluve contracts with edge erosion, and through root exposure ultimately die (Figure 49). Cattle further accelerate interfluve fragmentation as these remnant sand sheets become dissected by regular padding. Eventually interfluves are completely stripped away (Figure 47e).

Features of active erosion become superimposed over natural patterns. These surfaces are now so modified by extensive sheeting, scalding and sand redistribution that only remnant areas of sandy interfluves indicate the extent and form of the former natural state (Figures 47a, b).

Figures 47a (above), b (right) **Remnant sandy interfluves provide any indication to the form of the natural state, Clere land system**

Figures 47c (above), d (right) **Poor condition duplex surface being stripped by sheet flow. Sandy splays in foreground are from degrading remnant vegetation patches; once sand is removed the plain can not support grasses, Clere land system**

Figure 47e **Former interfluve in poor condition which has become completely stripped by erosion, Clere land system**

Figure 48 **A soil infiltration site assessing the infiltration in a remnant interfluve bush mound and a stripped interpatch**

Figure 49 **Soil loss from around the base of a bush mound**

The heavy clay and duplex soils of once sluggish drainage tracts are commonly sealed by scalding. With unrestricted overland flow causing extensive stripping, these surfaces are being eroded to hardpan (Figure 50). With hardpan exposure inhibiting further down-cutting, the erosive potential is directed at less resistant areas; the edges of sandy banks (Figures 51 & 52a, b). Through increasing bank fragmentation, drainage tracts become wide shallow channels draining the upslope areas.

Figure 50 **Duplex surface being stripped by sheet flow down to hardpan, Peedawarra land system**

Figure 51 **Disintegrating sandy bank, foreground shows redistributed sediments eroded from the side and rear of the bank, Peedawarra land system**

Figure 52a **Remnant bush clump on fragmenting sand bank. Sandy splays in the right of the photograph are eroding from the downslope side of the bank, Peedawarra land system**

Figure 52b **Isolated shrub after sand bank has disintegrated and eroded away. A few remnant sand splays remain immediately behind the shrub, Peedawarra land system**

The proximity to major rivers and alluvial plains has resulted in the overgrazing of calcrete platform vegetation communities (Figure 53) and associated highly favoured areas prone to preferential grazing, such as saline plains and drainage foci, are often severely degraded and eroded (Figures 54a, b, c).

Figure 53 **Degraded calcrete platform supporting scattered snakewood over Gascoyne bluebush (*Marianna polypterygia*), Warri land system**

Figure 54a **View upslope from a gully eroding into loamy plain, Warri land system (Gully head is part of the same erosion cell as Figures 54b & c)**

Figure 54b **Looking downslope over eroded surface behind extensive gully head, Warri land system (Gully head is part of the same erosion cell as Figures 54a & c)**

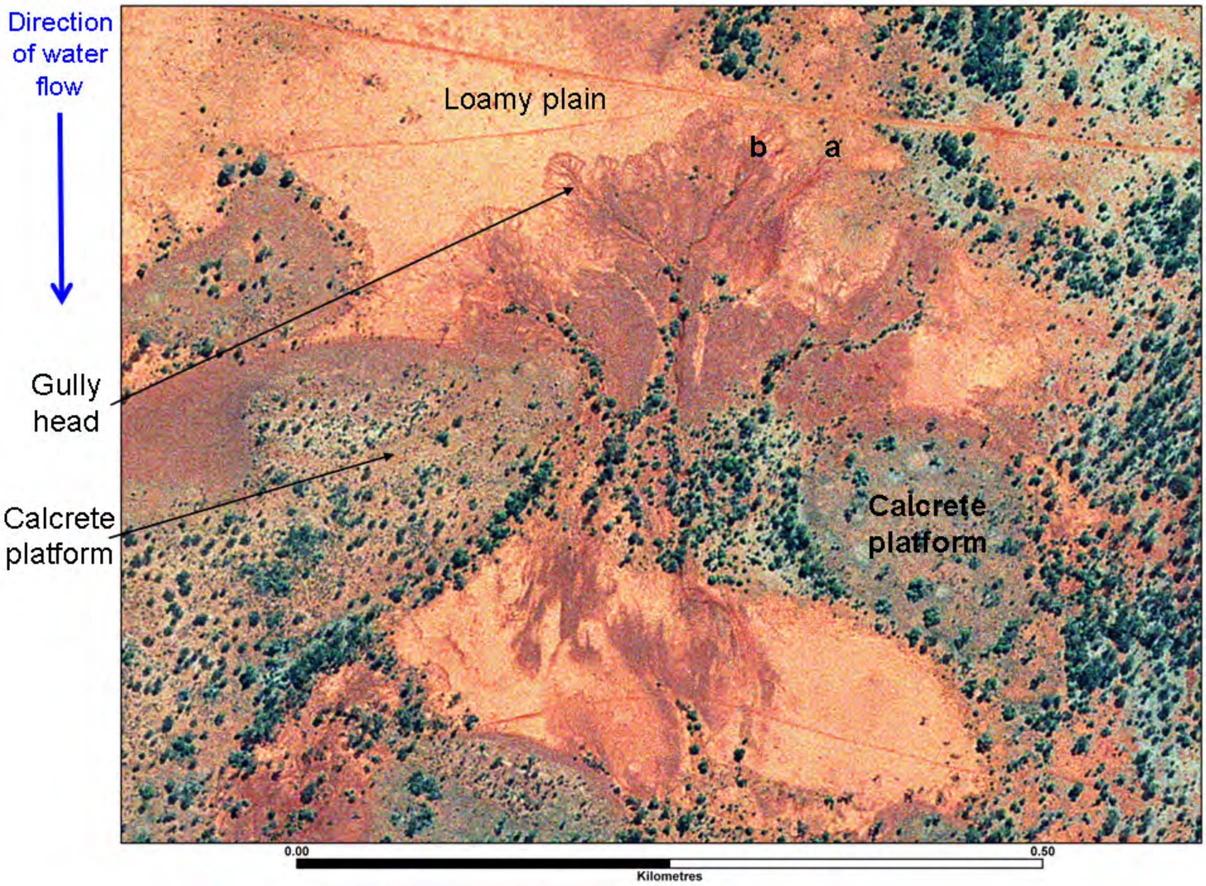


Figure 54c **Aerial photograph of extensive erosion cell migrating upslope through loamy plain, Warri land system; Gascoyne River catchment. Erosion cell is the same as shown in Figures 54a (point a) & 54b (point b)** (2007 aerial photograph provided by Landgate)

River plains form the lowest parts of the catena sequence, where upslope sediment and nutrients should be deposited. However, in the river plains of the Gascoyne River catchment, watercourse erosion is significant. If resources are not deposited or absorbed in these bottomlands then they are lost, via major drainage channels through the delta and out to sea.

Creek and river beds are now subject to episodic erosion from increased water discharge as less water is retained upslope. Widespread erosion throughout the upper catchment has increased bed deposits in the main channels of the Gascoyne and Lyons rivers. This has implications as reduced channel depth predisposes floodplains, further down the catchment, to flooding and scouring (Figure 55).

Where buffel grass is well established some rivers banks have stabilised, elsewhere erosion remains severe. Rilling and guttering are common on plains marginal to major drainage (Figures 56 & 57). Watercourse erosion is considerable; its role in catchment drainage is significant and a major factor contributing to resource loss and decline in catchment resilience.

Figure 55 **Scoured flood margin**

Figure 56 **Eroded lateral river channel, Gascoyne River. Mud staining on trees indicates flood level**

Figure 57 **Lateral channels associated with main channel become wider to compensate for greater flows and inability to erode deeper due to hardpan substrate**

In the lower reaches of the catchment sand sheets and dunes become more common, between which interdunal areas occur where flow is concentrated (Figure 58). Claypans and drainage foci infrequently occur within interdunal drainage tracts. Previously productive pastures, many interdunal areas are now scalded or gullied. The increased connectivity between interdunal areas, as sandy tracts fragment and banks erode, together with reduced infiltration, associated with scalding and sheeting, has increased water flow through these areas (Figure 59).

Figure 58 **Interdunal drainage tract where flow is concentrated**

Figure 59 **Fragmented sand sheet which is becoming increasingly dissected as infiltration diminishes and sheet flows intensify**

Table 13 summarises the susceptibility of each land type within the Gascoyne River catchment to accelerated erosion.

Table 13 **Land type susceptibility to accelerated erosion**

Susceptibility to accelerated erosion	Land type
Major	Mesas and breakaways
	Wash plains on hardpan
	Alluvial plains
	River plains
Moderate	Low hills
	Stony plains
	Calcrete platforms
Minor	Hills and ranges
	Sandy plains, sandplains and occasional dunes
	Coastal plains, cliffs, dunes, mudflats and beaches

3.3.4 Summation

Hills and ranges, despite their relief, have a lower susceptibility to accelerated erosion due to the protection offered by their abundant stony mantle. However, they do shed a significant volume of water from their surfaces, and thereby still contribute to erosion problems within adjacent landscapes. In comparison, the slopes of mesas and breakaways generally lack a stony armouring and are typically severely degraded. This is due to overgrazing of smaller areas of highly attractive forage within larger less palatable pasture units. This results in these features also contributing to erosion problems in the catchment.

Within the upland areas the drainage flats provide the most valued pastures, occurring as inclusions within less attractive pasture types. Chenopod communities formerly occupied sites of restricted drainage; however excessive grazing pressure has reduced these areas to unpalatable shrubs and seasonally dependent ephemeral species.

Along the valley floors and in the drainage foci, where vegetation loss has been considerable, channelisation as rill and gully erosion encourages watershedding. Infiltration is generally poor due to the abundant stony mantle. From these drainage areas increased discharge is affecting downstream landforms.

Downslope of the upland areas the landscape is dominated by extensive sheet wash plains. Here, especially during dry periods, it is the vegetation groves and bush clumps that provide sources of browse (Figure 60). Over-utilisation has increased run-off from upper slopes, causing soil instability and disrupting water flow and nutrient cycles (Figure 61). Where patches are breached by stock pads or erosion channels, less water is retained within the patch, leading to water stress and eventually death.

Figure 60 **Browse-line in mulga grove**

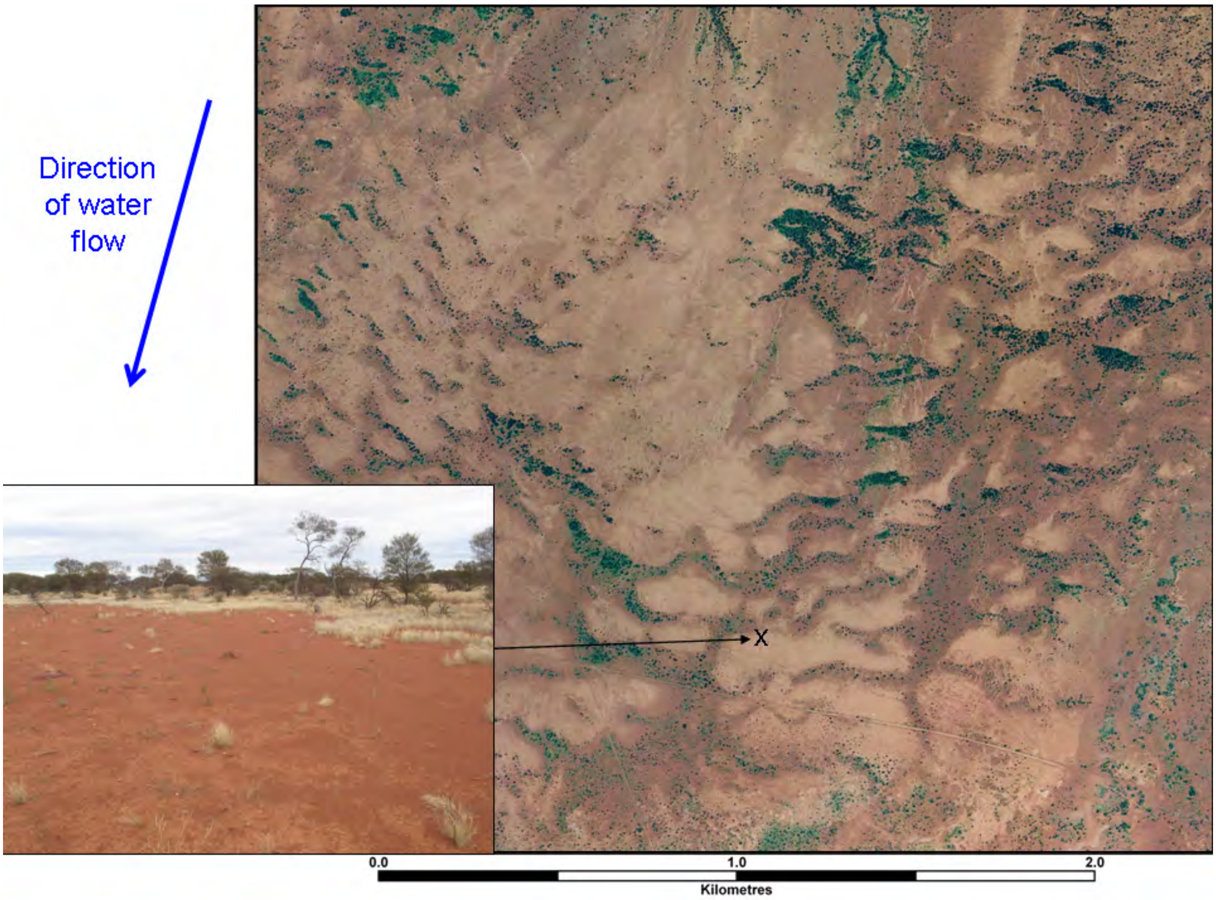


Figure 61 **Fragmenting vegetation banding, Jamindie land system; Gascoyne River catchment** (2006 aerial photograph provided by Landgate)**. Inset: Foreground shows stripped interpatch which progressively becomes covered by mobilised sediments eroding from the rear of degrading grove**

A significant problem within the wash plains of the catchment, as well as elsewhere, is the disruption to surface hydrology by infrastructure (e.g. roads, tracks, fencelines) (Figure 62). Where vegetation cover is drastically reduced infrastructure initiated erosion problems have a considerable impact on general rangeland condition. This problem is illustrated in the sequence of photographs shown in the section 3.2.2.3 (Erosion exacerbated by infrastructure—Figures 36 & 37a–c).

Figure 62 **Water-starved gidgee grove downslope of a road**

Being downslope of run-off areas increases the potential for wanderrie banks to produce useful pasture, especially when able to retain run-on (Figure 63). However, overgrazing has reduced the perennial grasses to such an extent that the low strata of many sandy banks now only supports annual grasses such as wind grass (*Aristida contorta*) and annual wanderrie grass (*Eriachne aristidea*) (Figures 64a, b).

Figure 63 **Wanderrie banks in fair condition supporting some perennial grasses; Buck wanderrie grass (*Eriachne helmsii*)**

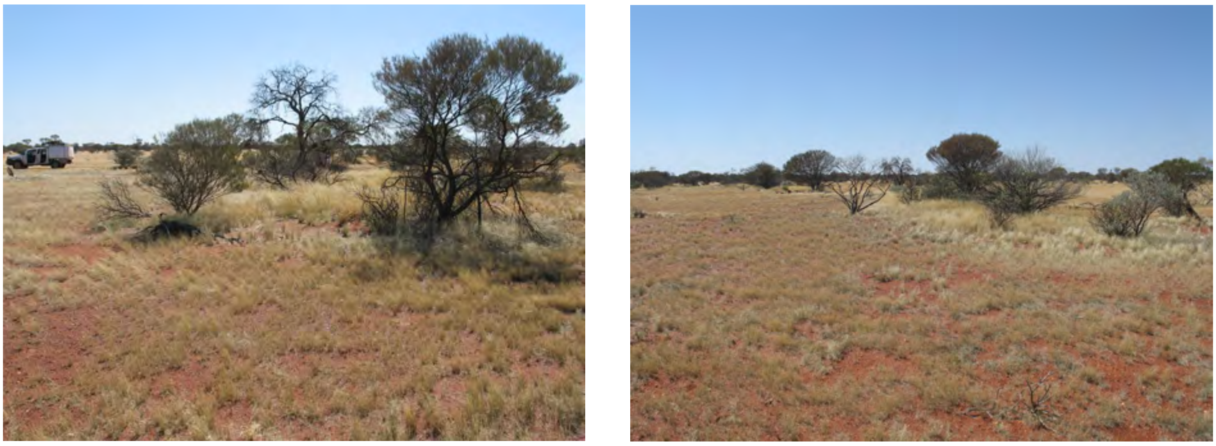


Figure 64a, b **Wanderrie banks reduced to supporting only wind grass (*Aristida contorta*) and annual wanderrie grass (*Eriachne aristidea*)**

Riparian pasture productivity is highly variable. Initial settlement of the Gascoyne catchment was along the river, with stock reliant on river pools and natural springs. Consequently, many riparian pastures are overgrazed and degraded. Where buffel grass is well established, it has a significant role in stabilising surfaces and preventing further erosion. In addition, buffel grass colonisation has increased the productivity of some riparian pastures in favourable seasons. However, stock numbers in favourable seasons are often above that which the surrounding native vegetation can support in the absence of buffel grass (Wilcox & McKinnon 1972; Payne, Curry & Spencer 1987) and this leads to areas of overgrazing. With the onset of dry conditions the protein content of buffel grass declines and livestock seek supplementary forage. Stock migrate upslope and fertile patches become the primary browse source. Without appropriate stocking rates, fertile patches are overgrazed, leading to deterioration as a forage source but also their capacity to retain water. This reduces their resource capture role and contributes to escalating erosion downslope.

In the catchment’s lower reaches, saline alluvial plains are one of the more dominant land types, the other being sandplains. Many of the land systems within these land types occur within the Lower Gascoyne Alluvial Plains Zone of the Carnarvon Province. Here the floodplains, levee sand banks and adjacent alluvial plains are dominated by buffel grass. However, such buffel grass dominated plant communities are now increasingly susceptible to fire following good seasons. Fire sensitive species, such as those belonging to the Chenopodiaceae, may disappear. Whilst buffel grass can re-establish, such landscapes become inherently fire prone and therefore susceptible to future periods with exposed surfaces prior to post-fire recolonisation.

4 Discussion

The Gascoyne River catchment is in poor condition (characterised by loss of cover, few perennial plants and ongoing soil loss), with many areas continuing to decline. The poor condition of the catchment is not a recent issue. Previous reports have established that the condition of the Gascoyne River catchment was in poor condition (Wilcox & McKinnon 1972; Jennings et al. 1979; Williams, Suijdendorp & Wilcox 1980; House et al. 1991; Hopkins, Pringle & Tinley 2006). Many of the areas in poor condition were likely to have been so since the 1930s or earlier (Williams, Suijdendorp & Wilcox 1980).

Within the catchment there has been a 15% decline in the number of perennial shrubs in the last five years (a 39% decline from the perennial plant numbers recorded in the above average seasons of 1995 to 2000), reduced resource capture (13% decline overall and 22% decline in groves) and an increase in erosion features (Section 2.2.2). Over 3.6 million hectares were assessed as being in poor condition for the years 2002 to 2009 (Section 2.2.2.1). The overall trend in vegetation cover (1989 to 2010) was stable, thus areas that were in poor condition are still in poor condition. The practice of continuous stocking through consecutive dry years (Annual Return of Livestock and Improvement forms, Pastoral Lands Board (PLB)), in excess of the carrying capacity of the resource (Wilcox & McKinnon 1972; Payne, Curry & Spencer 1987), has contributed to the poor condition of the catchment.

Large contiguous areas are declining in perennial vegetation cover in the catchment between the central Gascoyne and Lyons rivers. Plant numbers in 2011 at monitoring sites (WARMS) had declined to 1995 levels. In particular, satellite images indicate that the seasonal conditions for large areas of the central Gascoyne and lower Lyons rivers had poor seasons in four or more years prior to the December 2010 flood. The greenness index at the time of the flood was low and as a consequence the groundcover is likely to have also been low.

Vegetation, groundcover and obstructions are fundamental to sheet flow and erosion control (Coles & Moore 1968; Tongway & Ludwig 1996, 1997). However, it is difficult to determine to what degree catchment condition and groundcover contributed to the Gascoyne River 2010–11 summer floods.

The spatial arrangement throughout the catchment of sparse capture zones (patches) interspersed between long interpatches allows water energy to increase during run-off. Whilst capture zones have higher infiltration rates (Section 2.2.3) they are, in general, a relatively small component of the landscape (ratio of interpatch to patch estimated at 88:12). Increasing the number of capture zones through the number of plants or fallen timber obstructions would increase infiltration capacity over time. However, as the number of obstructions has declined erosion has increased in both shedding and capture zones. Fewer resources are being retained in the landscape as infiltration areas decline in size and quantity, as indicated by the reduction in RCI between 2006 and 2011. Clearly, the high ratio and extent of interpatches results in rapid watershed and would contribute significantly to flooding through the catchment.

However, the magnitude of the December rainfall event, in excess of 200 to 300 mm of rainfall over a 24-hour period, was such that the subsurface and surface storage capacities of the soil would have been exceeded irrespective of infiltration rates on the interpatches. Where soil profiles were described at the WARMS sites, they were frequently less than 30 cm deep and often consisted of a sandy loam over clay, hardpan or weathered rock. This was particularly common on the interpatches where hardpan was encountered. Assuming a maximum storage capacity of 20% gives total soil water storage of 60 mm, the December rainfall event exceeded this amount by at least three to five times when the profiles would have been dry. With subsequent rains, the soils would have already been moist and therefore had less storage capacity. It is therefore likely that many soils would have reached their storage capacity within a few hours of the January and February 2011 events.

As discussed in Section 2.2.1, the hydrographs for major floods since 1960s have been of similar magnitude and shape. It suggests that the catchment characteristics including catchment condition have changed little during this period; as mentioned above it is likely catchment condition has been poor at least since the 1960s. However, from the current analysis it is not possible to assess the impact catchment condition on the magnitude of the December 2010 flood.

Erosion from the December 2010 flood was large by comparison to other major flood events, based on estimates of the size of the sediment plume, sediment loads in the plume and observation of the Gascoyne River channel. However, the rainfall event was so exceptional that, as with the flooding, it is highly likely that the river channel would have experienced some erosion regardless of the condition of the catchment. Erosional features, assessed at WARMS sites (Section 2.2.2.2, Tables 5 and 6) and described in Section 3, are widespread throughout the catchment and have increased over the monitoring period. It is not always possible to attribute these features to the floods in the summer of 2010–11, but it is almost certain that these features have developed as a result of loss of groundcover since European settlement. Gully head migration upslope and straightening of drainage tracts, allowing faster drainage, are visible processes. Vegetative groundcover reduces erosion, and it is clear that erosion would be much less if the catchment was in better condition.

The catchment is naturally a high watershedding catchment. The loss of vegetative cover is causing accelerated erosion and the area within the catchment that sheds water has increased. This has significantly reduced the capacity of the land to retain resources. The Gascoyne River catchment continues to dry out and erode. Vegetation is increasingly dependent on in-situ rainfall, rather than run-on, and larger rainfall events are required to flood incised drainage tracts and return water to water-starved plains. The reduction in soil moisture balance increasingly favours plant species adapted to desiccating soil profiles and growth becomes increasingly episodic as run-off increases and deep soil moisture storage declines. The desiccation process will continue until new base levels are reached, resulting in water ponding, deposition and soil accumulation in equilibrium with erosive processes.

Natural recovery in arid and semi-arid shrublands is slow. To reduce the flood impact from large rainfall events vegetation groundcover and obstructions need to be increased. There was a substantial increase in shrub numbers between 1995 and 2000 in response to above average seasons across the catchment. However, new plant recruits require time to establish and develop as capture zones, with time increasing litter accumulation and, eventually, infiltration rate. Overlaying a pastoral operation on this regenerative process significantly adds to the challenges of vegetation recovery in a rangeland environment. As well as time, appropriate management strategies are crucial to the success of attempting to reverse the dysfunctional processes within the Gascoyne River catchment.

With many upper slopes, interfluves and drainage flats severely degraded the carrying capacity of the Gascoyne River catchment has significantly diminished. Analysis of WARMS site data indicates that the density of palatable perennial shrubs has declined (Section 2.2.2.2.1). Present day pastoral operations are increasingly reliant on riparian pastures, especially where drainage margins have become colonised by buffel grass which provide abundant forage in favourable seasons. However, stocking rates based on good season riparian pastures often exceed the carrying capacity of the rest of the impoverished landscape.

Secondly, with the increased fire susceptibility of buffel grass pastures, wildfire will significantly damage remnant vegetation communities and leave soil surfaces further exposed. Should a flood event follow a wildfire, the watershed across the burnt, bared surfaces, lacking in obstructions can only result in flooding and increased erosion.

Many vegetation communities throughout the catchment are under stress due to escalating catchment dysfunction, resulting in widespread erosion and desiccation. With the onset of dry conditions, the few remaining fertile patches (Section 2.2.2.2.2) receive increased grazing pressure as stock search for additional forage to supplement the nutrition formerly provided by seasonally dependent plants. This has resulted in overgrazing of favoured sites, especially prior to adjusting stocking rates to the changed conditions. Reported stock numbers in the catchment, as supplied by lessees to the PLB through Annual Return of Livestock and Improvement forms, do not appear to match seasonal changes. Dependence on riparian exotic buffel grass pastures accentuates this problem because these pastures in favourable seasons support stock numbers well above what can be supported by surrounding native vegetation. Until this is accepted, overgrazing of remnant fertile patches will continue and their value as resource capture mechanisms will eventually be lost.

5 Conclusions

The record December 2010 rainfall event was an extreme event exceeding the previous rainfall monthly record for December at Gascoyne Junction by about threefold. The December 2010 flood was also a record event exceeding previous floods by about 0.1 metres. However, the characteristics of the hydrograph were similar to previous major floods since the 1960s, suggesting the properties of the catchment have not changed in this time.

Erosion from the December 2010 flood is likely to have been much greater than the January and February 2011 floods or the January 2009 flood because an extended dry period preceded the 2010 flood. Examples of erosion described in Section 3 coupled with data from long-term monitoring sites and earlier published reports indicate that accelerated erosion has been occurring in the catchment at least since the 1960s.

At the time of the December 2010 flood the catchment was in poor condition especially between the central Gascoyne and Lyons rivers where the December rainfall event was centred. The condition of the Gascoyne River catchment is poor and has deteriorated since at least the 1930s. High soil infiltration rates are associated with patches of vegetation but these areas represent only a small proportion of the catchment. The catchment will continue to be a high water-shedding environment, whilst the majority of the catchment is dominated by sparsely vegetated areas with low infiltration rates.

Landscape function has deteriorated with the decline in plant numbers. In conjunction, the reduction in carrying capacity of the native perennial pastures through grazing pressure has implications for management in terms of setting appropriate stocking rates to manage any further decline of desirable plants, and therefore landscape function.

Due to the magnitude of the December 2010 rainfall event, coupled with large watershedding areas with relatively low infiltration rates, a major flood event would likely have occurred irrespective of catchment condition. Major floods can be expected in the future, with subsequent downstream consequences. This is especially likely due to Carnarvon and the horticultural area being situated on a river floodplain and levee built up by successive flood events and the climate being such that tropical cyclones can occur in summer when groundcover is naturally at its minimal.

Whilst it is not possible from the current analysis to assess the effect of catchment condition on the magnitude of the December 2010 flood, it is likely that were the catchment in better condition (more vegetative groundcover) soil loss would be reduced, particularly away from the major river channels. Improved catchment condition will reduce soil loss from minor and moderate flood events.

Based on the historical and recent review of the Gascoyne River catchment it is likely that future high rainfall events will continue to result in localised flooding, soil loss and damage to infrastructure unless catchment condition is improved.

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Appendices

1 Acronyms

2 Data sets and sources of data

3 Vegetation condition assessment based on recent traverse ratings

4 Soil infiltration and profile data

5 Peak river heights at Nine Mile Bridge 1960 to 2011

6 Average soil surface attributes for capture and shedding zones in 2011

7 Physiographic regions of the Gascoyne River catchment

Appendix 1 — Acronyms

The following acronyms are used in this report

AGO NCAS: Australian Greenhouse Office - National Carbon Accounting System

BoM: Bureau of Meteorology

CSIRO: Commonwealth Scientific and Industrial Research Organisation

DAFWA: Department of Agriculture and Food, WA

DoW: Department of Water, WA

Landgate: Western Australian Land Information Authority

LFA: Landscape Function Analysis

NASA/GSFC: National Aeronautics & Space Administration/Goddard Space Flight Center

NDVI: Normalised Difference Vegetation Index

PLB: Pastoral Lands Board of WA

RCI: Resource Capture Index

WARMS: Western Australian Rangeland Monitoring System

Appendix 2 — Data sets and sources of data

The following datasets have been sourced and used in the compilation of this report:

- Satellite imagery
  - Landsat TM imagery (AGO NCAS)
  - MODIS (NASA/GSFC)
  - NOAA NDVI 1992 to 2010 (DAFWA)
- Aerial photography (Landgate)
- Western Australian Rangeland Monitoring System (WARMS) sites (DAFWA)
- Land system descriptions (DAFWA)
- Vegetation condition traverse assessment (DAFWA)
- Hydrographs (DoW)
- Rainfall (BoM and SILO Patch Point dataset)
- Annual Return of Livestock and Improvement forms (PLB)

Appendix 3 — Vegetation condition assessment and summary (2002–2009)

Appendix Table 3.1 **Criteria used to assign a traverse point to a condition rating (Payne et al. 1987)**

Rating	Condition indicators
Very good	For the land unit-vegetation type the site's cover and composition of shrubs, perennial herbs and grasses is near optimal, free of obvious reductions in palatable species or increases in unpalatable species liable to reduce production potential.
Good	Perennials present include all or most of the palatable species expected; some less palatable or unpalatable species may have increases, but total perennial cover is not very different from the optimal.
Fair	Moderate loses of palatable perennials and/or increases in unpalatable shrubs or grasses, but most palatable species still present; foliar cover is less than sites rated as good or very good unless unpalatable species have increased.
Poor	Conspicuous loses of palatable perennials; foliar cover is either decreased through a general loss of perennials or increased by invasion of unpalatable species.
Very poor	Few palatable perennials remain; cover is either greatly reduced, with much bare soil, arising from loss of desirables, or has become dominated by a proliferation of unpalatable species.

Appendix Table 3.2 **Vegetation condition for land systems, grouped by land type, in Gascoyne River catchment based on recent traverse assessment (2002–2009)**

Land type	Land system	Number of points	Total area (ha)	Estimated shedding in optimal condition %	Good (%)	Fair (%)	Poor (%)	Area in poor condition (ha)
1	Agamemnon	111	349 667.6	95	11.7	38.7	49.5	173 085.5
1	Augustus	88	775 231.6	95	14.8	45.5	39.8	308 542.2
1	Glenburgh	21	66 411.4	100	9.5	52.4	38.1	25 302.7
	Hills and ranges with acacia shrublands							***506 930.4***
5	Pells	27	74 246.4	80	14.8	44.4	40.7	30 218.3
5	Sandiman	73	117 355.1	90	2.7	27.4	69.9	82 031.2
5	Thomas	64	246 361.8	88	7.8	43.8	48.4	119 239.1
	Mesas, breakaways and stony plains with acacia or eucalypt woodlands and halophytic shrublands							***231 488.6***
10	Collier	54	181 257.8	95	29.6	46.3	24.1	43 683.1
10	James	43	172 899.7	75	2.3	20.9	76.7	132 614.1
10	Phillips	238	756 181.7	94	4.2	30.7	65.1	492 274.3
	Low hills and stony plains with acacia shrublands							***668 571.5***
16	Sugarloaf	22	28 998.3	60	9.1	36.4	54.5	15 804.1
	Stony plains with acacia shrublands							***15 804.1***
17	Bryah	24	79 274.3	35	0.0	29.2	70.8	56 126.2
17	Durlacher	351	509 495.8	82	3.1	26.5	70.4	358 685.0
17	Jimba	115	187 196.2	45	2.6	28.7	68.7	128 603.8
17	Kurubuka	32	92 551.4	95	3.1	43.8	53.1	49 144.8
17	Mantle	49	85 483.1	91	0.0	38.8	61.2	52 315.7
17	Nadarra	122	89 060.5	90	4.9	22.1	73.0	65 014.2
17	Yinnietharra	54	81 420.0	38	0.0	38.9	61.1	49 747.6
	Stony plains with acacia shrublands and halophytic shrublands							***759 637.3***

Appendix Table 3.2 *(continued)*

Land type	Land system	Number of points	Total area (ha)	Estimated shedding in optimal condition %	Good (%)	Fair (%)	Poor (%)	Area in poor condition (ha)
25	Ella	145	51 910.1	0	22.8	55.2	22.1	11 472.1
25	Lyons	22	69 127.8	15	13.6	31.8	54.5	37 674.6
25	Yalbalgo	164	180 942.9	0	32.3	48.8	18.9	34 198.2
	Sandplains and occasional dunes with grassy acacia shrublands							***83 344.9***
27	Bidgemia	137	105 330.7	30	3.6	30.7	65.7	69 202.3
	Sandplains and drainage floors with acacia and halophytic shrublands							***69 202.3***
29	Bubbagundy	26	32 717.2	10	0.0	38.5	61.5	20 121.1
	Sandy plains with acacia shrublands and wanderrie grasses							***20 121.1***
31	Jamindie	123	631 345.3	70	15.4	25.2	59.3	374 387.8
	Wash plains on hardpan with mulga shrublands							***374 387.8***
32	Flood	60	115 459.0	20	1.7	41.7	56.7	65 465.2
32	Landor	79	127 237.8	30	1.3	43.0	55.7	70 871.4
32	Three rivers	90	456 390.8	14	2.2	17.8	80.0	365 112.6
32	Winmar	85	91 412.2	35	2.4	37.6	60.0	54 847.3
32	Wooramel	28	56 798.2	60	28.6	28.6	42.9	24 366.4
	Wash plains and sandy banks on hardpan, with mulga shrublands and wanderrie grasses or spinifex							***580 662.9***
36	Delta	50	37 197.4	51	24.0	48.0	28.0	10 415.3
36	Sable	101	95 023.4	11	54.5	33.7	11.9	11 307.8
	Alluvial plains with halophytic shrublands							***21 723.1***
37	Sandal	247	271 756.6	46	19.0	57.5	23.5	63 862.8
	Alluvial plains with currant bush shrublands							***63 862.8***
40	Warri	49	149 062.3	35	0.0	24.5	75.5	112 542.0
	Calcrete plains with acacia shrublands							***112 542.0***
42	Gascoyne	119	235 188.3	60	18.5	36.1	45.4	106 775.5
	River plains with grassy woodlands and tussock grasslands							***106 775.5***
	Total							***3 615 054.3***

Appendix 4 — Soil infiltration and profile data

Single ring falling head infiltrometer method

The ‘single ring falling head infiltrometer method’ used in this study is modified from Minasny and McBratney (2010).

A single stainless steel ring of 300 mm diameter and 200 mm height is hammered at least 20 mm into the soil surface. The inside perimeter of the ring is sealed using heavy textured soil or bentonite clay to ‘maintain the character’ of the surface. A steel rule is fixed to the inside of the ring to record the water level. A hessian cloth is then placed over the soil surface to protect it from disturbance and a large plastic sheet draped over the ring. Approximately 5 litres of fresh water is then poured inside the ring on to the plastic sheet. The plastic sheet is then carefully removed to release the water, so as to cause minimum disturbance to the soil surface.

The initial water level and time is measured once all the water has been released. Subject to the infiltration rate, further water level measurements are taken at 15 second intervals for the first several minutes, after which time the interval period may be increased to 30 second intervals or greater according to the infiltration rate. The water level measurements are continued until all the water has infiltrated or a steady state rate reached. Once the water has drained the extent of horizontal and vertical wetting fronts is also recorded.

Appendix Table 4.1 **Number of infiltration measurements and/or site profile descriptions**

	Not paired	Paired	Replicated	Total
Infiltration – WARMS sites*	36	26	2	64
Infiltration – Other sites*		2	1	3
Total infiltration	**36**	**28**	**3**	**67**
WARMS profile description only	4			4
Total data collected	**40**	**28**	**3**	**71**

* Infiltration measurements were undertaken at 49 WARMS sites and at one other site.

Appendix Table 4.2 **Land systems where soil profiles and infiltration measurements were recorded**

Land system	Number of profiles	Land system	Number of profiles
Augustus	1	Kurubuka	3
Bidgemia	2	Landor	1
Clere	3	Mulgul	1
Collier	2	Phillips	4
Durlacher	8	Sugarloaf	1
Ella	1	Thomas	1
Flood	1	Three Rivers	14
Fossil	1	Ullawarra	1
Frederick	7	Warri	4
Jamindie	11	Yalbalgo	1
Jimba	1	Yinnietharra	2

Appendix Table 4.3 **Number of infiltration measurements and number of sites**

	Not paired	Paired	Replicated	Total
Interpatch	30	14	1	45
Patch	6	14	2	22
Number of sites	36	28	3	67

Appendix 5 — Peak river heights at Nine Mile Bridge 1960 to 2011

Peak river heights at Nine Mile Bridge 1960 to 2011 with comments on rainfall distribution and intensity (source Brad Cox, Dept. of Water, Carnarvon WA). The DoW defined flood levels are Major – 7.6 m; Moderate – 6.5 m; Minor – 5.5 m (see highlighted rows).
(NB: G.Jn: Gascoyne Junction)

Year	Rainfall event	River height (m)	River height date	Rainfall catchment average (mm) east of G.Jn	Top 3 – daily rainfall (mm)
1960	31 Jan – 02 Feb	7.61	4 Feb	31 Jan 25 mm 1 Feb 35 mm 2 Feb 17 mm	Eudamullah (165) Mt Augustus (91) Mt Phillip (77)
1961	12–14 Feb	7.6	16–17 Feb	12 Feb 24 mm 13 Feb 79 mm 14 Feb 41 mm	Cobra (203) Minnie Creek (195) Eudamullah (177)
1963	11–14 Jan	3.75	16 Jan	11 Jan 23 mm 12 Jan 28 mm 14 Jan 23 mm	Errabiddy (143) Bidgemia (74) Doolgunna (65)
	9–10 Feb	4.74	12 Feb	9 Feb 36 mm	Doolgunna (88) Mt Augustus (86) Wanna (82)
1965	11–12 Mar	4.18	23 Mar	Only rain of significance was on 11 Mar (av. 25 mm) – 12 Mar (av. 17 mm) – well before flood date? Perhaps because in upper part of catchment – no Lyons River contribution	Three Rivers (149) Milgun (109) Doolgunna (102)
1967	20–22 Jan	5.07	23–24 Jan	22 Jan 33 mm 21 Jan 12 mm	Bidgemia (131) Jimba Jimba (117) Dairy Creek (110)
	31 Jan – 2 Feb	4.03	4 Feb	2 Feb 9 mm	Mt Augustus (41) Landor (26) Lyons River (25)
1968	28 Jan – 6 Feb	Variable flows 2 to 2.8 m	31 Jan to 13 Feb	28 Jan 22 mm	Dairy Creek (97) Eudamullah (73) Cobra (68)
	25–26 Mar	3.5	29 Mar	25 Mar 18 mm 26 Mar 10 mm	Mt Phillip (49) Mt Clere (39) Landor (32)
	17–18 Jun	4.45	20 Jun	17 Jun 27 mm 18 Jun 26 mm	Eudamullah (91) Lyons River (61) Dairy Creek (60)
1971		2.97	12 Jan	No recorded rainfall to support this river height – localised downpours?	
	4–5 Feb	2.99	11 Feb	4 Feb 10 mm 5 Feb 16 mm	Mt Clere (109) Mt Augustus (46) Milgun (41)
	4 Jun	2.7	14 Jun	3 Jun 11 mm 4 Jun 29 mm	Doolgunna (99) Milgun (89) Three Rivers (76)
	30 Jul	2.68	1 Aug	25 Jul 21 mm 30 Jul 13 mm 31 Jul 6 mm	Gascoyne Junction (54) Jimba Jimba (52) Bidgemia (46)
1974	13–14 Jul	6.3	15 Jul	13 Jul 20 mm 14 Jul 31 mm	Errabiddy (84) Eudamullah (77) Landor (64)
	28 Jul	4.44	31 Jul	27 Jul 13 mm 28 Jul 43 mm	Mt Clere (80) Mt Augustus (71) Milgun (69)
1975		5.1		3 Nov 38 mm 4 Nov 11 mm	Dairy Creek (86) Bidgemia (80) Gascoyne Junction (79)

Appendix 5 *(continued)*

Year	Rainfall event	River height (m)	River height date	Rainfall catchment average (mm) east of G.Jn	Top 3 – daily rainfall (mm)
1980	11 Jan	1.3	11–12 Jan	11 Jan 7 mm 12 Jan 19 mm	Cobra (61) Landor (54) Errabiddy (59)
	19–21 Jun	7.35	22–23 Jun	19 Jun 12 mm (heavy around G.Jn) 20 Jun 33 mm 21Jun 23 mm	Eudamullah (115) Minnie Creek (92) Errabiddy (85)
1984	1–4 Mar	5.06	4 Mar		
	20 May	4.16	22 May		
	27 May	5.5	29 May		
1989	9–13 Jun	6.32	15 Jun	11 Jun 12 mm 12 Jun 15 mm (Lyons R) 13 Jun 27 mm	Dairy Creek (86) Gascoyne Junction (63) Bidgemia (60)
1990	16–18 Jan	4.42	21 Jan	16 Jan 23 mm 17 Jan 26 mm	Mt Augustus (78) Wanna (60) Doolgunna (58)
	25–27 Jan	4.91	30 Jan	26 Jan 12 mm 27 Jan 22 mm	Eudamullah (47) Errabiddy (42) Lyons River (36)
1995	26–27 Feb	7.09	28 Feb – 1 Mar	Widespread 26 Feb 31 mm 27 Feb 16 mm	Mount Phillip (92) Peak Hill (79) Dairy Creek (77)
1996	19–20 Apr (variable distrib. around G.Jn)	2.19	22 Apr	19 Apr 19 mm 20 Apr 5 mm	Wanna (72) Bidgemia (52) Dairy Creek (38)
	15 Jul	4.58	17 Jul	More rain on Lyons and lower Gascoyne	
1998	1 Jul	3.05	4 Jul		
	1 Aug	4.29	4 Aug		
1999	14 Feb	3.5	17 Feb		
	22–25 Mar	6.49	25 Mar	Widespread – centred around G.Jn. Ave 23 Mar 50 mm 24 Mar 10 mm	Gascoyne Junction (154) Bidgemia (120) Jimba Jimba (115)
2000	8–10 Mar	7.58	10–12 Mar	8 Mar 33 mm (Lyons R) 9 Mar 63 mm (Lyons R) 10 Mar 27 mm (Lyons R)	Eudamullah (119) Minnie Creek (117) Lyons River (113)
	25–27 Mar	5.99	29 Mar	25 Mar 30 mm (Gasc. R) 27 Mar 18 mm (Lyons R)	Landor (90) Milgun (69) Minnie Creek (94)
2006	11 Jan	2.64	16 Jan		
	25 Jan	2.02	28 Jan		
	8 Feb – 12 Feb	2.99	14 Feb		Minnie Creek (46) Peak Hill (44) Gascoyne Junction (40)
	1 Mar	4.45	4 Mar	28 Feb 15 mm 1 Mar 45 mm	Mount Clere (153) Mt Augustus (137) Errabiddy (80)
		5.13	8 Mar	No rain recorded after 1 March. Cloudburst?	
	31 Mar	5.56	3 Apr	31 Mar 41 mm 1 Apr 12 mm	Wanna (75) Cobra (69) Mt Phillip (69)
2007	25–26 Apr	2.07	28 Apr	25 Apr 46 mm 26 Apr 20 mm	Lyons River (85) Dairy Creek (74) Gascoyne Junction (64)
		0.55	6 Jul		
		0.42	31 Jul		
2008		3.33	22 Feb		
	30 Mar	3.03	2 Apr		

Appendix 5 *(continued)*

Year	Rainfall event	River height (m)	River height date	Rainfall catchment average (mm) east of G.Jn	Top 3 – daily rainfall (mm)
2009	28 Jan	6.99	30 Jan	28 Jan 27 mm 27 Jan 17 mm	Minnie Creek (78) Mt Phillip (48) Doolgunna (48)
2010	17–18 Dec	7.77	19–20 Dec	17 Dec 29 mm (widespread) 18 Dec 61 mm (predominantly Lyons R and around G.Jn)	Dairy Creek (190) Bidgemia (174) Eudamullah (168) Lyons River (160)
2011	3–5 Jan	6.3	7 Jan	3 Jan 15 mm 4 Jan 22 mm 5 Jan 12 mm	Lyons River (60) Dairy Creek (50) Landor (39)
	12 Feb	4.8	15 Feb		
	17–18 Feb	7.07	19 Feb	17 Feb 40 mm 18 Feb 19 mm	Doolgunna (92) Three Rivers (83) Lyons River (70)
		5.85	20 Feb		
		6.37	23 Feb		
		4.36	28 Feb		

Appendix 6 — Average soil surface attributes for capture and shedding zones in 2011

Appendix Table 6.1 **Average soil surface attributes for capture and shedding zones in 2011**

Soil surface attribute	2011		General comment
	Capture	Shedding	
Soil cover rain interception: 1 = < 1% 2 = (1–2 %) 3 = (2–5 %) 4 = (5–15%) 5 = (15–50%) 6 = (> 50%)	4.3	2.9	Low rainfall protection: about 2 to 5% Higher rain interception in capture zones
Soil cover overland flow: 1 = nil 2 = (< 2%) 3 = (2–5%) 4 = (5–15%) 5 = (15–50%) 6 = (> 50%)	3.5	2.5	Few obstructions about 2 to 5% Higher overland flow (%) in capture zones
Crust broken-ness: 1 = extensive 2 = moderate 3 = slight 4 = intact	3.7	3.5	Intact crust
Cryptogam cover: 1 = nil (< 1%) 2 = slight (1–10%) 3 = moderate (10–50%) 4 = extensive (> 50%)	1.5	1.7	Low amount of cryptogam nil to < 10%
Erosion features: 1 = extensive 2 = moderate 3 = slight 4 = insignificant	3.4	3.1	Increasing number of erosion features – see Table 6
Eroded materials: 1 = extensive 2 = moderate 3 = slight 4 = nil	2.8	2.5	Slight eroded materials. In terms of type of material: gravels on 30%, rock on 23% and sand on 2% of quadrats
Litter cover: 1 = (< 10%) 2 = (10–25%) 3 = (25–50%) 4 = (50–75%) 5 = (75–100%)	3.5	2.4	Generally around the 10–25% More litter in capture zones
Microtopography: 1 = nil 2 = slight (3–8 mm) 3 = moderate (8–15 mm) 4 = high (15–25 mm) 5 = very high (> 25 mm)	1.9	1.8	Flat: 3 to 8 mm

Appendix 7 — Physiographic regions of the Gascoyne River catchment

Appendix Table 7.1 **Provinces and Zones of the Gascoyne River Catchment as described by Tille (2006)**

Carnarvon Province

Zone	Map-unit	Description
Yalbalgo Sandplain Zone	233	Sandplains (with some dunes and hardpan wash plains) on Quaternary deposits over Cretaceous and Permian sedimentary rocks of the Carnarvon Basin. Red deep sands with some Red loamy earths. Grassy bowgada shrublands and acacia scrub.
Lower Gascoyne Alluvial Plains Zone	235	Alluvial plains (with saline plains and sandplains and some floodplains) on Quaternary alluvial and aeolian deposits over Cretaceous sedimentary rocks of the Carnarvon Basin. Red deep sandy duplexes and Red deep sands with some Red/brown non-cracking clays and Red sandy earths. Currant bush shrublands and acacia scrub with halophytic shrublands.
Wandagee-Byro Plains and Hills Zone	236	Stony plains, sandplains and alluvial plains (with some mesas, hills and hardpan wash plains) on Quaternary deposits over Permian and Carboniferous sedimentary rocks of the Carnarvon Basin. Red deep sandy duplexes and Red deep sands with Red sandy earths and some Red loamy earths, Stony soils and Red shallow sandy duplexes. Snakewood-prickly wattle-mulga shrublands (with some spinifex grasslands and halophytic shrublands).
Kennedy Range Zone	239	Dissected plateaux, mesas, hills and elevated sandplains on Eocene marine limestone and sandstone over Permian sedimentary rocks of the Carnarvon Basin. Stony soils and Red deep sands with some Red shallow sands and loams and Red shallow sandy duplexes. Snakewood-prickly wattle scrub with spinifex grasslands.

Ashburton Province

Zone	Map-unit	Description
Bulloo Plains and Hills Zone	290	Hardpan wash plains, stony plains, hills and ranges (with some sandplains) on sandstone and shale of parts of the Collier and Bresnahan Basins and granite of the Sylvania Inlier. Red shallow loams (often with hardpans), Red loamy earths, Stony soils and Red deep sands with some Red shallow sands. Mulga shrublands (with some spinifex grasslands).
South Bangemall Hills Zone*	291	Hardpan wash plains (with hills, ranges and stony plains) on sedimentary rocks of the Edmund Basin. Stony soils, Red loamy earths and Red/brown non-cracking clays with some Red shallow loams and Red deep sands. Mulga shrublands with snakewood (and some halophytic shrublands).
Paroo Uplands Zone	293	Hills, hardpan wash plains and stony plains (with sandplains) on Yerrida, Bryah and Padbury Basins sedimentary rocks and Marymia Inlier granitic and volcanic rocks. Red-brown hardpan shallow loams with Red loamy earths and Stony soils and some Red shallow sands, Red shallow loams, Red sandy earths and Red deep sands. Mulga shrublands (with some spinifex, eucalypts and halophytic shrubs).
Yaragner Hills and Plains Zone	294	Undulating stony uplands, stony plains, hills and ranges on Gascoyne Complex granitic and sedimentary rocks. Stony soils with Red shallow loamy duplexes with Red deep sandy duplexes and Red shallow loams and some Red shallow sandy duplexes and Red/brown non-cracking clays. Mulga-snakewood-prickly wattle shrublands (with some spinifex grasslands and halophytic shrublands).
Gascoyne Valley Zone	295	Hardpan wash plains (with hills, stony plains and some calcrete plains and floodplains) on alluvial deposits over gneiss and volcanic rocks of the southern parts of the Gascoyne Complex and Edmund and Collier Basins. Red-brown hardpan shallow loams with Red deep sands, Red shallow sandy duplexes and Red loamy earths and some Red/brown non-cracking clays and Stony soils. Mulga shrublands (with some wanderrie grasses and chenopods).
North Bangemall Hills Zone	299	Hills, ranges and plateaux (with some stony plains) on sandstone, shale and volcanic rocks of the Edmund and Collier Basins. Stony soils with some Red loamy earths and Red shallow loams. Mulga-snakewood shrublands (with some spinifex grasslands).

* The South Bangemall Hills Zone is differentiated from the North Bangemall because hardpan wash plains are a major component of the former but are relatively rare in the latter.

Murchison Province

Zone	Map-unit	Description
Upper Murchison Zone	272	Hardpan wash plains (with stony plains, sandplains, hills and mesas) on granite and gneiss of the Yilgarn Craton (Narryer Terrane and Murchison Domain). Red-brown hardpan shallow loams and Red shallow loams with Red loamy earths and Red deep and some Red shallow sands and Red deep sandy duplexes. Mulga shrublands (with some halophytic shrublands).

Appendix Table 7.2 **Land types of the Gascoyne River catchment and their component land systems**

Hills and ranges with acacia shrublands (18%)	
Agamemnon land system	Rugged hills and ridges of schist, gneiss, granite and quartz above extensive stony slopes, supporting scattered tall shrublands of acacia and eremophila.
Augustus land system	Rugged ranges, hills, ridges and plateaux, supporting mulga shrublands or hard spinifex grasslands.
Billy land system	Low plateaux, mesas and buttes with stony footslopes and narrow drainage floors, supporting scattered tall shrublands of mulga and other acacias.
Charley land system	Dolerite hills and ridges and restricted plains, supporting mulga and cassia shrublands or spinifex grasslands.
Diorite land system	Low rough hills and domes of diorite or basalt, supporting sparse acacia shrublands.
Fossil land system	Flat-topped sandstone hills dissected by narrow streams and drainage floors, supporting mulga shrublands.
Glenburgh land system	Rugged granite hills, stony uplands and lower plains, supporting scattered tall shrublands of mulga and other acacias.
Mulgul land system	Rough dolomite hills, supporting sparse mulga and low shrubs.
Moogooloo land system	Intensely dissected plateaux, mesas and hills of sedimentary rocks with steep footslopes and dendritic drainage, supporting tall shrublands of mulga and other acacias.
Peak Hill land system	Rugged, sinuous ranges and rounded hills of Proterozoic banded ironstone and hematitic shale, supporting stunted mulga and cottonbush shrublands.
Prairie land system	Granite hills and gently undulating stony plains, supporting acacia-eremophila-cassia shrublands and minor soft spinifex grasslands.
Two Hills land system	Long, low hills and stony footslopes of sedimentary rocks, supporting tall shrublands of mulga and other acacias.
Ullawarra land system	Dolerite and shale hills, restricted stony plains and drainage floors, supporting mulga and minor chenopod shrublands.
Mesas, breakaways and stony plains with acacia woodlands and halophytic shrublands (5.5%)	
Laterite land system	Low lateritic plateaux, mesas, buttes and gravelly rises and plains, supporting mulga shrublands and short grass forbs.
Pells land system	Low hills, mesas and ridges of sedimentary rocks supporting, tall shrublands of mulga and other acacias.
Sandiman land system	Plateau remnants and breakaway slopes on sedimentary rocks, with ridge spurs above saline stony footslopes and interfluvial plains, supporting mulga and snakewood shrublands with Gascoyne bluebush and other halophytes.
Thomas land system	Lateritised mesas among hills of granite and gneiss, with stony footslopes above short, gently sloping interfluvial plains, supporting sparse acacia-dominated shrublands.
Waguin land system	Sandplains and stripped granite or laterite surfaces with low fringing breakaways and lower plains, supporting bowgada and mulga shrublands with wanderrie grasses and minor mixed halophytes.

Appendix Table 7.2 *(continued)*

Low hills and stony plains with acacia shrublands (15.2%)	
Beasley land system	Low ridges, hills and lateritised summits above stony footslopes and broad, stony lower plains, supporting scattered mulga and snakewood-dominated shrublands.
Collier land system	Undulating stony uplands, low hills and ridges and stony plains, supporting mulga shrublands.
James land system	Low hills and tors of granite, schist-gneiss ridges, with stony lower plains, rises and drainage floors, supporting scattered tall shrublands of mulga and other acacias.
Mindura land system	Low hills, ridges and outcrops of granite, gneiss and quartz above convex, quartz-strewn interfluves and lower plains, supporting sparse acacia shrublands becoming denser in drainage floors.
Phillips land system	Low hills and undulating uplands of crystalline rocks, supporting mulga and other acacia-dominated tall shrublands.
Stony plains with acacia shrublands (2%)	
George land system	Very stony lower slopes and interfluves below hill systems, supporting stunted acacia, eremophila and cassia shrublands.
Koonmarra land system	Quartz-strewn stony plains and low rises with outcropping granite, gneiss and schists, supporting scattered mulga and other mainly non-saline shrubs.
Mabbutt land system	Gently sloping stony plains supporting sparse mulga shrublands with eremophila and cassia, often with grove intergrove patterns with denser vegetation in the groves.
Sugarloaf land system	Gently undulating dolomitic stony plains, tributary slopes and drainage floors, supporting mulga and other acacia shrublands with halophytic and non-halophytic low shrubs.
Woodlands land system	Undulating uplands on Bangemall Series Dolomites: Stony short grass-forb pastures. Stony valley floors, plains and drainage floors, supporting mulga and other acacia tall shrublands with occasional eucalypts and spinifex.
Yagina land system	Stony plains and alluvial plains with occasional low dunes and claypans, supporting sparse tall shrublands.
Stony plains with acacia shrublands and halophytic shrublands (16%)	
Bryah land system	Stony plains and restricted internal drainage flats with sparse tall shrublands and low chenopod shrublands.
Durlacher land system	Stony plains, lower tributary drainage plains and low stony rises, supporting scattered tall shrublands of mulga, other acacias and chenopod low shrubs.
Horseshoe land system	Gently undulating stony plains and low rounded hills based on Proterozoic metamorphic rocks, with somewhat saline drainage foci and alluvial tracts, supporting scattered mulga and wait-a-while shrublands with halophytes.
Jimba land system	Gently sloping alluvial plains, mostly devoid of surface mantling, with disorganised and complex drainage features below minor ridges and pebbly plains, supporting scattered tall and low acacia shrublands with some chenopods.
Kurubuka land system	Saline stony plains and internal drainage plains, supporting prickly acacia, snakewood and other acacias, eremophila and cassia species and chenopod low shrubs.
Mantle land system	Gently undulating stony plains with sluggish drainage tracts, stony rises and low summits, scattered tall and low shrublands dominated by acacia and eremophila species.
Nadarra land system	Plains and sedimentary rock rises with chenopod shrublands.
Yinnietharra land system	Scattered granite tors and domes above stony slopes, broad sandy plains with groved vegetation and wide drainage tracts, supporting tall shrublands of mulga and other acacias.

Appendix Table 7.2 *(continued)*

Wash plains on hardpan with mulga shrublands (10%)	
Channel land system	Incised rocky streams and creeklines with truncated marginal slopes and stony narrow fringing plains, supporting scattered to very scattered shrublands of very variable composition.
Frederick land system	Hardpan wash plains characterised by broad, reticulate mulga groves and wanderrie banks, supporting tall acacia shrublands with grassy understorey.
Jamindie land system	Stony hardpan plains and rises supporting groved mulga shrublands, occasionally with spinifex understorey.
Wash plains and sandy banks on hardpan, with mulga shrublands and wanderrie grasses or spinifex (11.5%)	
Blech land system	Non-saline alluvial plains with sandy banks and transverse groves, supporting wanderrie grasses and short grass-forbs.
Doolgunna land system	Hardpan plains with numerous narrow, sandy banks and bands, central drainage tracts, supporting mulga shrublands and wanderrie grasses.
Flood land system	Hardpan wash plains with long, broad, interconnected wanderrie banks, supporting mulga shrubland and wanderrie grasses.
Jingle land system	Plains marginal to rivers with saline areas, supporting short grass-forbs, wanderrie grasses and chenopods.
Landor land system	Hardpan wash plains with numerous sandy banks also drainage tracts receiving more concentrated sheet flow, supporting mulga shrublands and wanderrie grasses.
Macadam land system	Stony hardpan wash plains with numerous sandy banks and central drainage dissection zone, supporting sparse mulga and other acacia shrublands with eremophila, cassia and wanderrie grasses on the banks.
Outwash land system	Alluvial plains with mulga groves and sandy banks, supporting short grass-forb pastures with wanderrie grasses on sandy banks.
Stonehut land system	Non-saline alluvial plains with large transverse sandy banks supporting mulga and other acacia tall shrublands with non-halophytic low shrubs.
Three Rivers land system	Hardpan plains with minor, longitudinal sandy banks supporting sparse mulga shrublands.
Winmar land system	Stony plains with sandy banks supporting mulga and other acacia shrublands with eremophila and cassia low shrubs and wanderrie grasses on banks.
Wooramel land system	Sandy-surfaced hardpan wash plains, sandy banks and sand sheets, supporting tall mulga and wanyu shrublands and patches of mulga woodlands.
Sandy plains with acacia shrublands and wanderrie grasses (0.4%)	
Bubbagundy land system	Wanderrie plains without banks, supporting wanderrie grasses.
Sandplains and occasional dunes with grassy acacia shrublands (5.8%)	
Brown land system	Sandy plains with sparse longitudinal dunes, supporting tall shrublands of acacias.
Cahill land system	Sandy alluvial plains and channelled flow zones with tall shrublands of various acacias.
Ella land system	Aeolian sandplain with low dunes and sandy swales, clayey interdunal plains and discrete drainage foci; tall shrublands and low woodlands of wanyu and sand dune gidgee.
Kalli land system	Elevated, gently undulating red sandplains edged by stripped surfaces on laterite and granite, supporting tall acacia shrublands and understorey of wanderrie grasses (and spinifex locally).
Lyons land system	Claypans and restricted plains with longitudinal and reticulate dunes, supporting tall acacia shrublands.
Sandplain land system	Extensive, gently undulating red sandplains with occasional dunes, supporting tall wanyu shrublands with mainly shrub (but locally grassy) understorey.
Yalbalgo land system	Gently undulating sandplain with parallel linear sand dunes and interdunal swales, supporting tall acacia shrublands and sparse wanderrie grasses.

Appendix Table 7.2 *(continued)*

Sandplains and drainage floors with acacia and halophytic shrublands (1.3%)	
Bidgemia land system	Tributary drainage plains partly overlain by broad low dunes and sandy banks, supporting tall shrublands of various acacias.
Sandplains and occasional dunes with spinifex grasslands (2.3%)	
Bullimore land system	Extensive sandplains supporting spinifex hummock grasslands.
Divide land system	Sandplains and occasional dunes, supporting shrubby hard spinifex grasslands.
Kennedy land system	Elevated sandy plains with large linear to reticulate dunes, supporting hard spinifex grasslands with numerous shrubs.
Alluvial plains with acacia shrublands (0.2%)	
Clere land system	Non-saline alluvial plains with extensive flood-outs supporting short grass-forb pastures.
Alluvial plains with halophytic shrublands (6.7%)	
Chargoo land system	Flat saline alluvial plains subject to temporary inundation, characterised by numerous drainage depressions, supporting low shrublands of saltbush and bluebush and tussock grasslands.
Delta land system	Floodplains of the major rivers, supporting low shrublands of bluebush and saltbush.
Gneudna land system	Plains with calcareous soils and parallel bands of siltstone and limestone outcrop, supporting sparse shrublands of acacia and bluebush.
Peedawarra land system	Saline alluvial plains and sandy banks supporting chenopod low shrublands and acacia shrublands with wanderrie grasses.
Sable land system	Nearly flat, saline, alluvial plains with occasional sandy rises, low shrublands of saltbush and Gascoyne bluebush and some tall acacia shrublands.
Sandal land system	Alluvial plains with numerous low sandy rises and banks with duplex and sandy soils, supporting tall shrublands of acacias with currant bush; also low shrublands of Gascoyne bluebush and Gascoyne mulla-mulla.
Target land system	Gently sloping plains with sandy banks and narrow interbank plains, supporting tall acacia shrublands.
Bibbingunna land system	Low clay flats with crabholes and sluggish drainage, supporting chenopods and grassy pastures.
Calcrete plains with acacia shrublands (1.9%)	
Mary land system	Calcrete plains, with minor low rises, supporting tall shrublands of acacias and cassias.
Warri land system	Low calcrete platforms and plains supporting mulga and cassia shrublands and minor halophytic low shrublands.
River plains with grassy woodlands and tussock grasslands (3.1%)	
Gascoyne land system	Major river systems and associated narrow alluvial plains and inclusions. River gum fringing woodlands also includes mulga and other acacias, cassias and buffel grass.
River land system	Active flood plains, major channelled watercourses, supporting moderately close, tall shrublands or woodlands of acacia and fringing communities of coolabah and river gum.
Coastal plains, cliffs, dunes, mudflats and beaches; various vegetation (0.1%)	
Littoral land system	Bare coastal mudflats with mangroves on seaward fringes, samphire flats, sandy islands, coastal dunes and beaches.