The Availability of Wetland Habitat for Waterbirds in Arid Australia

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Final Report to the National Wetlands Research and Development Program administered by Environment Australia

by

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Executive Summary

1. Researchers from the School of Science and Technology at Charles Sturt University and the New South Wales National Parks and Wildlife Service developed a cost effective methodology for identifying and mapping Australian arid zone wetlands using satellite data. We used the methodology to record changes in the distribution and abundance of wetlands across the whole arid zone of Australia between 1986 and 1997. We also investigated the relationships between climate and wetland filling events for different regions of the arid zone and the responses of waterbirds to changes in local, catchment and landscape-scale availability of arid zone wetland habitat in the eastern half of the continent during the period 1987 to 1993.

2. Advanced Very High Resolution Radiometer (AVHRR) data are of low resolution compared to other satellite data, but are particularly suited to understanding the hydrology of wetlands in the Australian arid zone owing to the large geographic coverage in each image and the daily coverage. A technique which used all spectral bands of the AVHRR and the Matched Filtering algorithm within the ENVI software package was employed to detect water surfaces and estimate their area. Choice of endmembers for different types of water surface (fresh, salt, turbid), but which excluded dry salt surfaces was based on a ground-truthed image from the Paroo River floodplain. An error matrix for the status of 115 lakes (wet lakes, dry lakes, subpixel wet lakes and subpixel dry lakes) in the region showed that 88% of lakes were classified correctly using this methodology.

3. The total surface area of wetlands in arid Australia varied by an order of magnitude over the 11 year period 1986 – 1997, from less than 315,000ha in September 1986 to 3,305,000ha in June 1989. Shifts in the distribution of wetlands was rapid. For instance, in March 1991 > 1,800,000ha of the floodplain of the Cooper Creek and the Diamantina and Georgina Rivers was covered with water, but this was reduced to 155,000ha six months later.

4. Some arid zone wetlands contained water most of the time during the 11-year period even in the driest part of the continent. Not including permanent water bodies created

by river regulation, the most persistent wetlands were Lakes Koolivoe and Mipia on the fringes of the Simpson Desert, some of the Coongie Lakes in northern South Australia and Lakes Wyara and Numalla in south western Queensland.

5. Wetland availability for waterbirds (measured as the recurrence of inundation integrated over different spatial scales) was estimated for the entire arid zone for the 11 year study period. As the spatial scale of reference was increased, the influence of isolated large water bodies diminishes and regions with frequently inundated mosaics of wetlands had relatively greater habitat availability than at smaller scales. At a spatial scale of 500km, the regions with the highest level of habitat availability during the 11 years of study were the upper and lower portions of the Lake Eyre Basin.

6. Analyses of the spatial pattern of wetlands revealed that the degree to which the arid zone wetlands act as a connected network for the movement of waterbirds changed dramatically with time. For a bird with a dispersal distance of 200km, in March 1993 the wetland landscape was connected in such a way that it would have been possible for bird to move from Victoria to the Kimberley region of Western Australia. In contrast in March 1988, a dry period, a bird would have been restricted to south eastern Australia and a few isolated regions in the Lake Eyre Basin and the Western Desert.

7. Comparison of rainfall during the 11 year study period, with the 100 year rainfall record for major regions of the arid zone revealed that with the exceptions of the regions around Lake Torrens and the Cobham region in North west NSW, mean monthly rainfalls for the study period were highly correlated with the long-term record.

8. Comparison of rainfall and changes in wetland area in major regions of the arid part of the continent for three and six month periods during 11 years, showed that a rainfall of 20mm was sufficient to result in a positive increment in wetland area. Using this information together with 100 years of rainfall records for each region we found that wetlands were available somewhere in the arid zone during the last century.

9. Analyses using the numbers of waterbirds (belonging to different functional groups) recorded on wetlands in the north western region of NSW and the areas of wetland in this region and the adjacent Lake Eyre Basin revealed something of the use of the wetland landscape by birds.

10. The numbers of most functional groups of waterbirds in the Paroo catchment responded more to changes in wetland areas in the Lake Eyre Basin than local changes in wetland area in the Paroo catchment. This was true for dabbling ducks, fish-eaters, diving ducks and deep-water foragers, grazing waterfowl, small and large waders but did not hold for shoreline foragers.

11. The implication of the above (10) is that many waterbirds respond to wetland availability at the landscape scale. Thus, management of wetland habitat for waterbirds will depend on the conservation of wetlands across many catchments.

12. The most significant climatic change impact for waterbirds would be alterations to the frequency, path and intensity of tropical systems, particularly cyclones, across inland Australia. If the intervals between flooding events increase, opportunities to breed for species that depend on the temporary wetlands of the inland become increasingly infrequent. Furthermore, habitat modification in the south-east of the continent may reduce options for species to adjust their distribution.

Section 1. Introduction

1.0 Preamble

This is the final report of the project 'The availability of wetland habitat for waterbirds in arid Australia' which was funded by the National Wetland Research and Development Program administered by Environment Australia.

The project had the following objectives:

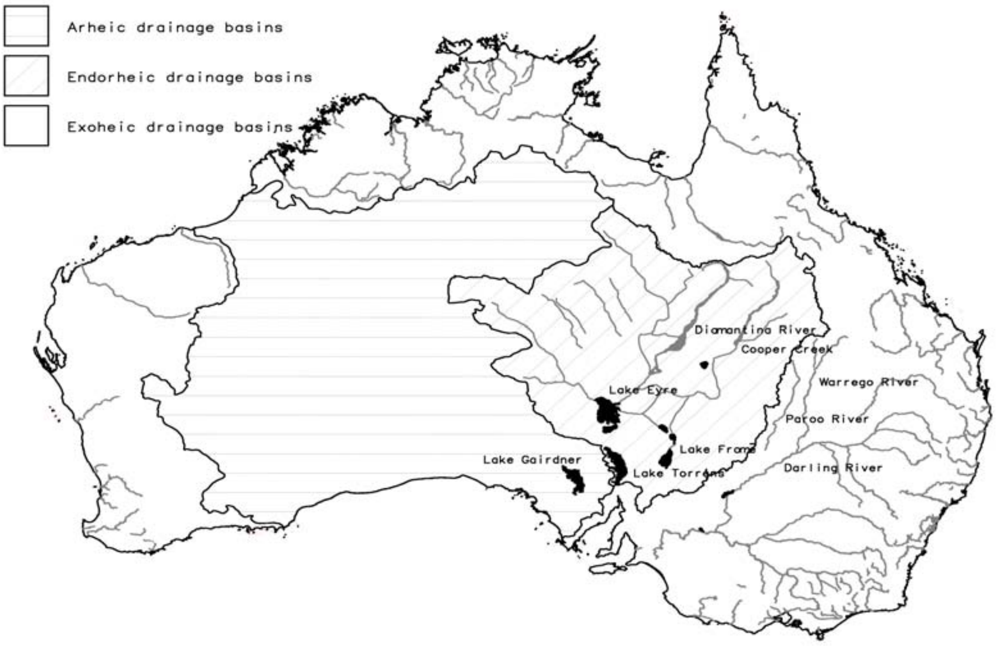
- To develop a methodology for rapid assessment of wetland occurrence in arid Australia,
- To determine the spatial and temporal characteristics of wetland occurrence at multiple scales,
- To determine the duration, extent and variability of surface water occurrence in arid-zone wetlands,
- To model wetland occurrence with rainfall or synoptic data, and
- To examine the effects of variation in wetland occurrence on the distribution and movement of waterbirds.

All of these objectives have been met, and details of the findings under each objective are provided in Sections 2 to 5 of this report. In order to put the results of the project into context, we first provide a short introduction on the justification for such a project.

1.1 Scientific and conservation background to project

Australia is a dry, flat continent. Rainfall in the arid interior is highly variable in timing, duration and intensity, even when compared to other arid regions of the world (Stafford Smith and Morton 1990). As a result, Australian rivers have greater variation in flow and flooding patterns than elsewhere on the globe (Williams 1981; Puckeridge *et al* 1998), and this flow variation increases with increasing catchment area - the reverse of the pattern on other continents (Finlayson and McMahon 1988; El-Hames and Richards 1994). Low topographic relief and the variation in flows combine to isolate many standing water bodies spatially and temporally (Williams 1981). Many of these standing waters are permanently or temporarily saline (see Bowler 1981, 1986; Kotwicki 1986; Kingsford and Porter 1991, 1994; Timms 1993, 1997, 1998*ab*).

There are many thousands of temporary wetlands found in the arid zone ranging in size from a few square metres to thousands of square kilometres. The nature and distribution of surface water in inland Australia is fundamentally related to drainage basin type. Many basins do not connect to other basins or the sea (Fig 1.1) and many receive insufficient rainfall for extensive surface drainage features to develop (Williams 1981, 1983). Standing waters can be terminal water bodies filled by major drainage systems (Fig 3.1) (eg Lake Eyre), lakes filled by local drainage (eg Lake Gairdner and Lake Torrens), and creeks and overflow lakes associated with major drainage systems filled by flood events, such as occurs along the Darling, Paroo and Warrego Rivers, Cooper Creek (see Bowler 1981, 1986; Kotwicki 1986; Kotwicki and Allan 1998; Timms 1993, 1997, 1998*ab*, 1999; Kingsford and Porter 1991, 1993, 1994; Knighton and Nanson 1994*ab*; Seddon, Thornton and Briggs 1997; Walker, Sheldon and Puckridge 1995; Puckridge 1998). Flood events range in duration from minutes to months as floodwaters flow quickly down dry drainage lines or traverse many hundreds of kilometres of river channel in the larger drainage basins.



(after Williams 1981)

***Figure 1.1** Drainage basin types in Australia. Arheic drainage basins have no significant drainage features and drainage patterns are determined by local topography, endorheic drainage basins have no downstream connection to other basins or the sea and exoheic drainage basins do. Grey lines are major rivers and drainage lines.*

While it is understood that the degree of variation in the spatial and temporal distribution of surface waters is high by world standards, the actual distribution of water is known from only a few locations at particular times. Rivers and lakes for which filling and drying events have been recorded include: Lake Gregory (Halse, Pearson and Kay 1998), Lake Eyre (Kotwicki 1986 and references therein; Prata 1990; Kingsford and Porter 1991, 1993), the overflow lakes of the Paroo River catchment (Maher and Braithwaite 1992; Timms 1993, 1997, 1998*ab*, 1999; Kingsford, Bedward and Porter 1994; Kingsford and Porter 1994), Lake Lefroy in Western Australia (Clarke 1994), Lake Wood and surrounding water bodies in the Northern Territory (Fleming 1993) and the lakes and channels of Cooper Creek (Kotwicki 1986; Kingsford and Porter 1991, 1998; Knighton and Nanson 1994*ab*; Walker, Sheldon and Puckridge 1995; Puckridge 1998; Kingsford, Curtin and Porter 1999). These observations of water distribution are widely separated in space and time and reveal little at the landscape scale of the spatial and temporal patterns of wetland filling and drying.

Waterbirds utilise mosaics of wetland habitat for feeding and breeding and many rely on networks of wetlands for their survival rather than on individual wetlands (Maher and Braithwaite 1992; Haig, Mehlman and Oring 1998; Halse, Pearson and Kay 1998). In Australia, the dynamics and structure of mosaics of wetland habitat in the arid zone is poorly known and speculation on their importance to waterbirds are divergent. One view states that the arid zone frequently dries out and is rendered temporarily useless to waterbirds (Frith 1982). As a corollary, waterbirds use of arid zone wetlands is opportunistic, with core breeding and feeding habitat concentrated in the more mesic southeastern and southwestern corners of the continent (Frith 1959*ab*, 1962).

More recently, large concentrations of waterbirds have been reported from the driest parts of the continent (Kingsford and Porter 1993; Halse, Pearson and Kay 1998; Kingsford, Curtin and Porter 1999; Kingsford and Halse 1999; Kingsford *et al* 1999). Given the variation in filling and drying patterns of individual wetlands and their abundance and extent (see Section 3, this report), there may be sufficient habitat in the arid zone to sustain waterbird populations, even at the driest of times. Kingsford (1996) reports the continual existence of wetlands in arid parts of eastern Australia over a 12-year period that included a severe drought. These wetlands may be refugia for arid zone waterbirds (see Maher and Braithwaite 1992), or part of a dynamic mosaic of wetlands. Either way, an alternate view is that the arid zone remains functional as a habitat for waterbirds most of the time as spatial and temporal variability in climatic processes and weather combine to ensure one or more refugia, or other wetlands, contain water (see Kingsford 1996).

Changes in waterbird abundance on a wetland may be a response to changes at the wetland, catchment or landscape scale. On individual wetlands, abundance of waterbirds may vary in response to food availability, availability of nest sites, predation risk or some other factor (eg Halse *et al* 1993; Kingsford and Porter 1994; Savard, Boyd and Smith 1994; Murkin, Murkin and Ball 1997; Timms 1997). Alternatively, waterbirds may feed on one wetland and roost or breed at another, depending on the local distribution of resources (Maher and Braithwaite 1992; Kingsford and Porter 1994).

At the catchment or landscape scale changes in abundance may reflect general behavioural responses at that scale or the hydrology of individual wetlands or groups of wetlands. For example, canvasback ducks (*Aythya valisineria*) in North America adjust their distribution by hundreds of kilometres in response to weather and ice conditions and changes in food abundance (Lovvorn 1989). Similarly, pintail ducks (*Anas acuta*) in North America may breed north of the Arctic circle when breeding habitat is scarce on the Canadian prairies during drought (Smith 1970). Thus, changes in waterbird abundance may occur in response to changes in habitat availability at different spatial scales and these may vary with geographic location. Such responses may vary among species or functional groups of waterbirds (eg dabbling ducks, fish-eaters, etc). Given the abundance of wetland habitat in inland Australia (see Section 3, this report), the presence of waterbirds on arid zone wetlands probably reflect relationships that range from opportunism to dependence.

Most arid zone wetlands in Australia are not protected (see Section 6, this report) and some of the remotest, such as the Cooper Creek and Paroo River are coming under development from agriculture (Walker, Puckridge and Blanch 1997; Kingsford, Bolton and Puckridge 1998; Kingsford 1999*b*; Puckridge 1999). Changes in land and water use on one or more wetlands has the potential to affect whole populations of waterbirds. In addition to water extraction, which may impact wetlands and their dependant bird populations, climate change through its impact on rainfall, is likely to have potentially catastrophic, but unpredictable consequences for arid zone habitats and biota (Jones and Pittock 1997). It was the aim of this project to provide information on the changes in wetland distribution and abundance in arid Australia, the climatic processes that control wetland filling and the responses of waterbirds to changes in wetland availability. Such information is central to an informed debate on the conservation and management of arid zone wetlands.

Section 2. Detection and Mapping of Arid Zone Wetlands

2.0 Introduction

A continental perspective on habitat availability or landcover change can only be achieved using satellite imagery (eg Goward, Tucker and Dye 1985; Iverson, Cook and Graham 1989; Running and Nemani 1988). Most remote sensing studies of wetlands in Australia have focused on specific regions and have used Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) or Spot satellite imagery (see Johnston and Barson 1993). These data have a spatial resolution of 20-80m and a coverage of 180km x 180km. These have enabled accurate mapping of surface waters (Johnston and Barson 1993; Smith 1997 and references therein). The detection of surface water over large geographic regions necessitates the use of a low spatial resolution sensor to minimise data processing time and costs, particularly when those surface waters occur within wetland mosaics that change in spatial distribution, size and extent. NOAA (National Oceanographic and Atmospheric Administration) Advanced Very High Resolution Radiometer (AVHRR) data (Campbell 1996) is the only realistic option to cover the entire arid zone of Australia. AVHRR data has a spatial resolution of 1.1km near nadir and a path width of ~2600km. In the absence of cloud this enables continental coverage with as few as two images, depending on the path of the satellite.

There are two major problems encountered in detecting and mapping water in an extensive terrestrial matrix. First, while water is usually easily differentiated from land using remotely sensed satellite data because water strongly absorbs near infrared radiation whereas land reflects it (Campbell 1996, p525), the contrast diminishes with increasing sediment load in the water (Campbell 1996, p523). Second, the temporary nature of most wetlands means the boundary between water and land is not constant and thus there are problems with boundary definition and area estimation (Harris and Mason 1989; Harris 1994; Verdin 1996).

In Australia, AVHRR NDVI data have been used to map the extent of lakes and floodwaters in the subhumid tropics of northern Australia and the Lake Eyre Basin

(Fleming 1993; Costelloe, Lewis and Leach 1998). While the above techniques have enabled the detection of surface waters using AVHRR data, reliable estimates of surface area depend on adequate delineation of wetland boundaries.

Figure 2.1 *Lake Wyara (28^{0} 42' S, 144^{0} 14' E) on 9th September 1996 in southwestern Queensland showing exposed sedimentary surfaces as lake contracts within its bed.*

Below we describe a robust methodology based on AVHRR data for detecting water bodies which have constantly changing boundaries within large geographic areas (10^{6}km^{2}) of the arid zone and estimating their area. This methodology was developed using knowledge of the distribution of surface water in a test area of ~ 100,000km^{2} in western New South Wales and southern Queensland (Fig 2.2).

2.1 Test area

The arid and semi-arid regions of western New South Wales and southern Queensland contain numerous lakes (~ 5000, AUSLIG (Australian Land Information group) 1:250000 water body data) and areas subject to temporary inundation (Fig 2.2). These vary in salinity, frequency of inundation, duration of inundation and associated vegetation (see Kingsford and Porter 1994; Kingsford, Bedward and Porter 1994; Timms 1993; Seddon, Thornton and Briggs 1997).

The most significant features of the test area are the Darling River floodplain and the Paroo Overflow. Floodwaters are usually the result of heavy rains outside the area that may take months to reach the lower reaches of the Darling River in the southern part of the test area. The Paroo River remains the only major river in the Murray-Darling Basin not regulated by large dams, weirs or diversions (Kingsford 1999*c*). The largest water storage in the test area is the Menindee Lake Scheme (Fig 2.2). Menindee Lake and the other overflow lakes the Scheme are made almost permanent by a series of levees and weirs (see Seddon, Thornton and Briggs 1997)

While technically a tributary of the Darling River most flood events within the catchment of the Paroo River do not reach the Darling, as a series of overflow lakes and swamps in the Paroo lower catchment must fill before floodwaters can flow into the Darling River. Water from the Paroo can enter the Darling via a number of shallow drainage lines. Which lakes fill and which parts of the Overflow become inundated is dependent on the volume of water and the height and duration of the peak flow.

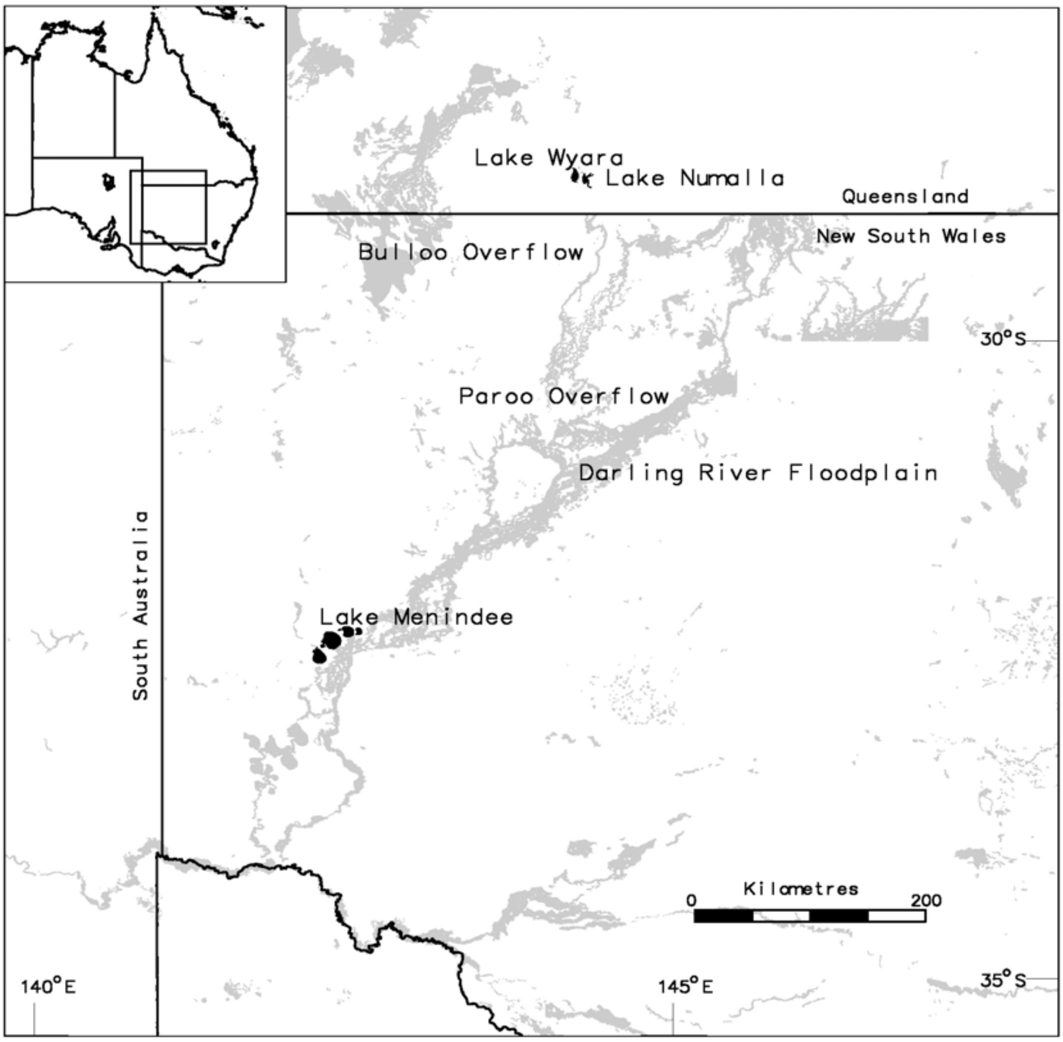


Figure 2.2 *Map of region of western New South Wales and southwestern Queensland used to ground-truth airborne video and AVHRR data. Grey areas are subject to inundation during flood events.*

Lakes and other wetlands in the test area occur in association with soils that range from heavy grey clays to coarse sandy soils (see Goodrick 1984; Milne and O'Neall 1990; Timms 1993). As water recedes in the beds of these lakes most exposed surfaces differ greatly from the surrounding land surfaces. Some of these lakebed surfaces may be salt encrusted with high reflectance of solar radiation (see Section 2.3.1) while others consist of fine dark sediments with low reflectance (Milne and O'Neall 1990).

A cloud-free, radiometrically corrected (McMillin and Crosby 1984) AVHRR image of eastern Australia (3/9/96) was acquired from CSIRO Marine Laboratories in Hobart. These data are geometrically accurate to within one pixel in coastal regions of Australia but can have errors of up to three pixels in inland regions (McVicar and Mashford 1993). The image was corrected for geometric error by warping it to 20 ground control points derived from 1:250,000 topographic maps within or adjacent to the test area. The location of water bodies and other surfaces were observed from an aircraft on 9/9/96 and their location and extent mapped onto 1:250000 topographic maps based on direct observation and the use of a Global Positioning System (GPS).

2.2 Preliminary work

Preliminary work where direct observations of wetland areas on the Paroo River floodplain using light planes and an airborne video system were compared with AVHRR and showed that all AVHRR bands contribute to the accurate discrimination of water from non-water surfaces in the arid zone of Australia. Methodologies that use a single AVHRR band to discriminate between water and non-water surfaces in arid environments (Harris and Mason 1989; Harris 1994; Verdin 1996) cannot be applied to varied water surfaces over large geographic areas. NDVI produced results no worse than classifications using linear combinations of bands but with reduced probability of correct classification of turbid waters. This suggested a multispectral approach to classifying water bodies but conventional statistical classifiers, eg nearest neighbour or Mahalanobis distance classifiers, were clearly inadequate when applied to a large geographic area.

Many water bodies in the test area were small relative to the resolution of the AVHRR data (ie < 20 pixels in total area) and widely dispersed in a cluttered background. Small targets embedded in a range of backgrounds can be difficult to detect using conventional statistical classifiers (Harsanyi and Chang 1994; Chen and Reed 1987), even when the signature of the target is completely known (Chen and Reed 1987). Furthermore, statistical classifiers do not differentiate between spectral signatures in mixed pixels (Harsanyi and Chang 1994) and an alternative methodology was developed using matched filtering (Research Systems, Inc. 1996).

2.3 Classification of surface waters

2.3.1 Matched filtering

Matched filtering is a ‘pixel unmixing’ algorithm which uses the spectral signature of a target to produce a linear transformation that enhances features similar to selected target pixels and suppresses non-target features (Chen and Reed 1987; Stocker, Reed and Yu 1990; Yu and Reed 1993; Harsanyi and Chang 1994). The resultant image has a distribution of digital values with zero mean and minimum variance, where target matches score unity and pixels with negative values contain none of the target feature. Pixels that partially match the target return a value between zero and one. These digital values can be related directly to proportion of the target in each pixel and can therefore be used to estimate area. The matched filtering routine in the ENVI software package was used to detect water surfaces and estimate their area in this study.

Matched filtering requires specification of the properties of the target in multidimensional spectral space. The number of dimensions correspond to the number of bands in the analysis. These properties can be specified from spectral libraries or derived from target pixels in the image, in this case water bodies. It is usual to derive the spectral properties from pixels whose spectral signature is only that of the target of interest. These pure pixels are the greatest distance in multidimensional spectral space from the background and are called endmembers. In this study the target of interest, water, has a range of spectral properties and specification of a pure endmember is not possible. In addition, turbid water cannot readily be separated from clear water in multidimensional spectral space using AVHRR data. As a result not all pure water pixels will return a value of one and not all pixels with positive values contain water. In these circumstances a threshold must be selected to define the boundary between water and the background and all pixels greater than the threshold within the perimeter of a water body then defined as being water.

Selection of endmembers and bands for analysis using matched filtering

A cloud-free, radiometrically corrected (McMillin and Crosby 1984) image of the test area from 17/4/97 was analysed in conjunction with aerial survey data from the same date. The AVHRR data were geometrically corrected by warping the image to ~ 35 ground control points located in the test area and elsewhere in eastern Australia.

Known clear (Lake Wyara) and turbid (Lakes Numalla and Menindee) water bodies (Fig 2.1), were used to select clear, turbid and combined turbid/clear water endmembers. The robustness of the classification with all bands in the analysis was tested for these endmember collections by examining the output of the matched filtering for known water and non-water surfaces (Table 2.1).

The use of clear water endmembers with all AVHRR bands in the analysis resulted in areas of turbid water being overmatched, ie having values > 1. This overmatching resulted from the inclusion of band 1 (red) in the analysis. At these wavelengths, turbid waters had much higher radiance values than clear water (Fig 2.3) and the matched filtering procedure showed turbid water to be more different to the background than clear water. That is, clear water is not a true endmember for all water surfaces in multidimensional spectral space with all AVHRR bands in the analysis. In addition, areas of vegetation and highly radiant surfaces, such as dry salt and bare rock, returned relatively high values (0.25 - 0.40), using a clear water endmember collection. These values are similar to values returned by mixed land/water pixels.

Table 2.1 *Typical results of matched filtering using clear water, turbid water and combined endmembers for water and non-water features. Value represents proportional match to endmember collection.*

Surface feature	clear water endmembers		turbid water endmembers	combined endmembers
	all bands	minus band 1	all bands	all bands
clear water (L. Wyara)	1.05	1.09	0.48	0.53
Turbid water (L. Numalla)	1.19	0.87	1.00	1.06
Shallow overland flows (Paroo)	0.78	0.81	0.38	0.41
dry salt lake (Salt Lake)	0.24	-ve*	0.55	0.57
dry salt pan (unnamed)	0.37	0.17	0.45	0.48
dry lake bed (L. Torrens)	0.03	-ve	0.31	0.32
non-wooded land	-ve	0.0	-ve	-ve
rock formation (Flinders Range)	0.47	0.63	0.05	0.07
Mallee vegetation	0.25	0.38	-ve	-ve
semi-arid woodland	0.31	0.42	0.01	0.02

* -ve indicates negative value

The use of turbid water endmembers, with all bands in the analysis, increased the separation between most land and water surfaces but returned similar values (~ 0.5) for known clear water pixels and salt affected surfaces (Table 2.1). These pixels could also be confused with mixed water/land pixels. Thus there is no true endmember collection for all water surfaces in multidimensional spectral space and the results of the matched filtering procedure do not give a true estimate of the proportion of water in all pixels. A combined clear and turbid water endmember collection increased the separation of water from non-water surfaces but also increased the values returned by salt surfaces. Nonetheless, as long as salt was excluded from the output the results of matched filtering procedure could be used to estimate the location of the boundary between land and water.

The combined endmember collection from the ground-truthed image of 17/4/98, and the spectral signature for water derived from that endmember collection, was used for the all subsequent analyses of AVHRR images.

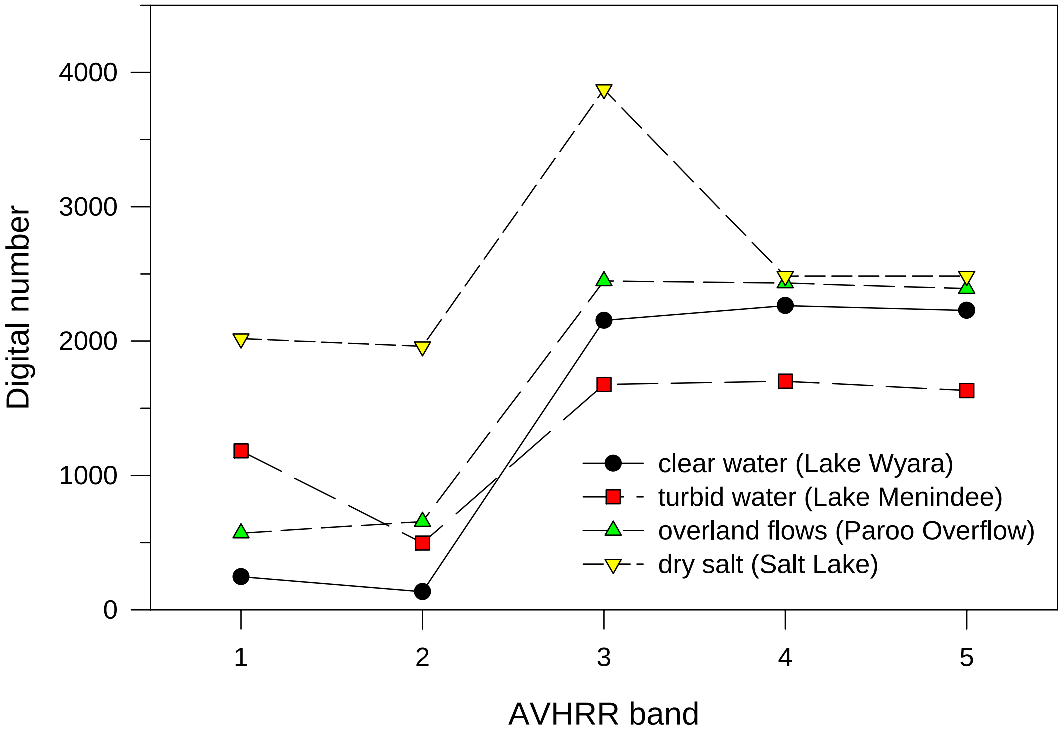


Figure 2.3 *Typical spectral response on 17th April 1997 of water and saline surfaces in arid regions of western New South Wales.*

Excluding salt affected surfaces from the matched filter result

Some salt crusted surfaces are spectrally similar to water bodies (Fig 2.4*a*). While crusted dry salt surfaces are spectrally different from most other surfaces due to their high reflectance in the visible (band 1) and near infrared (band 2) (Everitt *et al* 1988), the spectral signatures of damp salt surfaces are highly variable (Csillag, Pasztor and Biehl 1993; Verma *et al* 1994; Rao *et al.* 1995; Metternicht and Zinck 1997). Matched filtering does not discriminate between some salt surfaces and water (Fig. 2.4*b*).

In daylight AVHRR images a synthetic band, band 3 (3.55 - 3.93μm) subtracted from band 4 (10.3-11.3μm), can discriminate between most water and land surfaces (Fig 2.4*c*, see Verdin 1996). In this synthetic band, water surfaces have the lowest reflectance (appear dark) and salt surfaces the highest. Typically, water surfaces in the synthetic band (Fig 2.4*c*) have negative values and dry salt surfaces have values greater than 1200. Damp salt and dry lakebed surfaces produced values greater than 500. These differences mean that the synthetic band can be applied as a salt mask over the results of matched filtering.

A binary salt mask image, 0 to salt areas (above a threshold) and 1 to remaining areas, was multiplied to the output of the matched filtering in a GIS. The threshold was 382 in the image of 17/4/97. This threshold does not remain constant among images due to differences in the spectral response of most surfaces in the thermal infrared (bands 4 and 5) through the day and across seasons.

For consistency among images, the threshold value was 0.1 of the value corresponding to the 95th percentile in band 4 of all pixels in a large geographic area (approx. 600,000km^2). This area included Lake Eyre (approx 9,000km^2) and its surrounds to ensure that this area included surfaces of high reflectance such as salt crusts. It is assumed that the spectral relativities in band 4 of a range of surfaces are maintained among images. Threshold values were 180-250 in winter and 400-500 in summer. Although pure water pixels had negative values, selecting a threshold value lower than 10% risked excluding mixed pixels in some images.

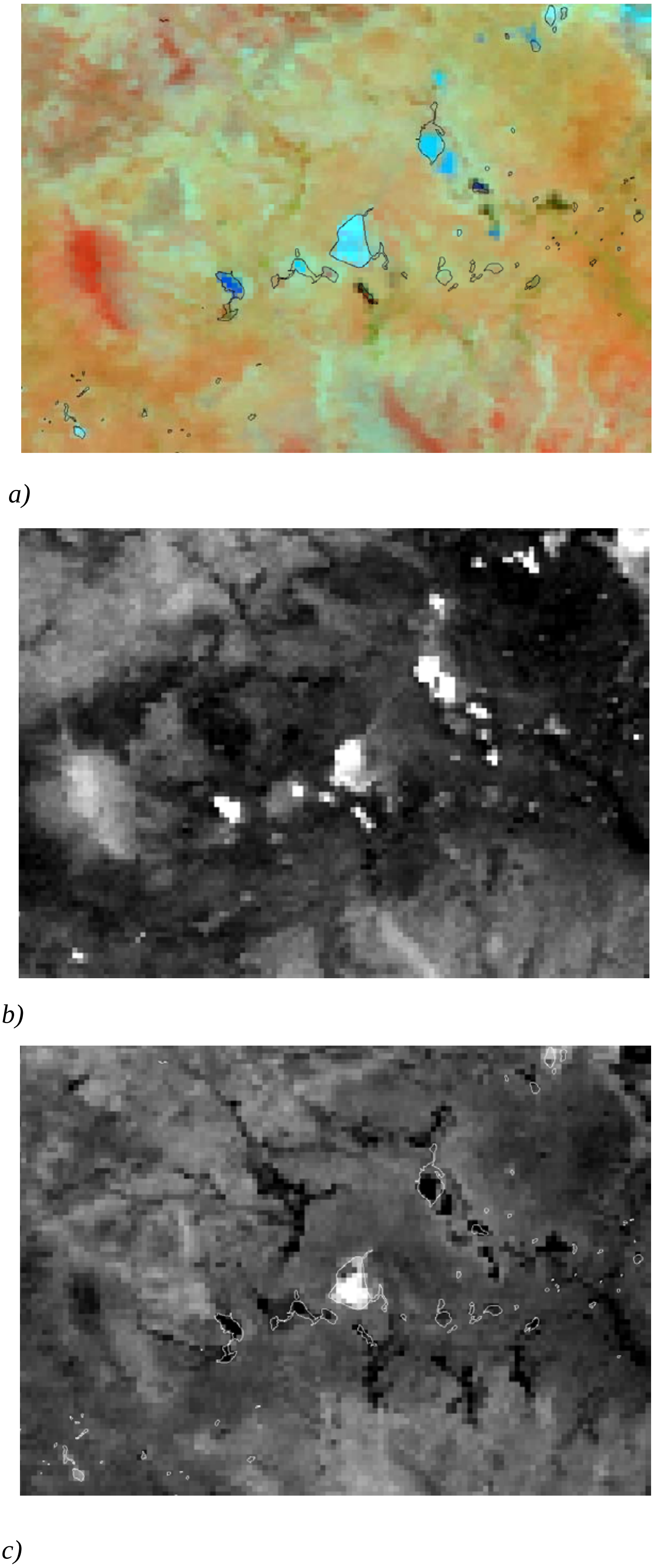


Figure 2.4 *Three views of lakes in northwestern New South Wales showing spectral response of water and salt surfaces:*

a) false colour composite image using AVHRR bands 4, 2, and 1; b) component image produced by the matched filtering procedure; c) result of subtracting band 4 from band 3 to highlight salt and non-water surfaces. The large lake (blue) in the centre of a) is a salt surface (note similarity in spectral signature to surrounding lakes).

Light areas in b) are water or salt surfaces.
Bright area in c) is area affected by salt. Terrestrial habitats are predominantly sparsely vegetated desert loam and sandy soils. Lines are lake boundaries as mapped by AUSLIG.

Accuracy of water detection

In this study different endmembers for turbid and clear water confounded the results of matched filtering. Since the accuracy of the matched filtering classification is dependent on the size of the signal-to-noise ratio (Harsanyi and Chang 1994), the estimates of water area in mixed pixels would vary with turbidity. Therefore, the reliability of the estimates diminishes as the proportion of water in each pixel decreases and continuous water surfaces may return values < 1 if the water is less turbid than the pixels used in the endmember collection. The lower limit for accurately detecting water in each pixel varied across the study area. In the vicinity of water bodies used in the endmember collection, the lower threshold for the reliable detection of water was 0.15 - 0.20 (Fig 2.5). Elsewhere, the distinction between water and non-water surfaces was less clear and a higher threshold was necessary.

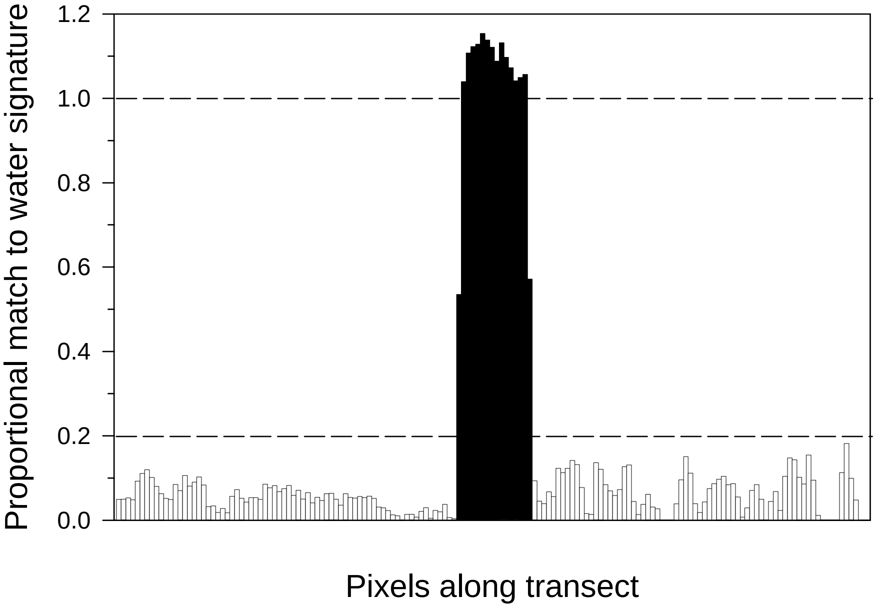


***Figure 2.5** Transect across Lake Menindee (solid bars) and surrounding terrestrial habitats (open bars) showing proportional match to water signature produced by matched filtering.*

The results of the matched filtering and salt exclusion were compared to the state of 115 lakes in western NSW and southern Queensland determined from an aerial survey conducted on the same day as the image date (17/4/97) and telephone surveys of pastoralists on whose properties the lakes were located. Error matrices (Congalton 1991) were derived for the lake survey using 0.2 and 0.3 as the lower threshold for acceptance of a positive (Table 2.2).

While the producer's accuracy (Congalton 1991) for wet lakes was the same (98%) using either threshold, the user's accuracy was considerably higher (98% cf 91%) using 0.3. All four dry lakes misclassified at the 0.2 threshold had predominantly dark, heavy grey clay soils on their bed. The dry lake misclassified at the 0.30 threshold contained surface water 6 - 8 weeks prior to the image date and it is unknown precisely when it dried out. There is no obvious explanation as to why the wet lake was misclassified at the 0.3 threshold.

Table 2.2 *Error matrix for status of 115 lakes (WL = wet lakes, DL = dry lakes, SWL = subpixel wet lakes and SDL = subpixel dry lakes) in western NSW using matched filtering with lower threshold of 0.3 and 0.2 (in parentheses).*

	WL	DL	SWL	SDL	Total
WL	42 (42)	1 (4)	-	-	43 (46)
DL	1 (1)	48 (45)	-	-	49 (46)
SWL	-	-	0 (3)	0 (0)	0 (3)
SDL	-	-	12 (9)	11 (11)	23 (20)
Total	43	49	12	11	115

Producer's Accuracy	User's Accuracy
WL = 42/43 = 98% (98%)	WL = 42/43 = 98% (91%)
DL = 48/49 = 98% (92%)	DL = 49/49 = 98% (98%)
SWL = 0/12 = 0% (25%)	SWL = 0/0 = 0% (100%)
SDL = 11/11 = 100 % (100%)	SDL = 11/23 = 48% (52%)

Overall Accuracy = 101/115 = 88% (88%)

2.3.2 *Sources of data and data quality*

AVHRR data with consistent radiometric processing and complete coverage continental are not available for Australia. There are two major sources of archived AVHRR data in Australia, CSIRO Marine Laboratories in Hobart and the Department of Land Administration (DOLA) in Perth. Each has different geographic coverage (Fig 2.6). Both archives have data from 1981 onwards but daily coverage does not exist for dates prior to September 1986. The data from DOLA are not radiometrically or atmospherically corrected and processing strips off the sensor calibration data for bands 3, 4 and 5 (Ron Craig, DOLA, *pers comm*) making it impossible to determine thermal and mid-infrared radiance. This limits use of the DOLA data to classification methodologies that use only bands 1 and 2, such as NDVI.

Band 3 in AVHRR data often contains periodic noise (Dudhia 1989; Warren 1989) or the data are saturated due to spectral flux from a pixel exceeding an upper limit because of high surface temperature (Harris *et al* 1995). This can occur at ground temperatures as low as 49° C (Robinson 1991), which is readily exceeded in the arid zone of Australia during summer (Hobbs 1997). While the periodic noise can be corrected for (Warren 1989), non-zero saturation of band 3 precludes the use of this band in multispectral analyses.

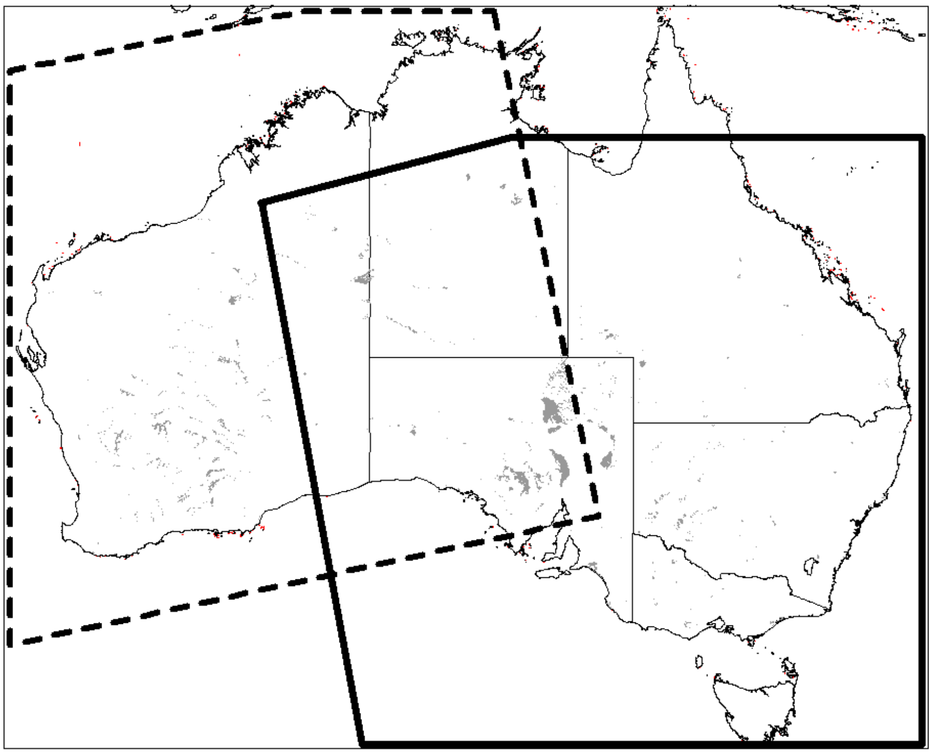


Figure 2.6 *Typical geographic coverage of data sourced from CSIRO Marine Laboratories in Hobart (solid line) and DOLA in Perth (broken line). CSIRO Marine Laboratories were occasionally able to supply data for the southern half of Western Australia.*

Other sources of error are due to the large geographic coverage of the AVHRR instrument on the NOAA satellites. The path width is large (~ 2600km) and afternoon passes in the data sourced from CSIRO span the Australian continent and two or three time zones. Surface temperatures in the SE of an image can be significantly lower than surface temperatures in the NW. As the contrast between a target and its background can be more important for detecting a target than the targets' energy flux (Robinson 1991) water bodies with similar properties may appear spectrally different depending on geographic location.

2.3.3 *Normalised Difference Vegetation Indices (NDVI)*

Negative NDVI (see section 2.2.2) had to be used as a proxy for water distribution for the western part of the continent using data sourced from DOLA. These data were not atmospherically corrected (see section 2.2).

There are strategies to deal with the problem of atmospheric attenuation of remotely sensed data. Firstly, it can be ignored (eg Rasmussen 1997). Most remote sensing investigations of land cover change have ignored atmospheric effects, particularly when the targets of interest have a strong and different signal relative to one another (Jensen 1996). Secondly, an index (eg NDVI) that employs a ratio of bands minimises the effects of atmospheric attenuation. Viewing and illumination geometry or atmospheric factors still affect such indices (Price 1987; Holben, Kaufman and Kendall 1990) but not to the same degree as absolute measures because the relativities between bands are generally maintained. Finally, the attenuation can be corrected (see Price 1987; Singh and Saull 1988; Holben, Kaufman and Kendall 1990; Goward *et al* 1991; Gutman 1991; Kaufman and Holben 1993; Hobbs 1997, and references therein). For this study atmospheric attenuation was ignored when the data were used to generate NDVI.

Table 2.3 *Error matrix for status of 115 lakes (WL = wet lakes, DL = dry lakes, SWL = subpixel wet lakes and SDL = subpixel dry lakes) in western NSW using NDVI.*

	WL	DL	SWL	SDL	Total
WL	33	0	-	-	33
DL	10	49	-	-	59
SWL	-	-	0	0	0
SDL	-	-	12	11	23
Total	43	49	12	11	115

Producer's Accuracy
WL = 33/43 = 77%
DL = 49/49 = 100%
SWL = 0/12 = 0%
SDL = 12/12 = 100 %
Overall Accuracy = 93/115 = 81%

User's Accuracy
WL = 33/33 = 100%
DL = 49/59 = 83%
SWL = 0/0 = 0%
SDL = 11/23 = 48%

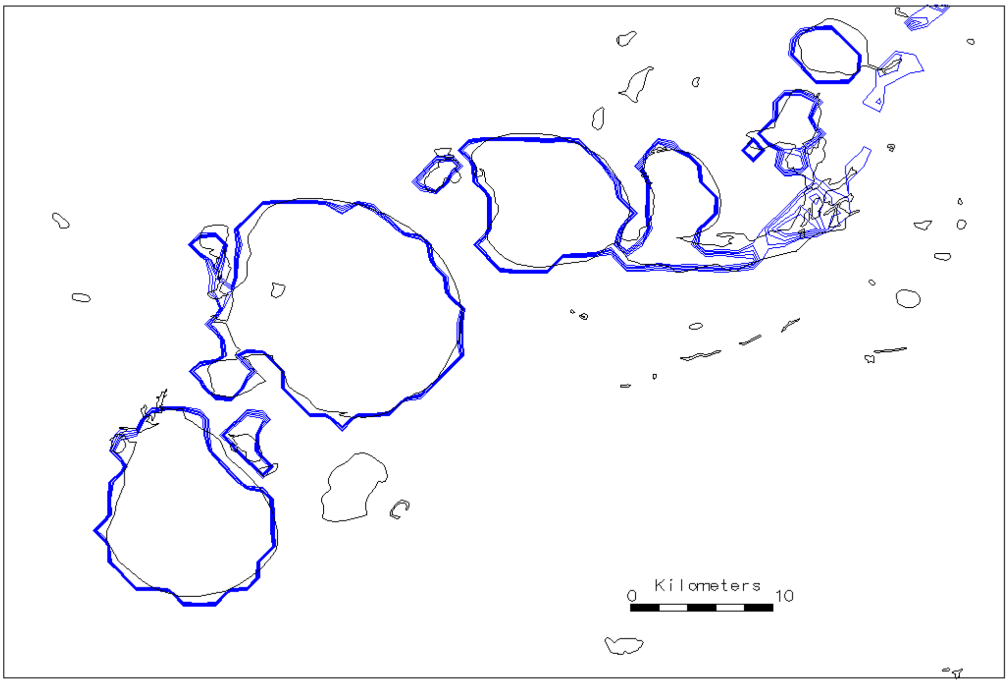
Using negative NDVI to detect water in the same 115 lakes in the test area corrected the anomaly of a dry lake classified as wet (Table 2.3) but the producer's accuracy was considerably lower (77% cf 98%) for lakes containing water. The most likely explanation is the relative insensitivity of NDVI to the water component of a mixed land/water pixel with a significant land component, resulting in the exclusion from the analysis of smaller water bodies or those with convoluted boundaries. Apart from the Bulloo Overflow, all water bodies that were misclassified using NDVI were less than 500ha.

2.4 Approximation of the land/water boundary and area estimation

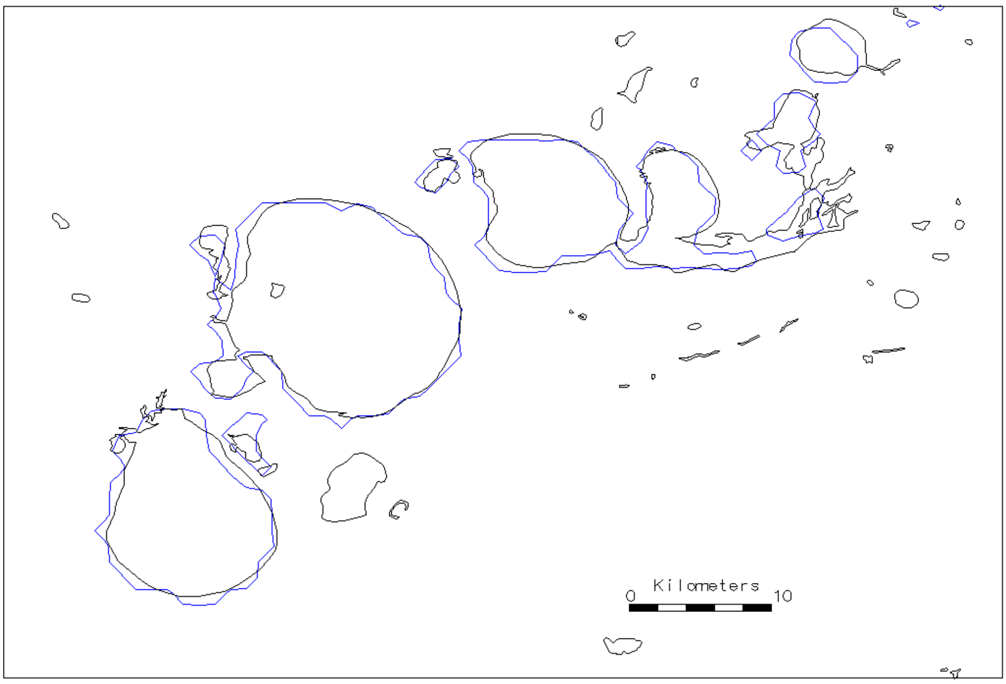
2.4.1 Vectorisation of matched filtering result

The output of matched filtering is the same pixel, or raster, format as the original satellite data. Area estimation of water bodies using raster data is restricted to the summation of pixels classified as water and conversion to units of area based on the resolution of the data. Using this method pixels can only be added to or excluded from the summation, resulting in large errors if the classification of the water body contains a large number of mixed pixels. Several authors have proposed methods based on spectral properties for determining the proportion of a pixel that should be added to an area summation. For this project the local isoluminance contours (LIC) technique (Harris 1994) for estimating lake boundaries was too computationally demanding for large numbers of water bodies. Also, assumptions of spectral uniformity (Harris and Mason 1989) would be violated when applied to a large geographic area and Verdin's (1996) manual technique would be too time consuming, so another technique was sought.

The digital values of the component image produced by matched filtering provide a ready measure of percentage surface water in each pixel (see section 2.3.1). These data were imported into a GIS and the results contoured to produce concentric polygons representing no water (0.0) and all water (1.0) (Fig 2.7*a*). Based on the capacity of the matched filtering to discriminate between water and non-water surfaces, the 0.3 contour was used to approximate the shape and area of the water bodies (Fig 2.7*b*).



a)



b)

***Figure 2.7** Contouring (blue lines) of component image produces concentric shapes representing the gradient between 0 (no water) and 1.0 (all water); a) all contours, b) selected contour (0.30) for area estimation. Dark lines are lake boundaries as mapped by AUSLIG.*

Vectorisation of the matched filtering result produces a reasonable approximation of the land/water boundary (Fig 2.7*b*). Results were compared to other data derived from aerial survey and satellite data at a higher resolution. As the nature and extent of these data differ, the estimates of accuracy can only be indicative but they can show if water elements are adequately described.

On the day of the aerial survey, 17th April 1997, the Paroo River was in flood (Fig 2.8*a*) creating a mosaic of water surfaces made up of shallow overland flows and fresh inflows into numerous lakes. A portion of the test area (10,630km^2) was surveyed systematically from the air and the extent of surface waters mapped visually onto 1:250000 topographic maps. Total estimated water area for overland flows and lakes from the matched filtering procedure (Fig 2.10*c*) were compared to mapped distribution data (Fig 2.8*b*).

Total mapped water area from 1:250,000 topographic maps was about 681km^2, or 6.41% of the survey area. Total estimated water area from AVHRR data was 347km^2 or 51% of mapped water area. Accuracy increased to 75% if overland flows were excluded and only water residing in lakes used in the calculation. These are probably underestimates of the accuracy of the matched filtering procedure. The only means of including areas subject to inundation in the total was to assume that any element with water in it was filled to capacity, overestimating mapped water area.

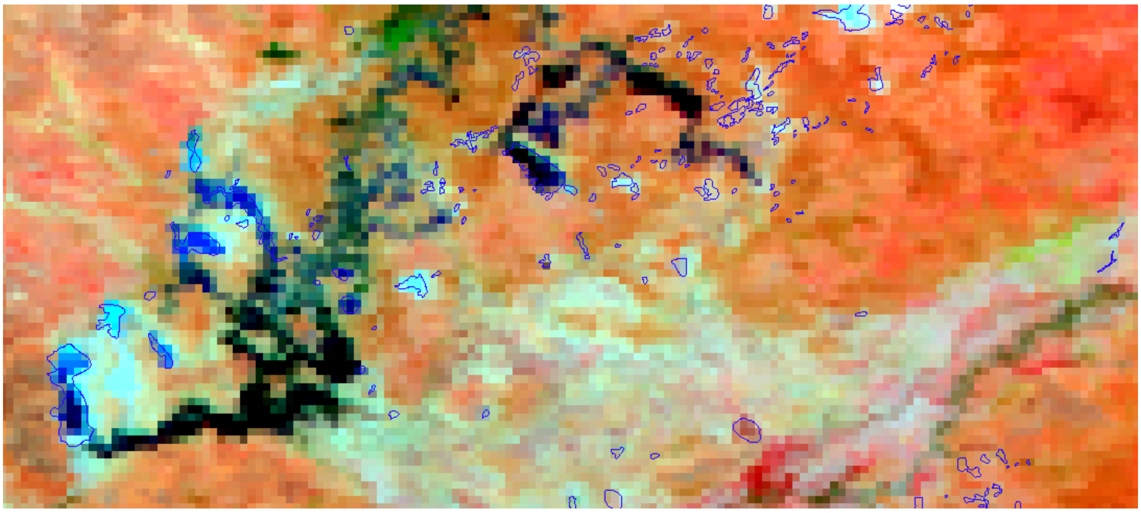


Figure 2.8 a) *False colour composite AVHRR image of Paroo Overflow on 17/4/97. Dark blue lines in a), are mapped lakes (AUSLIG 1:250000)*

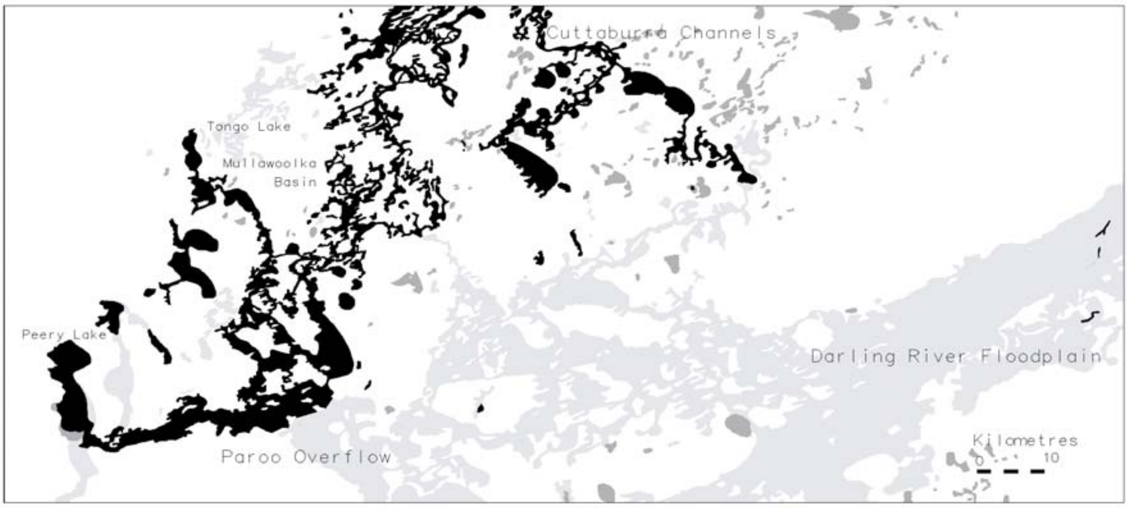


Figure 2.8 b) *Mapped distribution of water (black) determined from an aerial survey. Dark grey areas in b) and c) are mapped lakes (AUSLIG 1:250000) and light grey is areas subject to inundation.*

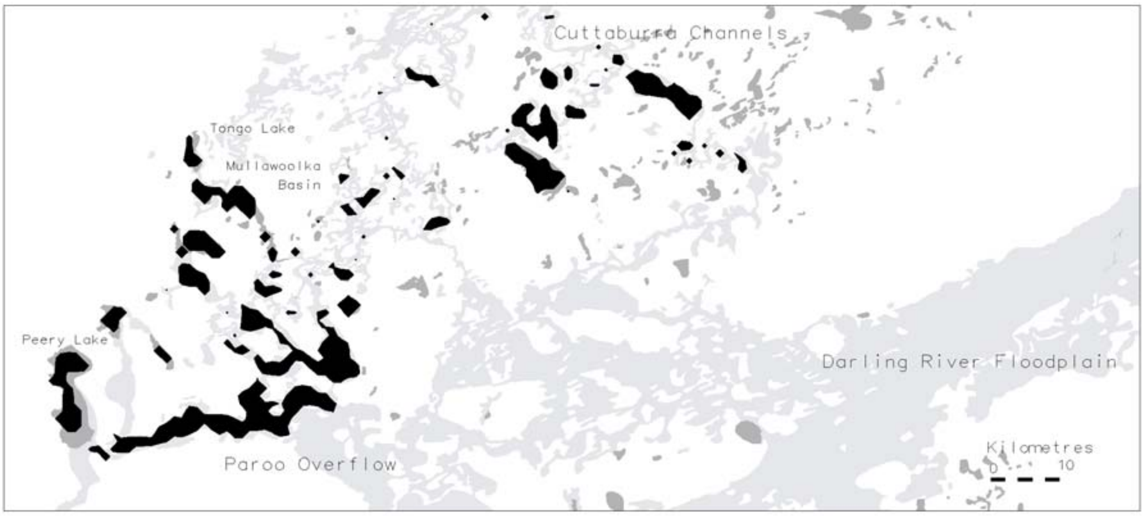


Figure 2.8 c) *Result of matched filtering for detection of water (black) using 0.2 threshold.*

During the aerial survey 12 water bodies in the test area were full. For these lakes the vectorised result was compared to the mapped shoreline determined from Australian Surveying & Land Information Group (AUSLIG) 1:250,000 digital map data for water bodies (Table 2.4).

Table 2.4 *Estimated surface area of lakes full to their natural shoreline on survey date using AVHRR data and mapped area determined from AUSLIG 1:250,000 data.*

Lake	Mapped area (ha)	Estimated area [a] (ha)	Shape factor [b]	Difference
Menindee	16,313	17,941	0.73	+ 10%
Barren Box	3,201	3,433	0.69	+ 7%
Yamarammie	2,505	1,769	0.46	- 29%
Mullawoolka Basin	1,740	1,857	0.19	+ 7%
Yanga	1,349	1,274	0.31	- 6%
Poloko	931	537	0.50	- 42%
Tongo	501	337	0.20	- 33%
Woolcunda	489	7	0.13	- 98%
Gilpoko	429	175	0.39	- 69%
Green	404	357	0.85	- 12%
Blue	234	207	0.68	- 12%
Barnato	220	47	0.35	- 79%

[a] Estimated surface area of water bodies using matched filtering
[b] Shape factor (sqrt(min. radius/max. radius)) describes departure from circle (1.0).

It is clear that the accuracy of the area estimates determined from the AVHRR data are dependent on size and shape of the water body (Table 2.4). Area estimates for irregularly shaped lakes (eg Lake Woolcunda) are poorer than similar sized features that are more circular (eg Green Lake). Area estimates for large, regularly shaped lakes (eg Barren Box Swamp, Lake Yanga) are within 10% of their actual size. The accuracy of the area estimates for small water bodies is poorer than that reported by Verdin (1996) who used prior knowledge of the size and location of water features to judge which edge pixels to include in area estimates.

Analysis of Landsat Thematic Mapper data

The gross underestimation of surface area of Lakes Woolcunda and Barnato suggests that some water bodies, larger than the 120ha resolution of the data, were not detected. To determine the extent to which small water bodies were not detected, Landsat Thematic Mapper (TM) data were analysed for an area of the Paroo Overflow that had numerous small water bodies. Landsat TM data has 7 spectral bands and a resolution of 30m (see Campbell 1996). Landsat TM data were available for 18/4/97, one day after the AVHRR were collected.

The accepted methodology for detecting water in TM data is to use a single value in band 5 (mid infrared) as a threshold, all pixels with values less than this threshold are classified as water (see Johnston and Barson 1993). This method over estimated water area for 18/4/97 by including dry pans and areas with salt crusts. Therefore, water area was estimated using the first two bands of minimum noise fraction (MNF) transformations (see Green *et al* 1988; Boardman and Kruse 1994) of Landsat TM bands 4, 5 and 6 in the matched filtering procedure (see section 2.3.1) and the component image vectorised using the 0.8 contour (see previous sub-section).

The analysis of TM data estimated water boundaries with a high degree of accuracy, including small wetlands and those with long, sinuous shapes (Fig 2.9*ab*). The analysis of AVHRR data for the same region underestimated water area by 61% (Fig 2.9*c*, Table 2.5). The analysis of AVHRR data was unable to detect long, sinuous water bodies except where the channel broadened. Some small (< 120ha) and/or irregularly shaped wetlands were not detected (Fig 2.10*c*, Table 2.5).

Table 2.5 *Measured water areas on Paroo Overflow (18th September 1997) using Landsat TM and AVHRR data. Number of water bodies in brackets.*

Data type	Total water area (ha)	Small water bodies (ha)
Landsat TM	45,095 (765)	4089 (23)
AVHRR	17,403 (43)	885 (25)

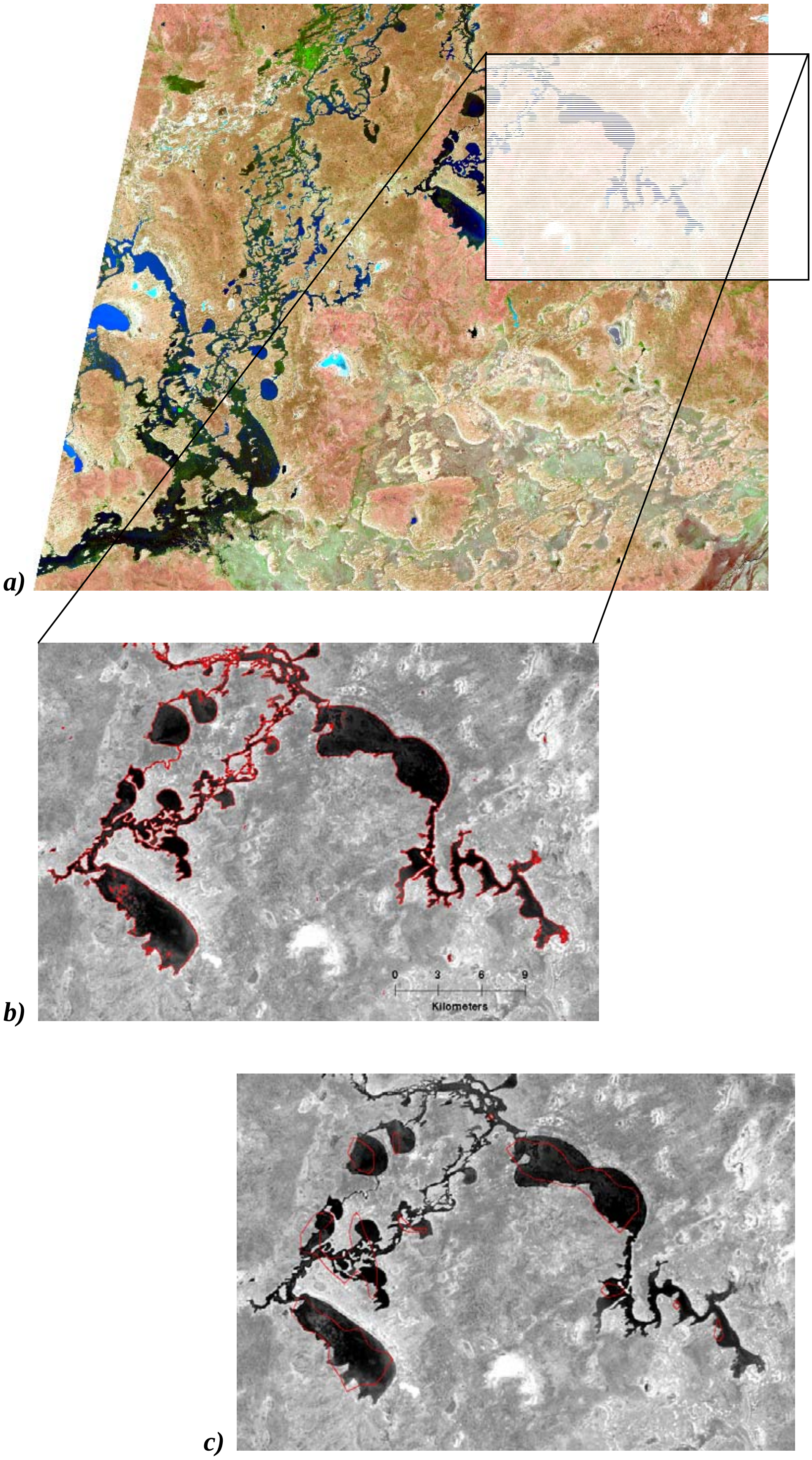


Figure 2.9 *Floodwaters on Paroo Overflow: (a) Landsat TM image (18th September 1997), (b) section of TM image overlaid with water boundary (red line) and (c) the same section overlaid water boundary derived from AVHRR data (17th September 1997).*

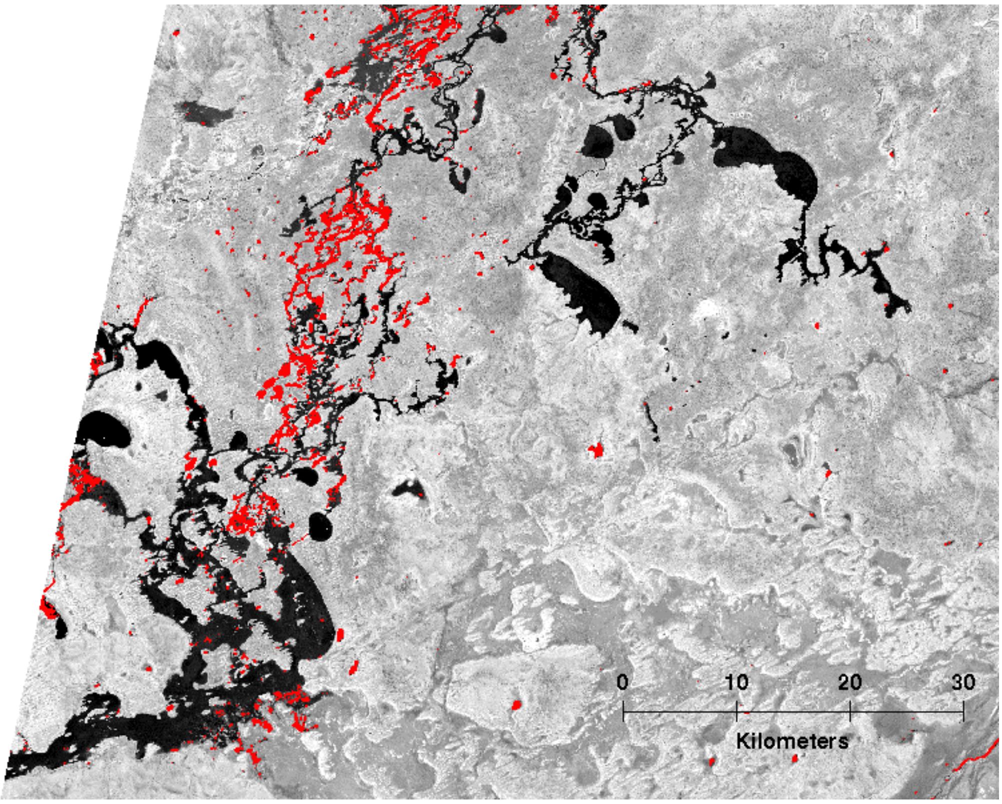


Figure 2.10 *Water bodies on the Paroo Overflow smaller than 120 ha (red polygons) as determined by matched filtering of Landsat TM data (18th September 1997). Dark areas are floodwater and damp surfaces.*

2.4.2 *Matched filtering and NDVI results for data derived from different sources*

Comparison of results of area estimation using matched filtering and NDVI on data sourced from CSIRO Marine Laboratories and DOLA, respectively, show that estimates of water area are similar (Table 2.6). The data are separated by two weeks and therefore are not a precise comparison. However, transmission times for floodwaters in the catchment of Cooper Creek are long (Knighton and Nanson 1994*a*) and the differences shown here are more likely to result from differences between the techniques than changes in the distribution of floodwaters.

While the boundary of water in Lake Eyre is similar using both techniques, the number and size of water bodies detected on the Cooper Creek floodplain differ markedly (Figure 2.11). Given the reliability of the matched filtering procedure for detecting water (Table 2.2) and shallow overland flows (Fig 2.8), NDVI probably cannot distinguish between water and wet soils (see Fleming 1993) and fails to detect the smaller water bodies.

Table 2.6 *Comparison of area estimates for water surfaces depicted in Figure 2.14.*

Date	Method	Total water (ha)	No of water features
28/8/89	NDVI	647,575	58
12/9/89	matched filtering	662,089	216

2.5 Discussion

The methods presented here can be used to reliably detect permanent and temporary water bodies with a variety of spectral signatures and successfully exclude saline surfaces from the result. Although the ability to detect and measure small water bodies is limited using AVHRR data, it is useful for mapping the distribution of surface water and monitoring inundation events across large geographic areas in arid Australia (Fig 2.12, see next section of report). The poor results in estimating the area of floodwater on the Paroo Overflow (Table 2.5) shows that in some circumstances errors in area estimation are large. However, this is an extreme case using the methods described here. Floods on the Paroo Overflow are largely confined to channels much narrower than the 1km resolution of the AVHRR data (Fig 2.8) and cannot be detected. However, the method more accurately estimates surface area of lakes and broad overland flows (Fig 2.8). For the purposes of mapping or monitoring changes in wetland area in the arid zone at regional or landscape scales the low accuracy in some geographic locations is not a major concern (see next section of report). While less reliable than matched filtering, NDVI is a useful proxy for determining areas of water.

AVHRR data are of low resolution compared to other satellite data, but have methodological and cost advantages over higher resolution data for understanding changes in the distribution of water in the landscape. It is particularly suited to understanding the hydrology of wetlands in Australia’s arid zone due to the large geographic coverage in each image and the daily coverage. Significant changes in wetland distribution can occur over large areas in a few days, as occurred in March 1989 (Fig 2.12*b*). The cost of monitoring these changes with Landsat or SPOT data would be prohibitive.

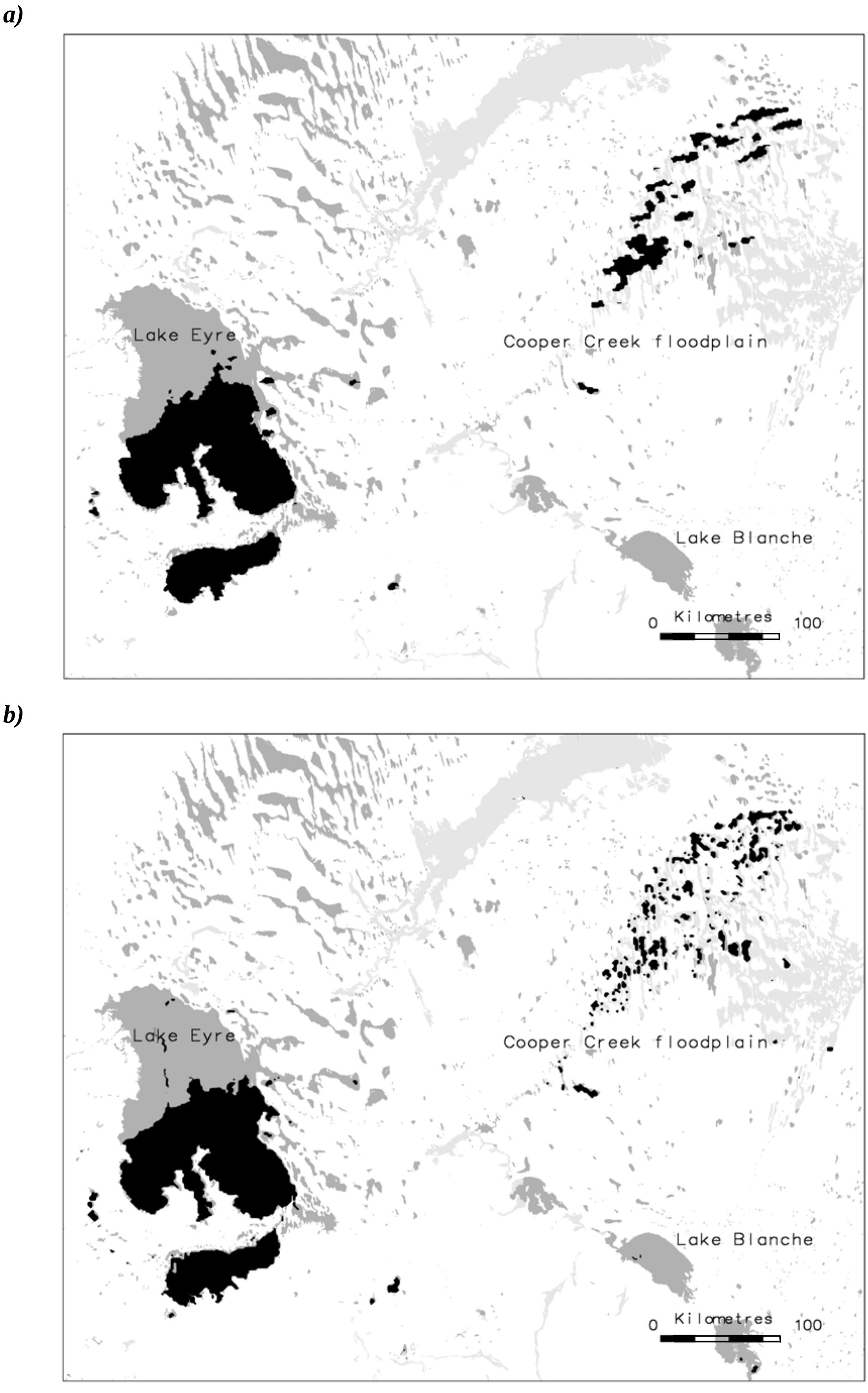
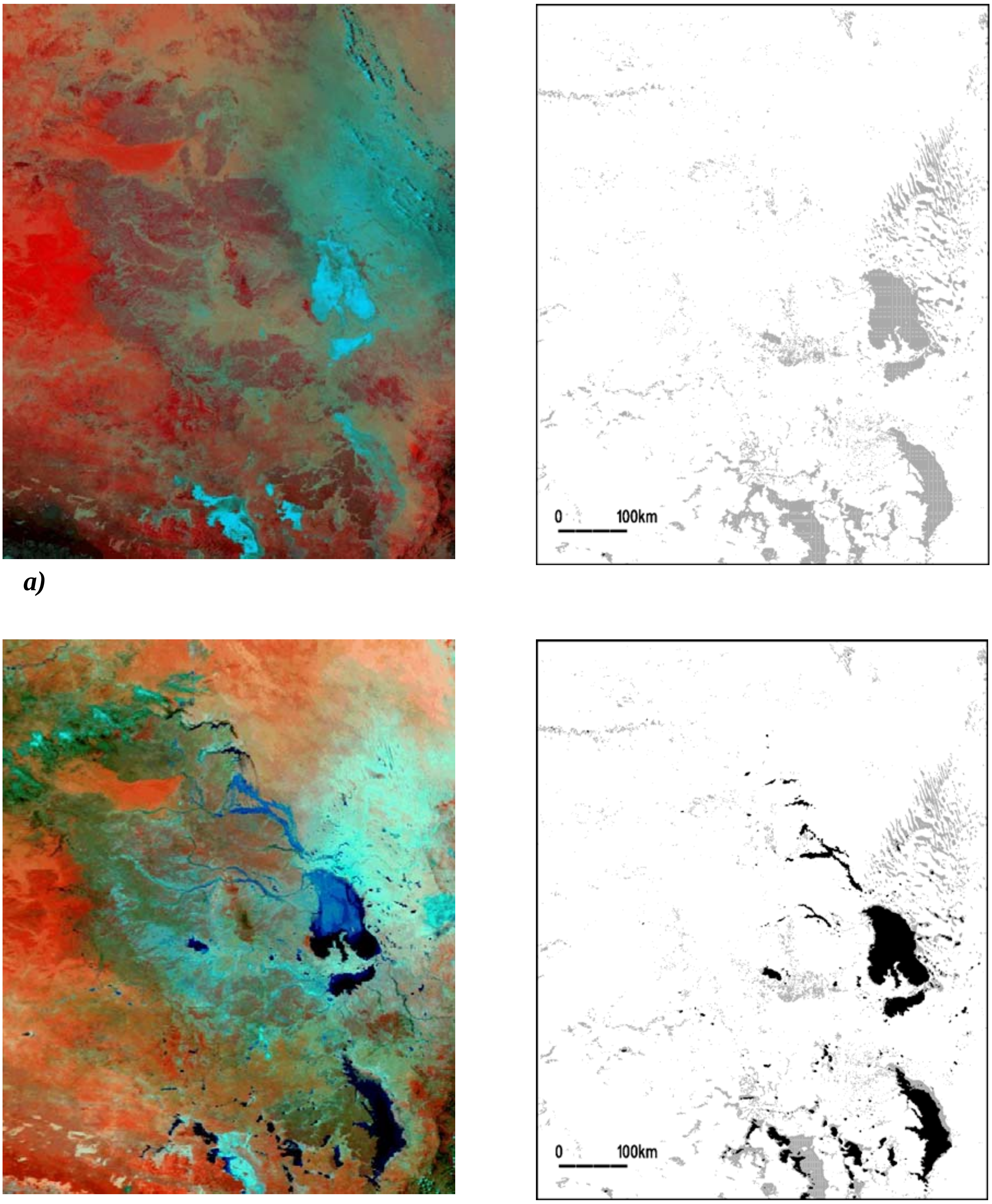


Figure 2.11 *Comparison of results using (a) NDVI (28/8/89) and (b) matched filtering (12/9/89) using data sourced from CSIRO Marine Laboratories and DOLA, respectively.*



a)

b)

***Figure 2.12** False colour composite images of Lake Eyre Basin in (a) March 1988 and (b) March 1989 and the mapped water distribution (black) from the same images (light grey tones are lake features as mapped by AUSLIG at 1:250,000).*