Mapping and Spatio-Temporal Analysis of Flooded and Inundated Areas in the Lower Balonne Floodplain, Queensland, Australia

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Abstract: Water storage infrastructure developments and other land use changes may impact the extent of water flows and inundation in the floodplain. This may bring negative environmental effects and conflicts between competing users of water. In a case study of the Lower Balonne floodplain in Queensland, Australia, this project was conducted to quantify the changes on the spatial extent and patterns of flooded and inundated areas in a large, ephemeral floodplain river system. The study employed digital image processing techniques to produce inundation maps from the 1994 and 2004 flood events captured by Landsat 5 imagery. Using a landscape patterns analysis program (*Patch Analyst*) linked with a geographic information system (GIS), selected landscape metrics pertaining to patch size, shape, and connectivity were calculated and analysed. The results show not only the significant reduction (44,658 ha corresponding to 43% decrease) in the extent of the flooded and inundated areas, but also the changes on the spatial configuration of these patches. They became more fragmented and isolated, particularly in the lower region of the floodplain. This study concluded that the use of landscape metrics could be valuable for floodplain monitoring.

Key-Words: Flood, Spatial pattern and extent, Landscape metrics, Lower Balonne, Australia

1 Introduction

As world's driest inhabited continent, receiving on average only 455 mm of rainfall annually [1], Australia is facing enormous tasks to manage its water resources in a sustainable manner. One requirement in virtually all aspects of water resource management is the availability of up-to-date, accurate and reliable information. This is especially the case with flooding, with its potential to significantly impact on life and property.

Flooding has additional significance in areas such as the Lower Balonne area in Queensland, Australia, where periodic inundation of the floodplain is seen to have beneficial effects. In arid to semi-arid regions, the wetting of rangelands encourages the growth of pasture crops and the recovery of degraded grazing lands [2]. In addition, natural flooding creates suitable nest sites and foraging areas for waterbirds [3]. When infrastructure developments and other land use changes occurred that may impact the extent of flows and inundation in the floodplain, conflicts between competing users may arise. Therefore, the ability to map floods and to analyse their impacts is critical. This will help to develop appropriate management regimes to ensure equity of access to floodplain flows by both the environment and agricultural industries.

Changes to the extent of flooding can be affected by at least two factors. First are the changes to the landscape through the construction of infrastructure. This has implications on all floodplains where new or modified infrastructure (raising roads, new rail lines, bunding, etc.) has the potential to redirect, and also to concentrate flows often with unintended consequences. Secondly are changes due to the level of extraction (hydraulic impact) either by pumping of river flows into storages and by interception of overland flows (also into storage).

To progress efficient and effective management of riverine ecosystems, an understanding of their variability and complexity in space and time is necessary [4]. The last few decades saw an increasing number of studies on this front, realising that anthropogenic disturbances could affect these fragile ecosystems. While there has been many studies on mapping flood extent and spatial analysis using remotely sensed data (e.g. see review of [5]), research on quantifying and analysis of flood spatial patterns (configuration) has been rarely conducted. Knowledge of the physical distribution or spatial character of inundation areas in terms of patch size, shape, connectivity, etc., will provide a different set of, but complementary, information for water resource monitoring.

In landscape ecology, quantifying landscape structure and its change over time involves the use of statistical measures (also called ''metrics'' or ''indices'') that describe the landscape configuration and composition. Vegetation fragmentation studies and wildlife habitat research are often the subject of the use of these landscape indices. Resource managers increasingly require spatial and temporal information to make decisions about landscape patch size, the dispersal or aggregation of activities, edge densities and connectivity in the landscape [6]. The use of landscape metrics can therefore be extended to quantify flooded and inundated areas to help assist in monitoring efforts.

The objectives of this study were to:

- quantify the spatial extent and patterns of flooded and inundated areas using satellite imagery;
- analyse the changes on the spatial extent and patterns of flooded and inundated areas between two flood events; and
- gain insights on how landscape metrics and spatial pattern analysis tool could be used to analyse and monitor future flooding events.

2 Methods

2.1 Study Area

The study area covered the Lower Balonne floodplain, with a total area of approximately 357,900 ha (Figure 1). A part of the Condamine-Balonne catchment, the Balonne region is located in Queensland on the New South Wales border, some 500 kilometres from the east coast of Australia. The catchment lies within the semi-arid zone and experiences sub-tropical weather.

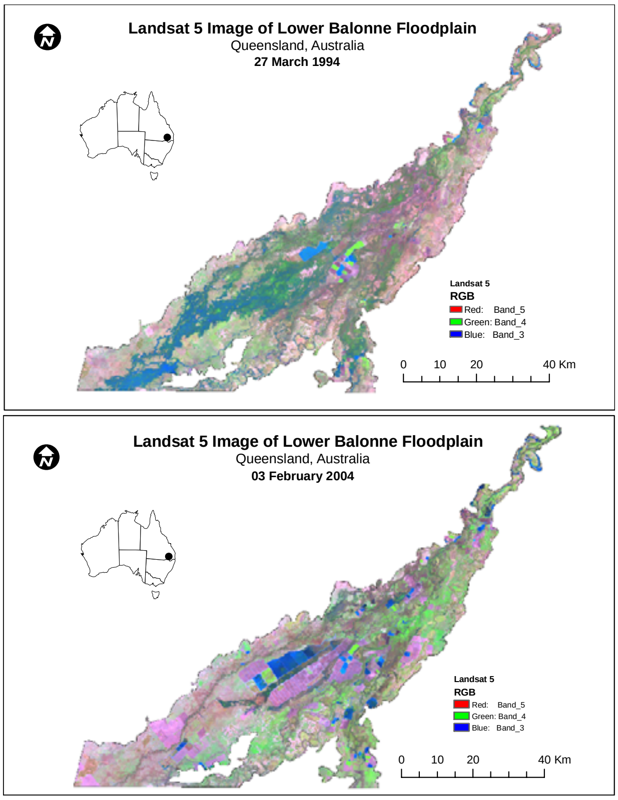

Figure 1. Landsat 5 image of the study area for 1994 and 2004. The bluish features correspond to flooded areas.

The Lower Balonne floodplain is composed of several channels, with the major ones include the Culgoa River, Narran River, Balandool River and Bokhara River. The flows in these ephemeral streams are highly variable, with flood events vary in size, duration and seasonality. This area of extensive alluvial plains is dominated by *coolibah* open-woodland or black box open-woodland and grassland ecosystems [7]. The soils are predominantly cracking clay soils (deep, brown and grey-brown) and duplex soils.

The towns of St George and Dirranbandi are the two main population centres in the region. The key industries principally consist of irrigated farming and sheep/cattle grazing. Significant development of water storage infrastructure to divert water from flood events in the Lower Balonne River System for irrigation of cotton and other crops has occurred in the last 20 years. Historically, floods in the system have had a beneficial effect by providing inundation to grazing lands. The total capacity of these private water storages is estimated to be 1.2 million megalitres. Sample photographs of major land use/cover features in the Lower Balonne are provided in Figure 2 below.

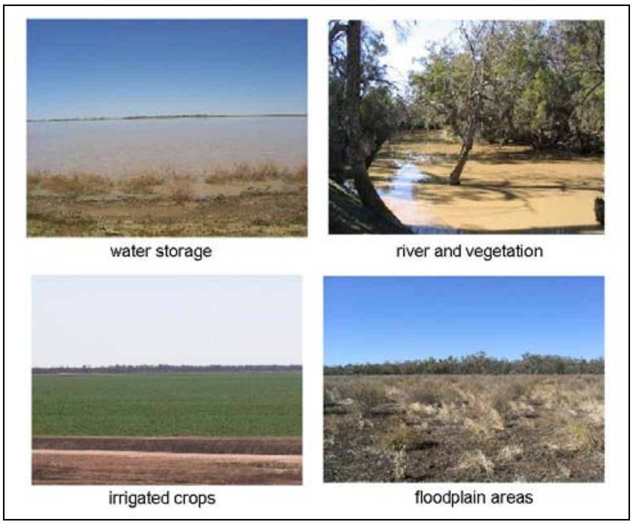

Figure 2. Sample photographs of major land use/cover features in the Lower Balonne floodplain.

2.2 Data Acquisition and Image Processing

The GIS database comprised of four primary data sets: (a) Landsat 5 satellite imagery (to map flooded and inundated areas), (b) floodplain extent map (to limit the study area), (c) digital elevation model (DEM) (to classify the area into three floodplain regions), and (d) water storage map. Other ancillary maps used to aid interpretation and analysis included aerial photographs, land systems and soils maps [7], topographic maps, and river/stream map. The selection of Landsat imagery in terms of acquisition dates presented a challenge.

Flood events in the Lower Balonne are infrequent and of varying intensity, but can be broadly categorised into low, medium and high events. In 2004, an event occurred which was classified as in the lower bound of medium events based on the flow of water past St George where a measurement point has been established for determining the characteristics of flood flows entering the Lower Balonne system. Medium events are considered important: it is in these events where the degree to which access to the water resource is most critical.

In terms of flood characteristics, the 1981 flood event was very close to the 2004 flood. However, the corresponding Landsat MSS imagery (with low radiometric and spatial resolutions) proved to be undesirable for comparison. Therefore, we opted for the comparison of the 1994 and 2004 events due the availability of suitable imagery, although there is some variance on flood characteristics. After assessment of various options, the two sets of Landsat 5 imagery captured on 27th March 1994 and 3rd February 2004 were selected. These images corresponded to flood events that are relatively comparable, as indicated by similar discharge peaks at Jack Taylor Weir at St George (Figure 3).

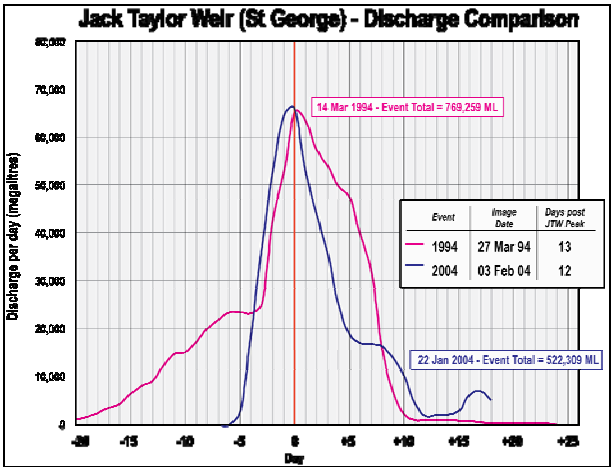

Figure 3. Discharge comparison between the 1994 and 2004 floods.

All primary datasets were sourced from the Queensland Department of Natural Resources and Mines. The two Landsat images were delivered as a georeferenced (UTM Zone 55) data product resampled to 25m x 25m pixel size. The floodplain extent map was produced by consultants of Connel Wagner in 1994. On the other hand, the DEM was extracted from the "*SEQ 25m DEM*" dataset generated from 1:100,000 mapsheets with a 20m contour interval. The source data used to built this DEM has a positional accuracy of ± 25m (horizontal) and ± 5m (vertical). The positional accuracies of the maps used in this research are sufficient for the goal of this catchment-scale (approximately 1:50,000) study.

The analysis techniques used in this study are presented in Figure 4. For image processing, spectral bands TM3, TM4, TM5 and TM7 were included in the supervised classification approach utilising the ENVI 4.2 software. For each of the 1994 and 2004 images, we collected 35 training samples for two main classes: a) *flooded areas* (comprising "open water", which can be distinguished from the composite image by using colour, pattern, shape, etc.) and b) *inundated areas* (apparently wet areas that can be recognised using the above visual interpretation criteria). Field data collection was conducted on 19-20th August 2004 to validate few unresolved sample site attributes and to collect ground truth data.

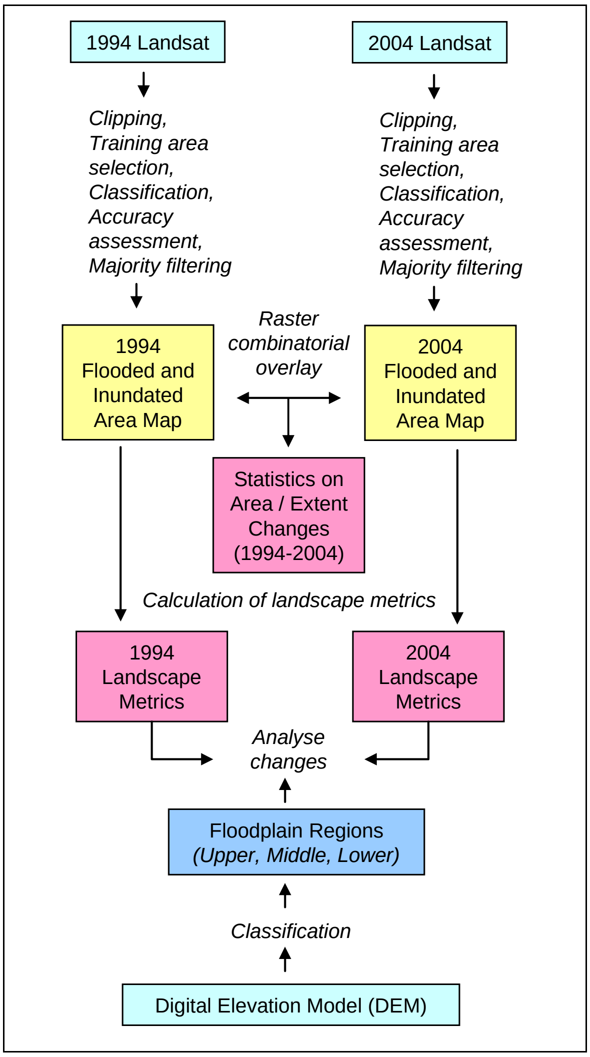

Figure 4. Major steps in mapping and analysis of spatial pattern and extent of flooded and inundated areas.

We examined the spectral properties of sample classes using statistics and graphical plots. Using spectral separability indices, such as transformed divergence and Jefferies and Matusita distance, some of the statistically similar classes were later merged. Each image was separately classified using the maximum likelihood algorithm with various (0%, 20%, 50% and 80%) probability thresholds. (Pixels with probabilities lower than the threshold value were not classified.). After classification and examination of various outputs, the classified image with 80% probability threshold was selected. It was a "conservative" (rather than liberal) image classification approach.

Two complementary approaches were implemented to assess the accuracy of image classification: *visual checks* and using *error/confusion matrix*. Visual checks depended on qualitative visual comparison of the raw and the classified image. On the other hand, error/confusion matrix involved a quantitative approach to compare a classified image with that of ground reference data. There were a total of 810 and 801 selected pixels for the 1994 and 2004 images, respectively. When the classification accuracy results were found acceptable, the two classes (*flooded and inundated*) were merged into a single super class. The rest of the image formed the second class "*non-flooded / non-inundated*".

2.3 Spatial Analysis

In this study, our analysis tasks focused on two major aspects: a) quantifying changes on the areal extent of flooded and inundated areas, and b) spatial pattern analysis of these areas. In addition, the extent and changes of water storages for 1994 and 2004 were calculated and analysed to explore their possible relationships with changes in flood extent and pattern. For all tasks above, we incorporated the use of a "region" layer that stratified the floodplain into three elevation-related regions: *upper*, *middle* and *lower*. This allowed us to analyse region-specific changes. To achieve this, the DEM layer was classified into three classes using the "natural breaks (Jenks)" method available in ArcGIS 9.1. Then, a raster map overlay in GIS was performed to create a thematic map depicting the possible combinations of change, i.e. flooded and inundated areas to non-flooded/non-inundated areas, and vice versa, between the 1994 and 2004 images, by region.

The program *Patch Analyst* [8], an extension to the ArcView 3.2 GIS system, was used to generate landscape metrics. The program includes patch analysis functions developed using avenue code, and an interface to the FRAGSTATS spatial pattern analysis program developed by [9]. It offers a comprehensive choice of landscape metrics at the patch, class, and landscape levels. This study utilised: *(a) area metrics; (b) patch density, patch size and variability metrics; (c) shape metrics;* and *(d) nearest-neighbour metrics*.

3 Results and Discussion

3.1 Mapping Flooded and Inundated Areas

The results of image classification (Figure 5) and accuracy assessment indicate that accurate mapping of flooded and inundated areas in the Lower Balonne is highly attainable. The 1994 image achieved an overall classification accuracy of 92.6% (Kappa coefficient of 0.86), while the 2004 image garnered an overall accuracy of 91.0% (Kappa coefficient of 0.81).

This high classification accuracy can be attributed to the following reasons:

- the number of classes used is relatively low (i.e. two) and hence, should limit spectral confusion;
- the inherent spectral separability of open water and other land cover types, such as woody vegetation and bare soil is high, and;
- the conservative 80% probability threshold used for the maximum likelihood classifier should have minimised misclassification.

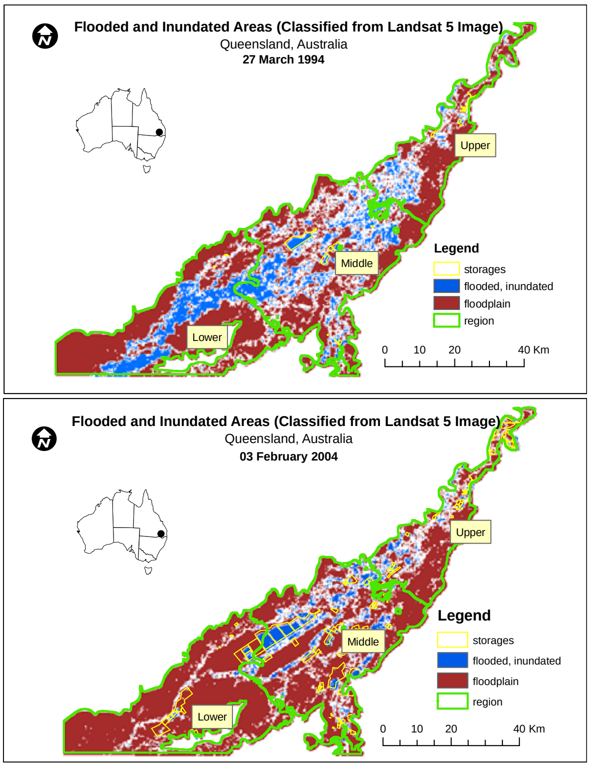

Figure 5. Classified Landsat 5 image showing the flooded and inundated areas for 1994 (top) and 2004 (bottom).

As expected, open water was the easiest to classify due its distinct spectral values in bands TM3, TM4, TM5 and TM7. However, the accurate mapping of inundated areas and flooded areas under vegetation canopies presents more difficulty due to their close or overlapping spectral values with other vegetation cover types. Fortunately, in the Lower Balonne region, most vegetation canopies are not of the closed canopy type. Thus, mixed (vegetation-water) pixels still enabled us to map these flooded and inundated areas.

The flooded and inundated areas in 2004 was mapped to be 58,375 ha, compared with the much larger area (103,033 ha) in the 1994 image (Table 1). This decrease of 44,658 ha corresponds to a 43.3% reduction in flooded and inundated areas. In 1994, the flooded and inundated areas correspond to about 28.8% of the total floodplain area. This was reduced to 16.3% in 2004.

Although there is no direct evidence that this reduction in flood extent was due to the construction of water storage infrastructures, it is but logical to identify these developments as the prime causal factor—they constitute the major man-made alteration in the land use /cover of the area during the period covered in this study. When the simple correlation (R) between changes in water storage area (column 5 of Table 2) and changes in flooded and inundated area (column 5 of Table 1) was computed by region, the result is a very high 0.98 value.

Table 1. Changes in the extent of flooded and inundated areas of the Lower Balonne floodplain (1994 to 2004)

Location	1994 (ha)	2004 (ha)	Change (ha)	Change (%)
Upper	15,511	12,484	-3,027	-19.5
Middle	54,098	38,117	-15,981	-29.5
Lower	33,424	7,774	-25,650	-76.7
Total	103,033	58,375	-44,658	-43.3

Figure 6 and Table 2 show that there were significant changes in the area of water storages in the Lower Balonne floodplain between the study period. In 1994, there were only 3,497 ha of water storages for the whole study area. This has significantly increased to 26,700 ha in 2004, which is equivalent to 663% increase.

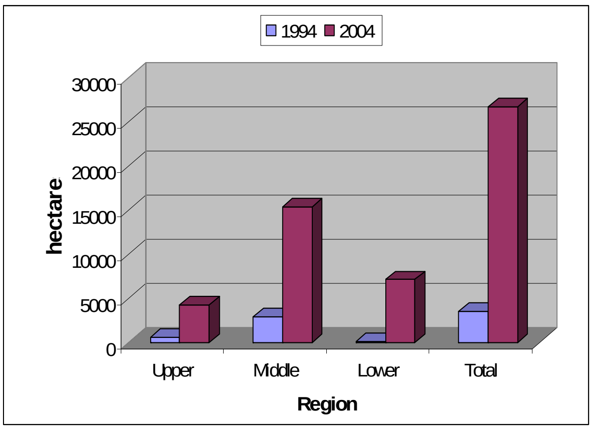

Figure 6. Area of water storages in the Lower Balonne floodplain (1994 and 2004)

Table 2. Changes in the area of water storages in the Lower Balonne floodplain (1994 and 2004)

Location	1994	2004	Change (ha)	Change (%)
Upper	588	4,230	3,642	619.4
Middle	2,869	15,364	12,495	435.5
Lower	40	7,106	7,066	17,665.00
Total	3,497	26,700	23,203	663.5

The differences in values by region have further highlighted the possible causal effect of water storage developments on the extent of flooding. The data in the lower floodplain region is worthy to emphasise: it has over 176-fold increase (from 40 to 7,106 ha) in the water storage areas. Correspondingly, it is in this lower floodplain region that registered the highest percentage change in the extent of flooding and inundation (76.7%). In the 1994 data, the flooded and inundated areas in the lower region correspond to about 25.1% of the total floodplain area. This was reduced to 5.8% in 2004 (see sample illustrations in Figure 7). This findings support the previous study of [10] who regarded that "*Large-scale water-resources and floodplain development has significantly altered the spatial and temporal patterns of hydrological characteristics in the Lower Balonne*" (p. 335).

3.2 Quantifying Spatial Patterns Using Landscape Metrics

The data on patch density, patch size and largest patch index (Tables 3 and 4) indicated that the spatial patterns of flooded and inundated areas in the Lower Balonne has significantly changed during the study period. When considering the total floodplain area, the number of patches has decreased by 12.6% (from 2,844 to 2,483 patches). This change can be attributed more to the overall decrease in flooded and inundated areas, rather than changes in the spatial configuration (e.g. integration or consolidation) of wet areas. However, the mean patch size index provided a more reliable result: it changes from 36.2 ha to 23.5 ha for 1994 to 2004, respectively, representing a 35.1% change. These values suggest that most of the wet patch areas have decreased in size. The largest patch index supports this view given that the largest flooded and inundated area patch has dramatically decreased from 13.35% to 2.9% of the area.

The mean shape index values for the patches in 1994 and 2004 are greater than one, indicating that many patches are irregularly (non-square) shaped. However, there was no significant change in the mean shape index values over the study period. This is supported by the mean patch fractal values. While the indices suggested a very slight convolution (complexity) of perimeters, the values for both years are the same. On the other hand, the mean nearest-neighbour distance values from the 1994 to 2004 data have increased from about 122 to 163 m (a 33.5% increase). This change indicates that the wet patches are becoming more isolated, and that inter-patch connectivity has decreased. This is supported by the mean proximity index values (decreased from 15,127 to 1,187 or a change of 92%).

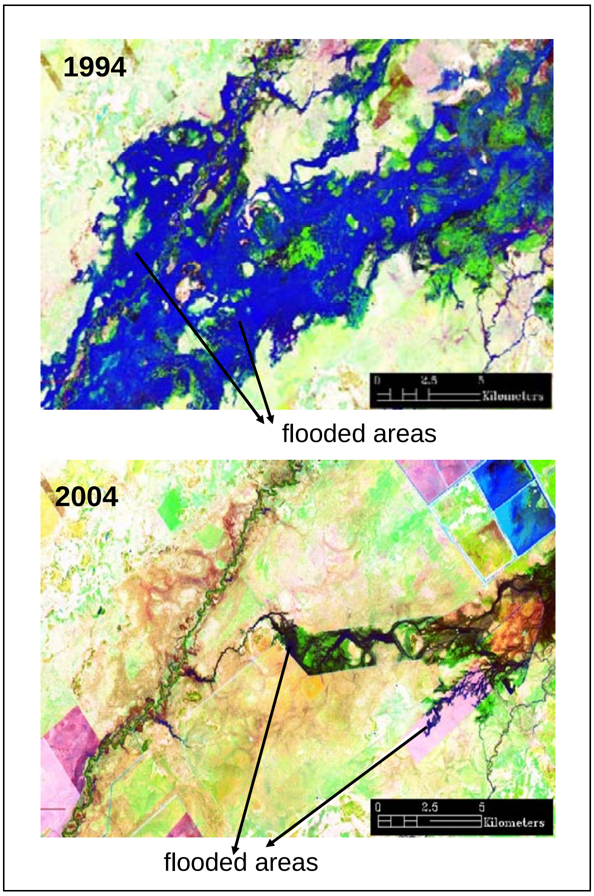

Figure 7. A portion of the lower floodplain region showing the extensive flooded areas in 1994, and the same area in 2004 showing reduced flood extent.

When assessed by region, the landscape metrics provide more insightful values. In the lower region, the number of patches has increased from 598 to 751 (25% change) and the mean patch size has decreased from 55.8 ha to 10.4 ha (81% change) (Table 4). Interpreted together, these two metrics indicate the "fragmentation" of wet areas. This claim is supported by two other indices related to patch isolation: the mean nearest neighbour distance has increased from 128 m to 193 (50% change), while the mean proximity index values correspond to 99% change, indicating that patches significantly became more isolated and more fragmented.

Table 3. Landscape metrics of the flooded-inundated areas in the Lower Balonne, 1994-2004

Landscape Metrics	**Total Floodplain**	
	1994	*2004*
Total floodplain area (ha)	357,901	357,901
Flooded-inundated area (ha)	103,033	58,375
Percent of floodplain (%)	28.78	16.31
No. of patches	2,844	2,483
Patch density (#/100 ha)	0.79	0.69
Mean patch size (ha)	36.19	23.49
Patch size CV (%) [a]	2,832.5	1,277.8
Largest patch index (%) [b]	13.35	2.9
Mean shape index [c]	1.39	1.41
Mean patch fractal [d]	1.05	1.05
Mean nearest-neigh. dist. (m) [e]	122.3	163.3
Nearest-neighbour CV (%)	128.04	147.23
Mean proximity index [f]	15,126.9	1,187.3

[a] Coefficient of variation. It is equal to 0 when there is no variability in patch size. [b] The percentage of total landscape area comprised by the largest patch. [c] The average patch perimeter divided by the square root of patch area. It is equal to 1 when all the patches of the corresponding patch type are square (due to raster cell structure). It increases without limit as the patch shapes become more irregular. [d] It approaches 1 for shapes with very simple perimeters such as circles; 2 for shapes with highly convoluted, plane-filling perimeters. [e] The average edge-to-edge distance from a patch to the nearest neighbouring patch of the same type. [f] It is equal to 0 if all the patches of the corresponding patch type have no neighbours of the same type within the search radius (100 m in this study); it increases as patches become less isolated and the patch type becomes less fragmented. (Adapted from: McGarigal and Marks, 1994).

Table 4. Landscape metrics (by region) of the flooded-inundated areas in the Lower Balonne, 1994-2004

Landscape Metrics	**Value**	
	1994	*2004*
A. Upper Region		
Total region area (ha)	67,103	67,103
Flooded-inundated area (ha)	15,511	12,484
Percent of region (%)	23.12	18.60
No. of patches	661	667
Mean patch size (ha)	23.47	18.72
Mean shape index	1.43	1.47
Mean nearest-neigh. dist. (m)	150.4	153.2
Mean proximity index	1,935.4	391.5
B. Middle Region		
Total region area (ha)	157,684	157,684
Flooded-inundated area (ha)	54,098	38,117
Percent of region (%)	34.31	24.17
No. of patches	1,711	1,148
Mean patch size (ha)	31.62	33.20
Mean shape index	1.38	1.40
Mean nearest-neigh. dist. (m)	114.4	159.7
Mean proximity index	9,281.8	1,297.9
C. Lower Region		
Total region area (ha)	133,143	133,143
Flooded-inundated area (ha)	33,424	7,774
Percent of region (%)	25.10	5.84
No. of patches	598	751
Mean patch size (ha)	55.89	10.35
Mean shape index	1.46	1.39
Mean nearest-neigh. dist. (m)	128.6	193.1
Mean proximity index	5,237.0	67.8

3.3 Implications for Monitoring

As demonstrated by this study, landscape metrics can be used to generate information on spatial patterns of flooded and inundated areas. They can provide additional set of information to complement the traditional “area-based, area-only” information. However, as a mapping and analysis tool, the use and interpretation of landscape metrics must be used with caution.

While previous studies emphasised the issue on spatial scale or resolution (e.g. [11]), this present study underscored the importance of segregating the area of interest into functionally relevant regions. The use of three floodplain regions (upper, middle, and lower) has provided us more meaningful landscape metrics compared with the total floodplain approach. It indicated that the lower region of the Balonne floodplain was the one that experienced the highest degree of spatial pattern changes in terms of flooded and inundated area.

Furthermore, it is important not to rely on a single landscape index to generate conclusions from a study. We found that the combination of the indices “number of patches”, “mean patch size”, “mean nearest-neighbour distance” and “mean proximity index” constitute a minimum requirement for inundation area mapping and analysis.

4 Conclusions

The spatial pattern and extent of the flooded and inundated areas mapped from the 1994 and 2004 imagery have changed. This study quantifies not only the areal extent of the wet areas (which has significantly reduced), but also the spatial configuration of the wet patches. They became more fragmented and isolated, particularly in the lower floodplain region of the Lower Balonne.

Spatial patterns and configuration of flooded and inundated areas can be quantified using landscape metrics. These metrics can generate sets of useful information that further characterise flooding attributes. Along with conventional mapping of inundation area/extent, these indices may be able to support water resource planning, implementation and monitoring. The use of region-based analysis, rather than solely focusing on total area, may provide more information and reveal some spatial relationships.

Acknowledgment

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