

Classifying landform at broad spatial scales: the distribution and conservation of wetlands in New South Wales, Australia

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Abstract. Relatively few large-scale inventories of the world's wetlands exist because of the difficulties of spatial scale, associated cost and multiple objectives, often temporally confounded, that drive classification. The extent of wetlands across a large part of Australia (New South Wales, 80.6 million ha) was determined using satellite image analyses. These data allowed analyses of the distribution of wetlands, their conservation status and potential threats at different spatial scales; that is, State, coastal and inland, and catchment. Approximately 5.6% of New South Wales is wetland (4.5 million ha), mostly (96%) in inland river catchments. Broad classification allowed identification of the extent of wetland types: (i) floodplains (89%); (ii) freshwater lakes (6.6%); (iii) saline lakes (< 1%); (iv) estuarine wetlands (2.5%); and (v) coastal lagoons and lakes (1.5%). Conservation reserves protect only 3% of wetland area. The analyses identified the north-west as the key area for wetland conservation as most other catchments have lower wetland extent and more potential threatening processes. The first stage of a large-scale inventory is to determine the extent and location of wetlands, with immediate benefits for strategic conservation and management. Other objectives (e.g. classification, biotic composition, hydrology and threats) seldom have sufficient data available for large-scale inventories but can be completed later with resources.

Extra keywords: catchments, classification, inventory, mapping, reserves, river regulation.

Introduction

Wetlands are among the most threatened ecosystems in the world (Lemly *et al.* 2000) and Australia is no exception (Finlayson and Rea 1999). The major factor implicated in their destruction is water resource development and the draining of wetlands (Kingsford 2000a), although urbanisation in coastal areas is significant (Adam 1995). Wetlands also support high levels of biodiversity and have important cultural and economic values. There is increasing international commitment to wetland conservation, with many countries signing the Convention on Wetlands (Ramsar Convention) but objective information is needed for effective conservation.

It is difficult to manage any natural resource without knowing its distribution, and wetlands are no exception (Finlayson *et al.* 1999). Large-scale inventories are necessary for conservation management and effective planning (Pressey and Adam 1995). Signatories to the Ramsar Convention resolved to develop low-cost and user-friendly methodology for inventories (The Ramsar Convention

Bureau 1999). Of existing inventories of wetlands, relatively few adequately define objectives, determine the distribution and size of wetlands, provide explicit methodology, differentiate wetland area according to classification or are publicly accessible (Finlayson *et al.* 1999). The notable exception is the large-scale inventory of wetlands in North America (Wilén and Bates 1995). Producing inventories of wetlands remains elusive, constraining effective management of these biodiverse ecosystems.

Part of the problem is attributable to multiple objectives for inventories. These may include identifying location and extent, geomorphology, soil type, water regimen, water chemistry, biota, anthropogenic threats and management regimen (see core essential data elements and additional categories in Finlayson *et al.* 1999). These represent a mix of spatial and temporal variables that are difficult to collect over large spatial scales. Some are seldom available (e.g. water regimen, chemistry or biota), except for small areas. A large-scale inventory should initially determine the extent and distribution of wetlands and this can be done with remote

sensing at large spatial scales, although trade-offs between resolution and budget exist (Wilén and Bates 1995). With the resulting spatial layer of wetlands, a second objective can be achieved; that is, analysis of the spatial distribution of wetlands at different scales (e.g. catchments), in relation to conservation effort or threats.

Classification of wetlands is not necessary for such analyses but it adds value in understanding representativeness. It remains a vexed question for inventories (Pressey and Adam 1995; Wilén and Bates 1995; Semeniuk and Semeniuk 1995, 1997) mainly because all classifications are simple representations of considerable spatial and temporal complexity. The hierarchical classification from North America is used globally (Cowardin *et al.* 1979; Wilén and Bates 1995) and adapted for parts of Australia (Pressey and Adam 1995) but it has problems with definition and lacks exclusivity in categories (Semeniuk and Semeniuk 1995, 1997). A suggested replacement, the hydro-geomorphic classification (Semeniuk and Semeniuk 1995, 1997), simplifies hydrological variability according to permanent, seasonal and intermittent, which are categories seldom known for wetlands across large areas. Ideally, classifications of wetlands should be quantitative and based on the objectives of the classifications that vary (Pressey and Adam 1995; Rempel *et al.* 1997).

Our primary objective was to do a large-scale inventory to identify the extent of wetlands across a large part of Australia (the State of New South Wales (NSW)) because Australia devolves responsibility for natural resource management, including water, to the provincial level of States. Second, we analysed the distribution of wetlands according to elevation, climate and different spatial scales; that is, statewide, coastal and inland regions, and catchments. The spatial framework was extended to an analysis of conservation effort (reserves) and threats to wetlands to provide a foundation for strategic policies for wetland conservation, including river management planning and conservation of aquatic fauna and flora.

Materials and methods

Wetland distribution and extent

For the 17 inland catchments, wetlands were mapped from Landsat Multi-Spectral Scanner (MSS) (80 m pixel) data (40 scenes), whereas the 22 coastal catchments wetlands were mapped from Landsat Thematic Mapper (TM) data (30 m pixel) (11 scenes) (Fig. 1). We chose the wettest times within a 10-year period (1984–1993) for inland areas. These were identified using monthly National Oceanographic and Atmospheric Administration (NOAA) satellite imagery, wetland data from aerial surveys across 10% of the State (Kingsford *et al.* 1999) and annual rainfall within each river catchment. Additional images were chosen for areas where high catchment rainfall did not coincide with high local rainfall. Cloud-free images and a period of 16 days for the imagery determined the actual dates of the images used. For coastal catchments where wetlands were less transient, cloud cover was the primary determinant of image suitability and we used cloud-free imagery within a 6-month period (September 1994 to January 1995). Each Landsat image was rectified and georeferenced to 1:250 000 and

1:250 000 topographic maps for the inland and the coast, respectively, using the Universal Transverse Mercator projection (Australian Map Grid) with 14–30 ground control points, and evenly distributed across each image.

For inland catchments, wetland boundaries were delineated from non-wetland areas using an unsupervised classification (Richards 1993) that was based on the variable spectral signatures for water (open water and inundated vegetation) and for adjacent areas of dependent aquatic vegetation. For coastal catchments, we used a band 5 density slice to delineate open water body boundaries (Frazier and Page 2000) and a supervised classification (ERDAS 2001) to delineate adjacent coastal wetland vegetation. Spectral similarities among wetland and non-wetland areas (Johnston and Barson 1993; Frazier and Page 2000) demanded an iterative process of systematic visual inspection and reclassification for each satellite image to initially validate wetland boundaries (Congalton 2001). This involved draping the wetland boundaries over satellite imagery, followed by comparison with the best available ancillary data. For the inland, this included aerial survey data (Kingsford *et al.* 1999), 1:250 000 topographic map sheets and digital coverage of water bodies (AUSLIG 1994), and for the coastal region, this involved 1:250 000 topographic maps and aerial photography. These data helped discriminate between wetland areas with similar spectral signatures to non-wetland areas (e.g. cultivated crops, flooded urban areas and hillslope shadows).

We classified wetlands *a posteriori* using a combination of spectral information and ancillary data. First, we separated water bodies into the three broad groups, which are recognised by the Ramsar Bureau: coastal, inland and man-made (reservoirs) (Semeniuk and Semeniuk 1997). We then used the broadly accepted major geomorphic groups: estuarine, riverine, lacustrine and palustrine (Wilén and Bates 1995) to classify wetlands but we could not objectively separate palustrine and riverine (Table 1). We used spectral and ancillary data to separate further the lacustrine group into freshwater lakes, saline lakes, and coastal lagoons and lakes (Table 1). A more detailed classification of wetlands was not possible because of the variable spectral signature, particularly of floodplains, and the poor availability of consistent ancillary data across the entire study area.

We derived error matrices of the mapped wetland boundaries and aerial photography reference data (Congalton 1991) using a stratified random sampling for two inland catchments (see Kingsford *et al.* 2001) and stratified random sampling for coastal catchments. This produced two quantitative measures of classification accuracy as a whole, overall classification accuracy (total per cent of correctly mapped polygons; Congalton 1991) and the Kappa statistic (actual agreement between mapped and reference data minus chance agreement; Congalton and Green 1999). Kappa also accounts for errors within individual classes of the error matrix (Rosenfield and Fitzpatrick-Lins 1986). We found an overall accuracy of 86% and a Kappa statistic of 0.76 for inland catchments of the Paroo and Warrego River (Kingsford *et al.* 2001). For the coastal catchments, overall accuracy for the Richmond, the north coast (Tweed to Macquarie–Tuggerah Lakes) and the south coast (Hawkesbury–Nepean to Snowy) were 80% (Kappa = 0.66), 85% (Kappa = 0.80) and 90% (Kappa = 0.87), respectively. Such overall classification accuracies are considered good (> 80%) (Congalton 1991), and the Kappa statistics represented strong agreement (> 0.80) (north coast and south coast) and moderate agreement (> 0.40) (Paroo and Warrego, and Richmond) between mapped data and reference data (Congalton 2001).

We determined the area and proportion of land area of wetland groups and reservoirs within each catchment across inland and coastal catchments. For river catchments within the Murray–Darling Basin across State borders, we analysed wetland distribution for the whole catchment and separately for each State. We compared the distribution (coastal and inland) and extent of wetlands in relation to elevation (above sea level) and mean annual rainfall between 1980 and 1999.

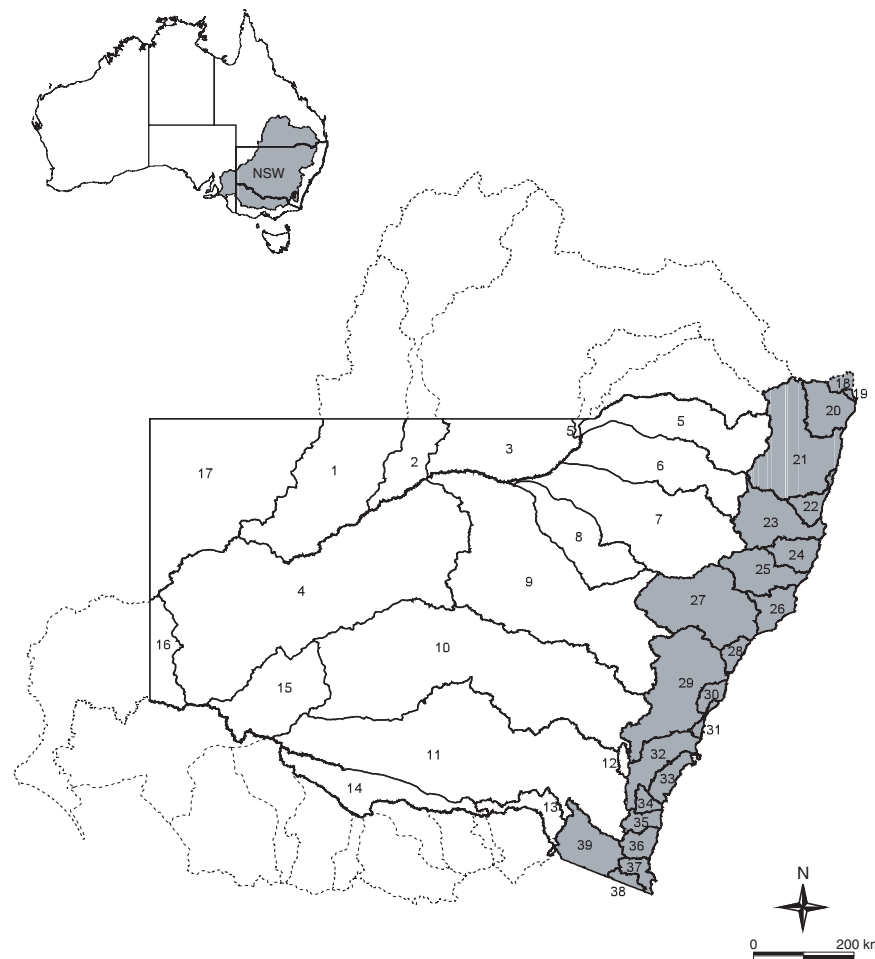


Fig. 1. Locations of 39 catchments in New South Wales (NSW) and the Murray–Darling Basin (grey inset in map of Australia with State borders), including 17 inland catchments of rivers flowing west of the Great Dividing Range (1–17) and 22 coastal catchments of rivers flowing east of the Great Dividing Range (22–39) (grey shading). Numbers for catchments match names given in Tables 3–6.

Wetland conservation

We used GIS analyses to determine the area of wetlands and reservoirs protected under legislative or policy instruments that confer status or protection on wetlands that were applied to the land area of the wetland. These represent the most used and applicable measures for assessing wetland conservation. They included four conservation measures: (i) National Parks and Wildlife Service (NPWS) reserves; (ii) State Environmental Planning Policy No. 14 (SEPP 14) for coastal wetlands (Farrier *et al.* 1999); (iii) the Directory of Important Wetlands in Australia (DIWA) (Environment Australia 2001); and (iv) wetlands listed under the Ramsar Convention. We also included State forest reserves because, although set aside primarily for timber production, some have become ‘quasi’ conservation areas for wetlands (e.g. Barmah–Millewa Forest). The wetland coverage for each catchment was clipped in Arc/Info (ESRI 2000) using digital boundaries for the relevant conservation measures. We also assessed potential threats to wetlands by overlaying the proportion of land in each catchment covered by intensive agriculture (National Land and Water Resources Audit 2001a), number of weirs and storage capacity of dams (Kingsford 1995; National Land and Water Resources Audit 2001b).

Results

Wetlands of New South Wales

There are almost 4.5 million ha of wetlands in NSW or 5.6% of the land area of the State (Table 2, Fig. 2). Most wetland area (96%) is in the inland, in the catchments of the Murray–Darling Basin and far west of the State (Fig. 2), with nearly half of all inland wetland area (46%) in the Far north-west, Paroo, Warrego and Condamine–Culgoa catchments (Table 3). Of the wetland types across the State, floodplain wetlands are the most ubiquitous, forming 89% of all wetland area and covering 5% of the land surface (Table 2). Freshwater lakes and estuarine areas make up most of the remaining wetland area in the State, with comparatively small areas of saline lakes and coastal lagoons and lakes (Table 2). There are more reservoirs than freshwater lakes, coastal lagoons and lakes, and salt lakes.

Most wetland area (> 95%) is below 250 m above sea level, and 93% is in parts of the State that receive less than 500 mm of annual rainfall (Fig. 3).

Inland wetlands

Most inland wetlands are floodplains that are distributed below 250 m and where there is less than 500 mm of annual rainfall (Table 2; Fig. 3). The highest proportion of wetlands in NSW is in two catchments, Warrego and Condamine–Culgoa, whereby 27% and 28% of their respective areas in the NSW part of the catchment is covered by wetlands (Table 3). The Condamine–Culgoa has the highest wetland area of any catchment in inland NSW, covering approximately 740 000 ha (Table 3). The Paroo and Murray–Riverina catchments have the next highest proportion of wetland with 16% and 17% of land area covered, respectively. Most of the wetland area and higher proportions in the Paroo, Warrego and Condamine–Culgoa are on the NSW side of the border, and there are similar proportions for the Lower Murray River catchments and the Border and Moonie Rivers on both sides of the border (Table 3). Nine of the 17 inland catchments in NSW have more than 200 000 ha of wetland and the remainder of the catchments has less than 100 000 ha of wetland (Table 3). Most catchments with lower areas of wetland also have a low proportion of wetlands, with the exception of Lake George catchment, which ranks fifth in terms of wetland proportion. Twelve of the 17 inland catchments each have 6% or less of wetland area in their catchment (Table 3). These include most of the major regulated rivers such as Darling, Border and Moonie, Gwydir, Namoi, Macquarie–Bogan, Lachlan, Murrumbidgee, Upper Murray and Lower Murray (Table 3). The Murray River and its tributaries flow through four of the catchments (Table 3). The Murray–Riverina catchment includes most of the floodplain of this river and when all catchments of the Murray River are combined, the proportion (7%) is similar to that of other regulated river catchments (Table 3).

There is more than 70% of wetland area identified as floodplain in all but two of the catchments and, in 12 catchments (Paroo, Warrego, Condamine–Culgoa, Border and Moonie, Gwydir, Castlereagh, Macquarie–Bogan, Lachlan, Murrumbidgee, Upper Murray, Murray–Riverina and Benanee), there is more than 90% floodplain wetland (Table 3). The Paroo and Condamine–Culgoa catchments have more than half a million hectares of floodplain wetland in NSW, and another seven each have more than 200 000 ha of floodplain (Warrego, Darling, Macquarie–Bogan, Lachlan, Murrumbidgee, Murray–Riverina and Far north-west).

The Darling catchment has the greatest area of freshwater lakes (130 730 ha) of any inland catchment, primarily the Menindee Lakes, and the Far north-west has an order of magnitude of more freshwater lakes (Table 3). Freshwater lake area exceeds 10 000 ha in each of seven other

catchments: Paroo, Condamine–Culgoa, Lachlan, Murrumbidgee, Lake George, Lower Murray and Far north-west. The Castlereagh, Murray–Riverina, Upper Murray, Macquarie, Gwydir, Border and Warrego have little (< 1%) or no freshwater lake area. Saline lakes cover 0.02% of the State (Table 2) but they are present in only five inland catchments: Far north-west, Paroo, Warrego, Murray–Riverina and Lower Murray (Table 3). The Paroo River and Far north-west catchments cover 93% of all saline lake area (Table 3).

Coastal wetlands

Approximately 1.3% of the coastal land area is wetland (Table 2), principally estuarine wetlands (59%) and coastal lagoons and lakes (35%) (Table 2). Floodplain wetlands rank lowest in wetland area in most coastal catchments, accounting for only 5% of wetland area (Table 4). Most wetlands are less than 250 m above sea level (Fig. 3a) but are more wide spread across different climatic zones than inland wetlands (Fig. 3b).

The proportion of wetland is highest in the Macquarie–Tuggerah Lakes catchment (Table 4), and > 5% proportion in the Karuah, Georges–Cooks and Illawarra–Port Hacking catchments (Table 4). Macquarie–Tuggerah Lakes and Karuah have more than 20 000 ha of wetland area, and Clarence, Hawkesbury–Nepean, Georges–Cooks and Clyde have more than 10 000 ha of wetland area. In 14 of the 22 coastal catchments, estuarine wetlands account for 50% or more of the wetlands in the catchment and more than 80% in six of these catchments (Table 4). Coastal lagoons and lakes are concentrated in the Clyde (22) and Bega–Dry (24), with Clarence, Bellinger, Hastings, Karuah, Macquarie–Tuggerah and Deua, and Tuross with 10 or more coastal lagoons and lakes (Table 4). The Karuah and Macquarie–Tuggerah catchments have most of the area of coastal lagoons and lakes (Table 4). Floodplain wetlands are proportionally greater than 10% in the Richmond, Clarence, Macleay, Manning, Hunter and Shoalhaven (Table 4). Compared to inland, there are few freshwater lakes in the coastal catchments and they cover a small part of the land area (Table 4).

Wetland conservation

Less than 1% of the State's wetland area is listed as internationally significant under the Ramsar Convention, whereas 3% is part of National Parks and Wildlife Service (NPWS) reserves and 21% of the State's wetland area is of national importance (DIWA) (Table 2; Fig. 4). There is an additional 3% of the State's wetlands in State forests (mostly inland) and 0.7% of all wetland area that is protected under SEPP 14 (Table 2; Fig. 4). Although the largest areas of wetlands in NPWS reserves are in inland catchments, the greatest proportion of wetlands is reserved in coastal catchments (Table 2; Fig. 4).

Table 1. Spatially derived wetland groups (and reservoirs) for inland (Murray–Darling Basin and Far north-west) and coastal wetlands across New South Wales

Global groups ^a	Categories	Description
Palustrine and riverine	Floodplain wetland	River and creek channels and adjacent inundated vegetation, which includes swamps, waterholes and shallow depressions. These areas are defined by the satellite imagery, which was chosen to reflect large floods over a 10-year period.
Estuarine	Estuarine wetland	Open water bodies and adjacent vegetation at the mouth of a river open to the sea where salt water and freshwater mix (e.g. Port Stephens). Estuarine extent was determined by tidal influences.
Lacustrine	Freshwater lake	Naturally occurring drainage basins of open water and not estuarine or coastal lagoons and lakes or saline on a 1:250 000 map and where surface aquatic vegetation did not dominate spectral reflectance.
	Saline lake	Inland naturally occurring drainage basins of saline open water, annotated as 'salt' or 'salt lake' on 1:250 000 topographic maps.
	Coastal lagoons and lakes	Open bodies of water and adjacent vegetation that were not obviously part of the river and were completely (e.g. Myall Lakes) or partly (e.g. Wamberal Lagoon) separated from the sea.
Reservoirs		Open bodies of water usually created by a wall or levee, including reservoirs, farm dams, off-river storages, mining and quarry dams, sewage ponds, evaporation basins, canals and open basins.

^aGlobal classification groups (Cowardin *et al.* 1977; Wilen and Bates 1995).

Table 2. Total area of wetlands and reservoirs (ha), and wetland areas in National Parks and Wildlife Service (NPWS) reserves, State forests, State Environmental Planning Policy No. 14 (SEPP 14), A Directory of Important Wetlands in Australia (DIWA), and listed under the Ramsar Convention within three regions; that is, New South Wales (NSW) (which includes the Australian Capital Territory), the inland (Murray–Darling Basin and Far north-west) and the coast (coastal catchments)

Region ^a	Group	Area	% ^b	Number ^c	Conservation land measure								Ramsar	
					NPWS		State forests		SEPP 14		DIWA			
					Area	% ^d	Area	% ^d	Area	% ^d	Area	% ^d	Area	% ^d
Inland (66 580 816 ha)	Saline lake	18 518	<0.1	218	0	0	0	0	—	—	7816	0.2	0	0
	Freshwater lake	295 805	0.4	2204	18 726	0.4	915	<0.1	—	—	160 951	3.7	1362	<0.1
	Floodplain wetland	4 003 979	6.0	—	84 909	2.0	136 201	3.2	—	—	672 910	15.6	18 490	0.4
	All wetlands	4 318 302	6.5	—	103 635	2.4	137 116	3.2	—	—	841 677	19.5	19 852	0.5
	Reservoir	84 416	0.1	1898	2881	—	61	—	—	—	393	—	0	0
Coastal (13 977 498 ha)	Freshwater lake	1927	<0.1	90	196	0.1	16	0.8	144	0.1	1429	0.8	100	0.1
	Estuarine	110 795	0.8	—	13 001	6.9	224	0.2	23 761	12.6	46 107	24.5	4360	2.3
	Coastal lagoons and lakes	65 871	0.5	194	17 755	9.4	44	0.1	6741	3.6	42 825	22.8	10 363	5.5
	Floodplain wetland	9304	0.1	—	1912	1.0	78	0.8	1386	0.7	1950	1.0	0	0
	All wetlands	187 897	1.3	—	32 864	17.5	362	0.2	32 032	17.0	92 311	49.1	14 823	7.9
	Reservoir	37 058	0.3	1158	512	—	30	—	45	—	164	—	140	—
New South Wales (80 558 314 ha)	Saline lake	18 518	<0.1	218	0	0	0	0	—	—	7816	0.2	0	0
	Freshwater lake	297 732	0.4	2294	18 922	0.4	931	<0.1	144	<0.1	162 380	3.6	1462	<0.1
	Estuarine	110 795	0.1	—	13 001	0.3	224	<0.1	23 761	0.5	46 107	1.0	4360	0.1
	Coastal lagoons and lakes	65 871	0.1	194	17 755	0.4	44	<0.1	6741	0.1	42 825	1.0	10 363	0.2
	Floodplain wetland	4 013 283	5.0	—	86 821	1.9	136 279	3.0	1386	<0.1	674 860	15.0	18 490	0.4
	All wetlands	4 506 199	5.6	—	136 499	3.0	137 478	3.1	32 032	0.7	933 988	20.7	34 675	0.8
	Reservoir	121 474	0.2	3056	3393	—	91	—	45	—	557	—	140	—

^aLand areas are given in parentheses.^bRelative to land area in each region.^cNumbers are counts of lakes, lagoons or reservoirs and may include more than one polygon.^dRelative to wetland area within each region.

Number of freshwater lakes, saline lakes, coastal lakes and lagoons and reservoirs are given. Percentages are wetland area relative to total land area within a region or, for conservation land measures (NPWS, State forests, SEPP 14, DIWA, Ramsar), relative to wetland area within a region. Categories of conservation land measures are inclusive.

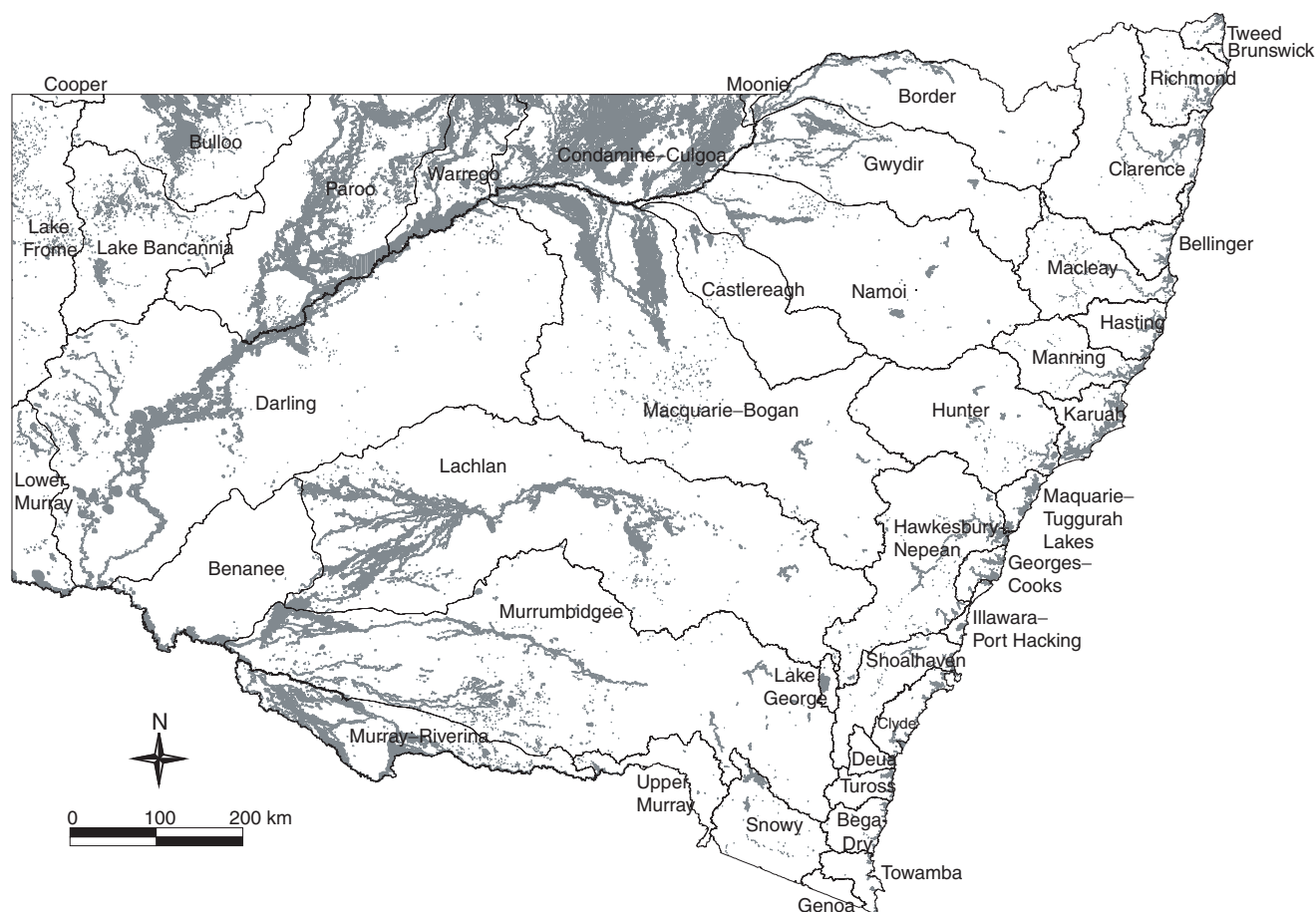


Fig. 2. Distribution of wetlands and reservoirs (grey shading) across New South Wales based on Landsat MSS satellite data (80 m pixel) from the period 1984–1993 for the inland and Landsat TM satellite data (30 m pixel) from the period September 1994–January 1995.

Despite 96% of wetland area occurring in inland catchments, only 0.5% of this area is listed under the Ramsar Convention, of which 2.4% occur in NPWS reserves, 3.2% in State forests and approximately 20% is defined as nationally important (DIWA) (Table 2; Fig. 4). In contrast, wetlands on the coast represent only 4% of the State's wetland area but nearly 8% are listed under the Ramsar Convention, of which 17.5% occur in NPWS reserves, almost 50% in the DIWA and 17% is protected under SEPP 14 (Table 2; Fig. 4). There were Ramsar-listed wetland areas in four inland catchments (i.e. Condamine–Culgoa, Gwydir, Macquarie–Bogan and Far north-west) (Table 5) and five coastal catchments (i.e. Clarence, Karuah, Hunter, Georges–Cook and Snowy) (Table 6). The highest proportions of inland wetland areas in NPWS reserves are in the Darling (5%), Paroo (4%), Macquarie–Bogan (4%) and Condamine–Culgoa (3%) (Table 5). Another three inland catchments, Warrego, Lachlan, and Far north-west, have more than 3000 ha reserved, whereas the Namoi and Lake George have none (Table 5). In contrast, all coastal catchments have some wetland area in NPWS reserves (Table 6). The Hunter catchment (57%) has the highest

proportion but the Brunswick, Richmond, Hastings, Manning, Karuah, Towamba and Snowy all have more than 20% of their wetlands reserved and Tweed, Bellinger, Macleay, Shoalhaven and Tuross have 10–20% of their wetlands reserved (Table 6). Tweed, Brunswick, Richmond, Bellinger, Macleay, Hastings, Manning, Karuah, Hunter, Shoalhaven, Deua, Bega–Dry and Towamba also have 20–47% of their wetland area protected under SEPP 14 (Table 6). Most wetland area in State forests (14–31%) is in the Murray–Riverina, Benanee and Lower Murray catchments (Table 5).

There are three inland catchments, Macquarie, Lake George and Murray–Riverina, with more than 50% of the wetland area listed as nationally important (DIWA) and a further two, Paroo and Gwydir, with 20–50% of the wetland area listed (Table 5). Most other catchments have relatively small areas listed as wetlands of national importance. The larger areas (> 30000 ha) of inland wetlands listed in the DIWA are in the Macquarie, Paroo, Murray–Riverina, Darling, Lachlan, Condamine–Culgoa and Far north-west catchments. Large areas on the coast (> 5000 ha) listed in the DIWA occur in the Clarence, Karuah, Macquarie–Tuggerah

Table 3. Areas (ha) of catchments, total wetlands of wetland groups and their proportions and reservoirs in inland New South Wales

Catchment name ^a	Catchment Area	Total wetland Area	% ^b	Saline lake Area	%	No. ^c	Freshwater lake Area	%	No. ^c	Floodplain Area	%	Reservoir Area	No. ^c
Paroo (Total) (1)	7412 774	996455	13	14085	1	155	36754	4	23	945616	95	688	30
NSW	4115249	666913	16	8854	1	118	26300	4	18	631759	95	177	7
Qld	3297525	329542	10	5231	2	37	10454	3	5	313857	95	511	23
Warrego (Total) (2)	6354301	851077	13	520	<1	15	7275	1	4	843282	99	1643	61
NSW	1138944	311952	27	520	<1	15	411	<1	3	311021	100	1000	9
Qld	5215357	539125	10	0	0	0	6864	1	1	532261	99	643	52
Condamine-Culgoa (Total) (3)	16359717	1453923	9	1071	<1	1	16888	1	29	1435964	99	11037	340
NSW	2611171	738867	28	0	0	0	15898	2	8	722969	98	102	24
Qld	13748546	715056	5	1071	<1	1	990	<1	21	712995	100	10935	316
Darling (4)	11258100	581135	5	0	0	0	130730	22	140	450405	78	2983	121
Border and Moonie (Total) (5)	6299664	108832	2	0	0	0	180	<1	14	108652	100	8457	191
NSW	2463285	60949	2	0	0	0	180	<1	14	60769	100	3309	88
Qld	3795253	47883	1	0	0	0	0	0	0	47883	100	5148	103
Gwydir (6)	2659603	58907	2	0	0	0	115	<1	2	58792	100	15650	193
Namoi (7)	4195075	52677	1	0	0	0	6902	13	4	45775	87	8721	162
Castlereagh (8)	1739480	16949	1	0	0	0	0	0	0	16949	100	1041	121
Macquarie-Bogan (9)	7463395	421516	6	0	0	0	2173	1	36	419343	99	13391	239
Lachlan (10)	9064850	471011	5	0	0	0	25217	5	24	445794	95	7769	163
Murrumbidgee (11)	8152712	277369	3	0	0	0	14436	5	33	262933	95	18526	337
Lake George (12)	94069	13018	14	0	0	0	12923	99	3	95	1	57	3
Murray catchments ^d	5081152	372717	7	800	<1	34	21697	6	55	350220	94	11179	271
Upper Murray (Total) (13)	1535302	940	<1	0	0	0	3	<1	2	937	100	23535	54
NSW	520544	292	<1	0	0	0	1	<1	1	291	100	6967	26
Vic	1014758	648	<1	0	0	0	2	<1	1	646	100	16568	28
Murray-Riverina (14)	1502859	262430	17	20	<1	1	2360	1	8	260050	99	3468	85
Benanee (15)	2129292	63834	3	0	0	0	3615	6	13	60219	94	0	0
Lower Murray (Total) (16)	5813578	280882	5	2449	1	42	127448	45	62	150985	54	2269	259
NSW	928457	46161	5	780	2	33	15721	34	33	29660	64	744	160
SA	4885121	234721	5	1669	1	9	111727	48	29	121325	52	1525	99
Far north-west ^e (17)	6543731	274322	4	8344	3	51 ^f	38823	14	1864 ^g	227155	83	511	160
Total of all wetlands ^h	66580816	4318302	6.5	18518	0.4	218	295805	6.9	2204	4003979	92.7	84416	1898

^aFor Murray-Darling Basin catchments that extend across State borders, a catchment total including separate state portions (NSW, New South Wales; Qld, Queensland; Vic, Victoria; SA, South Australia) is given. For all other catchments, areas are the NSW portions only. See Fig. 1 for locations of catchments signified by numbers in parentheses.

^bPercentages of wetland area relative to total land area within the catchment.

^cNumbers of wetlands are counts of lakes, lagoons or reservoirs and may include more than one polygon.

^dAll catchments in the Murray totalled.

^eIncludes Lake Bancannia and NSW portions of Lake Frome, Cooper Creek and Bulloo River (see Fig. 1).

^fFifty per cent of these wetlands are < 5 ha (53 ha or 0.6% of wetland area).

^gSixty-two per cent of these wetlands are < 5 ha (2836 ha or 1% of wetland area).

^hDoes not include parts of catchments within other States.

Percentage of total wetland area in each of the 17 catchments (1-17; see Fig. 1) and numbers of discrete freshwater lakes, saline lakes and reservoirs are given. Percentages for total wetland are relative to catchment land area and for wetland groups, relative to total wetland area.

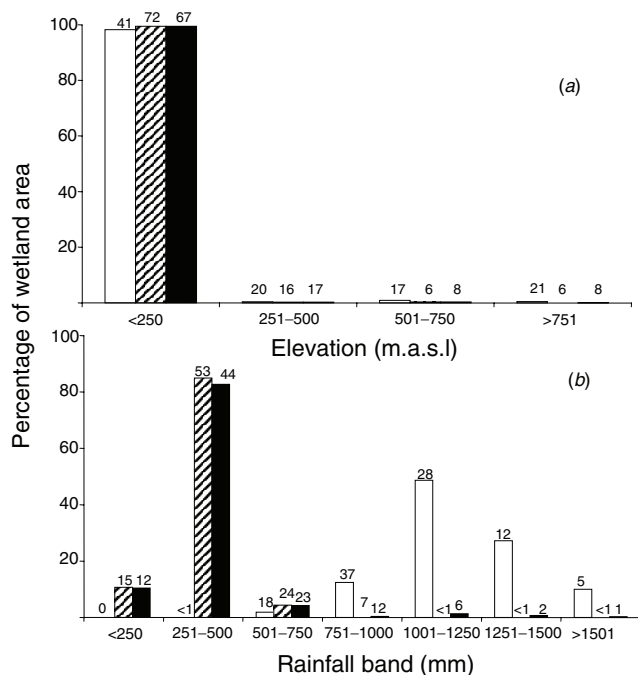


Fig. 3. Percentages of wetland area across New South Wales (filled), inland (hatched) and coast (open) in relation to: (a) elevation (metres above sea level) and (b) annual rainfall. Numbers indicate the percentage of land area in each of the elevation and rainfall classes.

and Clyde catchments, and the Macleay, Karuah, Hunter, Illawarra–Hacking and Shoalhaven catchments have approximately 50% or more of their wetland area listed in the DIWA (Table 6).

Water resource development and intensive agriculture

Nine of the 17 inland catchments have more than 10% of their catchment area used for intensive agriculture (Table 5), whereas four catchments (Far north-west, Paroo, Warrego and Darling), in the north-west of the State have less than 1% of their land area utilised by intensive agriculture. Of the inland catchments, the Murray–Riverina, Gwydir, Macquarie–Bogan, Murrumbidgee, Lachlan and Border catchments have more than 20% of their catchment area used for intensive agriculture. On the coast, Macquarie–Tuggerah Lakes, Brunswick, Illawarra–Port Hacking and Tweed catchments have more than 20% of their catchment area used for intensive agriculture (Table 6).

The potential capacity of dams across the State is 29347000 ML and inland catchments account for 64% of this capacity (Tables 5,6). Nine catchments have storage capacities greater than 1000000 ML; that is, Upper Murray, Murrumbidgee, Darling, Macquarie, Lachlan, Gwydir, Snowy, Hawkesbury–Nepean and Hunter (Tables 5,6). The Macquarie, Lachlan, Murrumbidgee and Hawkesbury–Nepean catchments have more than 300 weirs, and the Murray–Riverina, Namoi, Richmond, Hunter and Clarence

have more than 100 (Tables 5,6). In the inland, the Castlereagh, Condamine–Culgoa, Far north-west, Paroo and Warrego catchments have few weirs and a low storage capacity of Government-built dams (Table 5), whereas similar catchments on the coast include the Brunswick, Bellinger, Deua, Genoa, Hastings, Illawarra–Port Hacking, Karuah, Manning, Towamba and Tuross catchments (Table 6).

Discussion

Wetland inventory and classification

Lack of data for the large-scale distribution and extent of wetlands has hampered effective wetland conservation around the world usually because governments need to set conservation priorities at large jurisdictional or catchment scales. Despite the imperative for these data, the state of wetland inventory around the world remains parlous (Finlayson *et al.* 1999). Technology in the form of remote sensing makes large-scale inventory possible, given sufficient resources, but there are two other constraints to progress in inventory development: multiple objectives and classification.

Finlayson *et al.* (1999) advocated objectives that included eight essential core data elements and six additional information categories for inventories. We achieved only two of the former (area and boundary, and location) and two of the latter (land use and conservation status) in our inventory. Of these, the latter were based on overlaying other data layers but were not collected in the present study (Tables 5,6). Collection of additional essential data (water regimen, chemistry and biota) is confounded by temporal scale, with characterisation demanding considerable resources that are seldom available for large areas. Furthermore, a variable such as ‘biota’ includes a huge range of plants, animals and communities. Although other objectives are important, they are not easily achievable on a large scale.

The second constraint of *a priori* classification can also hamper progress. Classification of wetlands adds differentiation to an audit of location and extent (Semeniuk and Semeniuk 1995, 1997) and helps analysis of representativeness or loss or degradation (Wilén and Bates 1995). Yet, it is also specific to objectives and simplifies spatial and temporal variation. A geomorphic classification differs from an ecological one and, within ecological classifications, one based on vegetation will differ from one based on an animal species. Also, limits to methodology compound problems with definition. Even for our broad classification we could not adequately and objectively differentiate between palustrine and riverine areas from satellite imagery (Table 1; Wilén and Bates 1995). This is partly because of inherent problems with the definition for the palustrine category (see Semeniuk and Semeniuk 1997). Our broad classification was *a posteriori* and based primarily on location and broad

Table 4. Areas (ha) of catchments, total wetlands, wetland groups and their proportions and reservoirs in coastal New South Wales

Catchment name	Catchment Area	Total wetland Area	% ^a	Freshwater lake Area	%	No. ^b	Estuarine Area	%	Coastal lakes and lagoons Area	%	No. ^b	Floodplain Area	%	Reservoir Area	No. ^b
Tweed (18)	132561	3708	3	1	<1	1	3439	93	199	5	3	69	2	263	43
Brunswick (19)	27367	724	3	0	0	0	713	98	9	1	3	2	<1	14	2
Richmond (20)	703082	9072	1	45	<1	15	6965	77	657	7	9	1405	15	423	60
Clarence (21)	2265802	16105	1	197	1	4	10,810	67	3173	20	15	1925	12	252	36
Bellinger (22)	305264	4592	2	0	0	0	3988	87	409	9	13	195	4	78	46
Macleay (23)	1140210	4965	0	34	1	3	2882	58	642	13	8	1407	28	337	61
Hastings (24)	448394	8383	2	54	1	2	4553	54	3693	44	12	83	1	92	20
Manning (25)	821838	5708	1	0	0	0	3822	67	1201	21	7	685	12	155	68
Karuah (26)	449803	44384	10	5	<1	3	25,822	58	18424	42	11	133	<1	147	62
Hunter (27)	2142494	5979	0	64	1	10	4851	81	2	<1	1	1062	18	8632	270
Macquarie–Tuggerah Lakes (28)	183225	22768	12	20	<1	3	3350	15	19392	85	15	6	<1	203	41
Hawkesbury–Nepean (29)	2181872	15841	1	1086	7	10	13674	86	0	0	0	1081	7	10084	303
Georges–Cook (30)	182177	12514	7	1	<1	1	12158	97	336	3	5	19	<1	930	43
Illawarra–Port Hacking (31)	80029	5181	6	0	0	0	1686	33	3492	67	8	3	<1	39	13
Shoalhaven (32)	724089	4465	1	1	<1	1	3001	67	690	15	3	773	17	1247	30
Clyde (33)	328449	13060	4	0	0	0	6414	49	6633	51	22	13	<1	98	9
Deua (34)	149543	804	1	0	0	0	513	64	291	36	10	0	0	5	4
Tuross (35)	215890	3717	2	4	<1	3	665	18	3031	82	16	17	<1	3	4
Bega–Dry (36)	284302	2977	1	3	<1	3	687	23	2271	76	24	16	1	174	25
Towamba (37)	216600	2144	1	9	<1	3	802	37	1326	62	9	7	<1	27	6
Genoa (38)	111352	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Snowy (39)	883155	806	0	403	50	28	0	0	0	0	0	403	50	13855	12
Total of all wetlands	13977498	187897	1.3	1927	1	90	110795	59	65871	35	194	9304	5	37058	1158

^aPercentages of wetland area relative to total land area within the catchment.^bNumbers of wetlands are counts of lakes, lagoons or reservoirs and may include more than one polygon.

Percentage of total wetland area in each of the 22 coastal catchments (18–39; see Fig. 1) and numbers of discrete freshwater lakes, coastal lagoons, lakes and reservoirs are given. Percentages for total wetland are relative to catchment land area, and for wetland groups are relative to total wetland area.

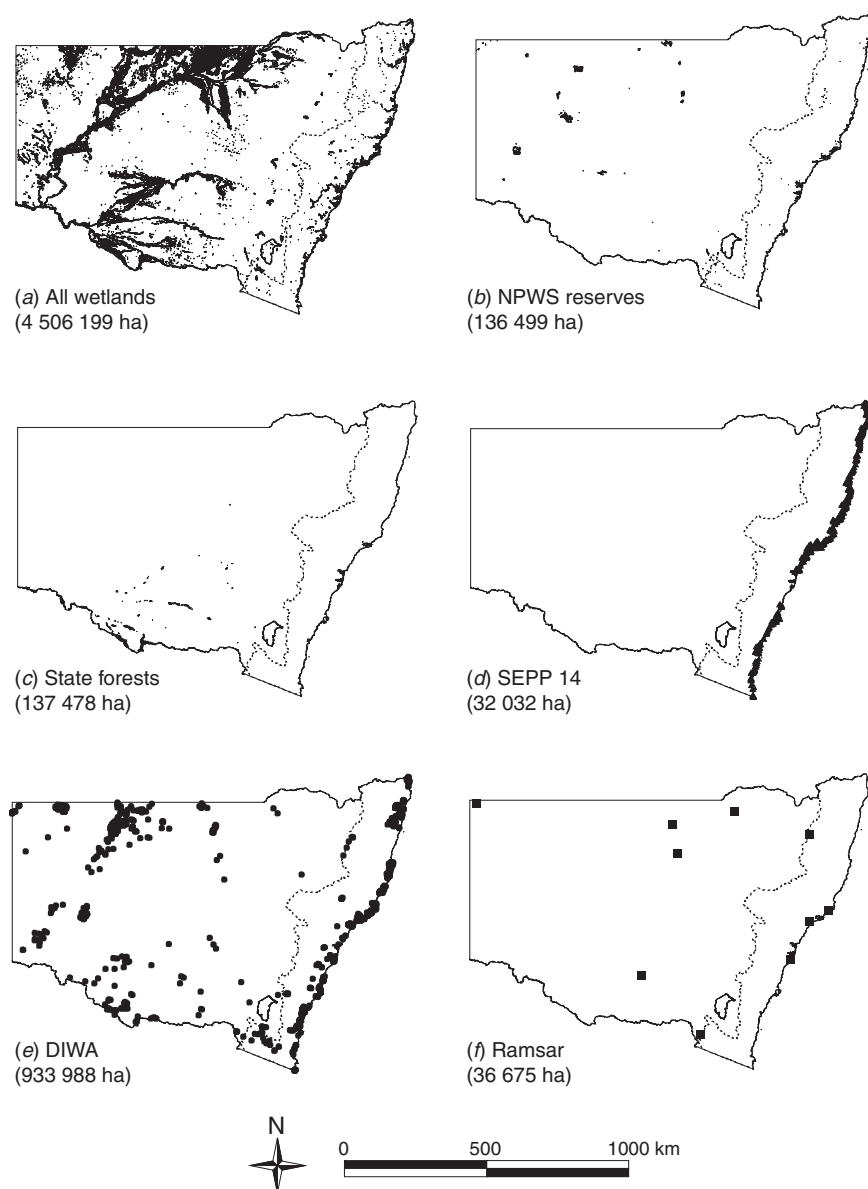


Fig. 4. Inland and coastal distribution of: (a) all wetlands and areas with conservation status in New South Wales; (b) National Parks and Wildlife Service (NPWS) reserves; (c) State forests; (d) State Environmental Planning Policy No. 14 (SEPP 14); (e) Directory of Important Wetlands in Australia (DIWA); and (f) wetlands listed as internationally important under the Ramsar Convention. Areas are given in parentheses. Dotted line (north–south) separates inland from coastal catchments.

geomorphic categories (Cowardin *et al.* 1979; Wilen and Bates 1995; Semeniuk and Semeniuk 1995, 1997), which were possibly less prone to problems of definition and coped with lack of data over large scales and effects of temporal changes. We showed that it was possible to develop a large-scale inventory (Fig. 2), determine the distribution and extent of those wetlands that allowed analyses of conservation priorities.

Wetland distribution and extent

Australia has no reasonable estimates of wetland area (Finlayson *et al.* 1999) and our estimate for NSW could form part of a future continental estimate. Approximately 6% coverage of land area in NSW is covered by wetlands (Table 2), which is similar to that covered in North America (Wilen and Bates 1995) but significantly lower than that covered in more mesic parts of the world such as northern

Canada (20%) and Eastern Europe (11.8%) (Stevenson and Frazier 1999). Most wetland area in NSW (83%) lies in arid regions (< 500 mm annual rainfall) (Fig. 3b) and not in humid regions; areas not well defined by national attempts to estimate wetland areas (Pajmans *et al.* 1985; Aselmann and Crutzen 1989). Freshwater lakes occur in many catchments but salt lakes are distributed primarily in the most arid regions of the State; that is, the Paroo and Far north-west catchments (Table 3).

Although occupying approximately 17% of the land area, the coastal region of NSW only has about 4% of the wetland area (Fig. 2), with relatively little floodplain wetland (Tables 2,3). Coastal catchments are considerably smaller than inland catchments (Fig. 1) and most (~60%) coastal catchments are above 250 m above sea level, the elevation below which most wetlands are located (Fig. 3a). Also, most (96%) of the mean annual run-off from rivers on the south-east coast flows out to sea, compared with only 24% of the flow in the Murray–Darling Basin in inland NSW (National Land and Water Resources Audit 2001b). Finally, drainage, alteration of the floodplain (Pressey 1989) and urbanisation (Adam 1995) have destroyed or degraded wetlands in coastal NSW. Ten of the 22 coastal catchments have more than 10% of their area under intensive agriculture (Table 6). Major population centres such as Sydney in the Hawkesbury–Nepean and Georges–Cooks catchments, Newcastle in the Hunter and Wollongong in the Shoalhaven also have large water resource developments (Table 6) that reduce flooding.

Wetland conservation

The main strategy for conservation of wetlands around the world is based on sites (Amezaga *et al.* 2002), such as National Parks and Wildlife Service (NPWS) reserves. This approach is also used to list wetlands of international importance under the Ramsar Convention, SEPP 14 or wetlands of national importance (Tables 2,5,6; Fig. 4). The overlap between NPWS reserves and wetland distribution is approximately 3% of the 4.5 million ha of wetland (Table 2; Fig. 4) and occurs disproportionately on the coast compared to inland (Tables 2,5,6; Fig. 4). Coastal catchments have up to 60% (Karuah) of their wetlands reserved (Table 6). This illustrates the problem for wetland conservation, which is focused generally on coastal systems around the world (La Peyre *et al.* 2000) where there is greater knowledge and more conservation effort. Until distribution of all wetland areas is known, conservation effort will remain biased.

Traditional conservation measures (e.g. reserves, Ramsar sites) seldom protect dependent biota and ecological processes adequately from threats operating at catchment scales (Barendregt *et al.* 1995). This is further complicated because many of the world's rivers flow between jurisdictional boundaries and so effective conservation requires integration of river management planning and

management of threats. Wetlands listed under the Ramsar Convention in Australia or the wetlands of national importance can trigger assessment of threatening processes under provisions of national conservation legislation. The building of dams, floodplain development and diversion of water resources are probably the most deleterious and pervasive threats to inland river systems (Lemly *et al.* 2000). About 89% of all surface water used in NSW (9000000 ML in 1996/1997) was for irrigation, increasing by 52% between 1983/1984 and 1996/1997 (National Land and Water Resources Audit 2001b). Our wetland inventory identifies the focus for conservation and management against potential threats (Tables 5,6). Most major regulated rivers (Murray, Murrumbidgee, Lachlan, Macquarie, Namoi, Gwydir and Border) have significant potential storage capacity and approximately 20% or more of their catchments is used for intensive agriculture, resulting in many wetland areas becoming reduced (Kingsford 2000a,b). The concentration of wetlands (46%) in four north-west catchments (Paroo, Warrego, Far north-west, Condamine–Culgoa) with relatively little water resource development should be a focus for wetland conservation and threat management. One of these, the Condamine–Culgoa, underwent considerable water resource development during the 1990s (Kingsford 2000b; Thoms and Parsons 2003), potentially affecting as much as half of the floodplain wetland identified in the NSW portion of the Condamine–Culgoa catchment (i.e. ~350000 ha). Apart from on the coast (Table 6), urban development is not a direct threat to wetlands because it is sparse (Tables 5 and 6) but, indirectly, people living on the coast have food and clothing requirements that affect the conservation of wetlands on inland rivers. The impact and threat of the draining of wetlands could not be quantified because of the lack of distributional data.

In conclusion, wetlands are among the more diverse ecosystems in the world but many continue to be destroyed or degraded by anthropogenic impacts. Mitigation of further degradation and loss is dependent partly on a strategic approach to wetland conservation and assisted by large-scale inventories. The first step is to produce a simple inventory that is not hampered by multiple objectives or disagreement about classification.

We developed such a wetland inventory for a considerable area of Australia (Fig. 2), with immediate applications. The inventory was the first step to developing priorities for conservation effort across the State and the management of threats at different scales; that is, catchments or the entire province (i.e. NSW). Much still remains unknown for wetlands of NSW, including relative conservation value; hydrology; the distribution of aquatic biota; and spatial scale of threats affecting ecological health. Our inventory can form the basis for related questions. It can also be used for other *a posteriori* classifications that relate to particular objectives (e.g. geomorphology and vegetation). Ideally, the physical,

Table 5. Areas (ha) of wetland covered by different land conservation measures (National Parks and Wildlife Service (NPWS) reserves, State forests, State Environmental Planning Policy No. 14 (SEPP 14), A Directory of Important Wetlands in Australia (DIWA) and listed under the Ramsar Convention) in each of the 17 inland catchments in New South Wales (1–17, see Fig. 1), and major threats in terms of water resource development and area covered by intensive agriculture

Catchment	NPWS		Land conservation measure ^a		Ramsar		Intensive agriculture ^c % ^d	Threat No. weirs	Storage capacity (× 10 ³ ML) ^e
	Area	%	State forests Area	%	Area	%			
Paroo (1)	26605	4	0	0	181962	27	0	0	0
Warrego (2)	3036	1	0	0	1095	0	0	0.8	42
Condamine–Culgoa (3)	18527	3	0	0	37716	5	3161	10.4	27
Darling (4)	29237	5	0	0	82755	14	0	0.6	9
Border (Moonie) ^f (5)	0	0	0	0	0	0	0	22.2 (14.6)	67
Gwydir (6)	82	<1	0	0	28304	48	708	25.7	71
Namoi (7)	0	0	0	0	6776	13	0	19.9	111
Castlereagh (8)	0	0	0	0	0	0	0	20.0	37
Macquarie (9)	15183	4	125	0	218326	52	15743	25.8	332
Lachlan (10)	3268	<1	5766	1	78584	17	0	22.9	323
Murrumbidgee (11)	146	<1	14676	5	7481	3	0	25.9	339
Lake George (12)	0	0	0	0	12833	99	0	15.4	—
Murray catchments	903	<1	116549	31	150863	40	0	50.0	118
Upper Murray (13)	0	0	0	0	0	0	0	8.4	15
Riverina (14)	0	0	95725	36	148879	57	0	30.1	101
Benanee (15)	903	1	14223	22	1964	3	0	2.2	2
Lower Murray (16)	0	0	6601	14	20	<1	0	9.3	0
Far north-west (Lake Bannania) ^f (17)	6648	2	0	0	34982	13	240	0.05 (0.0)	12
Total of all wetlands	103635	2.4	137116	3.2	841677	19.5	19852	<1	1504
									18751

^aConservation measure areas are mutually inclusive.

^bA Directory of Important Wetlands in Australia (Environmental Australia# 2001).

^cNational Land and Water Resources Audit (2001b) for catchments that cross the New South Wales border. Proportions include areas outside the state border.

^dPercentage relative to catchment land area.

^eDerived from Kingsford (1995) and National Land and Water Resources Audit (2001b) and where storage capacities differ, the larger storage capacity is used. Interstate catchments storage capacities include areas outside New South Wales.

^fSeparate estimates for agricultural land proportion only are given in parentheses.

Percentages are relative to total wetland area within a catchment.

Table 6. Areas (ha) of wetland covered by different conservation land measures (National Parks and Wildlife Service (NPWS) reserves, State forests, State Environmental Planning Policy No. 14 (SEPP 14), A Directory of Important Wetlands in Australia (DIWA), and listed under the Ramsar Convention) in each of the 22 coastal catchments in New South Wales (18–39; see Fig. 1), and major threats in terms of water resource development and area covered by intensive agriculture

Catchment	Conservation land measure ^a										Threat No. weirs	Storage capacity (× 10 ³ ML) ^d	
	NPWS		State forests		SEPP 14 ^b		DIWA ^c		Ramsar				
	Area	%	Area	%	Area	%	Area	%	Area	%			
Tweed (18)	689	19	0	0	841	23	853	23	0	0	22.8	36	17
Brunswick (19)	171	24	0	0	294	41	0	0	0	0	30.8	7	0
Richmond (20)	2370	26	62	1	3506	39	1787	20	0	0	9.9	188	34
Clarence (21)	1399	9	0	0	1943	12	11502	71	59	<1	5.1	106	7
Bellinger (22)	556	12	45	1	1513	33	0	0	0	0	11.9	23	0
Macleay (23)	904	18	34	1	1430	29	2452	49	0	0	14.3	42	19
Hastings (24)	3527	42	0	0	3333	40	2975	35	0	0	3.7	48	2
Manning (25)	1147	20	0	0	2134	37	1758	31	0	0	6.1	27	4
Karuah (26)	12973	29	170	<1	8962	20	35249	79	11224	25	6.6	11	0
Hunter (27)	3388	57	0	0	2807	47	3873	65	3099	52	12.1	123	1670
Macquarie–Tuggerah Lakes (28)	168	1	0	0	691	3	9516	42	0	0	34.0	49	89
Hawkesbury–Nepean (29)	1494	9	0	0	98	1	1069	7	0	0	19.0	444	2929
Georges–Cook (30)	443	4	0	0	0	0	974	8	400	3	8.5	47	124
Illawarra–Port Hacking (31)	132	3	0	0	225	4	3702	71	0	0	23.1	25	1
Shoalhaven (32)	819	18	0	0	1129	25	3486	78	0	0	13.7	48	178
Clyde (33)	981	8	0	0	1448	11	9223	71	0	0	1.6	15	7
Deua (34)	61	8	0	0	285	35	76	9	0	0	3.5	6	5
Tuross (35)	571	15	21	1	341	9	1126	30	0	0	7.5	8	0
Bega–Dry (36)	161	5	30	1	543	18	1324	44	0	0	9.1	56	16
Towamba (37)	639	30	0	0	509	24	1023	48	0	0	1.6	5	0
Genoa (38)	0	0	0	0	0	0	0	0	0	0	1.5	0	0
Snowy (39)	271	34	0	0	0	0	343	43	41	5	11.8	24	5494
Total of all wetlands	32864	17.5	362	0.2	32032	17.0	92311	49.1	14823	7.9		1338	10596

^aConservation measure areas are mutually inclusive.

^bState Environmental Planning Policy No. 14.

^cA Directory of Important Wetlands in Australia (Environment Australia 2001).

^dDerived from National Land and Water Resources Audit (2001a, 2001b) and Kingsford (1995) and where storage capacities differ, the larger storage capacity is used.

^ePercentage relative to catchment land area.

Percentages are relative to total wetland area within a catchment.

chemical or biotic data layers overlaid on an inventory of the distribution and extent of wetlands can derive objective classifications for biota (Munger *et al.* 1998) and landscapes (Gwin *et al.* 1999). Inventory information for wetlands allows priorities to be set for conservation but this is not a panacea. Further loss or degradation of wetlands will only be avoided with political, community and bureaucratic commitment to their conservation.

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