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# Monitoring waterbird populations with aerial surveys – what have we learnt?

*R. T. Kingsford*[A,B] *and J. L. Porter*[A]

[A]School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW 2052, Australia.
[B]Corresponding author. Email: richard.kingsford@unsw.edu.au

**Abstract.** We can use aerial surveys of waterbirds to identify high-conservation-value wetlands, estimate species' abundance and track changes in wetland condition. Two major approaches prevail. Transects to estimate a few species (1–20, often ducks) are predominantly used in North America and counts of entire waterbird assemblages on discrete wetlands are favoured in Australia. Such differences reflect wetland type, discrete (whole count) and continuous (transect) sampling, different objectives and history. There are few continuous large-scale aerial surveys of waterbirds, despite cost efficiencies and effectiveness. We review the eastern Australian waterbird survey that samples about one-third of the continent (2.697 million $km^2$). Each October, during 1983–2007, all waterbirds were estimated on an average of 811 wetlands, within ten 30-km-wide survey bands, separately extending across latitudes from the east coast to central Australia. The survey has demonstrated the importance of arid wetlands for waterbirds and provided management data on distribution, abundance and breeding of waterbirds. Most significantly, long-term temporal data for individual wetlands provided strong evidence for the impacts of water resource development (dam building, diversion of water). These data have influenced wildlife management, river rehabilitation and restoration policies at a national scale.

## Introduction

The collection of data on the distribution and abundance of organisms is fundamental to ecology, wildlife management and conservation biology. Key questions of habitat use, conservation of species or their management and measurement of anthropogenic impacts require well established and repeatable methods for data collection. Unlike many groups of organisms, research on waterbirds has a long history, primarily driven by the imperative to manage recreational hunting of populations of waterfowl or wildfowl (Anatidae, ducks, geese and swans). More recently, the focus has shifted to the potential of waterbird surveys to monitor anthropogenic impacts on freshwater aquatic ecosystems.

Aerial surveys have become an increasingly popular way of estimating the distribution and abundance of waterbird populations because large areas can be surveyed at relatively low cost (Kingsford 1999). As with most surveys, the objective is to develop repeatable methods that collect data effectively, allowing for spatial and temporal comparisons, while maximising coverage and minimising costs. Caughley (1974, 1977) and Jolly (1969*a*, 1969*b*) provided the rigorous framework for collection of aerial survey data for wildlife populations, identifying and separating sampling error from counting error (visibility bias). Sampling error affects all surveys that do not census wildlife populations and is catered for in survey design and data analyses. Counting error has proved the most serious problem for aerial surveys. The speed of the aircraft, limitations of the visual acuity of observers (including interobserver difference) and a plethora of 'habitat' characteristics obscure animals and produce errors, mostly underestimates (Caughley and Goddard 1972; Caughley 1974; Pollock and Kendall 1987). Following initial development of aerial survey techniques, research effort moved to estimation and 'correction' for visibility bias (Cook and Jacobson 1979) for a range of different animal species, mostly large mammals (Caughley *et al*. 1976; Barnes *et al*. 1986; Bayliss 1986; Marsh and Sinclair 1989; Crête *et al*. 1991) but also waterbirds (Broome 1985; Bayliss and Yeomans 1990*a*) and their nests (Jackson 1985; Bromley *et al*. 1995). This affected the value of aerial survey as a reliable technique for addressing wildlife management or environmental problems (Routledge 1981), largely because of the considerable error identified and range of contributory factors. The critical issue of effect size was seldom discussed but relevant to detection of large spatial and temporal change in the context of measurement error.

We briefly review the current use of aerial surveys for waterbirds and then focus on the successes and challenges of one of the longest-running wildlife surveys in Australia, the eastern Australian waterbird survey, particularly in its value for monitoring anthropogenic landscape changes to rivers and dependent aquatic ecosystems.

### *Aerial surveys of waterbirds*

In the late 1940s, the potential value of aerial surveys for waterbirds was first recognised for North American wetlands, subsequently developing into the world's most extensive waterbird survey (Martin *et al*. 1979). Much of the published research effort focussed on sampling and counting errors of aerial surveys of waterbirds. Aerial survey estimates of waterbirds are inevitably inaccurate and imprecise estimates of abundance (Diem and Lu 1960; Joensen 1968; Bromley *et al*. 1995; Gabor *et al*. 1995; Dolbeer *et al*. 1997; Kingsford 1999)

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because of the rapidity of the technique and factors that contribute to visibility error (Rodgers *et al*. 1995; Frederick *et al*. 1996; Hodges *et al*. 1996). Usually, aerial survey estimates underestimate waterbird or nest abundance compared with ground surveys (Bayliss and Yeomans 1990*b*; Dexter 1990; Frederick *et al*. 1996; Kingsford 1999; Rodgers *et al*. 2005), although relatively few studies have attempted to measure accuracy of ground counts that are also prone to error, including visibility bias. Double counting, poor visibility because of vegetation and often limited access to large wetlands affect estimates from ground or boat. Bias in aerial surveys of waterbirds is often density dependent (Joensen 1968, 1974; Dexter 1990; Kingsford 1999), possibly reaching a plateau (Dexter 1990). Aerial surveys are also imprecise where more than one survey has been done of the same population. Precision estimates for the same waterbird aggregation varied from 0.7, 0.38, 0.25 and 0.18 for waterbird species in the respective abundance categories of ≤10, 11–100, 101–1000, and >1000 (Kingsford 1999). Waterbirds are difficult to see under vegetation (Diem and Lu 1960; Bayliss and Yeomans 1990*b*; Smith *et al*. 1995; Frederick *et al*. 1996) or when they dive (Joensen 1968, 1974; Kingsford 1999). Glare, wind and rain, and water turbulence all affect estimates (Joensen 1968, 1974).

While research has focussed on identifying and quantifying sources of error, management and conservation agencies have expanded the use of aerial surveys for waterbirds globally, using different approaches. The advantages of extensive coverage at relatively low cost, coupled with the ability to survey inaccessible wetlands and avoiding double counting by flying faster than the waterbirds are distinct advantages. Sampling methodologies (survey design, habitats) and choice of species for aerial surveys of waterbirds have varied from single- to multispecies aggregations. Apart from the breeding waterbird survey that targets 20 duck species (Table 1), many North American waterbird surveys have focussed on a few or a single waterbird species and their nesting, mostly waterfowl (Anatidae) (McLaren and McLaren 1982; Johnson *et al*. 1989; Reinecke *et al*. 1992; Schneider *et al*. 1994; Drewien *et al*. 1996; Dolbeer *et al*. 1997; Drewien and Benning 1997). By contrast, many of the Australian waterbird surveys have surveyed all waterbirds using discrete wetlands, although not all (Table 1). Occasionally, quadrats (Eggeman *et al*. 1997), but more commonly transects, are used to survey waterbirds, particularly in North America (Conroy *et al*. 1988). This technique may reflect an imperative to increase accuracy and precision, as narrow transects increase the detection of waterbirds compared with wide transects (Briggs *et al*. 1985; Smith *et al*. 1995) and also allows for sampling and requisite replication (Eggeman *et al*. 1997). However, discrete wetlands may not be easily identifiable particularly making transects the only option. Transects are the preferred method for seaducks (Mosbech and Boertmann 1999; Johnson *et al*. 2005; Cranswick *et al*. 2006) and also large floodplain areas (Kingsford *et al*. 1999*a*; Halse *et al*. 2005). Most surveys in Australia estimate distribution and abundance of waterbirds on discrete wetlands, connected to rivers (Kingsford and Porter 1993; Halse *et al*. 1998; Kingsford 1999; Kingsford *et al*. 2004*a*).

There are a few large-scale aerial surveys of waterbirds around the world. One of the longer and more extensive wildlife surveys in the world is the breeding waterbird survey of North America that began in the 1950s (Diem and Lu 1960) (Table 1). Estimates are made of 20 species of ducks, systematically surveyed each year on the breeding grounds of North America (central and eastern parts) covering ~3.37 million km$^2$, using 65 strata within which a series of random 200-m-wide transects and within these 25.6- or 28.8-km segments are flown each year (Blohm *et al*. 2006). An additional 1.8 million km$^2$ was surveyed after 1996 in north-eastern United States and Canada. One side of the aircraft is counted by a pilot-biologist while the other side is counted by a biologist. The primary objective is to supply population data for the establishment of harvest or bag limits for waterfowl, estimated at 14 million waterfowl in 2002 (Padding *et al*. 2006).

A few regional aerial surveys of waterbirds have been conducted across eastern and western Europe but seldom maintained continuity (Table 1). In Denmark, the numbers of mostly ducks, geese and swans were estimated during 14 country-wide surveys (1966–73) to determine their distribution, abundance and potential implications for hunting (Joensen 1968, 1974). Coverage of areas varied. In Sweden, between 1969 and 1974, 14 districts were surveyed to estimate distribution and abundance of Anatidae and provide a total abundance of more than 200 000 (Nilsson 1975). Multispecies aggregations were estimated across 25–39 wetlands in Uzbeckistan in 1986–88 and 2000 (Kreuzberg-Mukhina 2006).

## Aerial surveys of waterbirds in Australia

In Australia, aerial surveys are a popular and effective method for estimating the distribution and abundance of waterbirds from the individual wetland to large regional scales (Fig. 1), with at least 17 major regional or large-scale aerial surveys of waterbird populations in Australia since the 1980s (Table 1). Most of these have monitored the distribution and abundance of waterbirds in response to flooding or documented the composition of waterbirds using a particular wetland or estuarine site (shorebirds). Total counts or partial counts of individual wetlands are the dominant method used, where documented, although when wetlands are extensive and homogenous (e.g. floodplains), transects are adopted (Morton *et al*. 1990*a*; Halse *et al*. 1995; Kingsford *et al*. 1999*a*). Of all aerial surveys on the continent, the longest-running and most extensive is the eastern Australian aerial survey of waterbirds, sampling about one-third of the continent (Table 1, Fig. 1).

In the early 1980s, there were estimated to be more than 100 000 recreational duck-hunting licences in eastern Australia, and this number was increasing. Abundance data for duck populations was relatively poor and primarily consisted of bag size indices and surveys of waterfowl populations before hunting seasons on a few major wetlands (Briggs *et al*. 1983, 1993). In contrast, there was good understanding of basic biology of many waterfowl species (movements, habitat use, food, breeding) (see review in Kingsford and Norman 2002). At the time, conservation authorities in the southern states of Australia (independently responsible for managing wildlife) decided to implement an aerial survey that extended across eastern Australia, given the mobility of waterbirds (Fig. 1). In the second year, the survey was extended north into the tropics with two additional northern survey bands (Fig. 1, Table 1) but these were not flown

**Table 1. Summary of large-scale aerial surveys of waterbirds outside Australia and regional and large-scale aerial surveys of waterbirds within Australia**

Superscript numbers refer to locations on Fig. 1

| Country | Name of survey[A] | Description | Time frame | References |
|---|---|---|---|---|
| Denmark | National survey | Two surveys (routes varied) of ducks, geese, swans, Great cormorant and Eurasian coot. Flocks counted individually | 1967–68 | Joensen (1968, 1974) |
| Sweden | National survey | Six national surveys (1969–74) of Anatidae across the country to compare seasonal and annual distribution | 1969–73 | Nilsson (1975, 1977) |
| Tanzania | Soda Lakes | Lesser flamingo (*Phoenicopterus minor*) populations on lakes | 1969–2004 | Mlingwa and Baker (2006) |
| USA and Canada | Winter and breeding waterbird survey | Aerial surveys of strata across central, northern (Alaska) and eastern North America focusing on 20 species of ducks | 1935–present, 1955–present | Martin *et al*. (1979); Hodges *et al*. (1996); Blohm *et al*. (2006) |
| USA–Mexico | Mexico | Wildfowl population trends in Mexico, 1961–2000, based on US Fish and Wildlife Surveys in mid-winter of 24 wildfowl species | 1961–2000 | Pérez-Arteaga and Gaston (2004) |
| USA | Florida Everglades | Monitoring wetland ecosystems using avian populations: 70 years of surveys in the Everglades | | Frederick and Ogden (2003) |
| Uzbekistan | Winter waterbird distribution | 23–39 water storages surveyed for distribution and abundance of 50 species of waterbirds | 1986–88, 2000–04 | Kreuzberg-Mukhina (2006) |
| Australia | Aerial survey of waterbirds in eastern Australia[1a] | Annual survey on 10 survey bands (30 km wide) across eastern Australia. Up to 50 waterbird species surveyed on up to 1250 wetlands | 1983–2007; 25 years of data | Braithwaite *et al*. (1985*a*); Kingsford *et al*. (1999*b*), Kingsford *et al*. (1997*b*) |
| | Two survey bands into northern Australia[1b] | Survey on two survey bands (30 km wide) across eastern Australia in northern Australia. Up to 50 waterbird species surveyed | 1984 | Braithwaite *et al*. (1985*b*) |
| | Two survey bands in Tasmania[1c] | Survey on two survey bands (30 km wide) across eastern Australia in Tasmania. Up to 50 waterbird species surveyed. | 1995 | Kingsford *et al*. (1997*a*) |
| | Murray–Darling Basin[1d] | Survey on seven survey bands (30 km wide) randomly placed within the Murray–Darling basin. Up to 50 waterbird species surveyed | 1995 | Kingsford *et al*. (1997*b*) |
| | Waterbirds of south-western Australia[2] | Surveys of ducks, swans and coots at ~350 waterbodies in stratified survey design across south-west WA used to estimate total waterfowl numbers in region. November counts in 1986–87, subsequently November and March. Ground comparisons made at selected wetlands | 1986–92 | Halse *et al*. (1990, 1992, 1994, 1995*a*); Jaensch and Vervest (1988) |
| | Waterbirds of north-western New South Wales[3] | Surveys on more than 20 wetlands every three months in north-western NSW. Surveys involved four counts at each time period | 1987–90 | Kingsford *et al*. (1994); Roshier *et al*. (2002) |
| | Waterbirds of the Alligator Rivers Region[4] | Fixed transects were surveyed once a month for all waterbird species on the Magela, Nourlangie, East Alligator and Boggy Plain floodplains | 1981–84 | Morton *et al*. (1990*a*, 1990*b*, 1993*a*, 1993*b*, 1993*c*) |
| | Magpie geese in Arnhem Land[5] | Abundance and nesting colonies of magpie geese were estimated on the coastal floodplains of Arnhem Land. Numbers varied from ~2 to 3 million while numbers of nests varied from ~1.5 million to 2.5 million. | 1984–86 | Bayliss and Yeomans (1990*a*, 1990*b*) |
| | Lake Gregory[6] | Counts of the Lake Gregory system 1989, 1990, 1991, 1993, 1995, 1998, 2000, 2005 | | Halse *et al*. (1998) |

(*continued next page*)

**Table 1.** (*continued*)

| Country | Name of survey[A] | Description | Time frame | References |
|---|---|---|---|---|
| | Migratory shorebirds in the Gulf of Carpentaria[7] | Four summer surveys and four winter surveys were done of different parts of the coast surveying shorebirds | 1981–84 | Garnett (1987) |
| | Mandora Marsh[8] | Transect counts in August 1999 and June and August 2000 | | Halse *et al*. (2005) |
| | Wetlands surveyed as part of Arid Flo[9a–d] | Observers counted wetland areas with transects and total or proportion counts | | Arid Flo Project, unpubl. info. |
| | Lower Cooper wetlands[10] | Three monthly surveys flown over the major wetland systems of the Lower Cooper including Lake Eyre | 1989–90 | Kingsford and Porter (1993); Kingsford *et al*. (1999*a*) |
| | Currawinya Lakes[11] | Surveys were done on two lakes (Wyara and Numalla) in south-western Queensland every three months. Surveys involved four counts in each period | 1987–90 | Kingsford and Porter (1994) |
| | Cape Barren Goose populations in Western Australia[12] | Helicopter survey of all but two islands/islets in the Archipelago of the Recherche and plane survey of surrounding coastline | 1995 | Halse *et al*. (1995*a*) |
| | Tanami Desert wetlands[13] | 19 wetlands surveyed for all waterbirds over a two-day period | 2006 | Reid *et al*. (2006) |
| | Cambridge Gulf[14] | Surveys in February and April 1993 of the Victoria–Bonaparte mudflat, adjacent coast (extending east of the Victoria River in NT) and wetlands on the Ord River floodplain | | Halse *et al*. (1996) |
| | Western NT[15] | Counts of waterbirds within ~15 200-m-wide transects in the Northern Territory in April 1993 after cyclonic rainfall in February | | Jaensch (1994) |
| | Fitzroy Valley[16] | Counts at selected wetlands in the Fitzroy Valley, WA, in April 1993 and 2005. Survey in 1993 was part of a wider survey of Magpie Geese in northern WA | | Halse and Pearson (1993) |
| | North-west WA shorebird counts[17] | Irregular counts of shorebirds in coastal sites since 1982, with focus on Roebuck Bay and Eighty-mile Beach (associated with ground counts) | | Minton and Martindale (1982); Minton and Jessop (1994) |

[A]Refer to Fig. 1 for locations.

again because these areas supported mainly tropical waterfowl species that seldom extend south to areas of recreational hunting in eastern Australia (Frith 1982). The western limit of the survey (Fig. 1) fitted with logistical constraints and reflected a belief that the arid zone was not suitable habitat for waterfowl (Frith 1982).

The first survey was in 1983, supported by the conservation authorities of the eastern states of Australia (New South Wales, Queensland, South Australia,Victoria), the Australian Government and CSIRO, under Wayne Braithwaite (CSIRO) and Mike Maher (NSW National Parks and Wildlife Service). The survey, designed by Graeme Caughley, sampled an area of 2.697 million $km^2$, covering 12%, with 10 survey bands of 30 km width, systematically spaced every 2° of latitude (Braithwaite *et al*. 1986; Kingsford *et al*. 1999*b*) (Fig. 1). Systematic survey bands were chosen, primarily for navigation ease. Knowledge of the distribution of wetlands within Australia, particularly inland Australia was poor in 1983 and there was the possibility of bias due to systematic variation in environmental features or waterbird populations, potentially lowering precision and possibly producing autocorrelation and affecting standard error estimates (Caughley 1977). This was outweighed by the practical constraints of surveying large expanses of inland Australia. In 1995, the survey was extended south to Tasmania (Fig. 1) but there were relatively few wetlands within the systematic survey bands and they were not continued.

On topographic maps (1 : 250 000), all wetland features >1 ha (lakes, swamps, floodplains, rivers, reservoirs) were marked within each survey band. We surveyed individual wetlands within the survey bands. The aircraft (high-winged Cessna) was then flown (167 km $h^{-1}$, 46 m height) from marked wetland to wetland, with each surveyed for the full complement of waterbirds, including cormorants, grebes, herons, egrets, ibis, waterfowl, wading birds. In addition, small (<1 ha) wetlands (usually farm dams) were surveyed on an *ad hoc* basis while travelling between marked wetlands. More than 50 taxa were identified and counted, mostly to species level although grebes, egrets and waders were grouped because of difficulties in differentiation (Kingsford *et al*. 1999*b*). Three different counting techniques were employed, depending on the wetland and the distribution of waterbirds. First, for most wetlands, circumnavigation was the preferred method, given the often clumped distribution of waterbirds. The aircraft was positioned at ~150 m from the shoreline where most

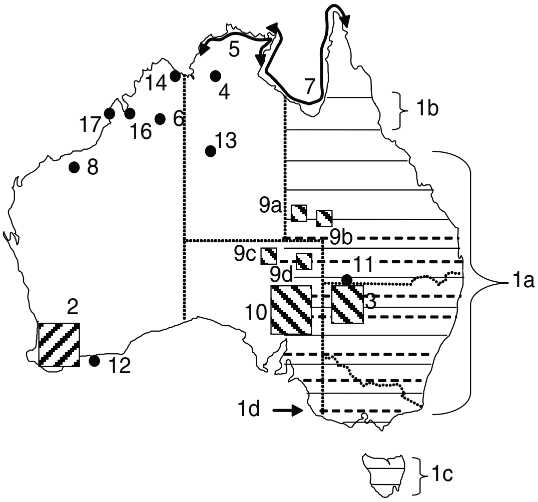


**Fig. 1.** Location and coverage of major aerial surveys in Australia. Horizontal lines (30 km wide) show the 10 survey bands of the eastern Australian aerial survey flown each October, 1983–2007 (1), the two northern survey bands flown in 1984 (1*b*) and the two survey bands flown across Tasmania in 1995. Dashed lines were flown in only 1985 and 1995. Hatched blocks were regional surveys of wetlands. See Table 1 for full details of surveys matching numbers.

waterbirds occur (Kingsford and Porter 1994), with one observer counting all waterbirds to the shoreline while the other counted to the middle of the wetlands using recorders. Second, a proportion was surveyed and estimated as it was difficult to cover an entire wetland with manoeuvrability constraints of the aircraft around narrow bays and inflowing creeks. Further, only half of some large wetlands (predominantly reservoirs with few birds) were surveyed because of constraints on fuel and flying time. Proportional counts were extrapolated to estimate total abundance on the wetland. Finally, transects were used to estimate numbers on a few large wetlands consisting of braided channels and vegetation (e.g. floodplains) without a defined edge and where waterbirds were distributed throughout the wetland. Each transect delineated a 200-m-wide strip (100 m each side) across the wetland. Final estimates for a particular wetland were an extrapolation of raw counts from the area surveyed relative to the entire wetland.

During a review workshop in 1987, the survey program was criticised for not surveying all key wetlands, for lacking correction factors, for employing transect bands and not strata (as in North America), and for using systematic sampling and not random sampling. Also, improvements to methodology were suggested. Inevitably, not all key wetlands were surveyed – a reality of sampling. At the time, arguments about actual numbers of kangaroos estimated during aerial surveys and associated correction factors were an area of considerable research focus and controversy, largely because of public concern about the mismatch between number of kangaroos harvested and aerial survey data – both indices of extant populations with different errors. Subsequently, estimates from waterbird surveys were communicated as an index, not a true estimate, on the recommendation of Graeme Caughley; little subsequent effort was invested in identifying forms of visibility bias. Use of systematic survey bands each year, as opposed to random selection, simplified navigation but this proved to be a critically important decision because it provided long-term data for individual wetlands and evidence of decline and wetland degradation. Survey methodology was maintained to ensure comparability across surveys although considerable improvements were implemented in recording and processing data and navigation (e.g. GPS).

After 25 years, the survey remains one of Australia's longest and most extensive wildlife surveys, ranging over a large expanse of the continent. It has assisted in the management of recreational duck hunting, provided evidence for the conservation importance of inland wetlands, influenced river protection and environmental flow policies, provided population estimates of up to 50 waterbird taxa across eastern Australia, and contributed to understanding the dynamic use of wetland habitat. Aerial surveys of waterbirds are logistically difficult to plan with specific flying requirements and trained expertise in the identification and estimation of abundance of waterbirds, particularly in multispecies aggregations.

### *Management of recreational hunting*

Each year, Victoria, South Australia and Tasmania (also New South Wales and Queensland before cessation of recreational hunting seasons in 1995 and 2006 respectively) request estimates and interpretation of aerial survey data to determine the timing or operation of their recreational duck hunting seasons. Trends in estimates of all game species of waterfowl and all waterbirds in total are provided in Fig. 2*a*. The trend in the index of breeding (numbers of nests and broods) is also provided in Fig. 2*b*. In addition, we report the status of inundation on all major wetland sites to provide an index of the availability of feeding, breeding and refuge sites away from hunting pressure in the south-east. Estimates of low numbers, poor breeding indices and lack of flooding in areas remote from recreational hunting are key factors considered by conservation authorities each year. There is no clear link between abundance estimates and trends and actual quotas decided for hunting, except if there is broad concern about effects of hunting on concentrated populations in Victoria and South Australia where there is still recreational hunting. In 2006 and 2007, recreational hunting seasons were not declared in Victoria or South Australia, substantially relying on the data from the aerial survey of eastern Australia combined with meteorological and river flow data for major river systems. As the main original objective was focussed on management of game species of waterfowl, October was chosen for surveys as it would provide an estimate of recruitment of birds breeding in the southern spring (Kingsford and Norman 2002) but also avoid poor weather for flying during the northern monsoons of November onwards.

### *Importance of inland Australia's wetlands*

Over the aerial survey period 1983–2007, a mean of 811.5 (±214.73 s.d., range 458–1223, $n = 25$ years) wetlands were surveyed annually, with the number primarily dependent on the extent of rainfall and flooding. About 80% of all waterbirds were on only 30 of the wetlands surveyed each year (3.7% of all wetlands) (Fig. 3*a*). Even fewer

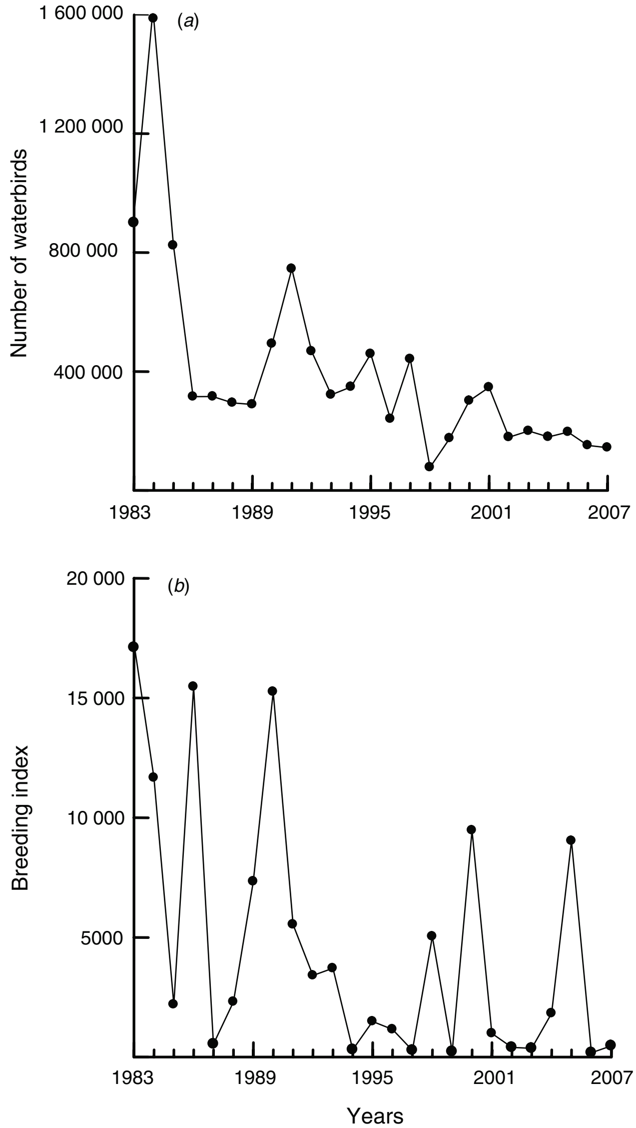


**Fig. 2.** Annual estimates of (*a*) total waterbird abundance (more than 50 taxa) and (*b*) breeding index from the eastern Australian aerial surveys of waterbirds (1983–2007).

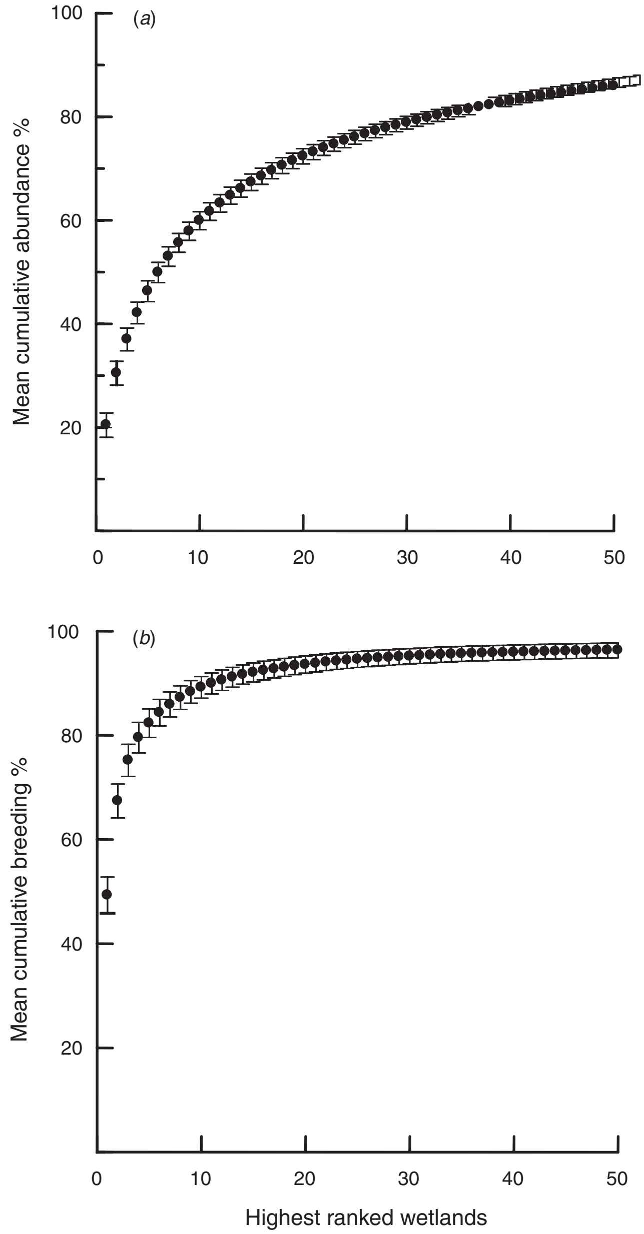


**Fig. 3.** (*a*) Mean (±s.e., $n=25$) cumulative percentage abundance and (*b*) breeding index versus abundance rank (within years) of the 50 highest-ranked wetlands each year over the 25 years of the survey of waterbirds in eastern Australia, 1983–2007.

wetlands support breeding birds (Fig. 3*b*). Data from 25 years of surveys allowed ranking of important wetlands within the area surveyed where most waterbirds have aggregated each year in terms of abundance and species diversity (Table 2). This provides a quantitative assessment of conservation importance in terms of waterbirds. Many of these wetlands (Table 1) were in the arid zone of Australia, comprising ~70% of the continent (Stafford Smith and Morton 1990). This area was originally undervalued for waterbirds by most biologists (but see Briggs 1982) because it was inhospitable and research effort was generally biased towards research institutions in more mesic regions (Kingsford 1995).

The composition and abundance data from the eastern Australian aerial survey and subsequent surveys (Table 1) clearly demonstrated the importance of arid-zone wetlands and the rivers on which they rely (Kingsford and Porter 1993, 1994; Halse *et al*. 1998; Kingsford *et al*. 1999*a*). In addition, understanding of the extent of wetland habitat in inland areas (Roshier *et al*. 2001*a*) and their use by waterbirds (Roshier *et al*. 2001*b*, 2002) has increased considerably. Waterbirds are capable of long-distance and varied movements across inland wetland habitats (Roshier *et al*. 2008*a*, 2008*b*). There is considerable potential to investigate how individual waterbird species respond to ecological processes or habitat distribution, availability and structure using the collected aerial survey data and increasing availability of habitat data (Kingsford *et al*. 2004*a*). Understanding the conservation importance of inland wetlands

**Table 2. Listing of 20 highest-ranked wetland by mean (±s.e.) abundance of waterbirds, over the entire period 1983–2007 of aerial survey of waterbirds in eastern Australia**

*n*, number of years of survey data (any wetlands with <25 were dry in some years)

| Wetland | *n* | Mean abundance | s.e. | Area (ha) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| Lake Galilee | 17 | 120 470 | 86 191 | 14 845 | 22°29′04″ | 145°46′13″ |
| Lake Torquinie | 6 | 63 144 | 9355 | 2417 | 24°33′26″ | 138°37′49″ |
| Lake Eyre | 3 | 49 918 | 36 222 | 203 021 | 28°22′00″–28°38′00″ | 137°20′59″ |
| Lowbidgee | 25 | 48 200 | 10 278 | 102 535 | 34°22′00″–34°38′00″ | 143°24′00″–144°18′00″ |
| Coorong and dune swamps | 24 | 46 979 | 20 257 | 32 636 | 36°22′00″–36°38′00″ | 139°44′00″–140°20′00″ |
| Cooper Creek | 13 | 45 601 | 9029 | 5634 | 28°22′00″–28°38′00″ | 137°40′00″–139°23′00″ |
| Mulligan River dunefield swamp | 1 | 39 280 | – | 50 | 24°31′46″ | 138°52′48″ |
| Mumbleberry Salt Lake | 7 | 33 236 | 13 341 | 1292 | 24°28′35″ | 138°39′24″ |
| Lake Hope | 12 | 21 343 | 7376 | 3164 | 28°23′37″ | 139°18′56″ |
| Menindee Lakes | 22 | 21 099 | 7374 | 25 713 | 32°22′00″–32°38′00″ | 141°54′00″–142°20′00″ |
| Cuttaburra Channels | 12 | 19 062 | 11 217 | 15 293 | 30°22′00″–30°38′00″ | 144°24′00″–144°32′00″ |
| Paroo Overflow | 24 | 17 947 | 4123 | 27 995 | 30°22′00″–30°38′00″ | 143°37′00″–144°25′00″ |
| Lake Moondarra | 25 | 12 446 | 2190 | 1715 | 20°35′01″ | 139°32′55″ |
| Tallywalka Creek | 12 | 12 169 | 5289 | 13 078 | 32°22′00″–32°38′00″ | 143°00′00″–143°30′00″ |
| Macquarie Marshes | 25 | 10 103 | 3773 | 8486 | 30°22′00″–30°38′00″ | 147°30′00″–147°42′00″ |
| Darling River | 25 | 7046 | 5538 | 75 509 | 30°33′51″ | 145°01′08″ |
| Werewilka Creek wetlands | 6 | 6868 | 5604 | 223 | 28°33′02″ | 144°16′06″ |
| Lake Phillippi (salt) | 2 | 5810 | 2680 | 16 086 | 24°24′31″ | 138°58′41″ |
| Coolmunda Dam | 24 | 4153 | 810 | 1640 | 28°25′43″ | 151°13′33″ |
| Copi Plains | 21 | 4114 | 2008 | 9245 | 34°24′47″ | 140°52′49″ |

for waterbirds has had policy implications for the management of the rivers that supply them. For example, the wetlands of Cooper Creek and the Paroo River were identified for their waterbird values in water policy discussions about the future of these rivers and proposed extraction of water for irrigation (Kingsford *et al*. 1998).

## *Changes in abundance*

Over the first 10 years of the survey (1983–92), abundances of 16 different species of waterbirds were variously related to rainfall (inside and outside the survey area), the Southern Oscillation Index and wetland area at different lags (Kingsford *et al*. 1999*b*). The importance of rainfall and associated flooding are important drivers for waterbird populations, creating habitats where many species can breed and recruit (see review in Kingsford and Norman 2002). Numbers of waterbirds estimated have declined significantly over time (1983–2007) ($R^2 = 0.477$, $P < 0.001$, $n = 25$, 4th root transformed to improve normality) (Fig. 2*a*) and, reflecting this trend, the breeding index has also declined significantly ($R^2 = 0.292$, $P = 0.005$ $n = 25$, 4th root transformed to improve normality) (Fig. 2*b*).

There have been a few analyses of trends and patterns of abundance for individual species (Dorfman 1997; Kingsford 1996; Kingsford *et al*. 1999*b*) or taxonomic groups (Nebel *et al*. 2008) for different periods of the survey. These have further shown that, even for these groups, there are a relatively few major wetlands where most of the population for a species occur. The migratory shorebird population was predominantly found to use 20 wetlands, most of which were inland Australia (Nebel *et al*. 2008). Pink-eared duck (*Malacorhynchus membranceus*) are highly nomadic with much of the population occurring on a few wetlands but the actual wetland varies each year (Kingsford 1996). Two of three species chosen for our analysis exhibited significant declines in abundance over the survey period (1983–2007) (Fig. 4): Australian pelicans (*Pelecanus conspicillatus*) ($R^2 = 0.347$, $P = 0.002$, $n = 25$, 4th root transformed) (Fig. 4*a*) and grey teal (*Anas gracilis*) ($R^2 = 0.524$, $P < 0.001$, $n = 25$, 4th root transformed) (Fig. 4*b*). Populations of migratory shorebirds (Charadriformes) have also declined significantly over time (Nebel *et al*. 2008). By contrast, the abundance of pink-eared ducks was highly variable and showed no significant trend over the survey period ($R^2 = 0.149$, $P = 0.478$, $n = 25$, 4th root transformed) (Fig. 4*c*). As well as estimates of trends in the number of a species estimated across the survey bands, it is also possible to estimate populations of species based on the 10 sample survey bands of the entire area, using methods for unequally sized transects (bands) (Caughley 1977). For example, mean populations of small migratory shorebirds varied between 24 954 ± 12 062 (s.e.) in the 1980s to 6683 ± 1190 (s.e.) in the 2000s, a decline of 65% over 25 years of the survey (Nebel *et al*. 2008). There remains considerable potential to investigate changing estimates of abundance for different species, including rare and endangered species, a focus of legislation and policy within government. It was not possible in this paper to report on the full range of potential biases and accuracy of these aerial surveys; some analysis is provided elsewhere, showing that ground and aerial counts track each other reasonably well but there are errors for both (Kingsford 1999). Further, we have standardised methodology throughout the surveys reported in this paper, to keep bias and errors constant over time. We are confident that the trends reported are real.

## *Effects of river regulation on wetlands*

Australia has developed many rivers over the past century, particularly in the Murray–Darling Basin for irrigation, with significant impacts on floodplain wetlands and their dependent

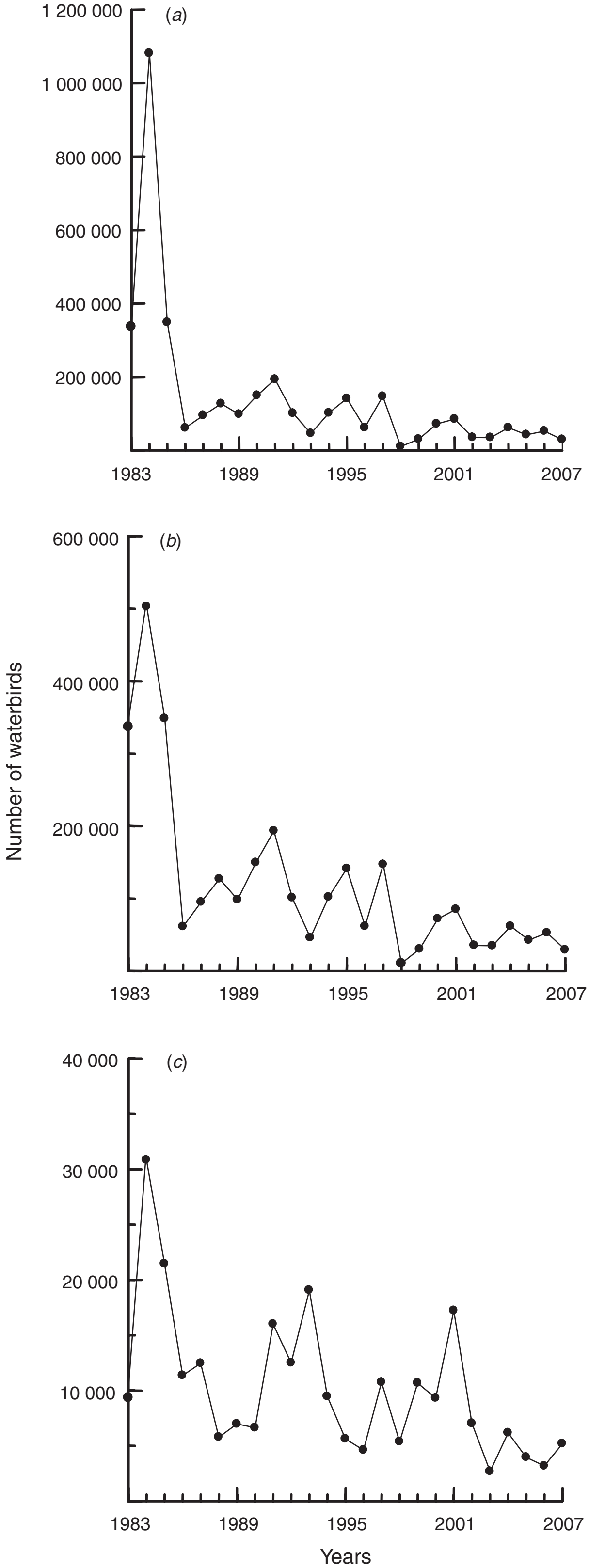


**Fig. 4.** Annual estimates of abundance of three species of waterbirds estimated during the aerial survey of waterbirds in eastern Australia: (*a*) grey teal, (*b*) Australian pelican and (*c*) pink-eared duck.

organisms (Kingsford 2000; Lemly *et al*. 2000). In 2004–05, Australia used ~24 million megalitres of water from its rivers each year. Most (~70%) of this amount was from only one of 12 river basins, the Murray–Darling Basin in the south-east of the continent (1.06 million $km^2$, 14% of continent: NLWRA 2001). Most rivers of the Murray–Darling Basin are regulated by large dams and diversions (Kingsford 2000). There is 1.4 times more storage capacity in dams as the mean annual flow and the median flow of the River Murray to the sea is reduced by 73% (Goss 2003). While comprehensive hydrological data are available for nearly all river systems and diversions, availability of biological data for the dependent ecosystems and their organisms is poor. What exists is usually confined to relatively small parts of the river basin, except for aerial surveys of waterbirds.

About 10% of the land surface area of the Murray–Darling Basin is covered by the eastern Australian waterbird survey, including some extensive floodplain wetlands. Aerial survey data collected each year over of the period of the survey were combined with analyses of satellite imagery and flows to show that significant degradation has occurred on three of the more important wetland sites in the Murray–Darling Basin. The Macquarie Marshes are listed as a wetland of international importance under the Ramsar Convention and abundance of waterbirds and number of species declined as flows to the area were reduced and the size of the wetland decreased by at least 40–50% (Kingsford and Thomas 1995). Separation of groups of waterbirds into guilds recorded about an 80% decline in total abundance but also in abundances of guilds on the Lowbidgee floodplain (Kingsford and Thomas 2004). The Lowbidgee floodplain was ranked third in all wetlands surveyed over the period of 25 years, despite its significant degradation (Table 2). Its ranking will decline further with each year as species richness and abundance on the wetland continue to decline (Kingsford and Thomas 2004). These analyses demonstrated that river-management policies in the Murray–Darling Basin did not effectively protect important wetlands and subsequently contributed to significant changes in water policy. Changes included a halt to increasing diversions from rivers of the Murray–Darling Basin and a commitment to buying water from the irrigation industry to return to rivers and augment remaining flows to wetlands such as the Macquarie Marshes.

Reductions in flows to wetlands were the most extensive anthropogenic impact but, as well, some large floodplain lakes close to the river (e.g. Menindee Lakes) were converted into storages. As a result, they were nearly always full, with water diverted for supply to towns or irrigation. Long-term data from aerial surveys of waterbirds demonstrated that this significantly affected the composition and density of the waterbird community (Kingsford *et al*. 2004*b*). Combining data from such regulated lakes with unregulated lakes, the aerial surveys showed that a variable flooding regime with natural flooding and drying cycles provided for the full range of waterbirds at high densities. As the waterbird community could be divided into foraging guilds, changes to the waterbird community implied changes to the distribution and abundance of other organisms (e.g. piscivores and fish species) and the ecosystem itself. This extended understanding of the potential impacts of river regulation on the suite of organisms in wetlands with relevance to river management.

Aerial surveys of waterbirds continue to provide long-term data on the wetlands covered during the survey each year, informing management authorities about the potential effectiveness of rehabilitation policies or demonstrating where there may be significant impacts of degradation on the entire wetland community. Systematic sampling has provided 25 years of data for ~800 wetlands, allowing for clear demonstration of significant environmental threats and problems for wetlands in the Murray–Darling Basin.

## Conclusions

Aerial surveys of waterbirds remain the only practicable way of answering the array of questions relevant to wildlife management and conservation (Caughley 1977). These range from those focussed on individual species to the relative value of freshwater ecosystems for waterbirds and the effects of anthropogenic impacts. For many waterbird populations, aerial surveys are proving the only way to collect data on waterbird populations over large areas at a relatively low cost (Kingsford 1999). Caughley (1977) summed it up: while the aerial survey 'estimate is usually inaccurate and often imprecise it answers a broad range of ecological questions to an acceptable level of approximation' (Caughley 1977). Major changes have occurred in the composition of waterbird communities on some wetlands over time. An effect such as an 80% decline in waterbird abundance (Kingsford and Thomas 2004) is so large that it swamps intractable visibility bias. Even for largely naturally functioning wetlands, there were orders of magnitude changes in the abundance of entire waterbird assemblages and individual species that subsumed the errors in the technique (Kingsford 1999).

A focus on quantifying visibility error and resulting relatively poor performance of aerial surveys for estimating abundance has meant that the effectiveness of the technique for demonstrating differences over time and space has probably been underestimated. The key is not so much tracking down every potential source of error but the measurement of how such error measures up to effect size. If effect size is large, estimates can be imprecise but effective and considerably less costly to collect the data. Then, there is little evidence that ground or boat surveys of waterbirds are any more repeatable or less prone to visibility bias. Where parallel ground and aerial surveys were done, aerial surveys were equally able to detect temporal changes in the waterbird community (Kingsford 1999). Where possible, effort should be made to estimate measurement error. Aerial surveys can be repeated relatively cheaply, providing more than one estimate of the population using a particular wetland (Kingsford 1999).

Once aerial surveys become the preferred method for data collection, sampling methodology and number of species need to be decided upon. Surveys of entire assemblages of waterbirds on discrete wetlands have provided sufficient information to track significant changes in waterbird communities over time (Kingsford and Porter 1993, 1994; Kingsford *et al*. 1999*b*), individual waterbird species (Roshier *et al*. 2002) and groups of species (Nebel *et al*. 2008). The decision about single (or a few) or multiple species surveys inevitably depends on the objectives of the survey. There is probably increased visibility error with increasing number of species counted and area of wetland. But as waterbirds usually congregate in multispecies assemblages, there are advantages in collecting data on the suite of species. Also given the number of different waterbird species (>50), abundances of some species may track environmental changes better than others. Tracking waterbird communities over time may assist in environmental flow management or detecting effects of climate change. Surveying an entire wetland more than once (Kingsford 1999) also allows measurement of visibility error relative to changes over time and space. Further, data from the eastern Australian waterbird survey indicate that most waterbirds collect on a relatively small sample of wetlands (Fig. 3; Table 2). We surveyed ~12% of one-third of the continent and found that 30 wetlands had 80% of the waterbirds. Extrapolating, there may be an estimated 250 wetlands within eastern Australia with the majority of waterbirds, or potentially an estimated 825 wetlands at the continental scale if the pattern is consistent across the continent.

The struggle over systematic or random sampling and the potential biases (Caughley 1977) was resolved early for the eastern Australian aerial survey of waterbirds primarily because of the logistic challenge. This produced long-term data for individual wetlands that effectively demonstrated significant anthropogenic changes to rivers and wetlands – an unexpected outcome of the aerial survey and not one of its original objectives. If objectives are about ecosystem change for the suite of organisms dependent on wetlands then long-term data for particular wetlands is essential to demonstrate ecological degradation (Kingsford and Thomas 1995, 2004). Demonstrating effectiveness of aerial surveys is essential for funding continuity. Funding cycles for research are generally short (3 years) and do not lend themselves well to a long-term program such as the eastern Australian aerial survey. Initial enthusiasm for this survey guaranteed funding for the first 10 years but the following 10 were more problematic, with diminishing resources for conservation agencies. The eastern Australian aerial survey was also a program that was collaborative across independent state conservation agencies and therefore vulnerable. Today, the program is high profile, largely through its success in demonstrating that anthropogenic change can be measured for wetlands using waterbird data and one state, New South Wales, has built it into a large program of environmental monitoring and assessment. Emphasising the importance of aerial surveys of waterbirds, the Australian government provided funding in 2008 to test the possibility of surveying all major wetlands for waterbirds in Australia, largely in relation to the management of rivers and dependent wetlands. Such an assessment would provide a continental assessment for the distribution and abundance of waterbirds across the continent.

Surveying wetlands for waterbirds will continue to be an important conservation and management pursuit. There is considerable worldwide focus on the monitoring of waterbird populations for a range of objectives (Boere *et al*. 2006) but often there are few details of the methodologies or errors of estimating waterbird populations. Better understanding of the scale of measurement and sampling error, relative to effect size, should be the focus. Waterbirds can provide information on conservation importance, understanding of ecological processes and also track potential impacts of water resource development and other anthropogenic impacts. Extending aerial surveys to the entire waterbird assemblage and ensuring that the focus for survey is the wetland, provides considerable potential to answer the range of potential questions essential in not just the management of this group of organisms but the entire freshwater ecosystem. Given the increasing demand on freshwater resources and increasing climate-change effects, some measure of their potential impacts on these rich ecosystems is essential. Aerial surveys of waterbirds are a rapid, efficient way of collecting large amounts of data over extensive areas and monitoring freshwater ecosystem changes.

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