PUBLISHING

SPECIAL ISSUE | RESEARCH PAPER
https://doi.org/10.1071/MF22063

MARINE & FRESHWATER RESEARCH

Oil and gas exploration and development in the Lake Eyre Basin: distribution and consequences for rivers and wetlands, including the Coongie Lakes Ramsar Site

R. T. Kingsford[A,*] and A. J. D. Walburn[A]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
R. T. Kingsford
Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, UNSW Sydney, NSW 2062, Australia
Email: richard.kingsford@unsw.edu.au

Handling Editor:
Max Finlayson

Received: 14 March 2022
Accepted: 25 July 2022
Published: 4 October 2022

Cite this:
Kingsford RT and Walburn AJD (2023)
Marine and Freshwater Research, **74**(3), 200–219.
doi:10.1071/MF22063

ABSTRACT

Context. Altered flooding regimes and pollution threaten the world's wetlands, including floodplains of the largely free-flowing rivers. **Aims.** We investigated the distribution of current and future oil and gas production and exploration on the floodplains of the Lake Eyre Basin. **Methods.** We compiled these data and their associated infrastructure across the basin floodplains, including the Coongie Lakes Ramsar Site. **Key results.** There were 831 oil and gas wells across the Lake Eyre Basin, predominantly (98.6%) on Cooper Creek floodplains, with 296 wells in the Coongie Lakes Ramsar Site, with 281 well pads, roads (870 km) and 440 storages. Only eight referrals occurred under the *Environment Protection and Biodiversity Conservation Act* 1999, despite potential Ramsar wetland impacts. Future oil and gas production licences, primarily unconventional gas production, covered ~2.91 × 10^6 ha (Cooper Creek), 0.63 × 10^6 ha (Diamantina) and 1.03 × 10^6 ha (Georgina) of the floodplains. **Conclusions and implications.** Oil and gas production and exploration disrupt flooding regimes, with pollution (spills and greenhouse gas emissions). Little rigorous environmental assessment existed to protect the Lake Eyre Basin rivers and Coongie Lakes Ramsar Site, despite state and Commonwealth legislation and policy for protection, which remain largely ineffective in controlling oil and gas development on this free-flowing river.

Keywords: biodiversity, coal seam gas, floodplain development, fragmentation, petroleum, roads, unconventional gas, wells, wetland conservation.

Introduction

Freshwater resources around the world are under increasing anthropogenic pressure, with resulting widespread degradation of ecosystems and their services (Dudgeon *et al.* 2006; Kingsford *et al.* 2016; Xi *et al.* 2021). Much of this degradation has occurred through the draining of wetlands and regulation of river flow, including the building of dams and diversion of water and development on floodplains (Micklin 1988; Richardson *et al.* 2005), reducing frequency and duration of flows and frequency and extent of flooding (Lemly *et al.* 2000; Kingsford *et al.* 2006). Developments on floodplains are built to protect urban or agricultural areas (Dang *et al.* 2016) or sometimes to capture water from the floodplain and divert this into private storages for later use (Steinfeld and Kingsford 2013). As a result, many floodplains on developed rivers of the world have been destroyed (Tockner and Stanford 2002; Kingsford *et al.* 2006; Liu and Xia 2004), detrimentally affecting flood-dependent biodiversity (Liu *et al.* 2004; Hupp *et al.* 2009; Steinfeld and Kingsford 2013; Kingsford *et al.* 2015).

In addition, pollution of freshwater ecosystems from multiple causes is increasingly affecting freshwater ecosystems around the world (Smith 2003; Junk 2013; Reid *et al.* 2019). This includes reduced water quality from exploration and development of sand, and oil and gas (Ramos *et al.* 1994; Varol 2011; Olmstead *et al.* 2013; Yao *et al.* 2019). Oil and gas production interrupts sediments, elevating concentrations of different elements, including sodium, chloride, barium, strontium and lithium (Olmstead *et al.* 2013;

Cozzarelli *et al.* 2021). Further, oil and gas production wastes can degrade floodplain vegetation (Strizhenok and Fedorova 2020). Such multiple threats to floodplain rivers from these anthropogenic factors challenge effective conservation and protection of large rivers, particularly over large catchments.

Nomination of wetlands of international significance under the Ramsar Convention provides some conservation focus for governments (Kingsford *et al.* 2021*a*), along with protected areas (Saunders *et al.* 2002). Unfortunately, neither approach adequately protects flow and flooding regimes from anthropogenic threats. For example, three Ramsar Sites, which are also protected areas, namely the Macquarie Marshes, Gwydir Wetlands, Lower Lakes and Coorong and Murray Mouth, in Australia's Murray–Darling Basin have degraded because of inadequate management of flow and flooding regimes (Kingsford and Thomas 1995; Powell *et al.* 2008; Kingsford *et al.* 2011). The Australian Government formally notified the Ramsar Secretariat that these Ramsar Sites had experienced changes in ecological character, resulting from anthropogenic pressures, with declining biota (Kingsford 2000, Kingsford *et al.* 2015).

The rivers of the Lake Eyre Basin largely remain free-flowing, supporting significant wetland and floodplain areas (Kingsford *et al.* 1998; Kingsford 2017*a*), including the Coongie Lakes Ramsar Site (Fig. 1), and significant biodiversity (Kerezsy *et al.* 2014; Arthington and Balcombe 2017; Kingsford *et al.* 2017*a*). They support 33 wetlands of national importance, identified by the Northern Territory, New South Wales, Queensland and South Australian Governments (Fig. 1; Supplementary Table S1). Many of these wetlands depend on river flows originating in northern and north-eastern Queensland on the Cooper Creek and Georgina–Diamantina River systems (Fig. 1), rivers described as discontinuous, with non-sinuous channels that decline in size downstream (Larkin *et al.* 2020). In large flood sequences, large flow volumes track through the system, inundating extensive areas of floodplains, lakes and other wetlands (Bunn *et al.* 2006; Costelloe *et al.* 2006; McMahon *et al.* 2008; Kingsford *et al.* 2014; Kingsford 2017*a*; Mohammadi *et al.* 2017). These wetlands sometimes extend over more than 60 km across the floodplain (Fig. 1), supporting booms of fish breeding and high biological production (Arthington and Balcombe 2017), also providing for highly significant cultural values (Gorringe 2017) and other ecosystem services, including grazing for livestock (Brook 2017; Emmott 2017) and tourism (Wright 2017). The rivers are largely unregulated, with no major dams and small diversions of water for irrigation (Kingsford 2017*a*), making the rivers of the Lake Eyre Basin among the few remaining free-flowing rivers of the world (Grill *et al.* 2019). It was this rare largely free-flowing status and the significant cultural and environmental values and ecosystem services supplied, that resulted in the Lake Eyre Basin receiving the National River Prize in 2014 and the International River Prize in 2015 (Kingsford *et al.* 2017*b*).

Most of the Lake Eyre Basin falls within the jurisdictions of Queensland, South Australia and the Northern Territory (and a small region of New South Wales, Fig. 1). Public concern about potential anthropogenic effects on flows and flooding, primarily irrigation (Walker *et al.* 1997; Kingsford *et al.* 1998), drove Australian, Queensland and South Australian Governments to commit to protect flow variability of the rivers in the Lake Eyre Basin Agreement area (2000, Table 1, Kingsford *et al.* 2017*b*), including the two main rivers, the Georgina–Diamantina rivers and the Cooper Creek (Fig. 1). The resulting Lake Eyre Basin Intergovernmental Agreement, signed in 2004 by the Northern Territory Government, was supported by a Community Advisory Committee, including First Nations representatives, and a Lake Eyre Basin Scientific Advisory Panel, with senior officers from each government and a Ministerial Forum. More recently, there is increasing concern about existing and future mining developments, particularly oil and gas exploration and production (Crothers 2017; Mudd 2017), and the subsequent disruption of flow and flooding patterns and pollution potential from wastewater (Gordalla *et al.* 2013), affecting its national and global conservation importance. Governments have also further committed to protect the rivers (Table 1).

The Queensland Labor Government introduced Wild Rivers legislation in 2013, but this was revoked in 2014 by the Liberal–National Party (Kingsford *et al.* 2017*b*; Tan 2017; Table 1). Subsequent Queensland Labor Governments committed to the protection of Queensland floodplains of the Lake Eyre Basin by prohibiting development within floodplain areas (called sensitive areas), but such policies are yet to be implemented. In South Australia, much of the focus has been on protection and management of the large area included in the Coongie Ramsar Site, including Coongie Lakes National Park (Fig. 1, Kingsford *et al.* 2021*b*). Under the *Environment Protection and Biodiversity Conservation Act* 1999 (*EPBC Act* 1999), developments that potentially affect Ramsar Sites are deemed matters of national environmental significance, assessable as potential controlled actions. There is increasing concern about existing and future mining developments in the Lake Eyre Basin, particularly oil and gas exploration and disruption of flow and flooding patterns (Crothers 2017; Mudd 2017), with additional concerns about pollution (Gordalla *et al.* 2013).

There is a history of more than six decades of oil and gas exploration and production in the Lake Eyre Basin, since 1954, focused primarily on the Cooper Basin, the geological basin underlying some of the floodplains of Cooper Creek (Mudd 2017, Fig. 1), with its 256 gas fields and 166 oil fields (Lech *et al.* 2020). In 2014, a record 119 petroleum wells were drilled in the South Australian part of this basin (Lech *et al.* 2020). Globally and nationally, there is an increasing shift from production of conventional to unconventional gas (McGlade *et al.* 2013; Bista *et al.* 2017). Production methods and potential impacts are different.

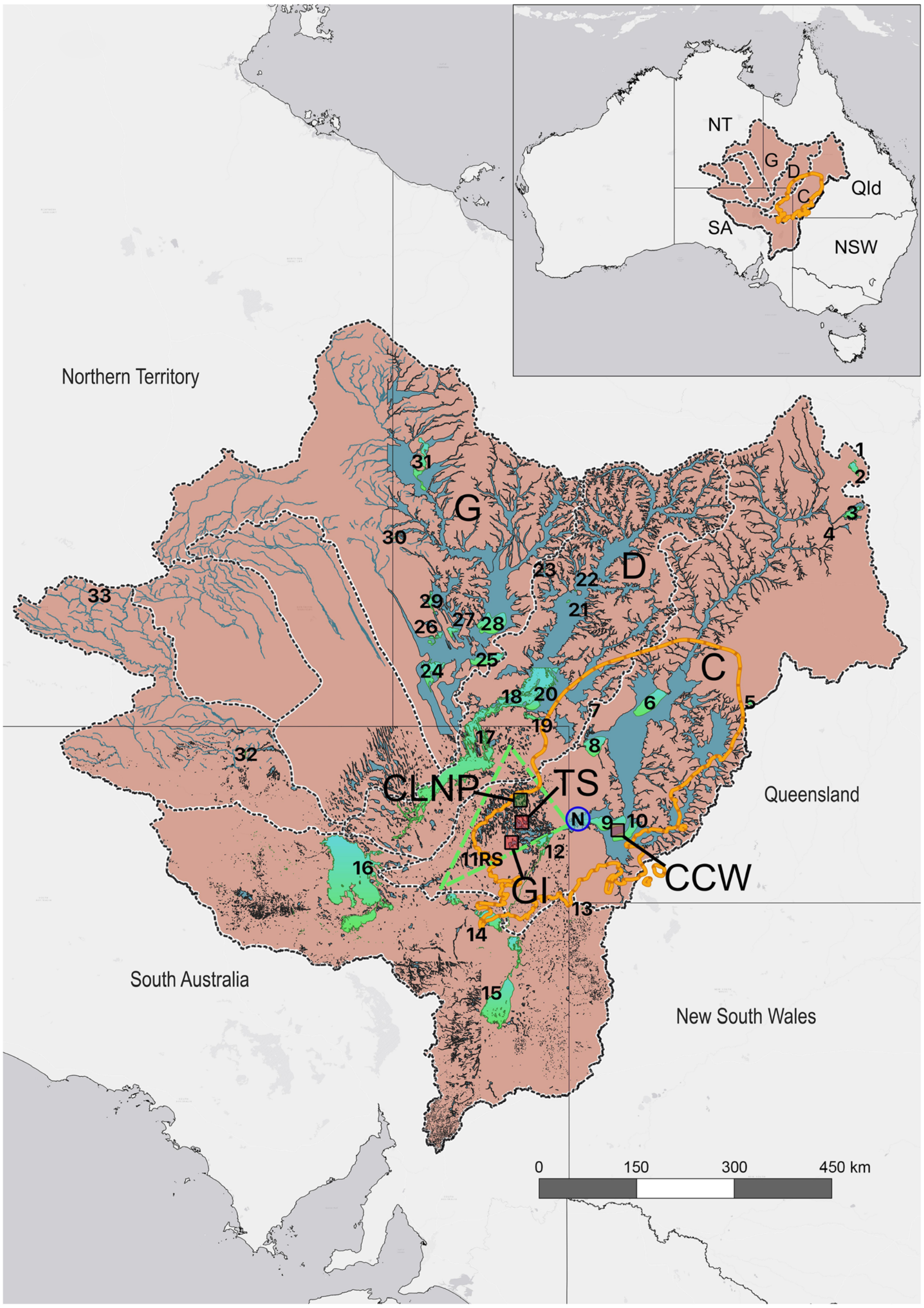

Fig. 1. Lake Eyre Basin and its two major rivers (Georgina River, G; Diamantina River, D; and Cooper Creek, C) in central Australia (inset) and the Cooper Basin (geological, orange), predominantly in Queensland (Qld), South Australia (SA) and the Northern Territory (NT; and a small part in New South Wales, NSW), and their floodplains and wetlands (blue), including the 33 nationally important wetlands (green polygons, see Table S1; names corresponding to numbers), including the Ramsar-listed Coongie Lakes (green triangle, 11RS), incorporating Coongie Lakes National Park (CLNP). Locations of the three highest-density oil and gas production infrastructure areas (wells, well pads, roads, water storages) are also identified on the floodplains: two within the Coongie Lakes Ramsar Site (Gidgealpa, GI; Tirrawarra Swamp, TS) in South Australia and one upstream (Cooper Creek–Wilson River floodplain confluence, CCW) in Queensland. Flows in Cooper Creek were measured at Nappa Merrie (N).

Table 1. Key political conservation protection and development instruments (strategies, legislation, policies, assessments) relevant to the rivers and floodplains of the Lake Eyre Basin.

Year	Instrument (reference)	Description	Implications	Reference
1987	Coongie Lakes Ramsar Site	Designation of the Coongie Lakes as a wetland of international importance under the Ramsar Convention	Commitment by South Australian and Australian Governments to wise use of wetland area (Fig. 1), recognised for representative or unique wetlands of natural or near-natural condition, value for particular ecological communities, animal or plant species, including waterbirds and fish	Butcher and Hale (2011)
2000	Lake Eyre Basin Intergovernmental Agreement	Formally signed by the Australian, Queensland and South Australian governments in 2000 (Northern Territory signed in 2004), supported by enabling legislation passed in 2001	Key relevant guiding principles for consideration in making decisions in relation to the rivers and wetlands included 1. '... naturally variable flow regimes and the maintenance of water quality are fundamental to the health of the aquatic ecosystems ...' 2. '... that the water requirements for ecological processes, biodiversity and ecologically significant areas within the Lake Eyre Basin Agreement Area should be maintained, especially by means of flow variability and seasonality ...' 3. '... that precautionary approaches need to be taken so as to minimise the impact on known environmental attributes, and reduce the possibility of affecting poorly understood ecological functions ...'	Commonwealth Government of Australia, State of Queensland, State of South Australia (2000)
2011–2012	Water Plan (Cooper Creek) 2011 and Cooper Creek Resource Operations Plan 2012	Management of water resources in Queensland	Severely restricted access to water from the Cooper Creek water management area for irrigation. Mining developments fall largely outside regulation by water management legislation	Crothers (2017)
2013	Wild Rivers declarations for Lake Eyre Basin Rivers	Declaration of the Channel Country rivers in Queensland by the Queensland Labor Government	This legislation and its subsequent policies protected the flows and floodplains of the Lake Eyre Basin rivers, until it was revoked just a few years later	Tan (2017)
2014	Revocation of Wild Rivers legislation and Wild Rivers declarations of Lake Eyre Basin rivers in Queensland	Removal of declarations by the Queensland Liberal–National Party	This legislative process removed protections from the floodplains of Cooper Creek and the Georgina–Diamantina Rivers	Tan (2017)
2014	*Regional Planning Interests Act* 2014	Regulation of rivers in Queensland in relation to development	Replaced the revoked Wild Rivers legislation, providing some regulation for areas identified as Strategic Environmental Areas on the floodplains of the major rivers (Cooper Creek, Diamantina River, Georgina River)	Queensland Government (2017)
2014	Queensland Department of Natural Resources and Mines	Cooper Basin industry development strategy	Outlined requirements to accelerate responsible development of the deep gas and oil resources, including exploration and production, including removing barriers and improving consistency between Queensland and South Australia	Queensland Department of Natural Resources and Mines (2014)
2019	Queensland Minister for Environment Media Statement	Commitment to delivering on 2017 election commitment to ensure Queensland's pristine rivers are protected	Focus on a framework to increase protections for streams and floodplains in the Queensland part of the Lake Eyre Basin	Enoch (2019)
2019	Independent scientific report on development risks to ecological values	Expert Panel Report for the Queensland Department of Environment and Science	Range of impacts identified affecting floodplains and wetlands including direct loss of habitat from linear and static	Fielder *et al.* (2019)

(*Continued on next page*)

Table 1. (*Continued*).

Year	Instrument (reference)	Description	Implications	Reference
			infrastructure; direct impacts on threatened species in permanent waterholes and; surface water impacts from well failure, spills of drilling and fracturing fluids, treated or untreated coals seam gas discharge, changes to water quantity in temporary creeks from discharges and overland flow paths. It recommended that gas wells be excluded from the floodplains of Queensland's channel country. This report was not publicly released, given a ruling about cabinet confidentiality (Smee 2020)	
2021	Lake Eyre Basin Bioregional Assessment	Investigated the impacts of coal seam gas and large coal mining developments on water resources and water dependent assets in Galilee, Cooper, Pedirka and Ackaringa Basin (Geological)	For the Cooper Basin, there were 393 km^2 of existing infrastructure (e.g. roads) for agriculture, tourism and oil and gas development as well as 145 km^2 of seismic surveys. There was an estimated 33% of riparian ecosystems (5626 km^2), 50% of wetland vegetation (12 143 km^2) and 30% of floodplains (12 143 km^2) intersected with prospective areas for development of unconventional gas with respectively 20, 33 and 29% of these areas of potential concern from development in the Cooper Basin. Bank instability and erosion from development removing vegetation were estimated to be of potential concern for up to 13% riparian vegetation, including national listed wetlands. Vegetation cover was reduced by 12–41% near gas extraction wells and unconventional gas resource development identified 1613 km^2 of floodplain habitat that support biodiversity was of potential concern	Holland *et al.* (2021)
2021	Queensland Resources Industry Plan (draft for consultation)	The development plan identifies global challenges for resource development, opportunities and collaborative opportunities for economic recovery with the Queensland Government	In relation to the Lake Eyre Basin River, the draft plan recommends establishment of a stakeholder advisory group to identify the balance between environmental and economic considerations. This will involve delivery of a regulatory impact statement to be released in 2022, which will identify what approvals are required and restrictions for planning	Queensland Government (2021*b*)

These are provided in relation to when they came into effect and their implications for flow and flooding regimes and biodiversity and cultural values (adapted and updated from Kingsford *et al.* 2017*b*).

Unconventional gas is distributed regionally and is generally dispersed, which requires more extraction wells, horizontal drilling and hydraulic fracturing (Jackson *et al.* 2013). The Queensland Government promoted development of unconventional gas (tight gas, shale gas, coal seam gas and deep goal gas) in its 2014 strategy for the Cooper Basin (Table 1, Queensland Department of Natural Resources and Mines 2014). Tight and deep coal gas were identified as having high prospectivity, whereas shale gas was medium in some areas, primarily requiring hydraulic stimulation (Lech *et al.* 2020), achieved using 'fracking'. At least 80 wells were drilled to target shale, tight and deep coal gas, with the first vertical shale gas well being drilled in 2011 (although not productive) and deep coal gas production starting in 2015 (Tirrawarra South 1; Lech *et al.* 2020).

There is increasing concern about identified ecological and health impacts of oil and gas exploration and production, well documented in the rapidly increasing industry of the United States (Adgate *et al.* 2014; Vengosh *et al.* 2014). At the same time, pressure is increasing to develop unconventional gas resources of the Lake Eyre Basin, particularly given the national political imperative for a 'gas-fired' energy recovery, focused on 'unlocking' additional gas supplies, driven by the 2021 National Gas Infrastructure Plan (Australian Government 2021). Further, the Cooper Basin was identified with considerable 'undiscovered' gas potential for future production (Australian Government 2021). This made the Cooper Basin a focus for the bioregional assessment to determine potential coal seam gas and coal mining impacts on water-dependent ecosystems (Holland *et al*. 2021). Despite this, there is no analysis of the intersection between oil and gas production on the entire rivers and floodplains of the Lake Eyre Basin, with most reporting being done at the scale of underlying geological basins (e.g. Lech *et al*. 2020). This is despite an acknowledgement by the Australian Government that potentially 1613 km^2 of the Cooper Creek floodplain could have small flood runners blocked or obstructed by construction activities for roads and development facilities (Holland *et al*. 2021).

We aimed to identify the distribution of current and potential future growth of infrastructure (wells, well pads, roads and water storages or ponds) in relation to oil and gas exploration and production on the rivers and floodplains of the Lake Eyre Basin. These will have increasing impacts on hydraulic movement of water and flooding, fragmenting landscapes and increasing pollution, with long-term impacts on cultural and environmental values of the rivers, including the Coongie Lake Ramsar Site. We had the following three specific objectives: (1) to determine the number of wells and associated structures and their growth over time, with a focus on the Coongie Lakes Ramsar Site and existence of any referrals under the *EPBC Act* 1999; (2) to examine growth in structures (wells, well pads, roads, water storages or ponds) in the three highest-density infrastructure focus areas (Fig. 1) and; (3) to investigate future oil and gas exploration and production (licences, well pads) on the floodplains of the Lake Eyre Basin. We discuss our findings in relation to this development and the potential impacts on the rivers and floodplains of the Lake Eyre Basin, in the context of the policy and legislative frameworks for conservation currently in place.

Methods

We first compiled and mapped a 'floodplain layer' encompassing all of the waterbodies, including rivers, lakes and other wetlands, across the Lake Eyre Basin, separately obtained for the Northern Territory (Northern Territory Government 2021), Queensland (Queensland Government 2021*a*), South Australia (South Australian Government 2020) and New South Wales (State Government of NSW and Department of Regional New South Wales 2010; Fig. 1). We also mapped the 33 wetlands of national importance, using the Directory of Important Wetlands in Australia (DIWA) Spatial Database (Australian Government Department of the Environment and Energy 2018).

Existing oil and gas infrastructure on floodplains

We identified and mapped infrastructure using available datasets and current and historical imagery on Google Earth and QGIS. All analyses on the numbers and the extent of existing oil and gas infrastructure were confined to the floodplains. We mapped existing wells by overlaying data for oil and gas infrastructure over the floodplain layer at Coongie Lakes Ramsar Site, in the Cooper Creek, Diamantina River and Georgina River catchments and at jurisdictional scales (i.e. Queensland, South Australia and Northern Territory) over time. We divided existing data on wells into the following three periods: before and during 2000, when the Lake Eyre Basin Agreement was signed; 2001–2014, the period during active development of river protection policies by governments including Wild Rivers legislation in Queensland (Tan 2017); and subsequently, up to latest available data (2021). Well locations were identified spatially and temporally using Queensland Government (2021*c*) and South Australian Government (2021*a*) data. There were no wells on the floodplain areas of the Lake Eyre Basin rivers in the Northern Territory (Northern Territory Government 2019) or New South Wales (State Government of NSW and Department of Regional New South Wales 2011). For wells, we tracked annual cumulative increase in numbers over time (1958–2021). We also overlayed the 33 wetlands of national importance over the distribution of this infrastructure to determine relative categorical impact in relation to proximity of wells (Table S1).

We also mapped the current (2018–2021, dependent on availability of imagery) extent of oil and gas exploration and production infrastructure (wells, well pads, roads, storages) on the floodplains of the Coongie Lakes Ramsar Site and the Cooper Creek–Wilson River floodplain confluence (Fig. 1). This included two of the three highest-density infrastructure areas (Fig. 1). For these three areas, we mapped changes over three time periods: oldest available satellite imagery (*c*. 1985), the most recent available high-resolution imagery (2020–2021 on Google Earth and QGIS at 0.5-m resolution) and a date between when there was cloud-free imagery (2006, 2013 and 2014). For each of these areas, we mapped the surface infrastructure, including wells, number and sizes of well pads, length of roads and number and size of water storages intersecting the floodplain. Roads were identifiable as straight, cleared passages connecting with other infrastructure on the floodplain. Well pad areas were identified as areas disturbed or cleared around each well. Storages were usually identified from their rectangular structure, presence of water or historical presence of water (confirmed using historical imagery; any not adequately identified were labelled as 'uncertain'). We used QGIS to map infrastructure. We also visually assessed effects of this infrastructure on flooding using Sentinel imagery available after 2015 (Sinergise Ltd 2021), identifying one of the higher floods in the area, guided by flow data at Nappa

Merrie on Cooper Creek (Fig. 1, Station 003103A; Queensland Government 2022), given its proximity to the high-density infrastructure focus areas (Fig. 1). We also compiled a list of referrals to the *EPBC Act* 1999 (data from http://epbcnotices.environment.gov.au/referralslist/) in relation to any developments that were either within the Coongie Lake Ramsar Site or upstream where they could affect its environmental value and were therefore assessable as potential controlled actions.

Future potential oil and gas infrastructure on floodplains

To determine the potential distribution of future oil and gas infrastructure on wetlands, we mapped wells that were at exploration, appraisal and development stages, given that all three stages may require infrastructure (such as well pads, access roads, drilling), potentially affecting water flows and flooding. We mapped the physical extent of leases and authorities to produce oil and gas across all catchments. Authorities are held and regulated separately by states and territories, with different definitions. For Queensland, we mapped four categories for oil and gas exploration and development, specified under the *Petroleum and Gas (Production and Safety) Act* 2004, including the authority to prospect (ATP), potential commercial area (PCA), petroleum lease (PL) and petroleum survey licence (PSL), obtained datasets from the Queensland Spatial Catalogue, provided by the Department of Resources (Queensland Government 2021*c*). An ATP allows exploration for petroleum and gas, including testing and evaluating feasibility of petroleum production; it can also be declared as a potential commercial area (PCA) for resource production. A PL permits exploration and testing for petroleum production, whereas a PSL allows entry to land to survey suitability for proposed infrastructure. For South Australia, we mapped the distribution of the three relevant licences required for oil and gas exploration and development under the *Petroleum and Geothermal Energy Act* 2000, including a petroleum exploration licence (PEL), petroleum retention licence (PRL) and petroleum production licence (PPL). We sourced these datasets from South Australian Resources Information Gateway (SARIG; South Australian Government 2021*b*). A PEL authorises exploration for resources to determine production feasibility; PRLs entitle exploration until commercialisation and; PPLs allow production in PEL- or PRL-covered areas. For the Northern Territory, we mapped three licence types listed under the *Petroleum Act* 1984, including the petroleum exploration permit, petroleum production licence, petroleum retention licence, as well as the petroleum acreage releases, which allow for release of land and multiple applications for permits simultaneously. We sourced these datasets from the Northern Territory Government data portal (Northern Territory Government 2014). We used QGIS to map where licences intersected all catchments.

Results

There have been a range of significant policies and legislative instruments for the development and protection of the rivers of the Lake Eyre Basin, particularly the Georgina–Diamantina and Cooper Creek catchments (Table 1). Competing drivers for protection or development, particularly in relation to river flows in Queensland and South Australia, remain largely unreconciled. All Governments for the Lake Eyre Basin committed to the protection of the natural variability of flows, under the Lake Eyre Basin Intergovernmental Agreement in 2000 (Table 1), further developed into protection of flood flows in Queensland under Wild Rivers legislation, which was subsequently repealed (Table 1). By contrast, policies to promote exploration and production of oil and gas have increased recently, particularly through commitment to accelerate development of deep gas and oil resources, including removal of 'barriers' to this development (Table 1). Most recently, the Queensland Government announced that a stakeholder advisory group development would be resolving the balance between environmental and economic considerations in the Queensland part of the Lake Eyre Basin (Table 1). Legislation and policies that drive development or protect the rivers and their flows remain largely unresolved, and challenging because of clashing objectives.

Within the Lake Eyre Basin, there are 33 wetlands of national importance, mostly in the catchments of the major rivers: Georgina River (8), Diamantina River (7) and Cooper Creek (12), as well as Lake Eyre (Fig. 1, Table S1). This also includes the Ramsar-listed Coongie Lakes in South Australia, which covers 21 889 km^2, predominantly in the Cooper Creek catchment (Fig. 1). The two remaining wetlands of national importance are in the Macumba River catchment, in the western part of the Lake Eyre Basin, flowing east to Lake Eyre (Fig. 1). Wetlands of national importance covered 5.45×10^6 ha, although a large terrestrial area was included in the Coongie Lakes Ramsar Site (Fig. 1), with $>32 \times 10^6$ ha of wetland area (Supplementary Table S2). Most of the floodplain area is in the Queensland parts of Cooper Creek, Georgina River and Diamantina River, with the eastern flowing rivers and lakes in South Australia the next-most prominent and small areas in New South Wales (Table S2).

The 831 existing oil and gas wells drilled on the floodplains of the Lake Eyre Basin rivers were overwhelmingly concentrated on the floodplains of the Cooper Creek (98.6%), with relatively few on the floodplains of the Georgina and Diamantina rivers (Fig. 2, Table 2). The highest density of wells was on the floodplains of Cooper Creek in South Australia, with the density being more than three times the next-highest density in the Queensland part of the Cooper Creek catchment (Fig. 2, Table 2). The earliest wells drilled on these floodplains were in 1958 in Queensland and 1963 in South Australia (Fig. 3*a*). There was then rapid development of wells from the early 1980s and this

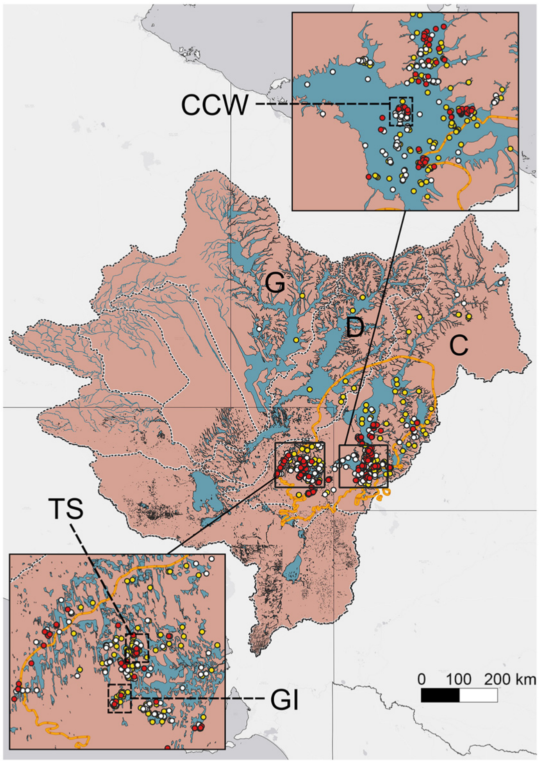

Fig. 2. Distribution and time period of oil and gas wells (closed circles: <2001, yellow; 2001–2014, white; >2014, red, note not actual size) developed on the floodplains (including other wetlands) of the Lake Eyre Basin rivers in Cooper Creek, Diamantina River and Georgina River catchments in Queensland and South Australia (see also Table 1), with concentrations expanded, including the three highest-density areas of oil and gas wells (Gidgealpa, GI; Tirrawarra Swamp, TS; Cooper Creek–Wilson River floodplain confluence, CCW), also showing the Cooper Basin (orange).

continued for the period of data assessment up to 2021 (Fig. 2*a*). Approximately half of the wells were drilled on the floodplains before 2001, with subsequent development of the other half, at a rate of 19 wells per year since 2001, predominantly in the Cooper Creek catchment, increasingly in Queensland compared with South Australia (Table 2, Fig. 2). Consequently, the number of wells on the floodplains of the Lake Eyre Basin rivers is now higher in Queensland than in South Australia, exceeding the number in South Australia in 1997 (Table 2). There were few wells on the floodplains of the Georgina and Diamantina rivers, all in Queensland, with little increase after 2001 (Table 2, Fig. 2).

Within the Cooper Creek catchment, the Ramsar-listed Coongie Lakes Site had 4494 km^2 of floodplain (Fig. 1). This trajectory of development of wells on the Cooper Creek catchment floodplains was also reflected in the Coongie Lakes Ramsar Site (Fig. 1–3), where there was a higher rate of development of wells on its terrestrial ecosystems than on its floodplains ecosystems (Fig. 3*b*). After the 1987 gazettal of the Coongie Lakes Ramsar Site as a wetland of international importance (Table 1), the number of wells in the Coongie Ramsar Site increased five times from 233 to 1236 wells. This included more than a three-fold increase in the number of wells on the floodplains, from 95 to 296 wells, and more than a six-fold increase in the numbers of wells on terrestrial ecosystems, from 138 to 940 wells.

The wells on the floodplains also had associated infrastructure (Table 3). For the 296 wells on the Coongie Lakes Ramsar Site floodplain, there was a similar number of well pads and more than 869 km of road, as well as 392 storages (Table 3). Together the well pads and storages covered 5.83 km^2, a relatively small part (0.13%) of the entire floodplain. The two highest-density areas for wells within the Coongie Lakes Ramsar Site, Tirrawarra Swamp and Gidgealpa floodplain (Fig. 1, 2), accounted for 103 wells on the floodplains, more than one-third of all wells. For the Tirrawarra Swamp focus area, the number of wells (54) on the floodplains doubled after 1985, with 50 well pads covering 46 ha, at a density of 0.58 km^{-2}. For the Gidgealpa floodplain focus area, the number of wells (49) increased more quickly, with subsequent roads and storages and 48 well pads covering 26 ha at a density of 0.42 km^{-2} (Fig. 4, Table 3).

There was a small flood in 2016 of 685 434 ML (Supplementary Fig. S1), significantly below the annual volume of large floods (Supplementary Fig. S2). For Tirrawarra Swamp, there was some evidence indicating alterations in flooding patterns, in relation to the road infrastructure (i.e. differences in colours either side of roads; Fig. 4*a*). These disrupted patterns of flooding, including potential overflow from storages, in relation to this flood were more easily identified in comparison to a nearby floodplain where there was no oil and gas development infrastructure (Fig. S2). A similar flood on the Gidgealpa floodplain was not sufficiently high to show any differences in flooding patterns in relation to infrastructure (Fig. 4*b*).

For the Cooper Creek–Wilson River floodplain confluence, there was rapid development of wells after 1985, with the number of wells more than doubling after 2006 (Fig. 4, Table 3). This included ~100 km of road and 74 storages, including some that were uncertain. There was relatively little evidence for a clear effect on flooding regimes for the 2019 flood (Fig. 4).

There were eight actions referred for potential controlled actions, under the *EPBC Act* 1999, of which five, one and two respectively, related to Cooper Creek, the Diamantina River and Georgina River (Supplementary Table S3). The earliest of these was in 2002 and the latest 2014. There were referrals to two pipelines (10 km, Cooper Creek–Wilson River floodplain and ~1000-km pipeline from Cooper to Abbot Point); two specific to seismic surveys on the Cooper floodplain affecting 19.59 and 126 km^2 of floodplain in the Cooper Creek–Wilson River floodplain; two related to seismic surveys (970 km) and

Table 2. Distribution, numbers, densities of oil and gas wells drilled (up to 2021) on the floodplains and other wetlands of the Lake Eyre Basin's three major rivers.

Catchment	Jurisdiction	Number of wells (percentage of total)			Total	Density of wells (ha^{-1})	Wells per year
		≤2001	2001–2014	>2014			
Cooper	Qld	218 (48)	160 (35)	79 (17)	457	0.187	11
	SA	199 (55)	117 (32)	46 (13)	362	0.681	8
	Total	417 (51)	277 (34)	125 (15)	819	0.276	19
Diamantina	Qld	9 (100)	0 (0)	0 (0)	9	0.008	0
Georgina	Qld	2 (67)	1 (33)	0 (0)	3	0.002	0.05
All	Total	428 (52)	278 (33)	125 (15)	831	0.148	19

Number of wells drilled in relation to Queensland and South Australia, with total numbers, numbers before 2001 (signing of the Lake Eyre Basin Agreement, Table 1), 2001–2014 (Wild Rivers legislation introduced in Queensland, Table 1) and number of wells established per year (2001–2021). There were no wells drilled on the floodplains of the Diamantina or Georgina River catchments in South Australia.

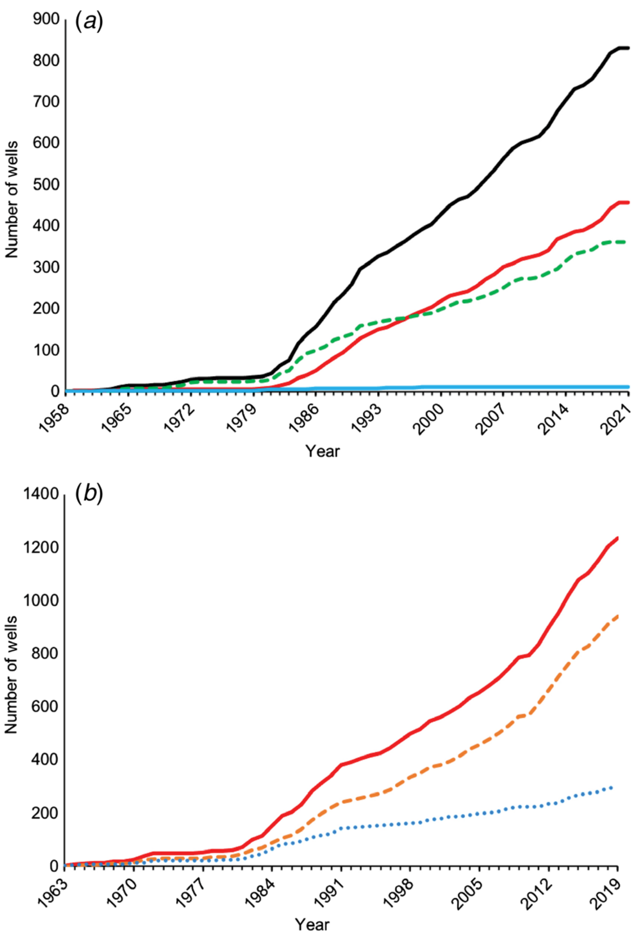

Fig. 3. Trajectories of development of oil and gas wells on (*a*) the floodplains and other wetlands of the Lake Eyre Basin rivers, including total number of wells (black) and number of wells in the Cooper Creek catchment in Queensland (red), Cooper Creek in South Australia (green dashed) and the Georgina and Diamantina catchments in Queensland (blue; see also Fig. 2 and Table 1) and (*b*) total number of wells built within the boundary of the Coongie Lakes Ramsar Site (red continuous), including those in terrestrial areas (orange dashed) and on the floodplains (blue dotted).

eight exploration wells (including hydraulic fracturing, rigs and clearing on the Georgina River; covering 1.4×10^6 ha). There was also one referral to six petroleum wells (6.32 ha of drill sites and camp, 7.93 ha of access tracks and 32.29 ha of existing seismic line, access tracks and workers' camp). Only the pipeline from Cooper to Abbot Point was deemed a controlled action, originating in terrestrial areas east of the Cooper Creek floodplain (Table S3).

For areas of potential future development of oil and gas, a range of authorities for exploration and development intersected the floodplains of the large rivers of the Lake Eyre Basin (Fig. 5, Table 4), covering 4.94×10^6 ha of floodplain (Table 4). Potential areas for future oil and gas exploration and development are dominated by authorities to prospect in application or granted for the Queensland part of Cooper Creek (Table 4, Fig. 5). These are predominantly focused on the channel country of Cooper Creek, where there is widespread flooding, around Windorah and the Cooper Creek–Wilson River floodplain confluence (Fig. 1, 5). In South Australia, petroleum production licences (also potentially for gas) are only in the Cooper Basin and other basins including the Lake Frome and Hay River (Fig. 5, Table 4). The Georgina River catchment contains only one petroleum exploration licence permit (granted). The Diamantina River and Cooper Creek hold petroleum retention licences and petroleum exploration licences (application and granted). Petroleum leases encompass large areas of the Georgina River, Diamantina River and Cooper Creek catchments in both South Australia and Queensland. There are also a range of licences covering the Northern Territory, although the extent of intersection with floodplains could not be resolved (Fig. 5, Table 4). For Cooper Creek in Queensland, a large proportion of the petroleum leases intersect with the floodplain. There is a high density of leases in the South Australian portion of the catchments, as well as the Southern Cooper Creek catchment in Queensland. In Queensland, the Georgina and Diamantina catchments have only one lease type, namely, authority to

Table 3. Number and distributions of oil and gas infrastructure on floodplain areas of the Lake Eyre Basin rivers.

Regional area	Focal area	Satellite imagery	Wells		Well pads		Density (number km^{-2})	Roads length (km)	Storages	
		Year	Number	Percentage increase	Number	Area (ha)			Number (uncertain)	Area (ha)
Coongie Lakes Ramsar Site	Tirrawarra Swamp	1985	32		32	33	0.37	56.00	11	62
		2014	47	46.9	45	35	0.52	90.88	26	68
		2020	54	14.9	50	46	0.58	91.93	28	68
	Gidgealpa floodplain	1985	17		17	23	0.15	41.14	1	3
		2013	46	170.6	44	25	0.39	94.93	7	12
		2020–2021	49	6.52	48	26	0.42	119.55	20	41
	All other wetland areas	2018–2021	193		183	195	0.04	658.20	392	207
	Total		296		281	267	0.06	869.68	440	316
Lower Cooper Creek (Qld)	Cooper Creek–Wilson River	1985	1		1	0.86	0.01	0	0	0
		2006	31	>200	30	35	0.33	101.37	52 (17)	14
		2020	50	61.3	46	42	0.50	95.30	74 (10)	33

This includes percentage increases over time as well as associated infrastructure, including number, areas and densities (in 2021) of well pads, length of roads and number, areas and densities (in 2021) of water storages within two focal areas (Tirrawarra Swamp, Gidgealpa), the focal area on the Cooper Creek–Wilson River in Queensland and all floodplains and lakes areas in the Coongie Lakes Ramsar Site (densities not included, see Fig. 1), with data collected from available satellite imagery on Google Earth and ESRI, using QGIS. Satellite imagery year varied depending on availability of a particular scene in Google Earth. Percentage increase was relative to the earlier estimate. Density was well pads per square kilometre for comparison with published estimates and for the discrete wetland areas, on the basis of a polygon circumscribing the main part of the wetland (see Fig. 4), closing off the inlet and, for other wetland areas in Coongie Lakes, this included the entire floodplain area in remaining areas.

prospect. The Cooper has all four types, including petroleum survey licences, authority to prospect, potential commercial areas and petroleum leases (granted and application). Combining all licencing, 47, 5 and 23% of the respective floodplains of Cooper Creek, Diamantina River and Georgina River in Queensland and South Australia are covered by oil and gas exploration and production licences (Table 4). Across these three catchments, there was 31% of the floodplain area in the Lake Eyre Basin covered by these licences (noting that there was no estimate possible for the Northern Territory). The amount varied across states within catchments, with less than half of Cooper Creek under licence in Queensland (41%), but most (91%) in South Australia; 27% of the Diamantina River in South Australia and little in Queensland and; 23 and 72% respectively of the Georgina River in Queensland and South Australia (Table 4). The total area of petroleum leases on the floodplain is 2.32×10^6, 0.22×10^6 and 1.03×10^6 ha for the Cooper Creek and Diamantina and Georgina rivers respectively (Table 4). For Queensland, the type of authority with the largest area is the authority to prospect (Cooper, 1.30×10^6 ha; Diamantina, 9294 ha; Georgina, 1.01×10^6 ha; Table 4). For South Australia, in the Cooper Creek retention licences make up the largest area (0.22×10^6 ha), compared with the Diamantina River where exploration licences (application and granted) have the largest area with a combined total of 0.61×10^6 ha (Table 4). The Georgina River has a much smaller area of authorities in South Australia, with the exploration licences (application and granted) making up 13 499 ha (Table 4). South Australia's Lake Frome and Hay River catchments had high proportions (respectively 65 and 77%) of their floodplains covered by licences in comparison to low coverage of the Finke River (Table 4, Fig. 5).

Discussion

The world's freshwater ecosystems, including its wetlands, are in serious decline, affecting biodiversity and ecosystem services (Vörösmarty *et al.* 2010). Most flow- and flood-dependent aquatic biodiversity require natural flow and flooding regimes and their connectivity, without which, much of this biota inevitably declines (Dudgeon *et al.* 2006; Kingsford *et al.* 2015). Despite the establishment of the Ramsar Convention for protecting wetlands of international importance, which has been operating for more than 50 years (Kingsford *et al.* 2021*a*), many Ramsar-listed Sites continue to degrade because of inadequate management of threats (Davidson *et al.* 2018). Globally, the most serious driver of these declines is alteration to water sources, affecting flow and flooding regimes (Lemly *et al.* 2000; Dudgeon *et al.* 2006). Much of the current global understanding in relation to impacts on flooding regimes, particularly for floodplains, relates to the effects of building dams and subsequent

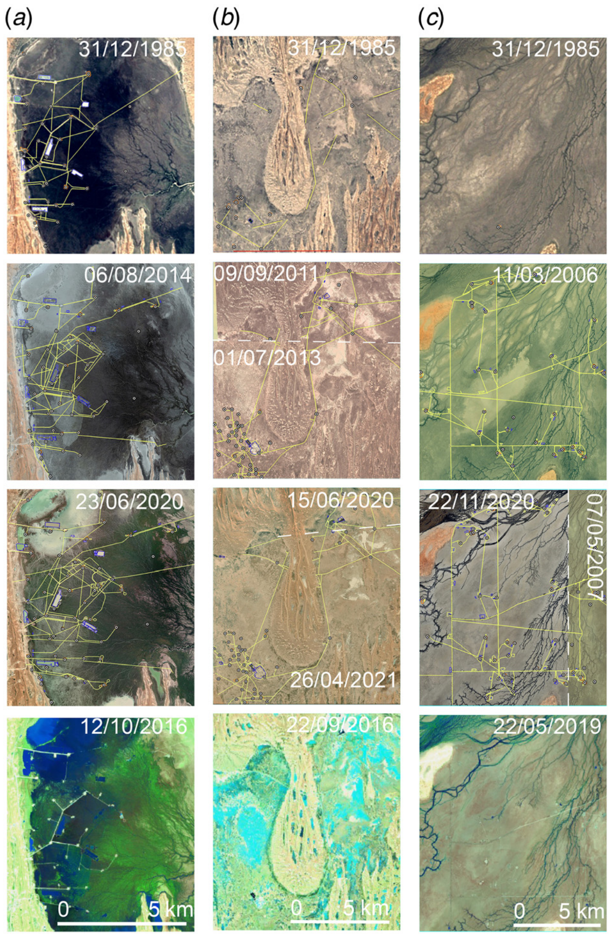

Fig. 4. Imagery from three focus areas for development of wells and infrastructure (see Fig. 1), two within the Coongie Lakes Ramsar Site, namely (*a*) Tirrawarra Swamp (Google Earth, 1985, using Landsat and Copernicus; 2014 using Maxar Technologies; 2020 using ESRI Satellite imagery), and (*b*) Gidgealpa floodplain in South Australia, and the third (*c*) the Cooper Creek–Wilson River floodplain confluence in Queensland at different dates, vertically, with the first three images showing the growth in infrastructure (wells, circles; well pads, orange; roads, yellow lines; and storages, blue) over time (see Table 2 for details). The fourth-lowest image (Sentinel image) shows a false colour image of a small flood (in 2016 for (*a*), (*b*) and 2019 for (*c*)), displayed with band 12 (shortwave infrared), band 8A (near infrared), and band 4 (red) as red, green and blue, with vegetation following flooding showing green because of its high reflectance in the near infrared, whereas water is blue and black with its low reflectance in both near and shortwave infrared. Imagery is from Landsat and Copernicus (1985), Maxar Technologies (2006, 2007 2011, 2014, 2020), ESRI Satellite imagery (2020, 2021) and the Sentinel Hub (2016, 2019).

diversion of water upstream (Nilsson *et al.* 2005; Vörösmarty *et al.* 2010). By contrast, understanding of the effects of infrastructure on floodplains remains reasonably poor (Kingsford 2015). This may be because many of the world's floodplains were destroyed or degraded by urbanisation and irrigated agriculture, combined with river regulation reducing inundation, before adequate assessment (Tockner and Stanford 2002; Kingsford 2015). Our examination of the issue in one of Australia's most important and larger river systems, the Lake Eyre Basin, has clearly identified impacts, with significant future potential impacts on ecosystems, including on the Coongie Lakes Ramsar Site.

The oil and gas industry has a significant and rapidly growing infrastructure footprint on the floodplains of the Lake Eyre Basin rivers, with most of the more than 800 wells concentrated in the Cooper Creek catchment (Fig. 2, Table 2). The current distribution of wells was available from Government databases but had not been not compiled, or infrastructure assessed, until we did our catchment-wide assessment, superimposed on the floodplains. Similarly, there were data for future licensing of oil and gas development but again these were not compiled across catchments, covering jurisdictions and each of the rivers' floodplains. The lack of such a comprehensive assessment may reflect the remoteness of the area and a relatively low population (~60 000 over the Lake Eyre Basin; Measham and Brake 2009). Nevertheless, the potential impacts on the conservation of ecosystem services will be significant and threaten the Lake Eyre Basin's status as one of the world's great free-flowing rivers (Kingsford *et al.* 2017*b*; Grill *et al.* 2019) with its 33 nationally important wetlands (Fig. 1, Table S1), including the Ramsar-listed Coongie Lakes (Kingsford *et al.* 2021*b*). The trajectory of this development has increased (Table 3, Fig. 2), despite commitments by governments to protect variability of flow and flooding regimes of the rivers of the Lake Eyre Basin, under a range of policy and legislative instruments (Table 1). Future oil and gas production is predicted to develop unconventional gas resources, with much potentially greater infrastructure development; this is reflected in the extensive coverage of authorities to prospect and proposed and granted licences within the Cooper Creek catchment and Georgina River catchment and to a much lesser extent in the Diamantina River catchment in Queensland (Fig. 5, Table 4). These extend across significant areas of floodplain (Table 4). Given that wells and well pads are likely to occur in areas with existing infrastructure and close to pipelines, it is likely that some of the areas with already well developed footprints for oil and gas production on the floodplain (Fig. 2, 4) may have increased concentrations of infrastructure in the future.

The Ramsar-listed Coongie Lakes Ramsar Site (Fig. 1) has also been the focus of significant development, reaching 296 wells on its floodplain areas (Table 2), most occurring after it was gazetted as a wetland of international importance to protect its wetland values in 1987 (Table 1, Fig. 3*b*). Given it is a matter of national environmental significance, it is not clear what assessment processes or referrals occurred, under the *EPBC Act* 1999. Clearly, relatively more of this development has occurred on terrestrial systems within the Ramsar-listed area, rather than on the floodplains (Fig. 3*b*). But each well on the floodplain was associated with a well

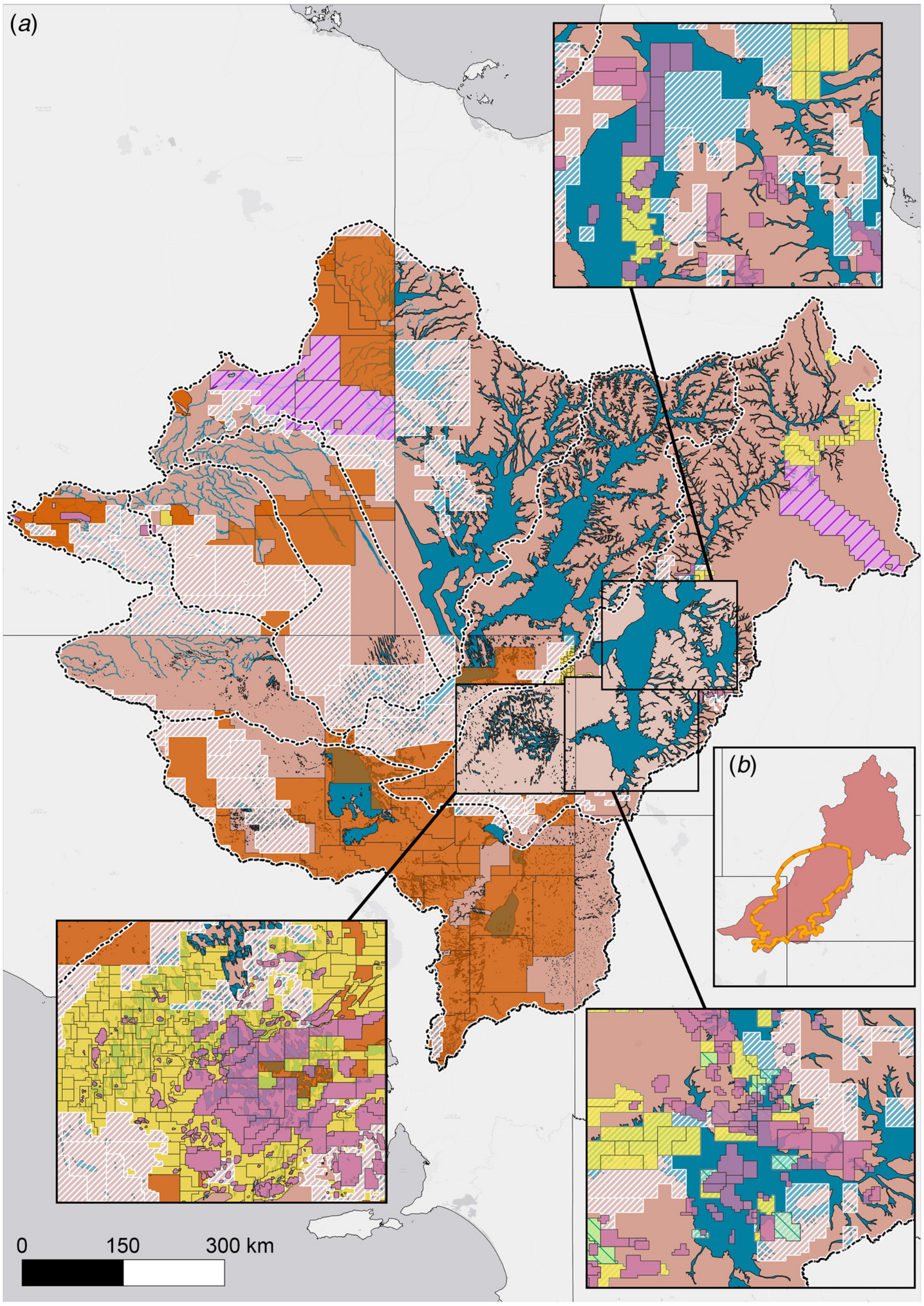

Fig. 5. (*a*) Distribution of different oil and gas licences across the floodplains and wetlands of the Lake Eyre Basin in Queensland and South Australia, with insets providing more detail for different areas on the floodplains of Cooper Creek (see also Table 2) and (*b*) the Cooper Basin overlaying the Cooper Creek catchment. There are different categories of oil and gas licencing for each state, including for the Northern Territory (petroleum retention licence, yellow; petroleum production licence granted, pink; petroleum exploration permit application, orange; exploration permit granted, white hatched; acreage release areas, purple hatched), Queensland (petroleum lease application, green hatched; petroleum lease granted, pink; potential commercial area, yellow; authority to prospect, white hatched; petroleum survey licence, purple hatched) and South Australia (petroleum exploration licence, white hatched; petroleum exploration application, orange; petroleum retention licence, yellow; petroleum production licence, pink). Where different licences overlapped (Table 4), only the licence most progressed for development shown.

Table 4. Distribution and areas of different petroleum and gas authorities in relation to floodplain areas.

Catchment	State	Petroleum and Gas Authority	Area of lease on the floodplain (ha)	Percentage of different licences	Percentage of floodplain area covered
Cooper	Queensland	Authority to Prospect	1 306 033	72	30
		Potential Commercial Area	498 886	28	11
		Petroleum leases – granted	475 457	26	11
		Petroleum leases – application	90 551	5	2
		Petroleum survey licence	33 054	2	1
		Subtotal	1 807 568	100	41
	South Australia	Exploration licences – application	66 695	13	12
		Exploration licences – granted	73 560	14	13
		Retention licences	215 852	42	38
		Production licences	154 877	30	28
		Subtotal	510 984	100	91
	Both States	Total	2 318 552		47
Diamantina	Queensland	Authority to Prospect	9246	99	<1
		Potential Commercial Area			
		Petroleum leases – granted	48	1	<1
		Petroleum leases – application			
		Subtotal	9293	100	<1
	South Australia	Exploration licences – application	283 544	137	37
		Exploration licences – granted	294 431	143	39
		Retention licences	8979	4	1
		Production licences			
		Subtotal	206 494	100	27
	Both States	Total	215 787		5
Georgina	Queensland	Authority to Prospect	1 013 231	100	23
		Potential Commercial Area			
		Petroleum leases – granted			
		Petroleum leases – application			
		Subtotal	1 013 231	100	23
	South Australia	Exploration licences – application	3047	23	16
		Exploration licences – granted	10 454	77	56
		Retention licences			
		Production licences			
		Subtotal	13 499	100	72
	Both States	Total	1 026 730		23
Lake Frome	South Australia	Exploration licences – application	1 078 083	94	61
		Exploration licences – granted	72 991	6	4
		Retention licences	0	<1	<1
		Production licences	5	<1	<1
		Subtotal	1 151 072	100	65
Hay River	South Australia	Exploration licences – application	828	<1	<1
		Exploration licences – granted	223 981	100	76
		Retention licences			

(*Continued on next page*)

Table 4. (*Continued*).

Catchment	State	Petroleum and Gas Authority	Area of lease on the floodplain (ha)	Percentage of different licences	Percentage of floodplain area covered
		Production licences			
		Subtotal	224 812	100	77
Finke River	South Australia	Exploration licences – application	6348	102	9
		Exploration licences – granted	205	3	<1
		Retention licences			
		Production licences			
		Subtotal	6246	100	9
All catchments	Queensland and South Australia	Total	4 943 198		31

This focuses on different stages of application and development (some overlap), on the floodplains, including wetlands of the Lake Eyre Basin across Cooper Creek and the Diamantina and Georgina River catchments, separated into different states and overall. Some leases on the floodplain licence types overlapped spatially and so subtotals and totals were calculated only on the overall coverage to avoid double counting and for this reason added percentages were not 100%. Percentage area was for the percentage of different licences covered by different types of licences, relative to each catchment and state

pad (almost a 1:1 ratio) and more than 850 km of roads and more than 400 storages (Table 3). Approximately one-third of all the wells in the Coongie Lakes Ramsar Site were concentrated in two focal floodplains, namely, Tirrawarra Swamp and Gidgealpa floodplain (Fig. 1, 4, Table 3). Both areas had increased the number of wells and associated infrastructure of well pads, roads and storages since 1985 (when imagery was available; Fig. 4, Table 3). There were also wells and their infrastructure scattered elsewhere throughout the floodplains of the Ramsar-listed area (Fig. 2, Table 3). In addition, the Cooper Creek–Wilson River floodplain confluence, a wetland system of national importance (Fig. 1, Table S1), underwent rapid development of oil and gas production infrastructure after 1985 (Fig. 3, Table 3).

There was limited publicly available satellite imagery at high resolution (i.e. Sentinel satellite imagery, only available from 2015) to identify effects on flooding regimes, given the rarity of flooding in this region and availability of Sentinel satellite imagery only from 2015. However, there was some disruption of a small 2016 flood, by roads and wells on the floodplain, particularly Tirrawarra Swamp in the Coongie Lakes Ramsar Site (Fig. 4, Fig. S2). There is clearly a need to identify the extent that such structures affect flow and flooding regimes wherever there is historical and future infrastructure, both locally and downstream. Given the low gradient of such floodplains and effects of even minor changes to channels (Knighton and Nanson 1994, 2002; Fagan and Nanson 2004), wells, well pads, roads and storages inevitably affect flow and flooding. It is surprising, given the conservation importance of the Coongie Lakes Ramsar Site, that we could not find any rigorous analyses of the impacts of such infrastructure on flow and flooding regimes for this wetland, or elsewhere in the Lake Eyre Basin rivers. The Bioregional Assessment (Holland *et al.* 2021) asserted that there were 'negligible impacts' of historic infrastructure on flood characteristics, on the basis of comparison of satellite imagery for 2000 and 2020 for the Cooper Basin, citing an analysis; however, neither the analysis nor data were available on the identified public data repository. This claim with absence of detailed analyses that could be critically assessed provides little confidence that a thorough analysis was attempted or that different floods were examined with some assessment of potential biotic impacts (Holland *et al.* 2021).

Current oil and gas production infrastructure on floodplains is already affecting natural flooding (Fig. 4, Fig. S2) and this will be worse with an increasing development of unconventional gas resources over the next 50 years, particularly in the Cooper Basin (Fig. 1, 5). The Cooper Basin is a focus for rapid development with 1000–1500 wells being planned over the next 50 years, with multiple wells (depths of 500–3000 m drilled laterally; Huddlestone-Holmes *et al.* 2018) on a single well pad (6–8 wells), each 3.5–4 km apart; 2–3-m borrow pits and; ~5 km of road for each well pad, estimated at a density of 0.125 well pads km^{-2} (EHS Support 2018; Holland *et al.* 2020). The highly concentrated current developments on Tirrawarra Swamp have a well-pad density of ~4.5 times greater than this (Table 4, Fig. 4), but this may not account for the increased well-pad footprint with 6–8 wells. However, the current development relates primarily to conventional development of oil and gas, whereas the future is likely to be unconventional development of oil and gas resources. There is already considerable growth in development on the Cooper Creek–Wilson River floodplain confluence (Table 3, Fig. 4). A report to the Queensland Government, Department of Natural Resources, Mines and Energy (released through freedom of information) described that activities of oil and gas production would be outside significant flood extents (e.g. 1990) but acknowledged that these areas could still be developed with four single well pads in 16 km^2 (EHS Support 2018). This inevitably means substantially increased infrastructure on the floodplain (see Table 3, Fig. 4), reflected in the growth of production wells on the floodplain (Fig. 3). Substantial percentages of the floodplains of the Lake Eyre Basin rivers are already under granted or applied licences for oil and gas exploration and production (Table 4, Fig. 5). Clearly, much of this area is under exploration that does not equate to production and development impacts. Assessment is most progressed for the Cooper Basin (Fig. 1). The Australian Government's assessment of development of the Cooper Basin (part of the Cooper Creek catchment) estimated that 586–7350 km^2 (up to 5.6%) will be disturbed by roads (5 km per well pad), well pads (up to 4 ha each) and seismic lines (Holland *et al.* 2021). There may also be surface-water extractions, currently ~2% of annual flows for Cooper Creek; these were assessed as of 'low concern' for the environment by the Australian Government (Holland *et al.* 2021) and, yet, this may compound environmental impacts to flooding regimes, particularly if increased for oil and gas production (estimated 400 ML $year^{-1}$, from ground and surface water; Holland *et al.* 2021). Further, the current infrastructure is affecting vegetation and ecosystem services. For example, direct removal of vegetation by pads and roads increasing over ~12 years destroyed $\sim 3 \times 10^6$ ha of vegetation and potentially permanently reduced net primary production by 10 Tg across central Canada and the USA, significantly affecting ecosystem services, increasing fragmentation and affecting wildlife (Allred *et al.* 2015). Increases of invasive plant species can also occur with oil and gas production (Bergquist *et al.* 2007). For future expansion in the Cooper Basin, there could be 13 800 km^2 of groundwater dependent ecosystems, 5626 km^2 of riparian areas and 16 200 km^2 of wetland affected by future expansion (Hall *et al.* 2018). There is 'potential concern' that up to one-third of wetland areas will be directly affected, with potentially concerning indirect impacts (e.g. increased fragmentation, altered fire regimes) affecting one-third of riparian areas. Direct impacts include infrastructure (e.g. roads), which can exacerbate indirect effects of introduced species, threatened species and habitat loss (Holland *et al.* 2021). Given the concentration of current wells on floodplains (Fig. 2, 3), much of this will occur on the floodplains of Cooper Creek, resulting in alterations to up to 1613 km^2 (Holland *et al.* 2021). Similar impacts are also likely elsewhere in the future in the Diamantina and Georgina River catchments, where licences are in application or granted (Table 4, Fig. 5).

As well as interrupting natural flooding regimes, production of unconventional gas inevitably carries pollution risks, both for local (spills) and global environments (greenhouse-gas emissions). These relate to processes of extraction, as well as infrastructure and transport. The development of unconventional gas resources requires use of hydraulic fracturing (fracking), which can include 4–28 different chemicals (potentially up to 1076) and water (Lefebvre 2017; Mallants *et al.* 2020), with toxic impacts on fish (Blewett *et al.* 2017). As a result, the highest risks are of contamination from chemical spills, including from storages, affecting groundwater and surface water (Huddlestone-Holmes *et al.* 2018; Soeder 2018; Bamberger *et al.* 2019). In the Cooper Basin, it was estimated that 8–16 ML will be needed for each vertical well and 24 ML for each horizontal well, with 40–60% being recovered as wastewater (Holland *et al.* 2020), resulting in substantial amounts of polluted wastewaters in storages on the floodplain. In Colorado's South Platte Alluvial Aquifer, there were 3449 surface spills (generally low volumes and areas) between 2010 and 2014 (Kanno and McCray 2021). Pollution was deemed of 'potential concern' in affecting 12% of the Cooper Basin, which could include release of wastewater into a watercourse if other options are not available (Holland *et al.* 2021). One of the highest risks not mentioned in any government assessments was overflow or over-topping of contaminated water storages built on the floodplain; this can clearly be seen during the 2016 flood of Tirrawarra Swamp (Fig. 4, Fig. S2) and this was only a medium flood (Fig. S1). The hundreds of water storages currently on the floodplain and future storages built with future increased oil and gas production will increase contaminated water spills onto the floodplain, affecting flood-dependent biota and ecosystem services. Large pastoral areas on the floodplain are marketed and managed for the production of organic beef, without use of chemicals (Brook 2017); increasing spillage of chemicals onto the floodplain could have devastating impacts on this sustainable industry.

There is also the significant issue of fugitive emissions, where greenhouse gases escape from unconventional gas operations; methane is of particular concern given its contribution to global warming (Caulton *et al.* 2014; Schneising *et al.* 2014; Bouman *et al.* 2015; Bista *et al.* 2017). With increasing development of unconventional gas resources in the Lake Eyre Basin, the emissions profile will inevitably increase (Australian Government Department of Industry 2021), including from underestimation of emissions from gas fields (Neininger *et al.* 2021), further affecting Australia's international targets for reduced emissions.

Impacts on floodplains from infrastructure and pollution will be predominantly local but may also affect downstream communities (human and ecological). As well as current and future impacts on the Ramsar-listed Coongie Lakes system and Cooper Creek–Wilson River floodplain confluence, two other wetlands of national importance, the Cooper Creek overflow swamps at Windorah and Nappa Merrie are likely to experience medium to high impacts (Fig. 1, Table S1). Downstream systems such as Lake Yamma Yamma and Lake Cuddapan on Cooper Creek and within the Cooper Basin may also be affected, although the risk may be low (Fig. 1, Table S1). There was no specific reference to such impacts in the government bioregional assessment (Holland *et al.* 2021) or in current policy or management relevant to the Lake Eyre Basin rivers. There are also many largely unknown potential impacts on ecosystem services, including cultural heritage, fishing, grazing and tourism. There is a need to adequately consider the long-term impacts of such developments in the Lake Eyre Basin river system. Further, there should be a focus and requirement on restoration of the floodplains once oil and gas production is completed, including ensuring that any contamination is removed and natural flow and flooding paths are restored.

The many different policies and legislative instruments (Table 1) focused on protecting the rivers of the Lake Eyre Basin have not adequately protected the natural variability of flows and flooding from oil and gas production infrastructure, as committed to by governments under the Lake Eyre Basin Agreement. Even for the more-protected site of the Ramsar-listed Coongie Lakes, there is little evidence of analyses of impacts or pollution effects from spills, despite the concentrated oil and gas production infrastructure in many areas (Fig. 2, 4). The major governments of the Lake Eyre Basin, namely, the Australian, Northern Territory, Queensland and South Australian Governments, have identified the importance of this river system over more than two decades, primarily through the establishment of the Lake Eyre Basin Agreement, focused on protecting the variability of flows and the dependent biodiversity and cultural values (Table 1). The community and governments raised significant objections to the development of the rivers for irrigation, which would divert flows from downstream floodplains (Gorringe 2017; Kingsford *et al.* 2017*b*; Morrish 2017). In particular, concern by the South Australian government about the potential impact of a cotton irrigation development on Cooper Creek, affecting flows to floodplains and the Coongie Lakes Ramsar Site, were a significant driver for the Lake Eyre Basin Agreement (Kingsford *et al.* 1998, 2017*b*). Subsequent development of policies, community and government programs and stakeholder groups provided a key focus of the protection of flows to the floodplain rivers of the Lake Eyre Basin (Table 1) (Kingsford *et al.* 2017*b*; Tan 2017).

Contrastingly, the focus on the potential impacts of oil and gas infrastructure on the floodplains was largely ignored by these processes. Exacerbating this lack of focus, there was no comprehensive analyses of the level or distribution of this threat across the floodplains and Ramsar-listed Sites. At the same time that the South Australian Government was concerned about the impacts of irrigation upstream, there was relatively little attention on the potential impacts of oil and gas infrastructure on the floodplains of the Coongie Lakes Ramsar Site. In South Australia, there was a 10-year moratorium on hydraulic fracturing over the south-east of the state, in the more populous regions, unlike the Lake Eyre Basin, which is remote and not receiving public concerns. The Queensland Government has attempted to protect their Lake Eyre Basin River floodplain, but pressure from resource development has effectively removed the essential protections. Under the degazetted Wild Rivers legislation, there was an attempt to protect the extent of floodplains, through the specification of Special Floodplain Management Areas, but these were not protected from oil and gas exploration and production (Table 1). A scientific review commissioned by the Queensland Government (Table 1, Fielder *et al.* 2019) pointed to all of the risks of oil and gas production identified on the floodplains and their dependent biota, including effects of spillages from storages on the floodplains of the Lake Eyre Basin, but this report was not released publicly. This underlines low government commitment to tackling this problem. Despite subsequent commitments by Queensland Governments (Table 1), no subsequent policies and regulations exist to protect these areas and their surface flows. Currently, resource development policies are primarily driving a significant oil and gas production in these areas, with unknown long-term detrimental impacts. Despite the operation of the *EPBC Act* since 1999 and requirements that potential impacts on Ramsar wetlands be referred, there were only eight referrals listed, with all but one deemed not to be controlled actions requiring rigorous environmental assessment (Table S3). Also, there are well recognised weaknesses in dealing with the effects of cumulative impacts from oil and gas production in terms of environmental assessment (Comino *et al.* 2014). The development has largely occurred in remote areas, with relatively little scrutiny about the impacts of this development and the likely scenarios for the future. Clearly, there is considerable future potential for increasing damage to these internationally important river systems, including the Coongie Lakes Ramsar Site, with impacts on hydrological connectivity, pollution, as well contributions to greenhouse-gas emissions. There are important issues of procedural justice and social licence in relation to these impacts and effects on the environments, ecosystem services and First Nations people (Luke *et al.* 2018).

Conclusions

There are many uncertainties and potentially high risks to the rivers of the Lake Eyre Basin and their floodplains, including their biodiversity and cultural values, as well as ecosystem services, resulting from current and future oil and gas exploration and development. The footprint of the oil and gas industry on the floodplains already raises serious issues about impacts on the ecological integrity and connectivity of these unique ecosystems and their biota, which have largely not been addressed by governments. Some of the risks were raised in the bioregional assessment for the Cooper region (Holland *et al.* 2021), but were largely dismissed as unimportant, with inadequate publicly accessible data and limited analysis. There is a need for more rigorous analyses of the impacts on flooding by structures already built on the floodplains, including well pads, roads and storages.

This could be undertaken through rigorous analyses of satellite imagery or more detailed drone analyses coinciding with flooding. In addition, there needs to be independent analysis and reporting of pollution effects, specifically spills, including overtopping of the hundreds of storages on the floodplain holding co-produced water and a monitoring of fugitive greenhouse gas emissions. Effects of these threats on dependent biota remain largely ignored and require a strong focus on assessment as a requirement of current and future developments. There is also a need to implement policies that avoid such high risks on floodplains for all future oil and gas exploration and development. There is increasing understanding that unconventional gas development, including associated infrastructure, is a significant disruptor of floodplain ecosystems, fragmenting their patterns of connectivity and ecological processes. In particular, the Queensland and South Australian Governments need to adequately meet their obligations for protection of these internationally important ecosystems for future sustainability of the economies and ecosystem services of the Lake Eyre Basin. The Australian Government also needs to meet its responsibilities in relation to protecting the Coongie Lakes Ramsar site, protection of other nationally important wetlands and meeting the intent and policies in the Lake Eyre Basin Intergovernmental Agreement.

Supplementary material

Supplementary material is available online.

References

Adgate JL, Goldstein BD, McKenzie LM (2014) Potential public health hazards, exposures and health effects from unconventional natural gas development. *Environmental Science & Technology* **48**, 8307–8320. doi:10.1021/es404621d

Allred BW, Smith WK, Twidwell D, Haggerty JH, Running SW, Naugle DE, Fuhlendorf SD (2015) Ecosystem services lost to oil and gas in North America. *Science* **348**, 401–402. doi:10.1126/science.aaa4785

Arthington AH, Balcombe SR (2017) Natural flow drive the 'boom and bust' ecology of fish in Cooper Creek, an arid zone floodplain river. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 43–54. (CSIRO Publishing: Melbourne, Vic., Australia)

Australian Government (2021) 2021 National gas infrastructure plan. Department of Industry, Science, Energy and Resources, Report, Canberra, ACT, Australia.

Australian Government Department of the Environment and Energy (2018) Directory of Important Wetlands in Australia (DIWA) Spatial Database. Available at https://data.gov.au/data/dataset/directory-of-important-wetlands-in-australia-diwa-spatial-database1 [Verified 25 August 2021]

Bamberger M, Nell M, Ahmed AH, Santoro R, Ingraffea AR, Kennedy RF, Nagel SC, Helbling DE, Oswald RE (2019) Surface water and groundwater analysis using aryl hydrocarbon and endocrine receptor biological assays and liquid chromatography–high resolution mass spectrometry in Susquehanna County, PA. *Environmental Science: Processes & Impacts* **21**, 988–998.

Bergquist E, Evangelista P, Stohlgren TJ, Alley N (2007) Invasive species and coal bed methane development in the Powder River Basin, Wyoming. *Environmental Monitoring and Assessment* **128**, 381–394. doi:10.1007/s10661-006-9321-7

Bista S, Jennings P, Anda M (2017) Cradle to grave GHG emissions analysis of shale gas hydraulic fracking in Western Australia. *Renewable Energy and Environmental Sustainability* **2**, 45. doi:10.1051/rees/2017014

Blewett TA, Weinrauch AM, Delompré PL, Goss GG (2017) The effect of hydraulic flowback and produced water on gill morphology, oxidative stress and antioxidant response in rainbow trout (*Oncorhynchus mykiss*). *Scientific reports* **7**, 46582. doi:10.1038/srep46582

Bouman EA, Ramirez A, Hertwich EG (2015) Multiregional environmental comparison of fossil fuel power generation: assessment of the contribution of fugitive emissions from conventional and unconventional fossil resources. *International Journal of Greenhouse Gas Control* **33**, 1–9. doi:10.1016/j.ijggc.2014.11.015

Brook D (2017) Clean green beef – the importance of free-flowing rivers in the Lake Eyre Basin. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 113–117. (CSIRO Publishing: Melbourne, Vic., Australia)

Bunn SE, Thoms MC, Hamilton SK, Capon SJ (2006) Flow variability in dryland rivers: boom, bust and the bits in between. *River Research and Applications* **22**, 179–186. doi:10.1002/rra.904

Butcher R, Hale J (2011) Ecological character description for Coongie Lakes ramsar site. Department of Sustainability, Environment, Water, Population and Communities, Report, Canberra, ACT, Australia.

Caulton DR, Shepson PB, Santoro RL, Sparks JP, Howarth RW, Ingraffea AR, Cambaliza MOL, Sweeney C, Karion A, Davis KJ, Stirm BH, Montzka SA, Miller BR (2014) Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 6237–6242. doi:10.1073/pnas.1316546111

Comino M, Tan P-L, George D (2014) Between the cracks: water governance in Queensland, Australia and potential cumulative impacts from mining coal seam gas. *Journal of Water Law* **23**, 219–228.

Commonwealth Government of Australia, State of Queensland, State of South Australia (2000) Lake Eyre Basin Intergovernmental Agreement. Available at https://www.agriculture.gov.au/sites/default/files/documents/lake-eyre-basin-intergovernmental-agreement.pdf

Costelloe JF, Grayson RB, McMahon TA (2006) Modelling streamflow in a large anastomosing river of the arid zone, Diamantina River, Australia. *Journal of Hydrology* **323**, 138–153. doi:10.1016/j.jhydrol.2005.08.022

Cozzarelli IM, Kent DB, Briggs M, Engle MA, Benthem A, Skalak KJ, Mumford AC, Jaeschke J, Farag A, Lane JW Jr, Akob DM (2021) Geochemical and geophysical indicators of oil and gas wastewater can trace potential exposure pathways following releases to surface waters. *Science of The Total Environment* **755**, 142909. doi:10.1016/j.scitotenv.2020.142909

Crothers T (2017) Sustainable management of the Lake Eyre Basin rivers – regulate, educate or open the gate. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 195–211. (CSIRO Publishing: Melbourne, Vic., Australia)

Dang TD, Cochrane TA, Arias ME, Van PDT, de Vries TT (2016) Hydrological alterations from water infrastructure development in the Mekong floodplains. *Hydrological Processes* **30**, 3824–3838. doi:10.1002/hyp.10894

Davidson NC, Fluet-Chouinard E, Finlayson CM (2018) Global extent and distribution of wetlands: trends and issues. *Marine and Freshwater Research* **69**, 620–627. doi:10.1071/MF17019

Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* **81**, 163–182. doi:10.1017/S1464793105006950

EHS Support (2018) Assessment of the potential scale of unconventional gas development in the Cooper Basin, Qld. Report prepared for the Department of Natural Resources, Mines and Energy.

Emmott A (2017) River sustainability – essential for the triple bottom line for landholders. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 107–111. (CSIRO Publishing: Melbourne, Vic., Australia)

Enoch L (2019) Queensland government committed to protecting Lake Eyre Basin. Minister for Environment and the Great Barrier Reef, Minister for Science and Minister for the Arts, Media Release, Canberra, ACT, Australia.

Fagan SD, Nanson GC (2004) The morphology and formation of floodplain-surface channels, Cooper Creek, Australia. *Geomorphology* **60**(1–2), 107–126. doi:10.1016/j.geomorph.2003.07.009

Fielder D, Grady S, Broadben L (2019) Assessing development risks to the ecological values of the free flowing rivers of the Kati Thanda–Lake Eyre Basin (Qld). An Independent Scientific Expert Panel Report prepared for the Department of Environment and Science, Queensland Government. (Redleaf Environmental: Brisbane, Qld, Australia) Available at https://environment.des.qld.gov.au/_data/assets/pdf_file/0036/259974/scientific-expert-panel-report-evs-lake-eyre-basin.pdf

Gordalla BC, Ewers U, Frimmel FH (2013) Hydraulic fracturing: a toxicological threat for groundwater and drinking-water? *Environmental Earth Sciences* **70**, 3875–3893. doi:10.1007/s12665-013-2672-9

Gorringe S (2017) Looking after the rivers – a view from about 40,000 years of experience. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 95–102. (CSIRO Publishing: Melbourne, Vic., Australia)

Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F, Babu S, Borrelli P, Cheng L, Crochetiere H, Ehalt Macedo H, Filgueiras R, Goichot M, Higgins J, Hogan Z, Lip B, McClain ME, Meng J, Mulligan M, Nilsson C, Olden JD, Opperman JJ, Petry P, Reidy Liermann C, Sáenz L, Salinas-Rodríguez S, Schelle P, Schmitt RJP, Snider J, Tan F, Tockner K, Valdujo PH, van Soesbergen A, Zarfl C (2019) Mapping the world's free-flowing rivers. *Nature* **569**, 215–221. doi:10.1038/s41586-019-1111-9

Hall L, Buchanan S, Totterdell J, Lai É, Langford R, Sundaram B, Ransley T, Glenn K, Heugh A, Inskeep C, Zhu R, Lech M, Skeers N, Stewart G (2018) Rapid regional prioritisation for tight and shale gas potential of eastern and northern Australian basins. Geological and bioregional assessments program: Stage 1 – Report. Prepared by Geoscience Australia for the Department of the Environment and Energy, Canberra, ACT, Australia.

Holland KL, Brandon C, Crosbie RS, Davies P, Evans T, Golding L, Gonzalez D, Gunning ME, Hall LS, Henderson B, Kasperczyk D, Kear J, Kirby J, Lech ME, Macfarlane C, Martinez J, Marvanek S, Merrin LE, Murray J, O'Grady A, Owens R, Pavey C, Post D, Rachakonda P, Raiber M, Sander R, Stewart S, Sundaram B, Tetreault-Campbell S, Williams M, Zhang Y, Zheng H (2020) Geological and environmental baseline assessment for the Cooper GBA region. Geological and Bioregional Assessment Program: Stage 2 – report. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.

Holland KL, Brandon C, Crosbie RS, Davies PJ, Doble R, Huddlestone-Holmes CR, O'Grady AP, Peeters LJM, Tetreault-Campbell S, Aghbelagh YB, Arjomand E, Bailey AHE, Barry K, Donohue R, Evans TJ, Evenden C, Flett D, Frery E, Gonzalez D, Herr A, Kasperczyk D, Kear J, Kim SSH, King D, Lawrence E, Lawson C, Li LT, MacFarlane C, Mokany K, Mallants D, Martinez C, Martinez J, Marvanek SP, Mateo C, McVicar TR, Merrin LE, Murray J, Northover S, Norton K, Pavey CR, Peljo M, Raiber M, Reese B, Sander R, Stewart SB, Taylor AR, Turnadge C, Vaze J, Woods M, Zhejun P (2021) Impact assessment for the Cooper GBA region. Geological and Bioregional Assessment Program: Stage 3 synthesis – report. Department of Agriculture, Water and the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.

Huddlestone-Holmes C, Horner N, Apte S, Day S, Huth N, Kear J, Kirby J, Mallants D, Measham T, Pavey C, Schinteie R (2018) Assessment of scientific knowledge of shale gas and shale oil potential impacts. Report, CSIRO, Australia.

Hupp CR, Pierce AR, Noe GB (2009) Floodplain geomorphic processes and environmental impacts of human alteration along coastal plain rivers, USA. *Wetlands* **29**, 413–429. doi:10.1672/08-169.1

Jackson RE, Gorody AW, Mayer B, Roy JW, Ryan MC, Van Stempvoort DR (2013) Groundwater protection and unconventional gas extraction: the critical need for field-based hydrogeological research. *Groundwater* **51**, 488–510. doi:10.1111/gwat.12074

Junk WJ (2013) Current state of knowledge regarding South America wetlands and their future under global climate change. *Aquatic Sciences* **75**, 113–131. doi:10.1007/s00027-012-0253-8

Kanno CM, McCray JE (2021) Evaluating potential for groundwater contamination from surface spills associated with unconventional oil and gas production: methodology and application to the south platte alluvial aquifer. *Water* **13**, 353. doi:10.3390/w13030353

Kerezsy A, Arthington AH, Balcombe SR (2014) Fish distribution in far western Queensland, Australia: the importance of habitat, connectivity and natural flows. *Diversity* **6**, 380–395. doi:10.3390/d6020380

Kingsford RT (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**, 109–127. doi:10.1046/j.1442-9993.2000.01036.x

Kingsford RT (2015) Conservation of floodplain wetlands – out of sight, out of mind. *Aquatic Conservation: Marine and Freshwater Ecosystems* **25**, 727–732. doi:10.1002/aqc.2610

Kingsford RT (2017*a*) Sustainability for the rivers of the Lake Eyre Basin. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 229–239. (CSIRO Publishing: Melbourne, Vic., Australia)

Kingsford RT (2017*b*) The Lake Eyre Basin – one of the world's great desert river systems. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 3–18. (CSIRO Publishing: Melbourne, Vic., Australia)

Kingsford RT, Thomas RF (1995) The Macquarie Marshes in Arid Australia and their waterbirds: a 50-year history of decline. *Environmental Management* **19**, 867–878. doi:10.1007/BF02471938

Kingsford RT, Boulton AJ, Puckridge JT (1998) Challenges in managing dryland rivers crossing political boundaries: lessons from Cooper Creek and the Paroo River, central Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**, 361–378. doi:10.1002/(SICI)1099-0755(199805/06)8:3<361::AID-AQC294>3.0.CO;2-V

Kingsford RT, Lemly AD, Thompson JR (2006) Impacts of dams, river management and diversions on desert rivers. In 'Ecology of desert rivers'. (Ed. RT Kingsford) pp. 203–247. (Cambridge University Press: Cambridge, UK)

Kingsford RT, Walker KF, Lester RE, Young WJ, Fairweather PG, Sammut J, Geddes MC (2011) A ramsar wetland in crisis – the Coorong, lower lakes and Murray mouth, Australia. *Marine and Freshwater Research* **62**, 255–265. doi:10.1071/MF09315

Kingsford RT, Costelloe J, Sheldon F (2014) Lake Eyre Basin – challenges for managing the world's most variable river system. In 'River basin management in the twenty-first century'. (Eds VR Squires, HM Milner, KA Daniell) pp. 346–367. (CRC Press: Boca Raton, FL, USA)

Kingsford RT, Mac Nally R, King A, Walker KF, Bino G, Thompson R, Wassens S, Humphries P (2015) A commentary on 'Long-term ecological trends of flow-dependent ecosystems in a major regulated river basin', by Matthew J. Colloff, Peter Caley, Neil Saintilan, Carmel A. Pollino and Neville D. Crossman. *Marine and Freshwater Research* **66**, 970–980. doi:10.1071/MF15185

Kingsford RT, Bassett A, Jackson L (2016) Wetlands: conservation's poor cousins. *Aquatic Conservation: Marine and Freshwater Ecosystems* **26**, 892–916. doi:10.1002/aqc.2709

Kingsford RT, Bino G, Porter JL (2017*a*) Continental impacts of water development on waterbirds, contrasting two Australian river basins: global implications for sustainable water use. *Global Change Biology* **23**, 4958–4969. doi:10.1111/gcb.13743

Kingsford RT, Norris V, Rodrigo M (2017*b*) Lake Eyre Basin Rivers: connecting the river champions. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 77–93. (CSIRO Publishing: Melbourne, Vic., Australia)

Kingsford RT, Bino G, Finalyson CM, Falster D, Fitzsimons JA, Gawlik DE, Murray NJ, Grillas P, Gardner RC, Regan TJ, Roux D, Thomas RF (2021*a*) Ramsar wetlands of international importance: improving conservation outcomes. *Frontiers in Environmental Science* **9**, 643367. doi:10.3389/fenvs.2021.643367

Kingsford RT, McLoughlin CA, Brandle R, Bino G, Cockayne B, Schmarr D, Gotch T, Norris V, McCann J (2021*b*) Adaptive management of Malkumba–Coongie lakes ramsar site in arid Australia: a free flowing river and wetland system. *Sustainability* **13**, 3043. doi:10.3390/su13063043

Knighton AD, Nanson GC (1994) Flow transmission along an arid zone anastomosing river, Cooper Creek, Australia. *Hydrological Processes* **8**, 137–154. doi:10.1002/hyp.3360080205
Knighton D, Nanson GC (2002) Inbank and overbank velocity conditions in an arid zone anastomosing river. *Hydrological Processes* **16**, 1771–1791. doi:10.1002/hyp.1076
Larkin ZT, Ralph TJ, Tooth S, Fryirs KA, Carthey AJR (2020) Identifying threshold responses of Australian dryland rivers to future hydroclimatic change. *Scientific Reports* **10**, 6653. doi:10.1038/s41598-020-63622-3
Lech M, Wang L, Hall L, Bailey A, Palu T, Owens R, Skeers N, Woods M, Dehelean A, Orr M, Cathro D, Evenden C (2020) Shale, tight and deep coal gas prospectivity of the Cooper Basin. Technical appendix for the geological and bioregional assessment: Stage 2 – Report. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, Canberra, ACT, Australia.
Lefebvre R (2017) Mechanisms leading to potential impacts of shale gas development on groundwater quality. *Wiley Interdisciplinary Reviews: Water* **4**, e1188.
Lemly AD, Kingsford RT, Thompson JR (2000) Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management* **25**, 485–512. doi:10.1007/s002679910039
Liu CM, Xia J (2004) Water problems and hydrological research in the yellow river and the Huai and Hai river basins of China. *Hydrological Processes* **18**, 2197–2210. doi:10.1002/hyp.5524
Liu H, Zhang S, Li Z, Lu X, Yang Q (2004) Impacts on wetlands of large-scale land-use changes by agricultural development: the small Sanjiang plain, China. *Ambio* **33**, 306–310. doi:10.1579/0044-7447-33.6.306
Luke H, Brueckner M, Emmanouil N (2018) Unconventional gas development in Australia: a critical review of its social licence. *The Extractive Industries and Society* **5**, 648–662. doi:10.1016/j.exis.2018.10.006
Mallants D, Bekele E, Schmid W, Miotlinski K, Taylor A, Gerke K, Gray B (2020) A generic method for predicting environmental concentrations of hydraulic fracturing chemicals in soil and shallow groundwater. *Water* **12**, 941. doi:10.3390/w12040941
McGlade C, Speirs J, Sorrell S (2013) Unconventional gas – a review of regional and global resource estimates. *Energy* **55**, 571–584. doi:10.1016/j.energy.2013.01.048
McMahon TA, Murphy RE, Peel MC, Costelloe JF, Chiew FHS (2008) Understanding the surface hydrology of the Lake Eyre Basin: part 2 – streamflow. *Journal of Arid Environments* **72**, 1869–1886. doi:10.1016/j.jaridenv.2008.06.001
Measham TG, Brake L (Eds) (2009) People, communities and economies of the Lake Eyre Basin, DKCRC Research Report 45, Desert Knowledge Cooperative Research Centre, Alice Springs, NT, Australia.
Micklin PP (1988) Dessication of the aral sea: a water management disaster in the Soviet Union. *Science* **241**, 1170–1176. doi:10.1126/science.241.4870.1170
Mohammadi A, Costelloe JF, Ryu D (2017) Application of time series of remotely sensed normalized difference water, vegetation and moisture indices in characterizing flood dynamics of large-scale arid zone floodplains. *Remote Sensing of Environment* **190**, 70–82. doi:10.1016/j.rse.2016.12.003
Morrish B (2017) 'Once more into the breach, dear friends . . . ' – the ongoing battle for the Cooper. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 151–158. (CSIRO Publishing: Melbourne, Vic., Australia)
Mudd GM (2017) Mining and the Lake Eyre Basin environment: past, present and possible futures. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 173–191. (CSIRO Publishing: Melbourne, Vic., Australia)
Neininger BG, Kelly BF, Hacker JM, Lu X, Schwietzke S (2021) Coal seam gas industry methane emissions in the Surat Basin, Australia: comparing airborne measurements with inventories. *Philosophical Transactions of the Royal Society – A. Mathematical, Physical and Engineering Sciences* **379**, 20200458. doi:10.1098/rsta.2020.0458
Nilsson C, Reidy CA, Dynesius M, Revenga C (2005) Fragmentation and flow regulation of the world's large river systems. *Science* **308**, 405–408. doi:10.1126/science.1107887
Northern Territory Government (2014) Northern Territory Petroleum Tenure. Available at https://data.nt.gov.au/dataset/strike—northern-territory-petroleum-and-pipeline-titles [Verified 10 March 2022]
Northern Territory Government (2019) AS/NZS ISO 19115 Geographic Information - Metadata, ANZLIC Metadata Profile, ver. 1.0: Northern Territory Mapped Streams. Available at http://www.ntlis.nt.gov.au/metadata/export_data?type=html&metadata_id=8003F6A9CD8F02C3E050CD9B21442D75 [Verified 13 August 2021]
Northern Territory Government (2021) Northern Territory Petroleum Wells. Available at https://data.nt.gov.au/dataset/strike—northern-territory-petroleum-wells [Verified 8 February 2022]
Olmstead SM, Muehlenbachs LA, Shih J-S, Chu Z, Krupnick AJ (2013) Shale gas development impacts on surface water quality in Pennsylvania. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 4962–4967. doi:10.1073/pnas.1213871110
Powell SJ, Letcher RA, Croke BFW (2008) Modelling floodplain inundation for environmental flows: Gwydir wetlands, Australia. *Ecological Modelling* **211**, 350–362. doi:10.1016/j.ecolmodel.2007.09.013
Queensland Department of Natural Resources and Mines (2014) Cooper Basin industry development strategy – report. Queensland Department of Natural Resources and Mines, Brisbane, Qld, Australia.
Queensland Government (2017) *Regional Planning Interests Act* 2014. Available at https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2014-011 [Verified 5 August 2022]
Queensland Government (2021*a*) Queensland Floodplain Assessment Overlay. Available at data.qld.gov.au/dataset/queensland-floodplain-assessment-overlay [Verified 6 July 2021]
Queensland Government (2021*b*) Queensland resources industry development plan. Draft for consultation. Report. Department of Resources, Brisbane, Qld, Australia.
Queensland Government (2021*c*) Queensland mines permits current web map service. Available at https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={31999657-7E6E-4530-AAAB-CE4973A944A5} [Verified 15 September 2021]
Queensland Government (2022) Water monitoring information portal. Available at https://water-monitoring.information.qld.gov.au/ [Verified 16 Septemeber 2021]
Ramos L, Hernandez LM, Gonzalez MJ (1994) Sequential fractionation of copper, lead, cadmium and zinc in soils from or near Donana National Park. *Journal of Environmental Quality* **23**, 50–57. doi:10.2134/jeq 1994.00472425002300010009x
Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews* **94**, 849–873. doi:10.1111/brv.12480
Richardson CJ, Reiss P, Hussain NA, Alwash AJ, Pool DJ (2005) The restoration potential of the mesopotamian marshes of Iraq. *Science* **307**, 1307–1311. doi:10.1126/science.1105750
Saunders DL, Meeuwig JJ, Vincent ACJ (2002) Freshwater protected areas: strategies for conservation. *Conservation Biology* **16**, 30–41. doi:10.1046/j.1523-1739.2002.99562.x
Schneising O, Burrows JP, Dickerson RR, Buchwitz M, Reuter M, Bovensmann H (2014) Remote sensing of fugitive methane emissions from oil and gas production in north American tight geologic formations. *Earth's Future* **2**, 548–558. doi:10.1002/2014EF000265
Sinergise Ltd (2021) Sentinelhub playground. Available at https://apps.sentinel-hub.com/sentinel-playground/ [Verified 17 November 2021]
Smee B (2020) Scientific advice recommending ban on fracking in Lake Eyre Basin kept secret and ignored. In *The Guardian*, 29 April 2020. Available at https://www.theguardian.com/australia-news/2020/apr/29/scientific-advice-recommending-ban-on-fracking-in-lake-eyre-basin-kept-secret-and-ignored [Verified 5 August 2022]
Smith VH (2003) Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research* **10**, 126–139. doi:10.1065/espr2002.12.142
Soeder DJ (2018) Groundwater quality and hydraulic fracturing: current understanding and science needs. *Groundwater* **56**, 852–858. doi:10.1111/gwat.12810

South Australian Government (2020) Waterbodies in South Australia. Available at https://data.sa.gov.au/data/dataset/waterbodies-in-south-australia [Verified 13 August 2021]

South Australian Government (2021*a*) Drillholes within South Australia. Available at https://data.sa.gov.au/data/dataset/drillholes-within-south-australia [Verified 14 July 2021]

South Australian Government (2021*b*) South Australian Resources Information Gateway. Available at https://map.sarig.sa.gov.au [Verified 15 September 2021]

State Government of NSW and Department of Regional New South Wales (2010) NSW Wetlands. Available at https://datasets.seed.nsw.gov.au/dataset/nsw-wetlands047c7 [Verified 1 February 2022]

State Government of NSW and Department of Regional New South Wales (2011) NSW Drillholes Petroleum. Available at https://datasets.seed.nsw.gov.au/dataset/nsw-drillholes-petroleum [Verified 8 February 2022]

Steinfeld CMM, Kingsford RT (2013) Disconnecting the floodplain: earthworks and their ecological effect on a dryland floodplain in the Murray–Darling Basin, Australia. *River Research and Applications* **29**, 206–218. doi:10.1002/rra.1583

Strizhenok AV, Fedorova AV (2020) Monitoring and assessment of the state of floodplain ecosystems exposed to oil and gas complex wastes. *Journal of Physics: Conference Series* **1515**, 032037. doi:10.1088/1742-6596/1515/3/032037

Tan P (2017) Water governance in Queensland: implications for wild rivers declarations in the Lake Eyre Basin. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 213–227. (CSIRO Publishing: Melbourne, Vic., Australia)

Tockner K, Stanford JA (2002) Riverine flood plains: present state and future trends. *Environmental Conservation* **29**, 308–330. doi:10.1017/S037689290200022X

Varol M (2011) Assessment of heavy metal contamination in sediments of the Tigris River (Turkey) using pollution indices and multivariate statistical techniques. *Journal of Hazardous Materials* **195**, 355–364. doi:10.1016/j.jhazmat.2011.08.051

Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A (2014) A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology* **48**, 8334–8348. doi:10.1021/es405118y

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM (2010) Global threats to human water security and river biodiversity. *Nature* **467**, 555–561. doi:10.1038/nature09440

Walburn AJD, Kingsford RT (2022) Oil and gas exploration and development on the rivers of the Lake Eyre Basin: distribution and consequences for wetlands, including the Coongie Lakes Ramsar Site. figshare. Dataset. doi:10.6084/m9.figshare.19352504.v3

Walker KF, Puckridge JT, Blanch SJ (1997) Irrigation development on Cooper Creek, central Australia-prospects for a regulated economy in a boom-and-bust ecology. *Aquatic Conservation: Marine and Freshwater Ecosystems* **7**, 63–73. doi:10.1002/(SICI)1099-0755(199703)7:1<63::AID-AQC218>3.0.CO;2-5

Wright T (2017) Kati Thanda-Lake Eyre – not just a wildlife paradise but an economic lifeline. In 'Lake Eyre Basin Rivers: environmental, social and economic importance'. (Ed. RT Kingsford) pp. 123–126. (CSIRO Publishing: Melbourne, Vic., Australia)

Xi Y, Peng S, Ciais P, Chen Y (2021) Future impacts of climate change on inland Ramsar wetlands. *Nature Climate Change*, **11**, 45–51. doi:10.1038/s41558-020-00942-2

Yao J, Zhang D, Li Y, Zhang Q, Gao J (2019) Quantifying the hydrodynamic impacts of cumulative sand mining on a large river-connected floodplain lake: Poyang lake. *Journal of Hydrology* **579**, 124156. doi:10.1016/j.jhydrol.2019.124156

Data availability. All data were obtained from government online databases, with links to similarly available floodplain extent data from government data and stored on Figshare (Walburn and Kingsford 2022).

Conflicts of interest. R. T. Kingsford was a member of the Lake Eyre Basin Scientific Advisory Panel until 2020, under the governance of the Lake Eyre Basin. The authors declare no other conflicts of interest.

Declaration of funding. This study was supported primarily by the Centre for Ecosystem Science, UNSW Sydney, and an Australian Research Council Linkage Project (LP180100159), with some funding from The Pew Charitable Trusts.

Acknowledgements. We thank Bryce Kelly for his comments, which improved an early draft of the paper.

Author affiliation

[A]Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, UNSW Sydney, Sydney, NSW 2062, Australia.