Environmental water management and H5 bird flu in waterbirds: Context and scenarios for decision-making

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Acknowledgements

We are grateful for the advice of the Commonwealth Environmental Water Holder's staff and avian influenza expert panel. We acknowledge the First Nations communities of the MDB and pay respect to their Elders past and present. We acknowledge First Nations people as the Traditional Owners of the land, water and sky Country across the MDB and value their expertise, wisdom and enduring connections that have informed their care for Country over millennia.

Abstract

The impact of animal viruses has dramatically increased over the last decade globally, exemplified by the disruption caused by the recent panzootic of high pathogenicity avian influenza (HPAI) H5N1 clade 2.3.4.4b (H5 bird flu), which has caused the deaths of millions of wild birds and mammals, as well as domestic animals such as poultry. Wild waterbirds play a role in the spread of H5 bird flu and suffer mass mortality from this virus. They are central to virus risk, given they undertake long-distance movements and often aggregate densely to breed, forage and roost. In many regulated river systems, wetlands and waterbirds can be influenced by managed 'environmental water', which is used to maintain habitats and support ecological processes such as waterbird breeding. However, the same water management levers that aim to support ecological processes may also influence host and environmental factors that can affect virus transmission and spread. Here, we explore potential virus incursion and outbreak scenarios relevant to decision-making about environmental water, including differences in outbreak location, timing, spread pathways and severity. We describe potential management levers and decisions, ranging from maintaining or increasing planned watering to altering, reducing or ceasing watering where disease risks outweigh ecological benefits. Overall, decision-making must balance ecological objectives, disease mitigation, operational feasibility and risks to threatened species and ecosystems. Improved understanding of relationships between water management, waterbird movements and disease dynamics will be essential to support predictive modelling and guide environmental water management under emerging virus threats.

Keywords

environmental water, avian influenza, H5N1, bird flu, colonial, waterbirds

Introduction

The impact of animal viruses has dramatically increased over the last decade globally, exemplified by the disruption caused by the recent panzootic of high pathogenicity avian influenza (HPAI) H5N1 clade 2.3.4.4b, which has caused the deaths of millions of wild birds and mammals, as well as domestic animals such as poultry (hereafter 'H5 bird flu', Peacock *et al.* 2025, FAO/WHO/WOAH 2026). Wild waterbirds are involved in the ecology of a range of viruses through maintenance of infection cycles, providing a reservoir of infection for other animals, contributing to spread of viruses to new areas, and being impacted by disease (Takakuwa *et al.* 1998, Klaassen *et al.* 2011, Klaassen and Wille 2023, WHA 2023, Moore *et al.* 2024). They can play a key role in the risk of incursion, establishment and spread of viruses because many species undertake long-distance nomadic or migratory movements from regional to global scales and congregate in large, dense, multi-species aggregations to breed, forage and roost (McGinness *et al.* 2024c, McGinness *et al.* 2025b, Teitelbaum *et al.* 2026).

Multiple international agreements exist to protect waterbirds and their habitats, including maintaining the ecological character of wetlands under the Ramsar Convention on Wetlands of International Importance (Ramsar 1971, Finlayson *et al.* 2011) and supporting the life cycles of species listed under the Convention on the Conservation of Migratory Species of Wild Animals (CMS 1979). Australia also has bilateral agreements pertaining to the protection of migratory birds with China (CAMBA 1986), Japan (JAMBA 1974) and the Republic of Korea (ROKAMBA 2006). Many waterbird species are also protected at national and state levels through their listings as threatened or migratory species (e.g. under Australia's federal *Environment Protection and Biodiversity Conservation Act 1999,* (EPBC 1999)). In addition, waterbirds are often important targets for multi-jurisdictional conservation management initiatives, including explicit waterbird objectives set in legislation governing water use, such as increasing waterbird abundances and maintaining waterbird species diversity (e.g. Australia's Murray–Darling Basin Plan; Australian Government 2024, MDBA 2025). One of the primary tools used to support these objectives is 'environmental watering' – managed water flows provided to sustain aquatic ecosystems (Arthington *et al.* 2018a) – entailing investments of millions of dollars annually (DCCEEW 2026).

Under certain conditions environmental watering has the potential to influence waterbird behaviour, thereby affecting the potential spread or impact of viruses such as H5 bird flu. For example, changes in water location, duration, timing, depth or extent may influence bird density or numbers (encourage or discourage *dispersion*), or influence bird movements (encourage or discourage *dispersal*). This presents a novel question: How might we manage water at broad geographic scales to mitigate a wildlife disease? However, understanding of the relationships between management of water in wetlands, waterbird responses, and disease outbreaks is still evolving. For example, avian cholera management has moved from suspecting wetlands were long-term reservoirs and consequently draining them, to finding that persistence was often short-lived, and shifting management emphasis toward carcass removal, reducing bird densities, and fine scale habitat management is substantially more effective at mitigating impacts (Samuel *et al.* 2004, Blanchong *et al.* 2006, Samuel *et al.* 2007). It has also been suggested that the impacts of avian botulism could be reduced through judicious use of environmental watering (Brandis *et al.* 2019), however the effectiveness of this has not been evaluated to-date. It can also be difficult to disentangle the effects of water management from other factors, as exemplified during management of an outbreak of H5 bird flu in Eurasian Cranes (*Grus grus*) in the Hula Valley of Israel, where diversionary feeding and carcass removal may have also affected outcomes related to the virus (Klein 2025).

Herein, we discuss potential H5 bird flu spread and outbreak management in the context of waterbirds and wetlands influenced by environmental water. Given the recent arrival of H5 bird flu on the Australian mainland, making it the last continent in the world to face the challenges involved (Klaassen and Wille 2023, WHA 2023, WOAH 2026), coupled with Australia's Murray–Darling Basin (MDB) being widely regarded as an internationally significant example of large-scale water management, policy reform and environmental watering success (Wheeler 2014, Grafton and Wheeler 2018, Grafton 2019), we use the MDB as a case study. We give examples of important dimensions of potential virus outbreaks and management scenarios relevant to environmental watering. We outline environmental water levers and expected waterbird responses and give examples of considerations for a range of watering decisions. Finally, we discuss priority information needs to support water and wetland decision-making in the context of bird-borne viruses and their impacts. The information and examples provided are widely applicable internationally, wherever water and wetlands are managed to support waterbird populations.

H5 bird flu incursion and establishment pathways and impacts

H5 bird flu has spread rapidly via bird movements across the world since 2021, initially from Eurasia into Africa, then North America in late 2021, South America in 2022, the sub-Antarctic in 2023 and Antarctica in 2024; however Australia remained the last continent free of the virus until 2026 (FAO/WHO/WOAH 2026). Prior to arrival of H5 bird flu in Australia, risk assessments identified three potential routes of incursion: (1) arrival with long distance migratory shorebirds and seabirds from the northern hemisphere; (2) arrival through seabirds from Antarctica or the Southern Ocean; or 3) arrival with nomadic waterbirds through the Austral-Papuan region (WHA 2023, Wille *et al.* 2024, Ryding *et al.* 2025, Breed *et al.* 2026). Following the long-distance spread of H5 bird flu through the sub-Antarctic in 2025 (Clessin *et al.* 2026) and confirmation of H5 bird flu on Australia's sub-Antarctic Heard Island (McInnes *et al.* 2026), the risk of incursion from the south increased and the first cases of H5 bird flu in Australia followed in June 2026, in a brown skua (*Stercorarius antarcticus*) and multiple giant petrels (*Macronectes* sp) found on the southern coast. The viral genome recovered from the brown skua confirmed that H5 bird flu had arrived in Australia via the sub-Antarctic (GISAID https://gisaid.org/). The risk of additional incursions from the north remains, increasing between August and October as hundreds of thousands of shorebirds (Charadriiformes) and other species migrate annually to Australia, travelling from and through regions with H5 bird flu (Clemens *et al.* 2016, Wille *et al.* 2019, Hansen *et al.* 2022). Some shorebird species stop over to forage in Australian inland wetlands during migrations (Clemens *et al.* 2021), and may mix with local waterbirds at these locations, creating opportunity for inland exposure and subsequent establishment of viruses locally.

Following establishment of H5 bird flu in local wildlife the virus can spread rapidly via highly mobile waterbird species and may affect species differently depending on their ecology. For example, ducks will likely play a key role as a primary reservoir and vector of H5 bird flu in Australia if the virus becomes established as they are important reservoir hosts of avian influenza viruses elsewhere, including H5 bird flu, known to be responsible for long-distance spread(Damodaran *et al.* 2026). Critically, some duck species have no observable clinical disease when infected, so may be responsible for 'silent spread', infecting more susceptible species (Kim *et al.* 2009, Wight *et al.* 2024, Teitelbaum *et al.* 2026). Moreover, many duck species tend to aggregate within agricultural and urban areas, increasing risk of transmission to humans and domestic stock including poultry (Kim *et al.* 2009) (Wight *et al.* 2024, Teitelbaum *et al.* 2026). While movements of ducks to Australia from overseas are thought to be rare, once viruses spread east from south-east Asia past the 'Wallace Line', the chances of movements of infected birds to Australia from the north increase (WHA 2023, Breed *et al.* 2026).

Other species are at particular risk because of their nesting behaviours. Group-nesting waterbirds (also referred to as 'aggregate' or 'colonial'-nesting waterbirds) congregate in dense multi-species groups of hundreds to tens of thousands for breeding, during spring, summer or autumn, depending on location and wetland conditions, however birds generally start moving to breeding sites from early spring (Arthur *et al.* 2012, Brandis *et al.* 2021, McGinness *et al.* 2024c, McGinness *et al.* 2025b). During breeding bird density is very high for months, putting aggregations at high risk of mass mortality events. Foraging sites can also host large numbers of birds and may be tens of kilometres away from nesting sites (McGinness *et al.* 2025b). In addition, many of these species use agricultural and urban areas for foraging, with the potential to encounter poultry and other domestic stock (McGinness *et al.* 2024b). Following nesting, these species are at risk of spreading viruses because they undertake rapid, long-distance nomadic or migratory flights when not breeding, particularly in spring and autumn, including in some cases crossing to Papua New Guinea (McGinness *et al.* 2024a, McGinness *et al.* 2024c, McGinness *et al.* 2025a).

Some threatened species may be at greater risk because of shared habitats with migratory seabirds, migratory shorebirds, or group-nesting waterbirds. Many migratory species use inland wetlands of Australia (Supplementary Table 3), including both breeding sites and foraging sites of group-nesting waterbird species, which increases the likelihood of virus arrival and spread at these sites (Reid *et al.* 2013, Clemens *et al.* 2021). For example, the migratory curlew sandpiper (*Calidris ferruginea*) occurs in wetlands of inland Australia and is critically endangered (Minton *et al.* 2006, ALA 2026), and the breeding strongholds of the endangered Australasian bittern (*Botaurus poiciloptilus*) are frequently at the same locations as group-nesting waterbirds such as ibis and spoonbills (Herring *et al.* 2021). Group-nesting waterbird families such as ibis, spoonbills, herons, egrets, pelicans and cormorants supported by environmental water in the MDB have all tested positive for H5 bird flu outside of Australia (Supplementary Table 4; FAO (2026)).

Predators and scavengers that feed on infected prey are also at high risk of infection (Fisher *et al.* 2025). In Australian inland wetlands, this is of particular concern for raptors such as white-bellied sea eagles, whistling kites, black kites, swamp harriers, and wedge-tailed eagles. More than 50 species of mammals have been impacted by H5 bird flu internationally, dominated by predators and scavengers (Peacock *et al.* 2025). In the Australian context, mammals at high risk of infection include feral species such as cats, foxes, and pigs, and native species such as dingoes, quolls, Tasmanian devils, rakali, seals and sea lions (Ulloa *et al.* 2023, Plaza *et al.* 2024, Bamford *et al.* 2025).

Distribution of water through the landscape may influence the spread and impact of H5 bird flu by influencing the density and movement of waterbirds. Large scale outbreaks and impacts of H5 bird flu are more likely to occur in areas with high bird numbers and densities (Ferenczi *et al.* 2021). Landscape-scale variations in water availability, such as flood events and environmental watering, can result in movement and concentration of waterbirds from a wide range of locations into one area. In this context, there is potential for environmental water managers to influence outcomes with a view to mitigating impacts.

Water management levers and waterbird responses

Water levers and limitations

Potential ecological management targets to influence waterbird numbers and movements include a) landscape-scale availability of foraging and breeding habitat (e.g. number, size and quality of wetlands across a region); b) site-scale wetland water regimes affecting local waterbird habitat and food availability; and c) site-scale management of non-water factors such as disturbance, hunting, and feral predators/competitors. Hydrological levers that can influence these management targets include inundation location, frequency, extent, duration, timing, depth, and rate of water level rise and fall (Yarnell *et al.* 2020). However, the applicability and feasibility of applying each of these levers depends on many factors including location, climate, and the practicalities of delivering water.

In Australia's MDB, water is managed via a combination of legislative, institutional, and market-based mechanisms that are internationally recognised for their progressiveness (Wheeler 2014, Grafton and Wheeler 2018, Grafton 2019). The MDB covers more than one million square kilometres across southeastern Australia (Figure 1), spanning multiple jurisdictions (Hart 2016). It supports internationally important wetlands, diverse waterbird populations and major agricultural industries. Within the MDB, the Commonwealth Environmental Water Holder (CEWH) and other water holders (public and private) influence water in a range of wetland areas (Swirepik *et al.* 2016).

The amount of environmental water available, used, and as a proportion of total surface water availability varies each year. For example, the CEWH as the MDB's largest environmental water holder manages approximately 3,000 GL of surface water entitlements (CEWH 2026). In 2023-2024 and 2024-25, the CEWH delivered 1,798 and 1,623 GL of environmental water respectively (DCCEEW 2025). By comparison, surface water availability across the Murray-Darling Basin in 2023-2024 was 39,048 GL (BOM 2024). Consequently, managed environmental water represents only a small fraction (4-5%) of the total water in the MDB system. Ecological responses to environmental watering usually occur within the context of a much larger volume of flows, making attributing ecological responses solely to environmental water intrinsically challenging. However, even small amounts of targeted environmental water at particular times and in certain areas can influence ecological outcomes, such as reaching flow and inundation thresholds for commencement of breeding or maintaining inundation area and depth to prevent nest abandonment, especially in dry years (Brandis *et al.* 2011, Arthur *et al.* 2012, Bino *et al.* 2014).

The MDB Environmental Watering Strategy (MDBA 2025) lists 28 areas of special importance for waterbirds, of which 18 can be influenced by environmental water (Figure 1). The feasibility of influencing hydrological levers for ecological outcomes varies between these areas and across the MDB. For example, the southern MDB is generally temperate with winter rainfall, spring flooding, and highly regulated rivers, in which water is managed via operation of dams, regulators, and pumps. In contrast, the northern MDB is semi-arid to subtropical, with summer rainfall, episodic flooding and a mix of regulated and unregulated rivers, with water management more focused on rules for water extraction (Stewardson *et al.* 2021, MDBA 2025). Consequently, direct control of levers such as inundation location, frequency, extent, duration, timing, depth, and rate of rise and fall is highly dependent on the location of the wetland of concern and management practicalities.

Climatic cycles such as the El Nino-Southern Oscillation (Taschetto *et al.* 2026) also affect the feasibility and outcomes of environmental water lever implementation. This is recognised in planning; for example, the MDB Environmental Watering Strategy (BEWS) describes environmental watering management objectives and strategies to achieve them for five scenarios: 'very dry', 'dry', 'moderate', 'wet' and 'very wet' (MDBA 2025). These scenarios are based on a combination of the past year's climate conditions and current water availability in storages (MDBA 2025). In this context, environmental water is more likely to influence bird aggregations and movements in 'dry' scenarios, when for example it could be a determining factor in affecting breeding or bird dispersal. In wetter scenarios, inundation thresholds that trigger bird responses are likely to be exceeded through natural rainfall and flooding, and the effects of environmental water levers may be reduced.

Frameworks for predicting and evaluating environmental water outcomes are currently not well equipped to quantify the role of environmental water in shaping waterbird aggregation and movement dynamics and, by extension, bird-borne disease risk (Lyons *et al.* 2022). However recent research efforts are building the analytical capability needed to begin filling this gap (Penton *et al.* 2023, Mokany *et al.* 2024, Teng *et al.* In review). These advances provide an emerging evidence base and pathway for quantifying how environmental water delivery decisions influence the inundation conditions that affect waterbird movements and aggregations — and, in turn, for informing water management as a lever for managing bird-borne disease risk.

Waterbird responses to watering actions

There are several key aspects of waterbird ecology that environmental water levers can influence that may affect the spread, transmission and impact of bird-borne viruses (**Error! Reference source not found.**).

The first is bird density (the number of individuals present per unit area) and, related to this, dispersion or distribution (the spatial pattern of how those individuals are located within that area). Density and dispersion can vary significantly among species and with other factors such as life stage, activities and location. For example, group-nesting waterbirds such as ibis, spoonbills, egrets, herons, pelicans and cormorants typically build nests immediately adjacent to each other in clumps, with high density and low dispersion of individuals (Arthur *et al.* 2012, Brandis *et al.* 2018). Each breeding area typically consists of multiple nest clumps dispersed across the area. Individuals in one clump of nests that is separated (dispersed) from another clump are more likely to exchange viruses with each other than with individuals from the other clump. When roosting, bird density is typically lower and dispersion higher, and when foraging, even more so – but individuals are still grouped together. This concept can be expanded to a regional or landscape scale, where the density and dispersion of suitable bird *habitats* (as well as birds) might be influenced by environmental water.

The second key aspect of waterbird ecology in this context is bird movement or dispersal. Bird movements also vary significantly among species and with other factors such as life stage, activities, location and weather (Pedler *et al.* 2018, Teitelbaum and Mueller 2019, McGinness *et al.* 2024c). A broad spectrum of movement strategies is used by waterbirds, where the behaviour of any one individual or species might range from a) residency or 'sedentary movements', where birds move consistently between established roost, nest and foraging sites; to b) nomadism, where individuals move different distances and directions irregularly and are generally responding opportunistically to resource availability, including choosing or leaving breeding or foraging sites; to c) migration, where individuals regularly move relatively long distances predictably between particular locations and in consistent directions, usually seasonally or annually (Mueller and Fagan 2008, Teitelbaum and Mueller 2019, Shaw 2020, McGinness *et al.* 2024c).

There is potential for environmental watering to influence a range of movements within this spectrum, by providing or altering the availability of water and associated food and habitat. Historically, environmental watering for waterbirds in the MDB has focused on supporting sufficient duration of flooding for successful completion of breeding of group-nesting waterbirds such as ibis, spoonbills, egrets, herons, cormorants and pelicans, on the assumption that if the needs of these species are met for breeding, the needs of many co-located species will also be met (Kingsford and Norman 2002, Brandis *et al.* 2024). For some wetlands there are known thresholds of water flow and inundation duration associated with movement to breeding sites and commencement of breeding by group-nesting waterbirds, and environmental water may be used to reach these thresholds (Arthur *et al.* 2012, Bino *et al.* 2014). Environmental water is also used to prevent breeding failures. For example, group nesting waterbirds are prone to abandon nests if water levels fall: in 2008, 74,095 pairs of ibis bred for the first time in seven years in the Narran Lakes Ramsar site, and when water levels fell prematurely environmental water was used as part of a crisis management response to prevent mass nest abandonment (Brandis *et al.* 2011). Thus, changes in watering that affect food or habitat availability might influence a range of bird responses, including movement to a location to breed, forage or roost, the duration of stay in a location, the distances travelled from nests or roosts to forage, nesting completion vs abandonment, and departure and dispersal to other sites (Kingsford *et al.* 2010, Reside *et al.* 2010, Cumming *et al.* 2012, Cottee-Jones *et al.* 2016, Kalle *et al.* 2018, Runge and Tulloch 2018, Watts *et al.* 2018, Teitelbaum *et al.* 2020). Understanding the relationships between environmental watering and waterbird ecological responses such as breeding and movements assists managers to make environmental water delivery decisions that will effectively support waterbird populations. At the same time, understanding 'non-flow' factors such as disease that affect waterbird responses to environmental water management is also essential (Lester *et al.* 2020, McGinness *et al.* 2024b).

A third key aspect to consider is timing. There are specific temporal periods in bird movement and breeding ecology relevant to the potential arrival, spread and impacts of bird-borne viruses. One of the most important frameworks for these is the timing of arrival of migratory shorebirds or seabirds. Millions of migratory birds arrive in Australia each spring on a very regular schedule, and many are highly site faithful, returning to the same wetlands at the same time every year. This creates a predictable period of increased risk of virus arrival (Wille *et al.* 2024, Breed *et al.* 2026, Ross *et al.* 2026). Because most of the sites used by these birds are coastal and their movement cues are almost entirely seasonal there is limited scope for influence of their movements or timing through management, but opportunities for structured preparedness. A second important period is the waterbird breeding season in the MDB, which starts in spring and may extend into autumn and winter depending on the location and conditions. This period overlaps with the arrival of migratory bird species in Australia; it results in mixing of species and individuals from different regions in high densities, and in production of juveniles that are potentially more susceptible to viruses. Prior to the breeding season (winter) is likely low risk, not just because of the low density and dispersion of birds, but also because there is typically less movement by waterbirds in the colder months (McGinness *et al.* 2024c). In spring, movements become more frequent and longer-distance, connecting stopover sites, residency sites and breeding sites (McGinness *et al.* 2024c). During the breeding season, movements between nests and foraging sites become important, as well as between roosts and foraging sites (McGinness *et al.* 2025b). At the end of the breeding season, both adults and juveniles disperse from breeding sites, often long distances (McGinness *et al.* 2024a, McGinness *et al.* 2024c, McGinness *et al.* 2025a). At inland freshwater sites, environmental watering can affect these movements in a range of ways. For example, changes in water levels in nesting sites can cause nest abandonment, with subsequent egg and chick mortality, and associated adult dispersal (Leslie 2001, Brandis *et al.* 2011, Brandis *et al.* 2018, Robinson and McGinness 2025). Changing water levels may similarly cause dispersal from foraging or roosting sites, or early dispersal by juveniles and adults from breeding sites. The extent of water available in each site and the distribution of watered sites in the landscape may also influence the density and dispersion of birds.

Environmental water is critical for supporting the resilience of bird populations and their habitats in both the short term and the long term, particularly where changes to natural hydrology have occurred. While there are many unknowns and permutations regarding the potential spread and impacts of H5 bird flu and the potential management of environmental water during preparation and response phases, continued support through watering and other actions will be essential for long-term recovery.

Considerations for environmental water decision making

In the event of a disease outbreak, environmental watering options and related decision making will be affected by a wide range of considerations and information needs. The locations and species affected will be critical first-line knowledge, including whether the detected outbreak is in domestic vs wild birds, and co-located species presence, status, abundance and movements. The species involved may have cultural importance, potentially affecting prioritisation of management actions (Clarke 2023). There may be ecological, economic or sociological trade-offs or strictures involved in changing environmental watering plans (Pahl-Wostl *et al.* 2013, Lester *et al.* 2020). For example, changing watering plans with the intention of mitigating disease impacts on birds and their habitats may have negative impacts on other species groups or variables (e.g. fish, vegetation, invertebrates, or water quality; Tonkin *et al.* (2021)). Climate, season and weather conditions will influence the feasibility of environmental watering plans (or changes to plans) as well as likely bird and ecosystem impacts and responses (Arthington *et al.* 2018b).

There are also many operational considerations and constraints for environmental watering, including dam and pump operational rules, joint watering operations with other jurisdictions, private land flooding, and supply or demand for irrigation, stock and domestic water (Banks and Docker 2014, Lester *et al.* 2020, Kahan *et al.* 2021, Nicol *et al.* 2021). Carcass management and associated water quality and secondary disease considerations may also influence watering decisions (Gold *et al.* 2026). For example, there is some evidence that carcass removal can help to reduce mortality within breeding aggregations and reduce viral accumulation at the site which in turn can reduce spillover effects including from scavenging (Gold *et al.* 2026), though it also risks disturbance and subsequent movement of birds and associated virus spread (DAFF 2025). Finally, contextual governance, legal, jurisdictional, economic, financial, and health and safety considerations will be important. Monitoring and evaluation of the effects of the virus as well as management actions, as part of adaptive management, will be critical for population and ecosystem resilience.

Potential reasons for watering decisions

Reasons for decisions to change environmental watering plans will vary but generally fall into three areas: a) Avoiding or reducing mass mortality; b) Reducing spread of disease between wetland, agricultural or residential sites; and c) Supporting resilience, survival and recruitment of affected populations.

Preventing or reducing mass mortality is particularly important during breeding. Chicks are often highly susceptible to disease (Robinson and McGinness 2025); for example, there was near 100% mortality of sandwich tern chicks (*Thalasseus sandvicensis*) from H5 bird flu in Europe in 2022 (Knief *et al.* 2024). Nest-bound young are unable to move away from infected areas, and high nest density is likely to increase transmission (Boulinier 2023, Breed *et al.* 2026, Kuiken *et al.* 2026). High chick mortality rates may negate the benefits of watering to support breeding completion and recruitment. During non-breeding periods, decision-making might focus on large aggregations during drought conditions, species known to be highly susceptible to the virus, and whether mortality risk exceeds the ecological benefit of watering.

Reducing virus spread between sites is also important. Spread may be facilitated by adult movements between sites at the beginning of the breeding season (e.g. prospecting), movements between sites during the breeding season (e.g. post nest abandonment, or post chick mortality, or between successive breeding attempts), or juvenile and adult dispersal post-breeding (Boulinier 2023, Grémillet *et al.*

2023). During non-breeding periods, migratory, nomadic or foraging movements may also facilitate spread.

In some circumstances, a balance will need to be found between avoiding mass mortality, reducing virus spread, and supporting bird resilience, survival and recruitment despite the incursion of virus to an area. During breeding, support might include allowing successful completion of breeding already underway, avoiding nest abandonment caused by rapid water drawdown, and maintaining adequate foraging habitat for juvenile recruitment and adults supplying chicks. During non-breeding periods, species support might include providing dispersed refuge and foraging habitat during regional drying and preventing aggregations.

Potential watering decisions at site scale

Potential watering decisions will be affected by a range of considerations and will require estimation of potential positive and negative effects (**Error! Reference source not found.**). For example, water managers may decide to conduct an environmental watering action as planned, with no changes, when disease risk is assessed as low or localised, or the site provides essential habitat not available elsewhere, or water delivery does not increase connectivity between outbreak sites, or ecological benefits outweigh disease risk. On the other end of the scale, water managers may decide to cancel a watering event when watering is likely to attract large aggregations of birds to infected habitat, or there is a high probability of mass mortality based on species ecology, life stage and location. This may be particularly applicable when there are alternative habitats available in the landscape, as water delivery increases connectivity with infected systems, and the risk to threatened species is disproportionately high.

More nuanced decision-making may also be feasible. For example, water managers may decide to cease watering earlier than planned when a disease is detected after watering has commenced but before birds begin breeding, or when increasing bird densities elevates transmission risk, or when environmental objectives have been already substantially achieved, or when continued inundation prolongs the exposure period, or when drying down reduces pathogen persistence or bird aggregations (**Error! Reference source not found.**). Conversely, continuing watering longer than planned may be the preferred option when rapid drying would disperse infected birds and increase spread, or when gradual drawdown reduces density (as compared to rapid drawdown increasing density), or when water or habitat is required for completion of an important breeding attempt already underway, or when disease risk is reduced by maintaining dispersed habitat.

The area or number of sites watered might also be altered under different circumstances. Watering less area or fewer sites than planned may be employed where reduced habitat reduces attractiveness for large regional aggregations of birds, or when infection risk is concentrated in certain parts of the wetland, or if managers are targeting refuge habitat rather than breeding habitat, and the aim is to support survival rather than stimulate breeding. Conversely, watering a greater area or number of sites than planned may be the preferred option when increasing habitat area reduces bird density and disease transmission is density-dependent, or when multiple areas reduce congregation at limited resources, or when supporting dispersal away from outbreak locations.

Enhancing carcass management goals may also be considered in water management. For example, if carcasses are not being removed, maintaining or increasing watering at a site where carcasses are present could reduce risk of mammal scavenging and/or human interaction with infected carcasses and/or reduce viral accumulation at the site. Alternatively, if carcasses are being actively removed, cancelling watering or early drawdown could facilitate carcass access and swift removal.

In summary, an environmental watering plan may be altered where modification can reduce risk without causing greater ecological harm. Environmental watering decisions during risk periods balance multiple potentially competing objectives; timely and high-quality information will be needed to support effective decision-making and achieve that balance.

Outbreak and management scenarios

There are several dimensions of virus outbreak characteristics that have important implications for management and mitigation. These include outbreak locations, timing, spread pathway, spread indicators, and impact severity. We present examples of some potential scenarios specific to the MDB in **Error! Reference source not found.**, including these characteristics.

Outbreak locations can significantly affect management considerations. This includes whether the outbreak occurs in a single location or simultaneously in multiple locations. Some important examples of location contrasts to consider include outbreaks in coastal islands or wetlands vs outbreaks in inland rivers or wetlands, and outbreaks in agricultural areas (e.g. irrigated agriculture or domestic stock production sites such as intensive poultry or feedlots) vs urban or suburban areas (e.g. recreational lakes, wetlands or domestic birds) vs rural or remote areas. The accessibility of an outbreak location will significantly affect options for management such as carcass removal.

The seasonal timing of an outbreak may have a significant effect on its severity. For example, an outbreak during the breeding season is likely to have more severe impacts than an outbreak during non-breeding season. If other concurrent impacts on species or their habitats occur at the same time as an outbreak, severity will almost certainly be exacerbated. For example, the Australian Government is currently considering release of a carp virus to reduce invasive carp populations, which will most likely need to be released during spring or summer during the bird breeding season, and will at least temporarily reduce food resources and habitat quality for waterbirds (McGinness *et al.* 2020). Algal blooms are also increasingly common in warmer months in wetland and coastal habitats that provide breeding habitats and food for breeding birds (Dinsdale 2026). Climatic and weather context also affect concurrent impacts, virus spread and transmission scenarios, as well as decision making and management options (Prosser *et al.* 2023).

Virus spread pathways including rates and directions can also vary (Hill *et al.* 2022, Fornasiero *et al.* 2026). Fast, multi-directional pathways might include migratory and nomadic flyway movements in spring or autumn; movements to breeding sites in spring or summer; or movements between large breeding and feeding aggregations of birds in response to weather or flooding. Moderate rate linear pathways could occur along corridors, including nomadic movements along rivers and coastlines, or movements to alternate foraging sites or in response to disturbance. Slow, centralised pathways may include carcass-mediated local amplification (e.g. through predation or direct contact), environmental persistence, or domestic stock spillover back into wild birds (Chrzastek *et al.* 2025).

Virus spread indicators vary by species, and there are multiple scenarios for how a virus might initially be detected, with different implications for management intervention. For example: a) routine surveillance at a single wetland leads to detection in an individual or small number of birds or environmental samples (reasonable opportunity for management/mitigation intervention), or b) unusual clustered mortalities are observed at a single site, such as ≥5–10 carcasses of same species in a wetland within 48–72 hours, or sudden chick losses across multiple nests, leading to ad hoc surveillance that detects the virus (some opportunity for management/mitigation intervention), or c) widespread mass mortality at multiple sites signals wide virus prevalence (limited opportunity for mitigation intervention) (AHA 2026c).

The current global outbreak of H5 bird flu has produced highly variable impacts by region, species and across years — some regions saw catastrophic bird population declines while others saw low-level circulation (Chrzastek *et al.* 2025, Krammer *et al.* 2025, Plaza *et al.* 2025). Europe, North America and Africa have experienced multiple introductions over different years with variation in species most affected over time – hence the scenarios and impacts that could occur in Australia initially may be different to those that occur over subsequent years. This heterogeneity is why ongoing adaptation and evaluation of multiple new scenarios are needed.

Priority information needs to support environmental water decision making

Effective decision-making support for environmental watering and waterbird conservation in the context of virus outbreaks and spread requires a combination of surveillance, monitoring and research. Virus surveillance can provide early detection of the presence of viruses in wild bird populations before spread and impacts are obvious, as well as confirming the causes of symptoms and mortalities. Monitoring of wild bird aggregations and movements can detect and track symptoms, mortalities and virus movement. Finally, research underpins and enhances both surveillance and monitoring by generating the fundamental knowledge needed to interpret patterns, anticipate risks and design effective interventions. Research reveals the mechanisms driving virus emergence, transmission, spread and ecological impacts, and provides the evidence base required to refine management strategies, improve predictive models and support long-term conservation outcomes.

Surveillance and monitoring

Effective surveillance and monitoring for virus presence in wild birds are both critical for well-informed preparation and for management responses to outbreaks (Klaassen and Wille 2023, Kuiken *et al.* 2026). There are different types of surveillance and monitoring involved in detection and estimation HPAI infections, disease spread and associated impacts (Duan *et al.* 2023, Shen *et al.* 2025). These may include virus surveillance and testing, wild bird aggregation and mortality monitoring, and wild bird movement monitoring.

Two key types of surveillance are critical: a) active targeted surveillance - the testing of live (apparently healthy) birds, for example through taking blood samples, oropharyngeal swabs, cloacal swabs, faecal samples from birds, faecal samples from the environment or water samples; and b) passive general surveillance - the testing of sick or dead birds via investigation of disease or mortality events (Duan *et al.* 2023, Shen *et al.* 2025). Monitoring involves surveying wild bird aggregations and recording bird sickness and mortality (e.g., recording numbers, species, ages, locations, timing, proportions sick/dead vs healthy birds). It may involve on-ground observations, drone flights or other airborne surveys, or solar-powered monitoring cameras with remote network connections. Wild bird movement monitoring involves quantifying movement routes, timing, and rates, and identifying stopover, foraging and breeding sites used by wild birds. Bird movement monitoring or ‘tracking’ may include techniques such as satellite-tracking, radar tracking, or radio tracking (Gould *et al.* 2024). Evaluation of the performance of surveillance and monitoring efforts for various objectives, including early detection of H5 bird flu, quantification of impacts, and provision of data for modelling and prediction, would help to guide future investment in surveillance, monitoring and research to manage and mitigate bird flu and other viruses.

Coordination and implementation of wild bird active surveillance efforts vary by jurisdiction. In Australia, most virus surveillance is coordinated by the multi-partner National Avian Influenza Wild Bird steering group (NAIWB). The NAIWB conducts targeted surveillance for avian influenza viruses at selected locations, collecting environmental faecal samples or swabs from live caught or hunter-shot wild birds. Sampling sites are determined on a risk-assessment basis, with consideration of the presence of typical host species, domestic poultry, and human populations. Consequently, these efforts have historically been focused near the Australian coastline where migratory birds often first arrive (Figure 1; Grillo *et al.* (2015)), however the number of surveillance sites further inland has recently expanded (AHA 2026b). Two main waterbird groups are sampled (Grillo *et al.* 2015, AHA 2023, WHA 2026): Anseriformes (ducks, geese and swans) and Charadriiformes (shorebirds, gulls and terns), as these are generally considered the main reservoirs for avian influenza viruses (Olsen *et al.* 2006). Passive general surveillance is also conducted via Australia’s national biosecurity system investigating significant or unexplained morbidity and mortality events reported by the public or poultry farmers (AHA 2026b). During an outbreak, the lead responding agencies are national and jurisdictional animal health agencies, who conduct testing and determine response objectives and actions. The national management agreement for H5 HPAI in wildlife supports rapid and coordinated action through a ‘One Health’ approach that seeks to mitigate risks to human health, animal health, and the environment (EADRP 2025, NMA 2025, AHA 2026c).

Until 2025, there was no targeted surveillance or monitoring program for avian influenza viruses in any of the priority group-nesting waterbird breeding sites of the MDB. Given concern about the expected arrival of H5 bird flu and potential impacts on waterbirds, the CEWH and CSIRO established a framework for a surveillance and monitoring program for selected priority waterbird breeding sites, with on-ground activities commencing in the 2025-2026 spring and summer (Doble *et al.* 2026). However there remain significant ongoing surveillance gaps for inland areas of Australia and for other bird groups. Consequently, absence of reports does not necessarily represent absence of cases. For the purposes of planning environmental water management in the event of virus incursions, key sites targeted for additional virus surveillance should at minimum include all important waterbird breeding sites, other areas where large bird aggregations occur (e.g. concentrations of foraging birds) and areas where international migrants stop over. Enhancing monitoring and surveillance efforts would improve the likelihood of early detection of the timing and locations of virus spread and outbreaks, supporting managers to actively prepare for and manage H5 bird flu impacts.

Species research

A range of vulnerable, endangered, or critically endangered waterbird species are potentially susceptible to H5 bird flu (FAO 2026)(Supplementary Table 2; EPBC (1999)). It is particularly important to include these species in surveillance, monitoring and research activities, to establish baseline infection data with low-pathogenicity avian influenzas (LPAI) as well as post-impact population sizes, distributions, movements and responses. Understanding how these species move within and between sites and respond to environmental cues has historically been a significant knowledge gap (Kingsford and Norman 2002, Roshier *et al.* 2008). Filling these knowledge gaps using satellite telemetry and other technologies helps managers to effectively plan and prioritise watering, including rapid responses to water needs at local scales, and annual and long-term planning and policy integrating local to continental scales. Improving knowledge of the movements of such species is of significant benefit to understanding and predicting disease movements and outbreaks (Talmon *et al.* 2025, Teitelbaum *et al.* 2026). Following development of quantifiable relationships between waterbird movements, breeding and cues such as surface water, telemetry datasets quantifying waterbird movements together with surface water and disease surveillance datasets can be used to model spatiotemporal exposure risk and predicted future spread of disease via waterbirds (Lv *et al.* 2022, McDuie *et al.* 2022, Teitelbaum *et al.* 2026). Waterbird movement telemetry data can also be used to establish the level of interaction with high-risk areas such as poultry farms, feedlots and urban areas and subsequent implications for disease transmission and movement (Teitelbaum *et al.* 2024). This type of information could be used to produce recommendations for water, wetland and waterbird management strategies to mitigate risk of disease spread and impacts.

Conclusion

Environmental water management and waterbird conservation are increasingly intersecting with the emerging challenges of bird-borne virus risks, particularly the global spread of high pathogenicity avian influenza. The same ecological processes that underpin waterbird population maintenance (e.g. breeding and long-distance movements) can also influence disease transmission, spread and impact. This creates a novel management challenge regarding whether environmental water can be strategically used to not only sustain ecosystems and species, but also to mitigate disease risks. Substantial uncertainty remains regarding how environmental water management may affect virus spread and impacts. Nevertheless, water availability is a known driver of waterbird movement and aggregation patterns, suggesting that environmental water may represent a unique and potentially important management lever. Addressing this challenge effectively will require adaptive, cross-jurisdictional decision-making supported by surveillance, monitoring and ecological research. Ultimately, integrating disease risk into environmental water planning will be critical for maintaining resilient waterbird populations, wetlands and broader ecological values in an increasingly uncertain future.

Figures

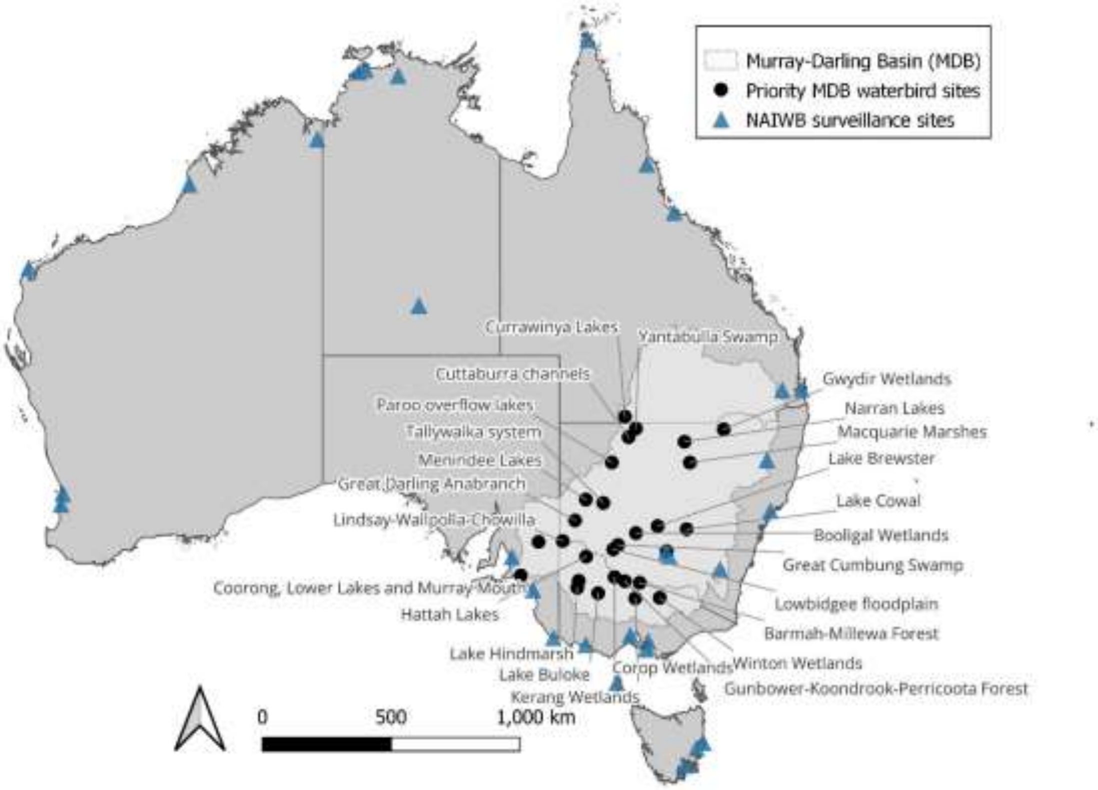

Figure 1 The locations of important wetlands for waterbirds in the Murray-Darling Basin (black circles; labelled wetlands are group-nesting sites), and Australian National Avian Influenza Wild Bird (NAIWB) Surveillance program sampling locations (blue triangles). Sources: (AHA 2023, MDBA 2025, AHA 2026a).

Tables

Table 1 Environmental watering levers and potential waterbird responses relevant to bird density (dispersion) and bird movement (dispersal). Ticks indicate where relationships between watering levers and bird responses may exist, dependent on broader factors, based on literature sources and author expertise.

		Environmental watering lever					
	Waterbird response	**Location**	**Area / extent**	**Duration**	**Timing**	**Depth**	**Rate of rise / fall**
Bird density / dispersion ***(Kingsford and Norman 2002, Brandis et al. 2011, Arthur et al. 2012, Bino et al. 2014, Brandis et al. 2018, Yarnell et al. 2020, Brandis et al. 2024)***	Number of locations birds are breeding, foraging or roosting	✓	✓	✓	✓		
	How far apart those locations are	✓	✓				
	Number of nests / birds per location	✓	✓	✓			
	Density of nests / foraging birds / roosting birds	✓	✓	✓			
Movement / dispersal ***(Mueller and Fagan 2008, Kingsford et al. 2010, Reside et al. 2010, Cumming et al. 2012, Cottee-Jones et al. 2016, Kalle et al. 2018, Pedler et al. 2018, Runge and Tulloch 2018, Watts et al. 2018, Teitelbaum and Mueller 2019, Shaw 2020, Teitelbaum et al. 2020, McGinness et al. 2024c)***	Movement to location to breed, forage or roost	✓	✓	✓	✓		
	Duration of stay in location		✓	✓	✓	✓	✓
	Changes in distances travelled from nest / roost to forage	✓	✓	✓		✓	✓
	Nesting completion vs abandonment		✓	✓	✓	✓	✓
	Departure and dispersal to other sites		✓	✓	✓	✓	✓

Table 2 Potential watering decisions, examples of key considerations, and examples of potential positive and negative effects. Note: this table presents illustrative examples only and is not exhaustive.

Watering decision	Examples of considerations favouring the decision	Examples of potential positive effects	Examples of potential negative effects
Maintain planned watering (no change)	• Disease risk low or localised • No increased connectivity to outbreak sites • Site provides essential or irreplaceable habitat • Ecological benefits outweigh disease risk • Breeding underway or critical habitat required • Limited alternative habitat • Carcasses are present and maintaining water levels to keep them covered or isolated could reduce risk of mammal scavenging and/or human interaction and/or reduce viral accumulation at the site	• Supports breeding completion and recruitment • Maintains population resilience • Avoids disturbance-driven dispersal	• May allow disease persistence at site • Continued aggregation may elevate transmission risk
Cancel planned watering	• Active outbreak present at site or highly likely • Active outbreak close to the site • Watering likely to attract large aggregations • • Alternative habitats available • Pre-breeding • No critical environmental watering required for other ecosystem components (fish, fauna, vegetation) • Few expected impacts on planned downstream water management or downstream ecosystems • Carcasses are present and low water levels will facilitate carcass access and swift removal	• Reduces attraction of birds to infected site • May reduce density-dependent transmission by reducing likelihood of bird breeding or density of breeding birds • Limits connectivity to infected systems	• May trigger dispersal of infected birds (spread risk) away from the site • May increase bird density at remaining sites with water due to lack of habitat, increasing density-dependent transmission risk• Loss of habitat may reduce survival/recruitment • Potential ecological trade-offs (fish, vegetation, water quality) • Could reduce management options in downstream wetlands during outbreaks or for other ecological purposes
Cease watering earlier than planned (early drawdown)	• Outbreak detected before breeding begins • Increasing bird numbers and density with ongoing watering elevates transmission risk • Environmental objectives already largely achieved • Prolonged inundation increases exposure period • Pre-breeding or early aggregation phase	• Reduces aggregation and exposure duration • Limits further attraction of birds	• Rapid drying may force dispersal and increase spread • May prevent breeding initiation or completion

	• Carcasses are present and low water levels will facilitate carcass access and swift removal (if this is an option)		
Continue watering longer than planned (delayed drawdown)	• Breeding already underway (eggs/chicks) that require habitat and food • Rapid drying would disperse infected birds • Gradual drawdown reduces density • Risk of abandonment if water removed • Maintaining dispersed habitat lowers transmission risk by minimising bird density and contact	• Supports breeding completion and recruitment • Avoids forced dispersal and spread • Lengthening drawdown times may reduce transmission	• Prolonged exposure to pathogen • Sustained aggregation leading to increased transmission risk • Potential trade-offs for other areas that could have received the additional environmental water
Reduce area or number of sites watered	• Risk linked to large regional aggregations • Infection concentrated in limited number of wetlands or parts of wetlands • Management focus is refuge (not breeding) • High regional connectivity between priority wetlands • Birds responsive to habitat extent	• Reduces attractiveness for large aggregations • May limit spread between sites • Supports targeted refuges	• Increased density at remaining sites • Potential density and local transmission
Increase area or number of sites watered	• Density-dependent transmission risk exists • High densities of birds in some locations due to limited water or habitat e.g. dry or drought conditions • Need to attract birds to locations away from outbreak • Carcasses are present and increasing water levels to keep them covered or isolated could reduce risk of mammal scavenging and/or human interaction and/or reduce viral accumulation at the site	• Reduces density via dispersion • Decreases density-driven transmission • Enables support away from infected area • Provides dispersed refuges in dry/non-breeding periods • Supports survival during resource limitation	• May increase landscape connectivity → spread • Could attract birds into region (including infected individuals)
Manipulate drawdown rate (gradual vs rapid)	• Trade-off between dispersal and density • Disease present and behaviour uncertain • Movement triggered by hydrological change	• Gradual drawdown: reduces density and stress • Limits abrupt dispersal	• Rapid drawdown: increases density and dispersal → spread

7

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Statements and Declarations

Funding

This work was funded by the Australian Government through the Commonwealth Environmental Water Holder, part of the Department of Climate Change, Energy, the Environment and Water. MW was supported by an Australian Research Council Future Fellowship and the WHO Collaborating Centre for Reference and Research, which is supported by the Australian Department of Health, Disability, and Ageing.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

The first draft of the manuscript was written by Heather McGinness. All authors commented on previous versions. All authors read and approved the final manuscript.

Supplementary material

Supplementary Table 1 Murray-Darling Basin outbreak and management scenario examples

The scenarios presented here are hypothetical and speculative only and are intended to provide environmental water and wetland managers and policy makers with tangible scenarios to assist with thinking through management practicalities and testing possible responses to an outbreak. They are necessarily simplified and limited in number, there is high uncertainty and unpredictability in both pathways and impacts, and they do not consider trade-offs (e.g. for agriculture or other ecosystem components). The Murray-Darling Basin Environmental Watering Strategy describes environmental watering management objectives and outcomes, and strategies to achieve them, for five hydrological scenarios: Very Dry, Dry, Moderate, Wet and Very Wet – these have been referred to where appropriate.

Scenario	**Initial outbreak location (timing)**	**Hypothetical spread pathway**	**Hypothetical indicators of spread**	**Hypothetical impact**	**Hypothetical water management decision examples (virus source and virus recipient sites) – short-term**
1	Coorong & Lower Lakes (Nov)	Upstream movement of infected nomadic waterbirds along the River Murray via stepping-stone wetlands (lower–mid Murray → Barmah–Millewa)	Initial detection in nesting seabirds and shorebirds (adults + chicks) with concurrent deaths in small numbers; increasing carcasses at lower Murray wetlands (≥5–10 same species within 48–72 hrs); rapid escalation of chick mortality in breeding sites once reached	High–catastrophic due to amplification in dense breeding colonies and multi-species chick mortality; compounded by concurrent toxic algal bloom reducing food and water quality	Very Dry–Dry to Moderate context: Maintain existing inflows to sustain habitat stability during breeding; avoid rapid hydrological change that forces movement. Source (Coorong/Lower Lakes): Avoid drawdown during active nesting; if possible, maintain or slightly broaden shallow habitat to reduce crowding pressure. Recipient (Barmah–Millewa Forest): Avoid new watering that creates aggregation hotspots; if already watered (Moderate/Wet scenario), distribute inundation across multiple wetland units to reduce contact rates rather than concentrating water in core breeding colonies.
2	Barmah–Millewa Forest (Dec)	Post-breeding dispersal of infected nomadic waterbirds downstream and laterally into irrigation districts and major inland wetlands (Lowbidgee, Macquarie	Detection via carcass clusters in riverbank settlements (e.g. ibis, herons at recreational sites); ≥5–10 same-species carcasses within 48–72 hrs in multiple wetlands; sudden chick losses in active colonies; spillover into poultry/pig operations near wetlands	Lowbidgee: moderate–high (local breeding failure + spread risk). Macquarie Marshes: moderate–high. Agriculture/poultry interface: high–catastrophic with potential widespread production collapse	Moderate–Wet MDB context: Maintain planned environmental watering through breeding completion where already initiated (Barmah), consistent with MDB objective of supporting recruitment. Avoid abrupt recession events. Recipient wetlands (Lowbidgee, Macquarie Marshes): Prioritise spatial dispersal of inundation across wetland complexes to increase bird dispersion and reduce bird density. Agricultural interfaces: Explicitly avoid creating or maintaining artificial attractants (irrigation spills, shallow

		Marshes) plus agricultural interface zones			ponds) near poultry/pig production zones during high-risk dispersal period.
3	Lower Murrumbidgee Floodplain (Dec)	Movement of infected birds through Lachlan system wetlands via foraging and post-breeding dispersal corridors (Gayini/Yanga → Lower Lachlan wetlands → Lake Brewster)	Mortality clusters in Paika Lake and adjacent wetlands; ≥5–10 carcasses within 48–72 hrs; multiple species affected; collapse events in pelican rookery at Lake Brewster (large chick mortality pulse)	Lower Lachlan: moderate–high (breeding disruption + propagation risk). Lake Brewster: high–catastrophic due to dense pelican rookery collapse	Moderate–Dry to Moderate MDB context: Maintain stable hydrology in active breeding wetlands (North Redbank, Paika Lake) through recruitment phase, consistent with MDB objective of sustaining breeding success. Source wetlands: Avoid abrupt recession that forces mass dispersal into connected systems. Recipient wetlands (Lower Lachlan): Spread environmental water across multiple wetlands (Great Cumbung, Booligal, Willandra, Merrimajeel) to reduce aggregation risk. Lake Brewster: Maintain steady water levels during pelican breeding; avoid rapid operational drawdown during peak breeding, to reduce chick mortality and reduce risk of virus spread through bird movement or nest abandonment.
4	Macquarie Marshes (Dec)	Simultaneous dispersal from multiple colonies due to disturbance (tourism + movement between shared foraging sites) into Gwydir Wetlands and Narran Lakes	Rapid emergence of multiple mortality clusters across systems; ≥5–10 carcasses of same species within 48–72 hrs; synchronous chick deaths across colonies; multi-site spread within short timeframe	Narran Lakes: high–catastrophic. Gwydir Wetlands: moderate–high. Basin-wide amplification risk due to concurrent breeding events across wetlands	Moderate–Wet MDB context: Continue planned environmental watering in Macquarie through breeding window if already supporting recruitment (Wet scenario principle). Source (Macquarie): Avoid abrupt drying or flow interruption that forces dispersal. Minimise disturbance at key colonies (critical in Moderate–Dry scenarios). Recipients (Gwydir, Narran): Carefully evaluate whether additional watering would create concentrated attractant habitat during active outbreak; under high-risk conditions, prefer distributed wetland mosaics over large single inundation events.
5	Gwydir Wetlands (Jan)	Forced movement due to rapid drawdown under extreme heat/drought	Large-scale chick mortality detected during extreme heat; carcass clusters across wetlands; movement of stressed birds into remaining refuges; mortality	Macquarie Marshes: moderate–high. Lake Cowal: high–catastrophic	Dry–Very Dry MDB context: Prioritise maintenance of refuge habitat where feasible to prevent forced long-distance dispersal (key MDB objective under Dry conditions). Source (Gwydir): Avoid abrupt drawdown; if unavoidable, stage

		conditions into Macquarie Marshes and Lake Cowal breeding sites	≥5–10 same species within 48–72 hrs at recipient sites	due to large multi-species breeding aggregation	recession slowly to reduce mass movement. Recipients (Macquarie, Lake Cowal): avoid creating large dense aggregations under heat stress conditions.
6	Narran Lakes (Feb)	Downstream dispersal through Darling–Baaka system into Menindee Lakes complex via riverine movement corridors	Rapid increase in carcasses in drying lake system; ≥5–10 same species within 48–72 hrs; multi-species mortality in juvenile cohorts; spread along river refuges	Moderate–high overall, with downstream amplification risk due to contraction of refuge habitat under drawdown conditions	Dry–Very Dry MDB context: Maintain minimal refuge habitat where possible; prioritise sustaining water quality over volume during late-stage drawdown (Narran). Recipients (Darling–Baaka/Menindee): Emphasise network of dispersed refuge pools rather than concentrating flows into single lakes..
7	Lake Brewster (Jan)	Localised amplification within growing pelican breeding rookery under heat stress and competing water demands	Rapid escalation of chick mortality across rookery; dense carcass clusters within breeding raft; multiple age classes affected	Severe local breeding collapse (catastrophic for rookery) with limited but possible downstream dispersal of infected birds	Moderate–Dry MDB context: Maintain stable water levels through pelican breeding cycle to support recruitment (MDB environmental watering objective). Avoid rapid operational drawdown driven by irrigation demand during peak chick vulnerability. If unavoidable, stage reductions to minimise forced rookery breakup and dispersal.
8	Kerang Lakes / Kow Swamp / Johnsons Swamp (Dec)	Interface spillover between wild waterbirds and intensive poultry/pig production adjacent to wetlands	Simultaneous outbreaks in livestock and wild birds; ibis/spoonbill nesting in nearby wetlands with chick mortality; repeated contact at farm–wetland edges; multi-site agricultural infection clusters	High wildlife–agriculture interface risk; potentially catastrophic livestock production losses and sustained environmental transmission cycle	All MDB conditions (esp. Dry–Moderate): Avoid environmental watering actions that increase waterbird aggregation near livestock operations. Source wetlands (Kow Swamp/Kerang system): Reduce or pause non-essential inundation that draws birds toward agricultural interface zones. Recipient wetlands: Redirect environmental water to lower-risk wetlands away from intensive agriculture. Maintain separation between wetland habitat and poultry/pig production zones (critical under all scenarios).

Supplementary Table 2 Waterbird species listed as vulnerable, endangered or critically endangered by the EPBC Act that occur in the Murray-Darling Basin

Common Name	Scientific Name	EPBC Act Status
Curlew Sandpiper	*Calidris ferruginea*	Critically Endangered; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Australasian Bittern	*Botaurus poiciloptilus*	Endangered
Northern Siberian Bar-tailed Godwit, Russkoye Bar-tailed Godwit	*Limosa lapponica menzbieri*	Endangered
Nunivak Bar-tailed Godwit, Western Alaskan Bar-tailed Godwit	*Limosa lapponica baueri*	Endangered
Australian Painted Snipe	*Rostratula australis*	Endangered; Marine
Black-tailed Godwit	*Limosa limosa*	Endangered; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Common Greenshank, Greenshank	*Tringa nebularia*	Endangered; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Lesser Sand Plover, Mongolian Plover	*Charadrius mongolus*	Endangered; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Eastern Hooded Plover, Eastern Hooded Plover	*Thinornis cucullatus cucullatus*	Vulnerable; Marine
Great Knot	*Calidris tenuirostris*	Vulnerable; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Sharp-tailed Sandpiper	*Calidris acuminata*	Vulnerable; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Latham's Snipe, Japanese Snipe	*Gallinago hardwickii*	Vulnerable; Marine; Migratory (Bonn, JAMBA, ROKAMBA)
Greater Sand Plover, Large Sand Plover	*Charadrius leschenaultii*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Grey Plover	*Pluvialis squatarola*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Red Knot, Knot	*Calidris canutus*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Ruddy Turnstone	*Arenaria interpres*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Terek Sandpiper	*Tringa terek = Xenus cinereus*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)

Supplementary Table 3 Waterbird species listed as 'migratory' by the EPBC Act that occur in the Murray-Darling Basin

Common Name	Scientific Name	EPBC Act Status
Bar-tailed Godwit	*Limosa lapponica*	Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Black-tailed Godwit	*Limosa limosa*	Endangered; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Bridled Tern	*Onychoprion anaethetus*	Marine; Migratory (CAMBA, JAMBA)
Broad-billed Sandpiper	*Limicola falcinellus = Calidris falcinellus*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Caspian Tern	*Hydroprogne tschegrava = Hydroprogne caspia*	Marine; Migratory (JAMBA)
Common Greenshank, Greenshank	*Tringa nebularia*	Endangered; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Common Sandpiper	*Tringa hypoleucos = Actitis hypoleucos*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Curlew Sandpiper	*Calidris ferruginea*	Critically Endangered; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Double-banded Plover	*Charadrius bicinctus*	Marine; Migratory (Bonn)
Garganey, Garganey Teal	*Anas querquedula = Spatula querquedula*	Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Glossy Ibis	*Plegadis falcinellus*	Marine; Migratory (Bonn)
Great Knot	*Calidris tenuirostris*	Vulnerable; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Greater Crested Tern	*Thalasseus bergii*	Marine; Migratory (JAMBA)
Greater Sand Plover, Large Sand Plover	*Charadrius leschenaultii*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Grey Plover	*Pluvialis squatarola*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Grey-tailed Tattler	*Tringa brevipes*	Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Gull-billed Tern	*Gelochelidon nilotica*	Marine; Migratory (CAMBA)
Latham's Snipe, Japanese Snipe	*Gallinago hardwickii*	Vulnerable; Marine; Migratory (Bonn, JAMBA, ROKAMBA)
Lesser Sand Plover, Mongolian Plover	*Charadrius mongolus*	Endangered; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Long-toed Stint	*Calidris subminuta*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Marsh Sandpiper, Little Greenshank	*Tringa stagnatilis*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Oriental Plover, Oriental Dotterel	*Charadrius veredus*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Pacific Golden Plover	*Pluvialis fulva*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Pectoral Sandpiper	*Calidris melanotos*	Marine; Migratory (JAMBA, ROKAMBA)
Red Knot, Knot	*Calidris canutus*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Red-necked Phalarope	*Phalaropus lobatus*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Red-necked Stint	*Calidris ruficollis*	Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Ruddy Turnstone	*Arenaria interpres*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Ruff (Reeve)	*Philomachus pugnax = Calidris pugnax*	Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)

Sanderling	*Calidris alba*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Sharp-tailed Sandpiper	*Calidris acuminata*	Vulnerable; Marine; Migratory (Bonn, CAMBA, JAMBA, ROKAMBA)
Swinhoe's Snipe	*Gallinago megala*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Terek Sandpiper	*Tringa terek = Xenus cinereus*	Vulnerable; Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Wandering Tattler	*Tringa incana*	Marine; Migratory (JAMBA)
White-winged Black Tern, White-winged Tern	*Chlidonias leucoptera = Chlidonias leucopterus*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)
Wood Sandpiper	*Tringa glareola*	Marine; Migratory (CAMBA, JAMBA, ROKAMBA)

Supplementary Table 4 Examples of group-nesting waterbird species affected by HPAI H5 bird flu outside Australia (FAO 2026) that are either the same as or closely related to species supported by environmental water in the Murray-Darling Basin

Species	Affected internationally?	Present in the Murray-Darling Basin?
Glossy ibis (*Plegadis falcinellus*)	Yes	Yes
Cattle egret (*Bubulcus ibis*)	Yes	Yes
Great egret (*Ardea alba*)	Yes	Yes
Little egret (*Egretta garzetta*)	Yes	Yes
Intermediate egret (*Egretta* or *Ardea intermedia*)	Yes	No, but closely related to the plumed egret (*Ardea plumifera*) – the latter has only recently been taxonomically separated from *Ardea intermedia*
Black-crowned heron (*Nycticorax nycticorax*)	Yes	No, but closely related to the nankeen night heron (*Nycticorax caledonicus*)
Sacred ibis (*Threskiornis aethiopicus*), and Black-headed ibis (*Threskiornis melanocephalus*)	Yes	No, but closely related to Australian white ibis (*Threskiornis molucca*) and Straw-necked Ibis (*Threskiornis spinicollis*)
Eurasian spoonbill (*Platalea leucorodia*) and Black-faced spoonbill (*Platalea minor*)	Yes	No, but closely related to royal spoonbill (*Platalea regia*) and yellow-billed spoonbill (*Platalea flavipes*)
Seven pelican species in the Pelecanus genus	Yes	No, but closely related to the Australian Pelican (*Pelecanus conspicillatus*)
Eleven cormorant species in the *Phalacrocorax* genus	Yes	No, but closely related to multiple Australian cormorant species