Abundance estimates for game ducks in Victoria

Results from the 2024 aerial and ground surveys

D.S.L Ramsey, B. Fanson and J.G. Cally

March 2025

Arthur Rylah Institute for Environmental Research Technical Report Series No. 386

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Citation: Ramsey, D.S.L., Fanson, B., and Cally, J.G. (2025). Abundance estimates for game ducks in Victoria: Results from the 2024 aerial and ground surveys. Arthur Rylah Institute for Environmental Research Technical Report Series No. 386. Department of Energy, Environment and Climate Action, Heidelberg, Victoria.

Front cover photo: Pink-eared Duck (Justin Cally)

Edited by Fox Writing Services

ISSN 1835-3835 **(pdf)**
ISBN 978-1-76176-101-0 **(pdf/online/MS word)**

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Acknowledgements

This project was commissioned by the Victorian Game Management Authority, and we thank Simon Toop and Graeme Ford for facilitating the funding for this project. Aerial surveys were conducted by Ecoknowledge Pty Ltd (www.ecoknowledge.com.au). The authors thank Simon Toop, Jason Flesch, Chris Davies (Game Management Authority) and Michael Scroggie, Pia Lentini and Matt White (DEECA) for providing valuable comments on a draft of this report.

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Context:

The Victorian government has committed to adopting Adaptive Harvest Management (AHM) by implementing a proportional harvest scheme to regulate the recreational harvest of game ducks. A proportional harvest scheme simply means that a set percentage of the total game duck population can be harvested each year, to ensure that the harvest is sustainable. Proportional harvest quotas are currently set at 10% of the total population of game ducks in Victoria for at least the first three seasons (i.e. 2025–2027) of AHM application as set by the Victorian Game Duck Harvest Strategy. Implementing a proportional harvest scheme relies on comprehensive monitoring to estimate the abundance of game ducks, which has been undertaken yearly since 2020 using statewide aerial and ground surveys (e.g. Ramsey 2020; Ramsey and Fanson 2022). Additional research is also required to identify the most appropriate seasonal harvest regulations (i.e. daily bag limits and season length) that would result in the desired proportional harvest. This report details the results of the statewide aerial and ground survey of game ducks in Victoria conducted during 2024, and the analysis of historical harvest data to identify harvest regulations that would achieve the government's harvest quota for the 2025 season.

Aims:

This report aimed to:

- Conduct an analysis of the monitoring data from the aerial and ground surveys of game ducks undertaken in 2024 to estimate the abundance of each game species within their main habitat types in Victoria. This also involved estimating the amount of surface water in the major waterbody types in Victoria for the period when surveys were undertaken to define the amount of suitable habitat available for game ducks.
- Analyse historical game duck harvest data to identify the seasonal harvest regulations that would most likely achieve the desired proportional harvest of the estimated total game duck population. Recommendations will also be made to refine and/or improve the current approach.

Methods:

Waterbodies, selected using a stratified random sampling design, were subject to aerial surveys from November–December 2024. At each waterbody, two observers on the left side of the aircraft (one forward and one rear) independently conducted counts of game ducks. Ground surveys were conducted for those waterbodies that could not be surveyed from the air due to airspace or safety restrictions. Ground surveys used a similar double-observer method. The abundance of game duck species at each sampled waterbody was estimated using a zero-inflated N-mixture model and Bayesian inference.

Estimates of surface water area for waterbodies in Victoria (wetlands, dams, sewage treatment ponds, rivers and large streams) were derived from the most recent Landsat and Sentinel-2 satellite imagery around the time of the surveys to estimate the number of waterbodies of each type in Victoria containing surface water. Model-based methods were then used to estimate total game duck abundance for each species by extrapolating abundance estimates from sampled waterbodies to the number of available waterbodies with surface water of each type across the state.

To determine the appropriate seasonal harvest regulations, we analysed 16 years of historical harvest data that recorded total game duck harvest, daily bag limit, season length and number of game duck licence holders to identify the relationship between total harvest and seasonal regulations, including a variable indicating years when COVID-19 restrictions were in place. We then used this relationship to predict the bag limit that was most compatible with achieving a 10% level of harvest, assuming a season length of 83 days and 21,383 game licence holders.

Results:

Surface water estimates for Victoria revealed that the amount of surface water in dams, wetlands and sewage ponds decreased by around 21% compared with surface water estimates for 2023. Calibration of surface water presence from satellite imagery with observations during surveys indicated relatively high accuracy for wetlands and sewage ponds (>90% true positive rate), but lower accuracy for river/stream segments and small farm dams (78% and 55% true positive rate, respectively).

A total of 883 waterbodies were subject to aerial (822) or ground surveys (61). Of these, 697 were observed to contain surface water, and the counts of game duck species on these were used to estimate their abundance on each waterbody using the zero-inflated N-mixture model. Model-based estimates of the total abundance of the eight species indicated that the population of game ducks on dams, wetlands, sewage ponds, rivers and streams in Victoria was 4,018,600 (95% confidence interval: 3,770,400–4,283,000). Australian Wood Duck was the most abundant game species (c. 1.4 M), followed by Pacific Black Duck (c. 0.82 M), Chestnut Teal (c. 0.80 M) and Grey Teal (c. 0.69 M). The precision of the overall model-based estimate of abundance was excellent, with a 3% coefficient of variation, well within the target threshold of 15%.

Analysis of the historical harvest data revealed that the modelled relationship between total harvest and seasonal regulations was a reasonable fit to the data, with a Bayesian R^2 value of 0.78 (95% CI: 0.62–0.85). Daily bag limits and the effect of COVID-19 restrictions in 2020 and 2021 had the highest effects on the total harvest while season length and the number of licence holders had only minor effects. Analysis revealed that a daily bag limit of nine was the smallest value that would result in an expected proportional harvest of at least 10% of the total abundance of game ducks. A bag limit of nine would be expected to result in a total harvest of approximately 416,600 ducks (90% CI: 255,900–631,300), which equates to 10.4% (90% CI: 6.4%–15.7%) of the estimated statewide duck population.

Conclusions and implications:

Estimates of surface water on waterbodies, but especially small farm dams, need to be improved by updating the relevant spatial layers and adopting the latest water detection algorithms.

The total statewide abundance of game ducks has decreased by around 32% from the levels seen in 2023, most likely due to the continuing decline in surface water availability since the high levels seen in 2022. Similar declines were also noted in the recent Eastern Australian Waterbird Aerial Survey (Porter et al. 2024).

Recent investigations of proportional harvest strategies for Victorian game ducks have shown that annual harvest fractions of 10–20% of the current Victorian abundance of the main game species would be sustainable (Prowse 2023). Furthermore, a 10–20% harvest fraction was also shown to be robust to additional losses due to the wounding of up to 23% of the total harvest.

Recommendations:

To implement and improve the adoption of AHM for the regulation of the Victorian recreational game duck harvest, it is recommended that:

- There is a daily bag limit of nine ducks/day for the 2025 season, which is predicted to result in an average expected total harvest of 416,600 ducks (10.4% of the total population). This is consistent with achieving a proportional harvest of at least 10% of the total abundance of the seven species of game duck that can be legally harvested in 2025.
- The current approach to estimating surface water for Victoria be updated to incorporate the latest spatial data products and water detection algorithms. In particular, the Victorian farm dam layer is becoming increasingly out-of-date and requires updating with the latest spatial information (e.g. Malerba et al. 2021).
- Additional variables that potentially influenced the historical harvest of game ducks, be investigated, so that they can be used to improve the modelled relationship between total harvest and seasonal regulations.

1 Introduction

In Victoria, eight species of native duck are declared to be game, and seven of these have open seasons and are subject to legal recreational harvest: Grey Teal (*Anas gracilis*), Pacific Black Duck (*Anas superciliosa*), Australian Wood Duck (*Chenonetta jubata*), Australian Shelduck (*Tadorna tadornoides*), Pink-eared Duck (*Malacorhynchus membranaceus*), Chestnut Teal (*Anas castanea*) and Hardhead (*Aythya australis*). The Australasian Shoveler (*Anas rhynchotis*) is not currently allowed to be legally harvested. Combined, these species are hereafter called game ducks. The Victorian Government manages recreational duck hunting sustainably by setting seasonal daily bag limits for each species, as well as determining the timing of the start and end of the hunting season (i.e. season length). These arrangements have historically changed each year, depending on the information available about the status of populations and the prevailing environmental conditions.

For the current and future seasons, the Victorian Government has committed to implementing Adaptive Harvest Management (AHM) (e.g. Ramsey et al. 2010; Ramsey et al. 2017) to guide the setting of seasonal recreational harvest arrangements. Comprehensive monitoring to estimate the statewide abundance of game duck species is vital if an adaptive harvest management framework (e.g. Nichols et al. 2007) is to be adopted for managing game ducks (Ramsey et al. 2017). As part of this process, research has recently been undertaken to identify sustainable levels of harvest that could be used for setting a proportional harvest scheme, being a percentage of the total game duck population that could be sustainably harvested each year (Prowse 2023). This research identified that proportional harvests of between 10% and 20% were sustainable and were robust to additional wounding rates of up to 23% of the number harvested (Prowse 2023). Based on the findings of this research, seasonal harvest quotas will be set at 10% of the total population of game ducks in Victoria for at least the first three seasons of AHM application in line with the precautionary approach set by the Victorian Game Duck Harvest Strategy.

In addition to undertaking surveys at a sample of waterbodies, estimation of the abundance of game ducks across the state would also require an estimate of the availability of surface water for each of the waterbody types considered to provide suitable game duck habitat during the period within which the surveys are undertaken. Surface water availability can be determined by applying appropriate algorithms to satellite imagery (Mueller et al. 2016; Pekel et al. 2016).

Sampling designs and survey methods suitable for estimating the abundances of games ducks on waterbodies in Victoria were identified by Ramsey (2020). Game duck habitat waterbodies were stratified into types (wetlands, dams, rivers/streams, sewage treatment ponds), size classes (<6 ha, 6–50 ha, >50 ha) and bioregions (North, South, East, West). Following a pilot study of the survey design in 2020, an independent review of the survey design and methods was undertaken (Prowse and Kingsford 2021), which led to some improvements to aerial survey methods and analysis that were subsequently implemented for the 2021 and subsequent surveys (Ramsey and Fanson 2022; Ramsey and Fanson 2023). The revised survey design includes sampling approximately 850 waterbodies across the state using a stratified random sampling design.

Implementing a proportional harvest approach for Victoria's recreational harvest requires that the seasonal regulations regarding the daily bag limit and season length be set to achieve the desired 10% harvest fraction. The relationship between annual total game duck harvest and seasonal regulations was investigated initially by Ramsey and Fanson (2021) by analysing historical harvest data for Victorian game ducks. To determine the appropriate seasonal regulations for the forthcoming season, we conducted a re-analysis of the historical game duck harvest data to identify how bag limits and season length relate to the total number of harvested ducks to determine the daily bag limits that were most compatible with a 10% proportional level of harvest.

This report summarises the results from the 2024 aerial and ground surveys of game ducks in Victoria as well as the analysis to determine the most appropriate seasonal harvest regulations that should achieve a 10% proportional harvest for the 2025 duck season.

1.1 Objectives

The objectives of this report were to:

1. Estimate the abundance of each game duck species within the main habitat types in Victoria. This was achieved by:

- estimating the current amount of surface water available for use by game ducks within Victoria, using the most recent satellite imagery (LandSat and Sentinel-2) combined with vector layers of waterbodies (including farm dams and rivers/streams)
- analysing the aerial and ground survey data to determine the numbers of ducks on the surveyed waterbodies and then extrapolating these estimates to the entire state based on the estimates of surface water availability. This approach yields statistical estimates of the abundance and distribution of each game duck species in Victoria.

2. Identify the seasonal harvest regulations that would most likely achieve the desired proportional harvest of the estimated total game duck population. This involved an analysis of historical game duck harvest data to identify the seasonal harvest arrangements that would be most likely to result in a 10% proportional harvest of the estimated total game duck population.

2 Methods

2.1 Estimates of surface water availability

To extrapolate the estimates of the abundance of game ducks at sampled waterbodies to regional or statewide estimates of abundance, an estimate of total surface water availability across the state for the period the surveys were undertaken, was required. Waterbodies in Victoria were stratified according to waterbody type and size class, with the number of waterbodies within each stratum containing surface water used to set the sampling frame. The sampling frame is the total number of objects that could be sampled and is also the scope of estimation. In other words, estimates of duck abundance obtained from each sampled waterbody are then extrapolated to all waterbodies in the sampling frame to estimate the total abundance. It follows that the sampling frame also delimits the total size of the regional duck population, and excludes ducks residing in habitats that are outside the sampling frame (i.e. waterbodies) and therefore not available to be sampled. For the 2024 survey, the surface water types estimated included wetlands, dams, sewage treatment ponds, rivers and large streams. Irrigation channels, estuaries and small streams were excluded from the surface water estimates. Irrigation channels were excluded as the available spatial data on the locations of channels contained too many spatial errors to be a reliable indicator of water availability, and small streams (i.e. width < 5 m) were excluded as these could not be reliably surveyed from the helicopter. Since estimates of surface water will change each year due to prevailing environmental conditions and rainfall patterns, the sampling frame will also change each year and must be re-estimated.

Surface water estimates were derived from GIS layers to quantify the number and size of waterbodies and rivers/streams in Victoria (Figure 1A). For wetlands and sewage ponds, we utilised the Digital Earth Australia (DEA) waterbody layer ('DEA' – https://www.dea.ga.gov.au/) derived from LandSat imagery taken every 16 days. This layer defines the wetland boundaries (waterbody's spatial area) and uses Water Observation from Space (WOfS) (Mueller et al. 2016) to estimate water surface area over time. WOfS uses a machine learning algorithm for classifying surface water in Australia and has been shown to have good accuracy (~97%) (Mueller et al. 2016). After obtaining the waterbody polygons and surface water areas, we used an additional spatial layer (VIC_hydro - https://www.data.vic.gov.au/) to assign waterbody attributes (Figure 1A). At this stage, this process excludes rivers and streams, which are dealt with separately.

As WOfS uses LandSat (which has a ~ 30 m pixel size), it uses an area threshold of 2700 m^2 (0.27ha); detections of surface water for waterbody areas below this threshold area are not reliable. However, many farm dams are below this area threshold and therefore, we used a Victorian farm dam spatial layer to obtain polygons for all farm dams present pre-2015. After removing any duplicates between the datasets, we then used Sentinel-2 ('S2') satellite imagery (taken every 5 days) to assess each farm dam polygon for the presence of water (Figure 1A). Sentinel-2 uses a Normalised Difference Water Index – NDWI to detect surface water (Mueller et al. 2016). For both WOfS and S2 imagery, we obtained the most recent estimates of surface water extent for each waterbody at the time of the aerial and ground surveys, and averaged the three most recent observations.

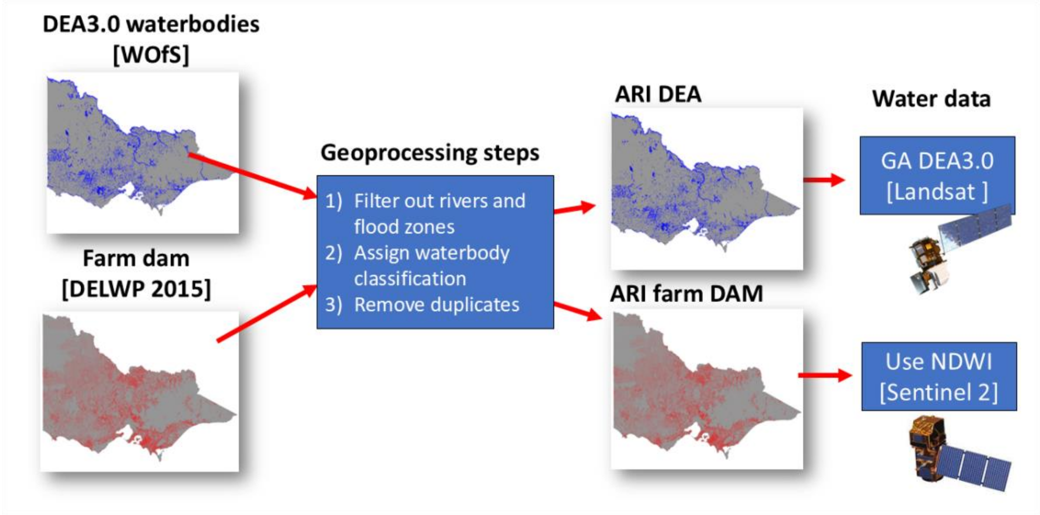
Finally, we used the Index of Stream Conditions (ISC) project for rivers and streams to define the major river system. This project mapped streambeds using LiDAR and therefore provided stream areas (Quadros et al. 2011). Small streams in dense forest are missing from this dataset. For the sampling frame, we divided the river network lines into 1-km segments and then used these segments to extract out the overlapping riverbed to obtain surface area. We then used flow gauge information to assess flow conditions in the river/stream around the time of the survey, and supplemented this information with satellite imagery from S2 (Figure 1B).

During the last year, the DEA waterbody Version 2.0 (Geosciences Australia) was updated to Version 3.0 (Dunn et al. 2024). Unlike the v1.0 to v2.0, this update was minimal with respect to changes to waterbodies with the main consequences relating to waterbody naming. Therefore, we migrated all our previous DEA2 waterbodies to the most appropriate DEA3.0 waterbody.

2.2 Selecting the sample of waterbodies

The majority of waterbodies sampled during the previous years' surveys were sampled again in 2024. Strata consisted of waterbodies of different types, including wetlands, dams, sewage treatment ponds, and waterways (rivers and large streams), which were also categorised according to size class (<6 ha, 6–50 ha, >50 ha). Size classes for waterways were calculated by multiplying the segment length (1-km) by the width of the segment. Waterbodies were further stratified into four broad geographic regions in the state (North, South, East and West). Further details of the stratification of waterbodies across Victoria can be found in Ramsey and Fanson (2022).

A)



B)

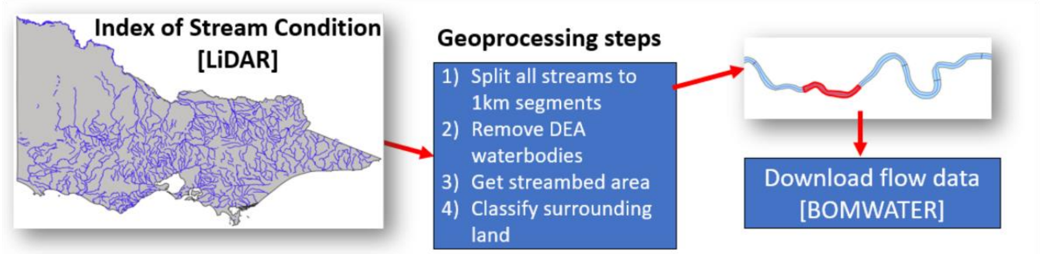


Figure 1. Overview of the waterbody (A) and river/stream (B) GIS layers and processing steps used to estimate the number of waterbodies, rivers and streams with surface water in Victoria.

2.3 Aerial and ground sampling of game ducks

Aerial sampling of each waterbody was undertaken from a Bell 206 Long Ranger helicopter from November–December 2024. Two observers on the left side of the aircraft (one forward and one rear) conducted counts of game ducks at each waterbody independently. For smaller waterbodies and farm dams, each waterbody was approached, and counts were conducted while the aircraft completed a low circuit around the waterbody circumference at a height of around 30–50 m. For some of the largest waterbodies (>50 ha), only a portion of the waterbody, usually 30% (selected at random), was surveyed by flying inside the perimeter of the waterbody and counting towards the waterbody edge and then towards the waterbody centre. This addresses the propensity of ducks to concentrate on the shoreline, sometimes in clumped aggregations, and avoids overestimating density by only counting the shoreline. The counts for each observer for the entire surface area were then imputed using the fraction of the waterbody surveyed.

Other data were also collected for each waterbody including predominant habitat type (i.e. open [little or no vegetation present], presence of reeds, presence of woodland), presence of surface water, weather conditions and the presence of glare from the water surface.

Ground surveys of waterbodies that could not be sampled from the air due to airspace or other safety restrictions were undertaken using a similar double-observer methodology with two ground-based observers working independently with the aid of a spotting scope. For large wetlands subject to ground surveys, counts were obtained from multiple vantage points to maximise the coverage of the surface water of the wetland. Where coverage was incomplete, counts were again adjusted based on the fraction of the waterbody surveyed.

Since aerial surveys cannot distinguish between female Chestnut Teal and Grey Teal, ground surveys were used to estimate the ratio of male/female Chestnut Teal, which was then used to adjust aerial counts of Chestnut and Grey Teal. Counts of male and female Chestnut Teal on waterbodies surveyed from the ground were used to determine the mean ratio of male/female Chestnut Teal. This ratio was subsequently used to adjust the counts of Chestnut Teal counted during aerial surveys, which only included observations of males. Only waterbodies where both Grey Teal and male Chestnut Teal were counted during aerial surveys were subject to this adjustment. The adjusted Chestnut Teal count was calculated by dividing the aerial count of male Chestnut Teal by the male/female Chestnut Teal ratio to determine the expected number of female Chestnut Teal that were likely present but included in the Grey Teal count. This expected number was then added to the Chestnut Teal count and subtracted from the Grey Teal count.

2.4 Abundance estimation

Waterbody level estimates

The two independent replicate counts of game ducks at each sampled waterbody were used to estimate the abundance of ducks at each waterbody, corrected for imperfect detection (birds missed by the observers) using a zero-inflated N-mixture model (Royle 2004; Ramsey and Fanson 2021). The standard N-mixture model has two components: an abundance component, representing the true (but unknown) number of ducks present on each waterbody at the time of the survey, and a detection component, representing the measurement (detection) error, consisting of an estimate of the fraction of birds that were present but missed by the observers. The abundance component can also be a function of the covariates likely to explain variation in abundance between waterbodies, such as waterbody type, size class, and geographic region. Likewise, the detection component can also depend on covariates that affect the detection process, such as the presence of vegetation, or glare from the water surface. The standard N-mixture model was modified to account for the presence of excess zeros in the count data, caused by some waterbodies being unsuitable for ducks at the time of the survey, by adopting a zero-inflated Poisson (ZIP) distribution for the counts. Therefore, this model includes a component that accounts for the probability that ducks are present on the waterbody during the survey. This N-mixture ZIP model was similar to that used by Ramsey and Fanson (2021).

The covariates used to potentially explain the variation in abundance of ducks were waterbody type, size class, and bioregion, with the probability of presence considered to depend on the same set of attributes. Detection probability was modelled as a function of the presence of glare from the water surface, habitat type (open, reeds or woodland), waterbody size class, survey type (aerial or ground), and the interaction of survey type with habitat and survey type with size class. The parameters for the covariates for abundance and presence probability were estimated separately for each duck species, while the parameters for the probability of detection were common to the different species of ducks. The N-mixture ZIP model was estimated in a Bayesian framework using Hamiltonian Markov chain Monte Carlo (MCMC) methods in Stan (version 2.35) with cmdstanr in R (Gelman et al. 2015; Gabry and Češnovar 2022). Weakly informative prior distributions were used for all parameters in the model specified as $N(0,5)$. A total of 2000 MCMC iterations were run for the model for each of three parallel chains, with the first 1000 iterations considered to be ‘warmup’ (tuning) iterations and discarded. This left 3,000 samples for each parameter to form the inference. Model convergence was assessed with trace plots and by confirming all parameters had Gelman-Rubin statistics < 1.05 (Brooks and Gelman 1998).

Statewide abundance estimates

Predictions of game duck abundance for the entire sampling frame (i.e. waterbodies containing water within Victoria) were made using a model-based approach (e.g. Ramsey and Fanson 2022). The model-based approach was undertaken by predicting the expected abundance for every waterbody in the sampling frame (i.e. both sampled and unsampled), conditional on their covariate values (waterbody attributes and region) using the fitted N-mixture ZIP model relationship for each species (section 2.4). The variance of the total abundance estimate was estimated using posterior predictive simulation based on the posterior distributions of the parameters from the fitted model (Gelman and Hill 2007). A total of 2,000 posterior estimates of total abundance were calculated for each species and used for inference.

2.5 Effects of seasonal regulations on total harvest

To determine how seasonal hunting regulations (daily bag limits and season length) relate to the total number of harvested ducks, we analysed 16 years of historical game duck harvest data that recorded total harvest, daily bag limit, season length and number of game duck licence holders. A model was fitted with these variables, with total harvest as the response and the remaining variables as predictors. This also included a variable indicating years when COVID-19 restrictions were in place. The model can be described as:

$$\log(H_i) \sim N(\mu_i, \sigma) \qquad Eqn. 1$$

$$\mu_i = \beta_0 + \beta_1 B_i + \beta_2 D_i + \beta_3 L_i + \beta_4 C_i$$

Where H_i was the total game duck harvest during year i, which was assumed to be log-normally distributed with mean $\boldsymbol{\mu_i}$ and standard deviation σ. B_i, D_i, L_i and C_i were the daily bag limit, season length (days), number of licensed hunters and a binary variable indicating the years of COVID-19 restrictions, respectively, and β_0, β_1, β_2, β_3, β_4 and σ were parameters to be estimated. Models were run in STAN (Gelman et al. 2015) using the brms package (Bürkner 2017; Bürkner 2018; Bürkner 2021).

We then used this model to predict the bag limit that was most compatible with achieving a 10% level of harvest, calculated as 10% of the aggregate total abundance estimates for each game species that could be legally harvested. Predictions assumed a season length of 83 days and the number of licence holders as of June 2024 of 21,383.

3 Results

3.1 Survey summary

Aerial surveys of game ducks were undertaken from 14 November – 5 December 2024, with ground counts undertaken from 6 November – 20 November 2024. A total of 883 waterbodies were successfully surveyed, with 822 waterbodies surveyed from the air and a further 61 surveyed from the ground (Table 1; Figure 2). Not all the scheduled waterbodies could be sampled due to access issues (ground surveys) or the presence of obstructions impeding the safe approach of the helicopter (aerial surveys). A total of 638 of the 822 waterbodies subject to aerial surveys (78%) and 59 of the 61 waterbodies subject to ground surveys (97%) were observed with surface water (Table 1). Conversely, 21% of surveyed waterbodies were observed to be dry.

From the ground surveys, a total of 512 Chestnut Teal males were observed from 18 waterbodies where at least one male Chestnut Teal was present. The maximum counts of male and female Chestnut Teal on these waterbodies were then used to estimate the male:female sex ratio. The median numbers of male and female Chestnut Teal observed were 17.5 and 32, respectively, with a trimmed mean estimate of the male/female sex ratio of 0.54 (median absolute deviation = 0.39). This meant that, for waterbodies with observations of Chestnut Teal males, there were around twice as many Chestnut Teal females present.

Table 1. Waterbodies sampled by aerial and ground surveys during 2024. The percentage of these waterbodies observed with surface water are given in parentheses.

Waterbody type	Aerial surveys	Ground surveys	Totals
Dams	209 (86%)	17 (100%)	226 (87%)
Sewage ponds	5 (100%)	32 (100%)	37 (100%)
River/streams	95 (100%)	0 (0%)	95 (100%)
Wetlands	513 (70%)	12 (83%)	525 (70%)
Total	**822 (78%)**	**61 (97%)**	**883 (79%)**

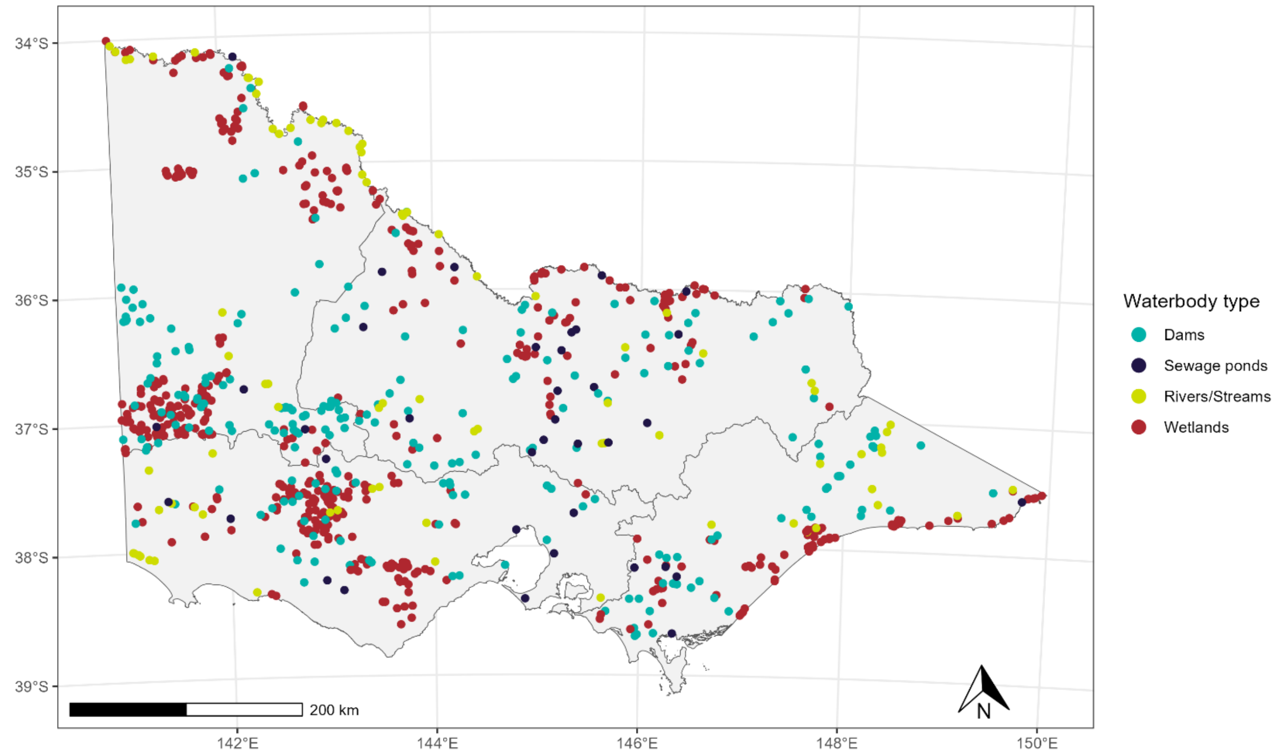


Figure 2. Locations of the 883 waterbodies (dams, sewage ponds, wetlands and rivers/streams) that were subject to aerial and ground sampling during the period from November – December 2024. Bioregion boundaries are (clockwise from top left) West, North, East and South.

3.2 Surface water availability

The number of waterbodies (dams, sewage ponds, wetlands and rivers/streams) categorised as containing surface water following calibration of the satellite imagery was estimated at 139,440 (Table 2). This was a 34% decrease compared with the estimate for the previous survey in 2023 (212,045). Overall, surface water availability in 2024 decreased by 21% compared to 2023, resulting in a total surface water area of 183,196 ha (Figure 3).

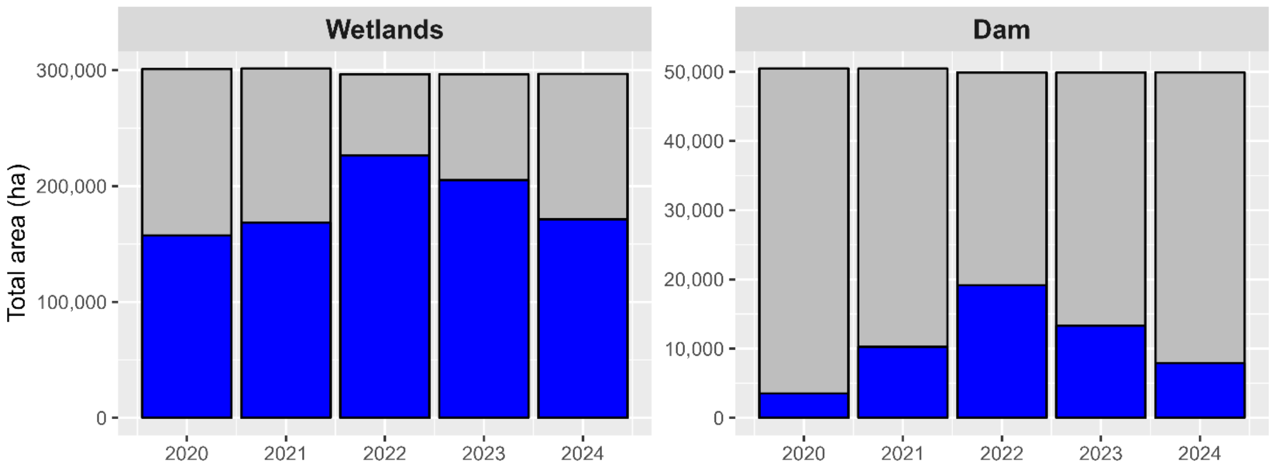


Figure 3. Temporal changes in surface water availability in wetlands and dams since 2020.

Table 2. Number of mapped waterbodies of each type and size class. The percentages of these waterbodies estimated to have surface water from satellite imagery during spring 2024 are given in parentheses.

Waterbody type	<6 ha	6–50 ha	>50 ha	Total
Dams	509,762 (24%)	141 (88%)	58 (98%)	509,961 (24%)
Sewage ponds	50 (92%)	56 (95%)	9 (100%)	115 (94%)
Rivers/streams	10,038 (100%)	1,864 (100%)	0 (0%)	11,902 (100%)
Wetlands	7,181 (80%)	1,917 (56%)	437 (67%)	9,535 (74%)
Total	**527,031 (26%)**	**3978 (79%)**	**504 (71%)**	**531,513 (27%)**

Calibration of surface water predictions

The results from the calibration of the Sentinel-2 satellite imagery with the observations of surface water for each sampled waterbody suggested that correct predictions of waterbodies containing water were high (>90%) for wetlands and sewage ponds, and lower for river/stream segments (78%) and small dams (55%) (Figure 4a). The farm dam accuracy of 55% was the lowest recorded to date (74% – 2020, 79% – 2021, 88% – 2022, 70% – 2023). Exploration of mismatches identified that vegetation obscuring water was obvious in several qualitative checks of smaller waterbodies. Larger dams were correctly predicted to be wet by DEA-3.0, and classification of wetlands using DEA-3.0 was lower than for Sentinel-2 (Figure 4b).

Prediction of dry dams was poor, with 100% of dry dams (n=6) predicted to contain water using DEA-3.0 (Figure 4b), which improved to only 24% inaccuracy when using Sentinel-2 (Figure 4a). Further investigation suggested that some misclassifications resulted from a mismatch in temporal alignment between helicopter and surface water measurements (i.e. some waterbodies may have been partially wet during satellite observations, but had dried by the time the helicopter survey was undertaken). This appeared to affect dams mainly in western Victoria. Due to cloud cover partially obscuring some satellite images, some waterbodies may have had an observation date differing by as much as 35 days from the aerial survey date.

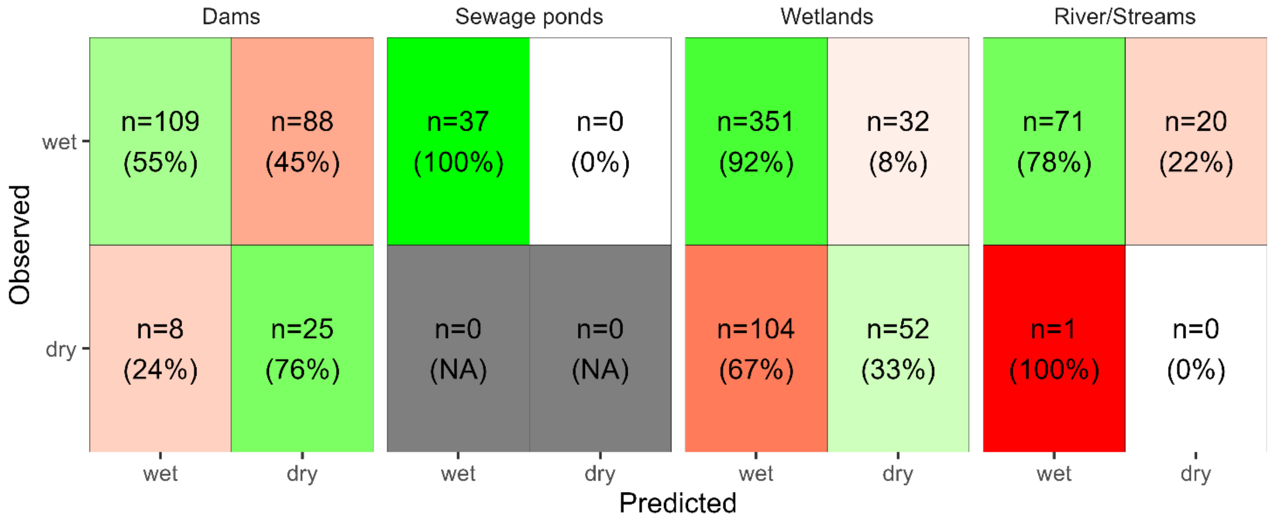


Figure 4a. Confusion table for observed (actual) versus predicted (Sentinel-2) surface water presence for small dams, sewage ponds, wetlands rivers/streams and storage dams. Red indicates incorrect predictions and green indicates correct predictions, with shading indicating relative (in)accuracy. White and grey indicates no data. Wet = surface water present; Dry = surface water absent.

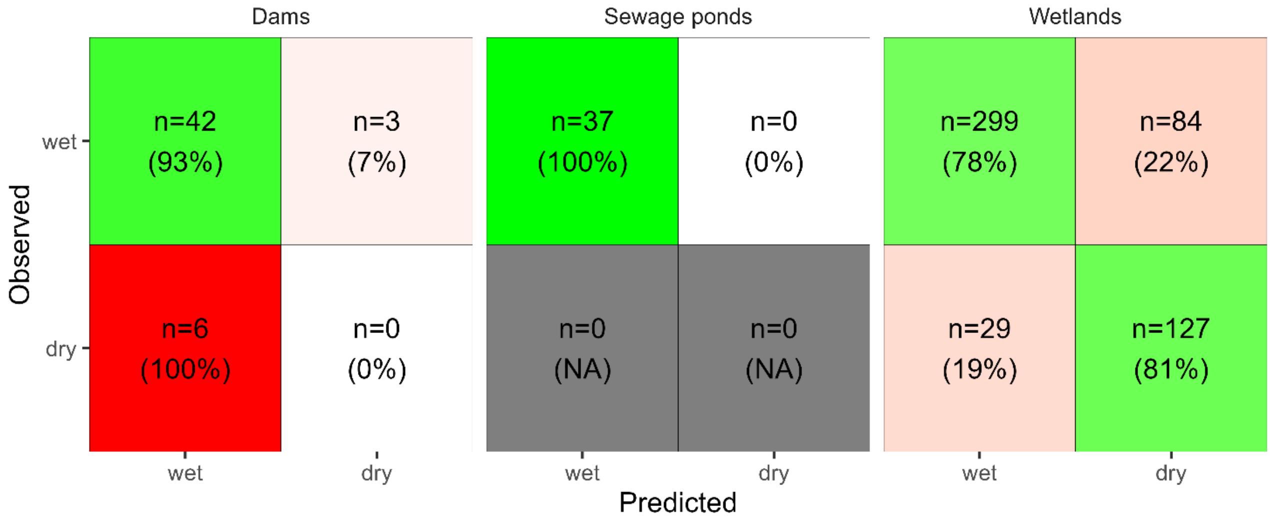


Figure 4b. Confusion table for observed (actual) versus predicted (DEA-3.0) surface water presence for large dams, sewage ponds, wetlands, rivers/streams and storage dams. Red indicates incorrect predictions and green indicates correct predictions, with shading indicating relative (in)accuracy. White and grey indicates no data. Wet = surface water present; Dry = surface water absent.

3.3 Waterbody-level abundance estimates

The total counts of game ducks (based on the maximum observed in each waterbody) on the 697 waterbodies with surface water are presented in Table's 3 and 4. Grey and Chestnut Teal were the most abundant species counted, followed by Pacific Black Duck. In contrast, the least abundant species counted was the Australasian Shoveler (Table 3). Counts of most species were higher within the South and North bioregions compared with the West and East (Table 4).

The monitoring data were adequate for estimating the abundance of all eight species of game duck. The N-mixture ZIP model (section 2.4) appeared to be a good fit to the aerial and ground survey data for each species, with posterior predictive distributions indicating strong positive relationships (Figure 5). Bayesian R^2 values (Gelman et al. 2019) were high for all species (Grey Teal (GT) = 0.96; Australian Wood Duck (WD) = 0.86; Australian Shelduck (AS) = 0.86; Pacific Black Duck (PBD) = 0.90; Chestnut Teal (CT) = 0.92; Hardhead (HH) = 0.97; Pink-eared Duck (PED) = 0.97; Australasian Shoveler (BWS) = 0.94). In particular, the fits indicated adequate prediction of the proportion of waterbodies with zero ducks, as well as of the mean duck abundance (Appendix A). However, the models generally showed some negative bias in the predicted standard deviation and maximum count, indicating some residual overdispersion that was unaccounted for in the model (Appendix A). However, attempts to add additional structure to this model by adding random effects proved to be unsuccessful due to a lack of convergence of the MCMC chains.

Table 3. Total counts of each species by waterbody type and size class (ha). The maximum of the two counts for each waterbody was used to calculate the total. Species codes are: GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; PBD = Pacific Black Duck; AS = Australian Shelduck; HH = Hardhead; PED = Pink-eared Duck; BWS = Australasian Shoveler. n = number of waterbodies with surface water.

Waterbody type	Size class	n	GT	WD	AS	PBD	CT	HH	PED	BWS
Dam	<6 ha	157	273	610	5	236	150	18	0	10
	6–50 ha	24	988	242	620	318	926	620	463	14
	>50 ha	16	1,432	1,405	1240	1,521	3,290	650	24	54
Sewage pond	<6 ha	11	769	46	26	176	574	290	84	0
	6–50 ha	21	6,887	261	232	817	1,399	2,029	3,468	45
	>50 ha	5	4,111	168	379	126	494	1,828	4,883	56
River/stream	<6 ha	94	415	1,308	6	1,232	276	6	1	6
Wetland	<6 ha	135	622	726	22	492	643	32	0	4
	6–50 ha	135	3,399	447	981	1,162	6,230	386	221	32
	>50 ha	99	20,772	871	5,816	8,924	31,253	3,112	1,650	402
Total		697	39,668	6,084	9,327	15,004	45,235	8,971	10,794	623

Table 4. Total counts of each species by bioregion. The maximum of the two counts for each waterbody was used to calculate the total. Species codes are: GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; PBD = Pacific Black Duck; AS = Australian Shelduck; HH = Hardhead; PED = Pink-eared Duck; BWS = Australasian Shoveler. n = number of waterbodies with surface water.

Region	n	GT	WD	AS	PBD	CT	HH	PED	BWS	Total
East	136	7,574	740	867	3,178	4,577	1,013	292	60	18,301
North	183	13,552	2,137	1,601	4,541	8,245	3,688	6,674	305	40,743
South	154	14,511	1,258	6,160	5,155	23,606	2,104	2,083	190	55,067
West	224	4,031	1,949	699	2,130	8,807	2,166	1,745	68	21,595

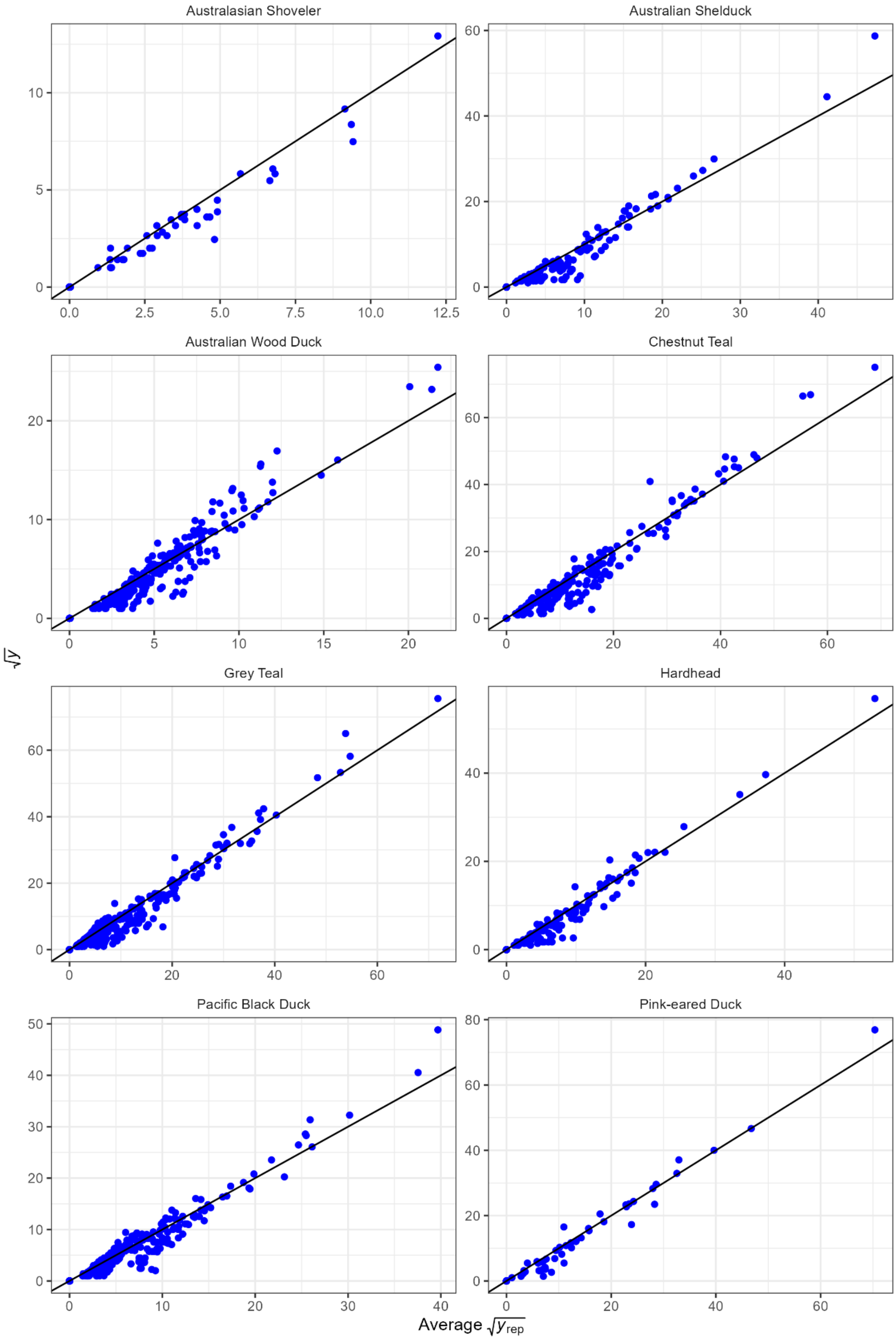


Figure 5. Posterior predictive distributions of the counts of eight game duck species. y = observed counts (sum of both observers); y_{rep}= average predicted count from the fit of the zero-inflated N-mixture model. The predicted and observed counts were square root transformed to aid the visibility of the small counts. The black line shows a 1:1 relationship.

Detection probability of ducks varied with habitat, waterbody size, glare and survey type (aerial or ground, Figure 6). Aerial detection probability was highest in open and reed habitat and lowest in wooded habitat, for all waterbody sizes. In contrast, ground detection probability was highest in open habitat and lower in reed and wooded habitat. Waterbody size impacted detection probability of ground counts in that small (<6 ha) or large (>50 ha) waterbodies had better detection probability than medium waterbodies. The presence of glare on the water surface appeared to have a small negative influence on detection probabilities (Figure 6).

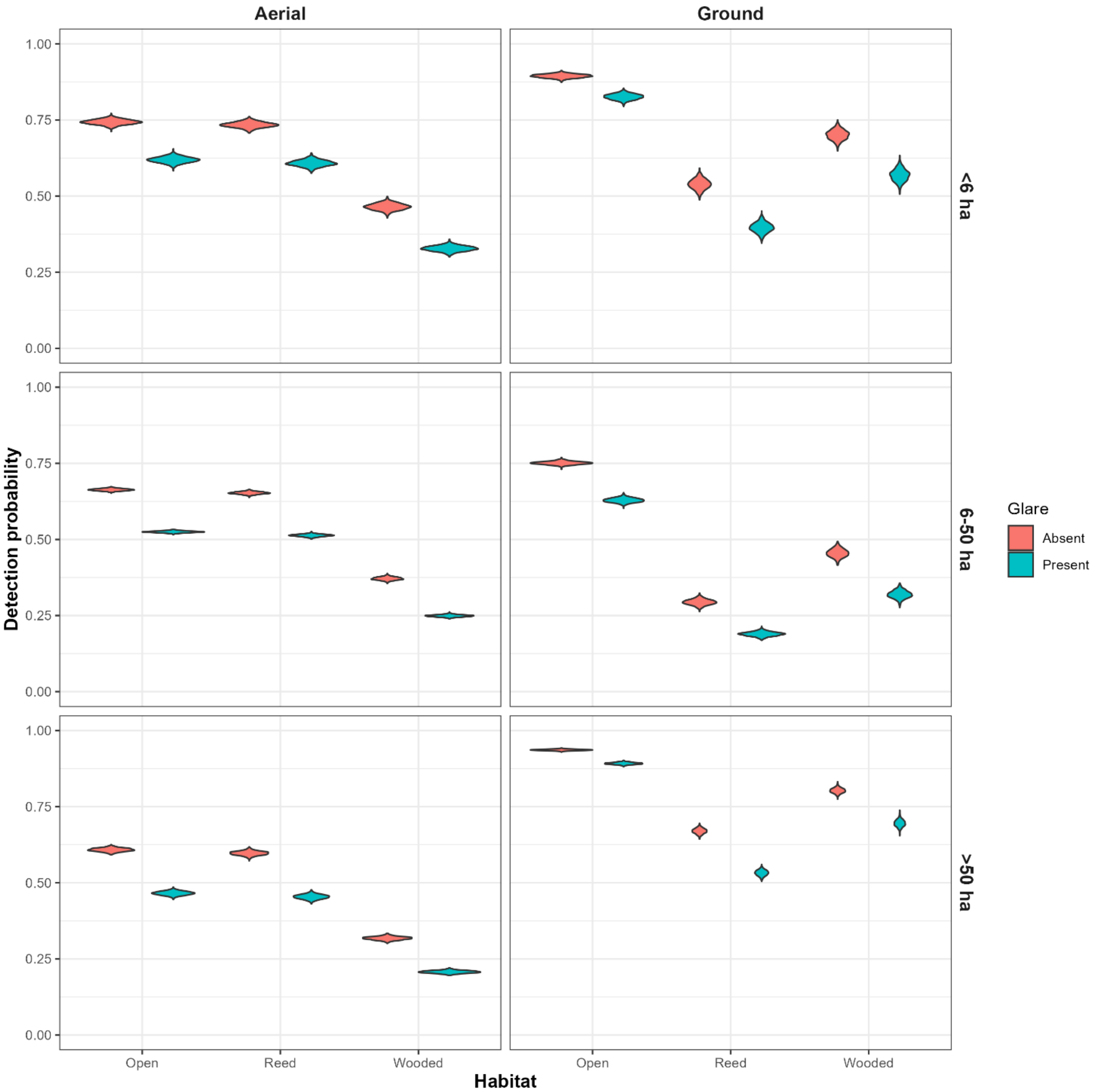


Figure 6. Detection probabilities of game ducks from aerial and ground surveys by habitat type and waterbody size class (<6 ha; 6–50 ha; >50 ha) in the presence or absence of glare from the water surface.

3.4 Statewide abundance estimates

Aerial and ground survey data were adequate to estimate the abundance of eight species of duck, including the major game species. Model-based estimates indicated that the population of game ducks on dams, sewage ponds, wetlands and rivers/streams in Victoria was approximately 4.0 M birds (Table 5). Australian Wood Duck were the most numerous game species (~1.4 M), followed by Pacific Black Duck (~0.82 M) and Grey and Chestnut Teal (~0.69 M and ~0.80 M, respectively). The overall estimate of abundance was precise, with a 3% coefficient of variation (CV), lower than the target threshold of 15% identified by Ramsey and Fanson (2021) as being of adequate precision. However, as model-based estimates tend to underestimate the variation in the counts (Appendix A), the CVs should be interpreted with some caution. The precision of estimates for the individual game species was variable, ranging from 30% for Australasian Shoveler to 5% for Black Duck (Table 5).

Most game ducks occurred on small farm dams (<6 ha), especially Australian Wood Duck, Pacific Black Duck, Grey Teal and Chestnut Teal (Figure 7). Australian Wood Duck and Pacific Black Duck also occurred in relatively large numbers on rivers and streams. The most abundant species in wetlands were Chestnut Teal and Grey Teal (Figure 7).

Table 5. Summary of model-based estimates of total abundance for eight species of native duck in Victoria. SE – Standard error; CV – coefficient of variation; L95 – lower 95% confidence limit; U95 – upper 95% confidence limit.

Species	Estimate	SE	CV	L95	U95
Australian Wood Duck	1,389,400	103,000	0.07	1,205,900	1,581,200
Australian Shelduck	110,900	14,100	0.13	87,500	139,400
Australasian Shoveler	13,000	3,900	0.30	7,300	22,100
Chestnut Teal	805,100	52,900	0.07	709,500	905,100
Grey Teal	693,200	35,200	0.05	630,000	757,800
Hardhead	149,400	24,700	0.17	109,500	200,600
Pacific Black	815,300	40,000	0.05	743,600	892,400
Pink-eared Duck	42,300	4,200	0.10	35,300	51,000
Total	**4,018,600**	**130,700**	**0.03**	**3,770,400**	**4,283,000**

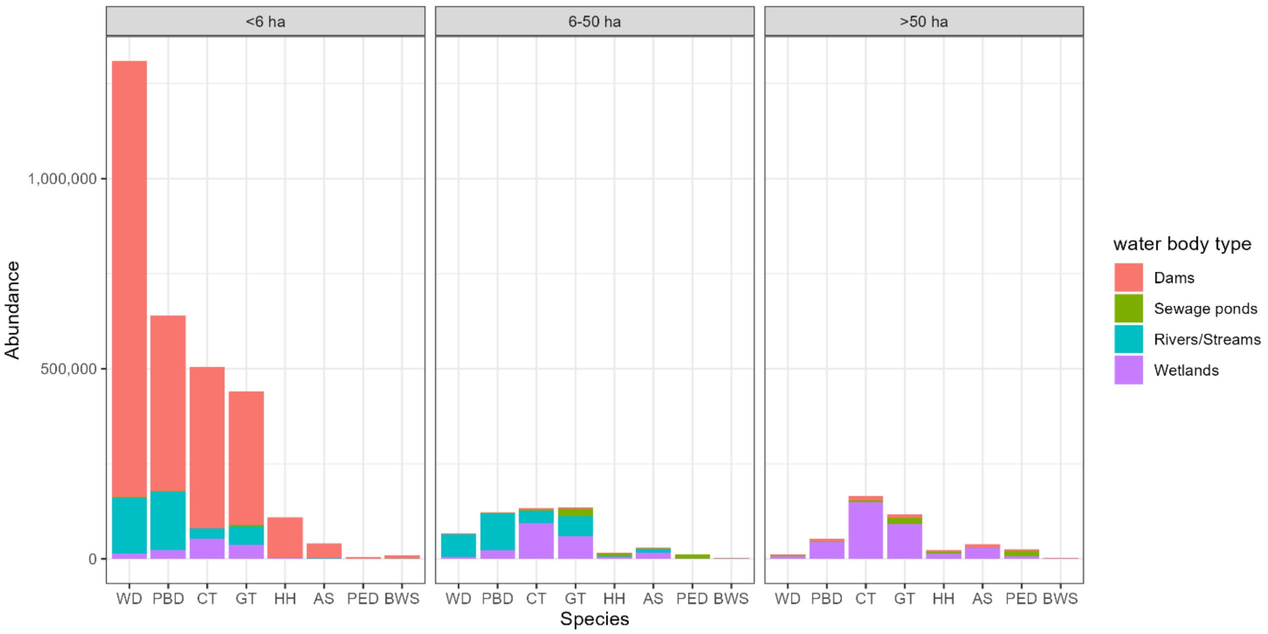


Figure 7. Abundance of game duck species by waterbody type and size class. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck; HH = Hardhead; PED = Pink-eared Duck; BWS = Australasian Shoveler.

3.5 Trends in game duck abundance

Trends in the abundance of each game duck species were examined from 2021–2024. Results from the 2020 pilot survey were not included, because separate estimates for Grey and Chestnut Teal were not available for that survey. Trends in abundance revealed that the major game species have declined from 2023, but are still above the abundances recorded in 2021 and 2022 (Figure 8). However, the abundance of Australian Shelduck was the lowest recorded to date (Figure 8).

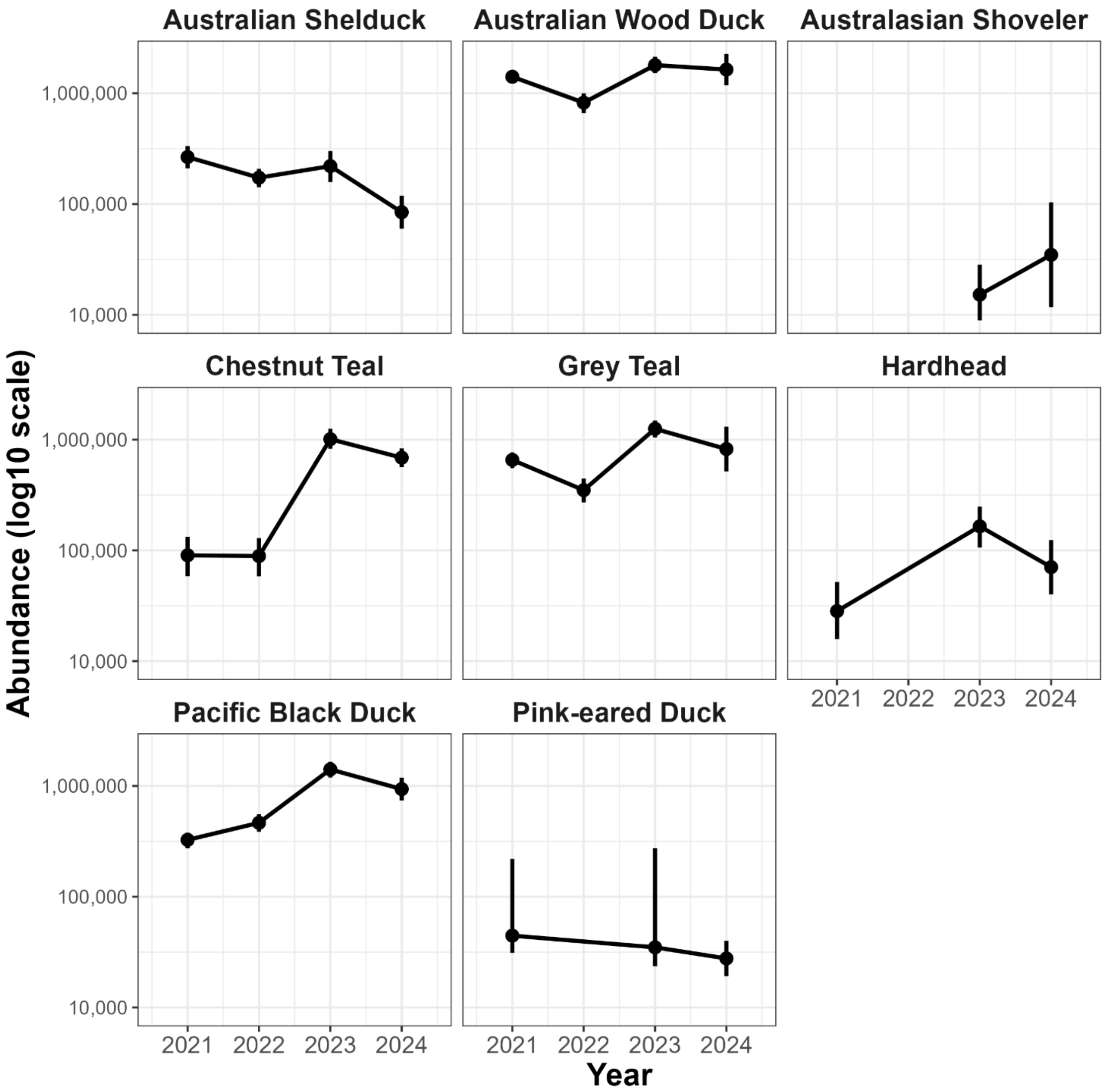


Figure 8. The trends in the abundance of the eight species of game ducks from 2021–2024. Abundance is given on the log10 scale using the model-based estimates from each year. Estimates could not be obtained for some species in some years due to inadequate data. Error bars are 95% credible intervals.

3.6 Effects of seasonal regulations on total harvest

A model with bag limits, season length, licenced hunters and whether the hunting season was subject to COVID-19 restrictions was a reasonable fit to the data, with a Bayesian R^2 value of 0.78 (95% CI: 0.62–0.85) (Figure C1, Appendix C). Daily bag limits and the effect of COVID-19 restrictions in 2020 and 2021 had the largest effects on the total harvest, while season length and the number of licenced hunters had only minor effects (Table 6).

Table 6. Standardised parameter estimates from the model fitted to the relationship between the total game duck harvest (on the natural log scale) and seasonal regulations. Season – season length (days), Bag limit – daily bag limit, Hunters – number of licensed hunters, COVID-19 restrictions – whether travel restrictions were in place during hunting season, σ – residual standard deviation. SE – standard error; L95 – lower 95% confidence limit; U95 – upper 95% confidence limit.

Term	Mean	SE	L95	U95
(Intercept)	12.72	0.07	12.58	12.85
Season	0.02	0.12	-0.22	0.27
Bag limit	**0.23**	**0.08**	**0.07**	**0.38**
Hunters	0.01	0.09	-0.17	0.18
COVID-19 restrictions	**-1.51**	**0.3**	**-2.08**	**-0.92**
σ	0.23	0.06	0.15	0.37

Using the expected total abundance estimates for game ducks that are subject to legal harvest (i.e. 4,005,600 ducks excluding Australasian Shoveler), a 10% proportional harvest rate equates to 400,500 ducks. We then used the fitted harvest model to predict the bag limit that was most compatible with achieving this level of harvest, assuming a season length of 83 days and the number of licence holders as of June 2024 (21,383). Both the assumed season length and number of licence holders were within the range of the data used to fit the model (Appendix D).

Analysis revealed that a daily bag limit of 9 was the smallest value that would result in an expected proportional harvest of at least 10% (10.4% – Table 7). A bag limit of 9 would be expected to result in a total harvest of approximately 416,600 ducks (90% CI: 255,900 – 631,300) (Table 7). Based on the estimated uncertainty from the model, there was only a 1.4% chance that the total estimated harvest exceeded a 20% proportional harvest (i.e. expected total harvest exceeded 801,000 ducks).

Table 7. Expected total duck harvests under different bag limits conditions, including the proportion of the total duck population harvested (expressed as a percentage). These predictions assumed a season length of 83 days and 21,383 licence holders. Analysis revealed that a daily bag limit of 9 was the smallest value that would result in an expected proportional harvest of at least 10%.

Daily bag limit	Expected duck harvest (90% CI)	Percentage harvested (90% CI)
1	212,727 [117,460, 339,027]	5.3% [2.9%, 8.4%]
2	232,408 [134,754, 368,118]	5.8% [3.4%, 9.2%]
3	252,577 [150,068, 385,143]	6.3% [3.7%, 9.6%]
4	274,183 [163,183, 421,972]	6.8% [4.1%, 10.5%]
5	296,712 [180,682, 443,515]	7.4% [4.5%, 11.1%]
6	323,566 [199,982, 488,755]	8.1% [5%, 12.2%]
7	351,986 [216,802, 525,886]	8.8% [5.4%, 13.1%]
8	381,900 [235,012, 572,311]	9.5% [5.9%, 14.3%]
9	416,582 [255,933, 631,303]	10.4% [6.4%, 15.7%]
10	456,912 [276,240, 686,444]	11.4% [6.9%, 17.1%]

4 Discussion

The total statewide abundance of game ducks has decreased by around 32% from the equivalent model-based estimate from 2023 (Ramsey and Fanson 2024). This decrease was most likely driven by the lower surface water available in Victoria compared with in the previous years, driven by generally drier conditions experienced by most of eastern Australia during 2024 (Porter et al. 2024). Although abundance estimates for the main game species (Grey and Chestnut Teal, Wood Duck, Pacific Black Duck) have declined since 2023, they are still greater than the abundances recorded in 2021 and 2022. Declines were also noted during the Eastern Australian Waterbird Aerial Survey, with surveys recording half the number of birds compared to 2023, placing abundance estimates closer to their long-term averages (Porter et al. 2024).

Calibration of surface water estimates from satellite imagery with observations from the aerial surveys revealed that the classification accuracy of small farm dams using S2 imagery was the lowest recorded to date, with a true positive rate of 55%. This lower accuracy was likely due to several reasons, including the presence of vegetation obscuring water occurrence, which was noted in several qualitative checks of smaller waterbodies. Other classification inaccuracies were likely due to differences in temporal alignment between the date of the last satellite observation and the aerial survey observation. Due to cloud cover and the timing of satellite observations, many waterbodies had satellite observations before the aerial survey observation period. Overall, 46% of waterbodies had satellite observations within the aerial survey observation period, with 81% of satellite observations within one month of the aerial survey observation period. In addition, newer classification approaches for farm dams have highlighted the increasing inaccuracy of the current farm dam layer for Victoria (based on data from 2015), where it was estimated that around 11% of existing farm dams are missing from the layer (Malerba et al. 2021). Given the reliance of the game duck abundance estimates on surface water estimates, it is highly recommended that the current surface water approach be re-assessed to determine if improvements can be implemented.

The Victorian Government has recently committed to implementing Adaptive Harvest Management (e.g. Ramsey et al. 2010; Ramsey et al. 2017) to ensure the transparency and sustainability of the seasonal recreational harvest arrangements. A key step in the transition to Adaptive Harvest Management is the use of a proportional harvest strategy to set the maximum allowable recreational harvest. Proportional harvest strategies have been shown to be safe and effective for populations inhabiting fluctuating environments (Engen et al. 1997; Pople 2008). Recent investigations of proportional harvest strategies for Victorian game ducks have estimated that annual harvest fractions of 10–20% of the current Victorian abundance of the main game species would be sustainable (Prowse 2023). Furthermore, a 10–20% harvest fraction was also shown to be robust to additional losses due to wounding of up to 23% of the total harvest (Prowse 2023). Since the seasonal harvest arrangements only apply to Victoria, using the current Victorian abundance for game ducks to set a maximum proportional harvest fraction should be sustainable, even if environmental conditions become unfavourable (Prowse 2023).

Analysis of the relationship between total game duck harvests and the prevailing seasonal harvest regulations over the last 16 years revealed that the daily bag limit and COVID-19 restrictions had the greatest influence on the size of the total harvest. This model was then used to predict the daily bag limit that was most compatible with achieving a 10% harvest fraction of the total abundance of the seven game species that can be legally harvested (i.e. 400,500 ducks). To provide predictions for the daily bag limit, the model required inputs for the length of the recreational duck hunting season and the number of licence holders assuming no COVID-19 restrictions would be in place. The length of the 2025 recreational duck hunting season has already been determined and is to be set at 83 days (i.e. 19 March – 9 June 2025), while the number of licence holders as of June 2024 (21,383) was also used for prediction purposes. Results suggest a daily bag limit of 9 was the smallest value that would result in an expected proportional harvest of at least 10%, with an expected total harvest of approximately 416,600 ducks (90% CI: 255,900 – 631,300).

Additional sources of variation that are not accounted for in this estimate are the variation in statewide abundance and the variation in total predicted yearly harvest (Moloney et al. 2022). Although this prediction has high uncertainty, it does provide an objective basis for relating total harvest to prevailing seasonal arrangements. Since total game duck harvests are estimated annually from data derived from surveys of hunters undertaken during the season (Moloney et al. 2022), it will be possible to evaluate the total harvest predicted by the model with the harvest estimated following the completion of the hunting season. Consequently, this relationship should improve over time as estimates of total harvest continue to accumulate. In addition, there are likely to be other relevant variables related to hunter effort and effectiveness that may better explain variation in total harvest, and an examination of such variables is worthy of further research.

Adaptive Harvest Management offers the potential for a more rigorous scientific approach to the setting of seasonal harvest arrangements for game duck populations. As more monitoring data accumulate, it should be possible to implement more detailed models that can examine the potential drivers of the population dynamics of the major game species. Additionally, the current harvest strategy assumes an equal harvest proportion across species (Prowse 2023). However, historical harvest data suggests that harvest proportions tend to vary among species. For instance, the 2024 predicted harvest of Wood Ducks (94,250) was 5% of the estimated 2023 population (1,797,700), but the harvest of Pacific Black Ducks (153,117) was 11% of the 2023 population (1,411,000). Models that incorporate variable harvest rates (bag limits) across species may be better able to predict expected harvest, and are worthy of further investigation. This, in turn, will further our understanding of the effects of recreational harvest on game duck populations under a range of environmental conditions, which should allow greater flexibility to tailor seasonal arrangements for individual species.

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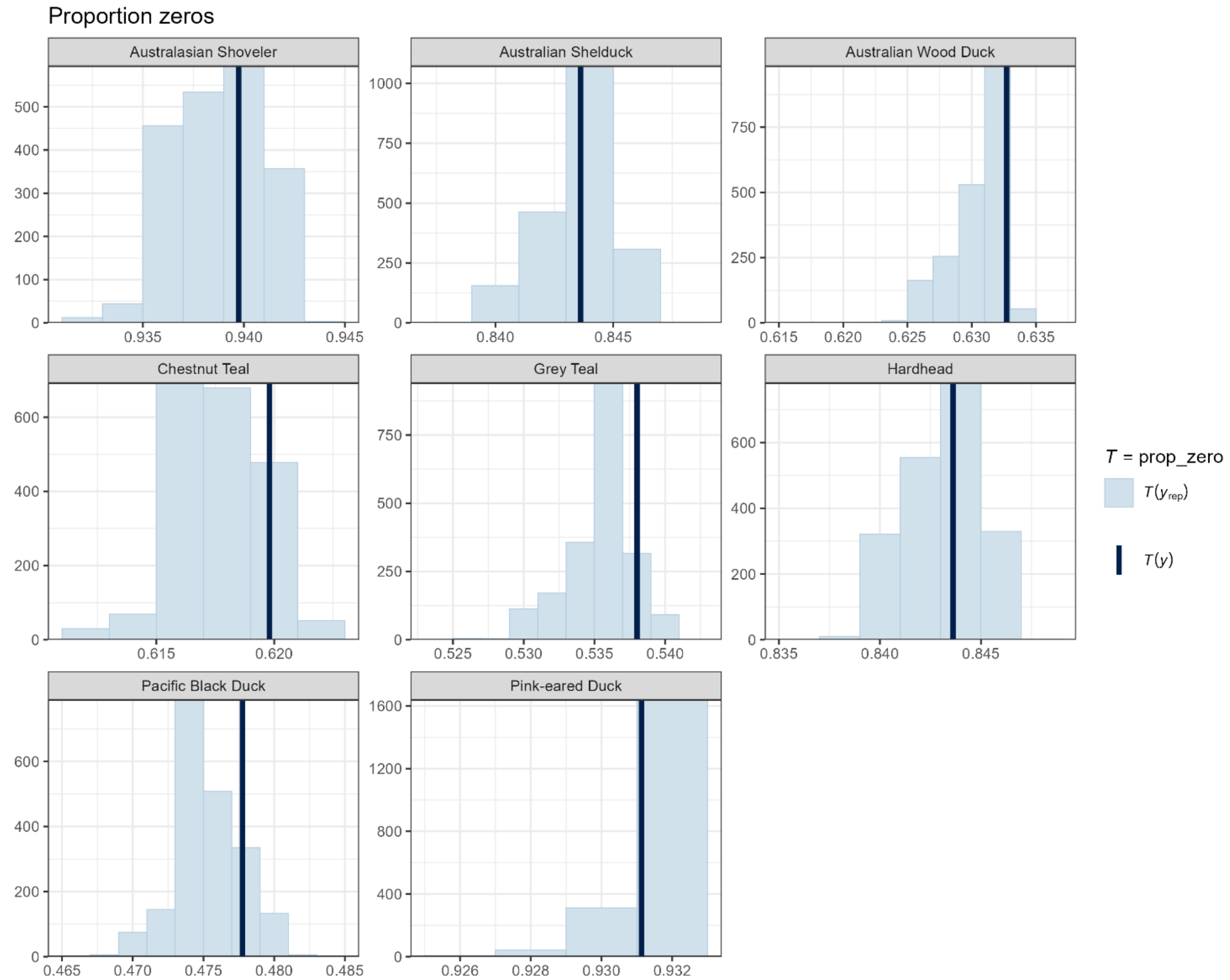
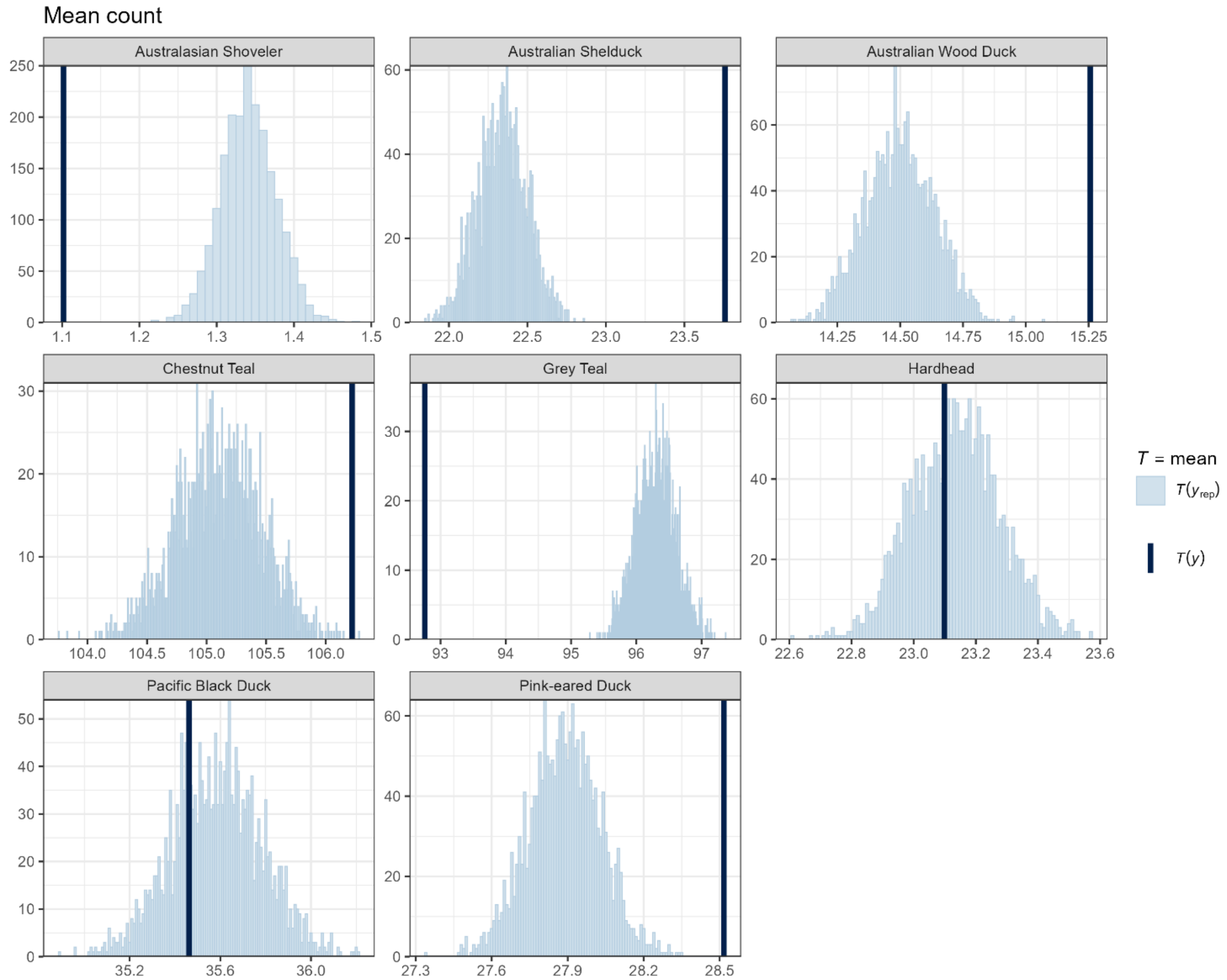
Appendix A

Posterior predictive checks (Gelman et al. 1996) comparing summary statistics $\boldsymbol{T}$ of the predicted counts for each game duck species under the model (Equation 1), with the observed counts on each waterbody. The summary statistics are the proportion of waterbodies with zero counts, the mean total count, the standard deviation of the total count, and the maximum total count. Total counts for each waterbody were calculated by summing the counts for each observer. Pale-blue histograms give the distribution of the summary statistic predicted by the model $\boldsymbol{T}(\boldsymbol{y}_{rep})$, and dark-blue bars give the summary statistic for the observed counts $\boldsymbol{T}(\boldsymbol{y})$.

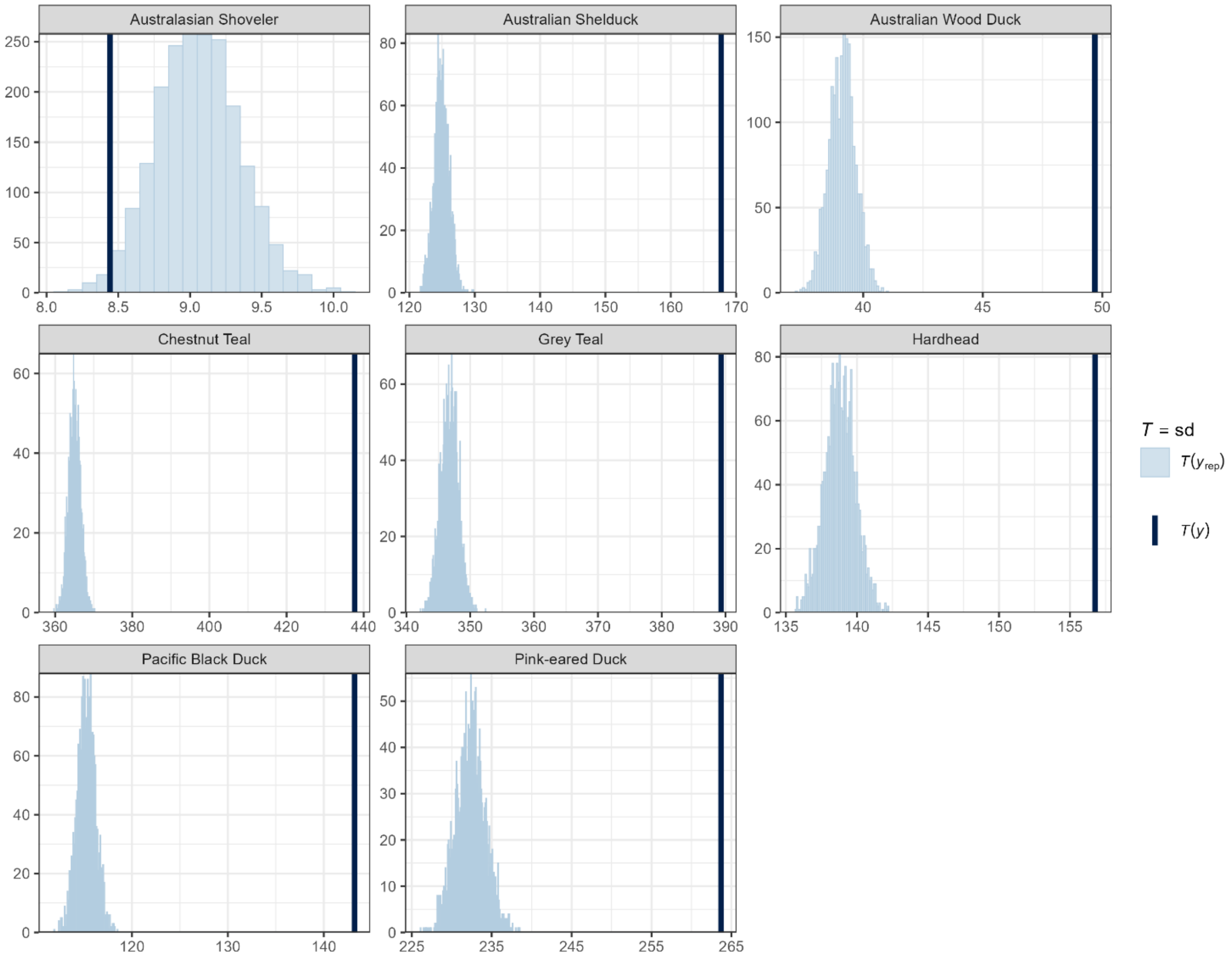
In general, the ZIP model used to estimate abundance had good correspondence between the proportion of zero counts in the data with that predicted by the model. There were small discrepancies between observed and predicted overall mean counts, but larger discrepancies between the predicted and observed standard deviation and maximum counts. Despite these discrepancies, the overall fit of the model was deemed to be adequate as judged by the good correspondence between observed and predicted counts (Figure 5).

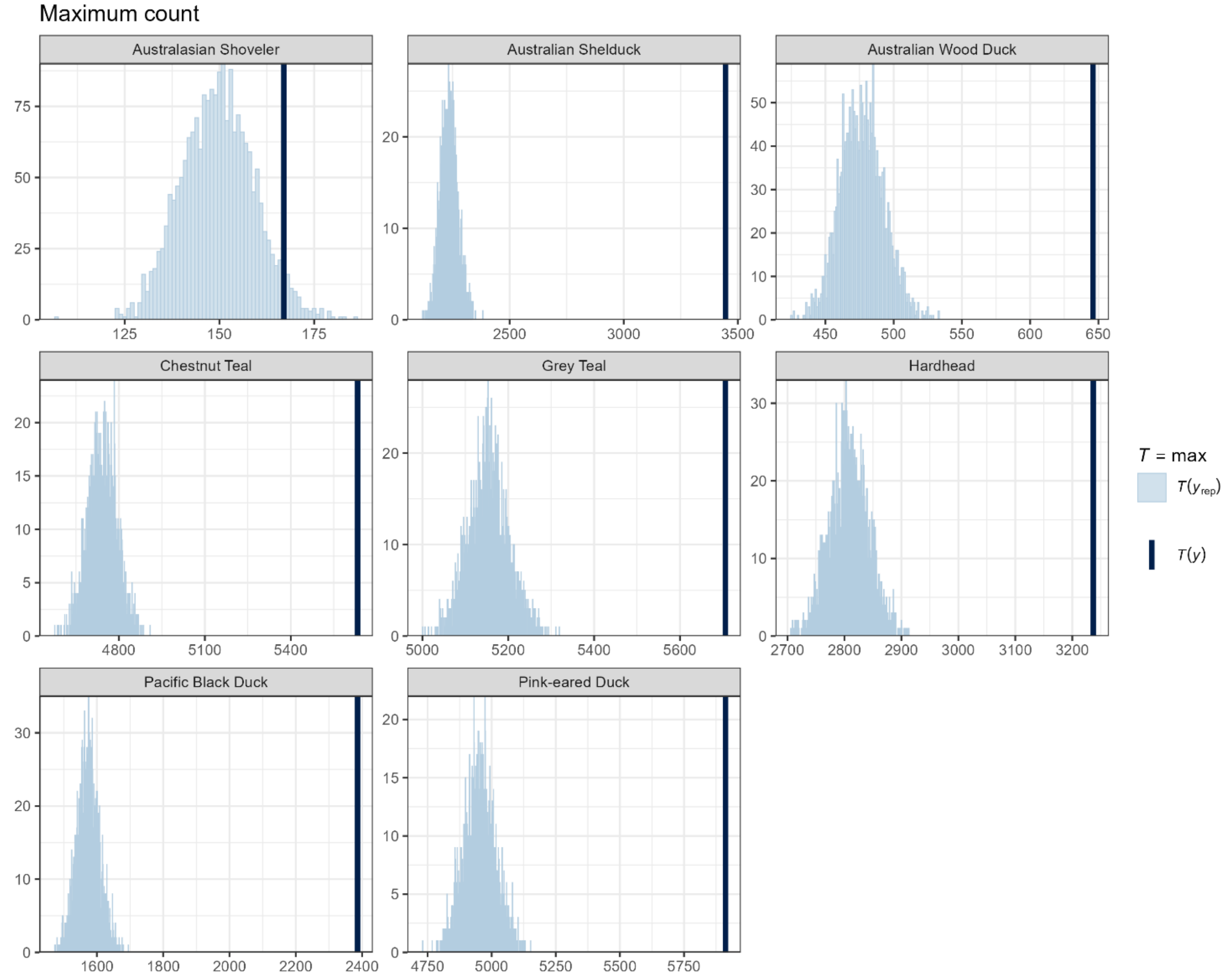




Mean count
Australasian Shoveler
Australian Shelduck
Australian Wood Duck
Chestnut Teal
Grey Teal
Hardhead
Pacific Black Duck
Pink-eared Duck
T = mean
$T(y_{rep})$
$T(y)$

Standard deviation





Maximum count
Australasian Shoveler
Australian Shelduck
Australian Wood Duck
Chestnut Teal
Grey Teal
Hardhead
Pacific Black Duck
Pink-eared Duck
T = max
T(y_rep)
T(y)

Appendix B

Table B1. Estimates of abundance for each species and stratum (*N*). SE = standard error; CV = coefficient of variation; LCL = lower 90% confidence limit; UCL = upper 90% confidence limit.

Species: Grey Teal

Waterbody	Size class	*N*	SE	CV	LCL	UCL
Dam	<6 ha	352419	32446	0.09	294094	412360
Dam	6–50 ha	3304	381	0.12	2585	3976
Dam	>50 ha	8771	1051	0.12	6841	10650
Sewage pond	<6 ha	2548	120	0.05	2293	2742
Sewage pond	6–50 ha	19420	502	0.03	18253	20114
Sewage pond	>50 ha	15691	474	0.03	14171	16198
River/stream	<6 ha	49085	4471	0.09	41041	57454
River/stream	6–50 ha	52890	5395	0.1	42705	62911
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	36951	2924	0.08	31645	42386
Wetland	6–50 ha	60078	3506	0.06	53560	66550
Wetland	>50 ha	92370	5640	0.06	81688	102726

Species: Australian Wood Duck

Waterbody	Size class	N	SE	CV	LCL	UCL
Dam	<6 ha	1147509	100836	0.09	968745	1336410
Dam	6–50 ha	1841	288	0.16	1326	2381
Dam	>50 ha	3768	735	0.2	2442	5185
Sewage pond	<6 ha	251	42	0.17	174	329
Sewage pond	6–50 ha	595	90	0.15	429	758
Sewage pond	>50 ha	432	105	0.24	236	620
River/stream	<6 ha	146927	8461	0.06	131066	162524
River/stream	6–50 ha	58945	4438	0.08	50499	67021
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	14704	1629	0.11	11890	17824
Wetland	6–50 ha	6132	719	0.12	4866	7485
Wetland	>50 ha	8370	1196	0.14	6196	10604

Species: Australian Shelduck

Waterbody	Size class	*N*	SE	CV	LCL	UCL
Dam	<6 ha	38299	9672	0.25	22672	58053
Dam	6–50 ha	2600	519	0.2	1672	3571
Dam	>50 ha	7634	1100	0.14	5535	9566
Sewage pond	<6 ha	42	15	0.35	18	72
Sewage pond	6–50 ha	1429	163	0.11	1110	1712
Sewage pond	>50 ha	1114	131	0.12	831	1313
River/stream	<6 ha	1568	1212	0.77	167	4613
River/stream	6–50 ha	9918	7750	0.78	946	29612
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	1245	359	0.29	679	2019
Wetland	6–50 ha	15823	2181	0.14	11962	19929
Wetland	>50 ha	29684	3015	0.1	24264	35495

Species: Pacific Black Duck

Waterbody	Size class	*N*	SE	CV	LCL	UCL
Dam	<6 ha	462464	38083	0.08	395867	536683
Dam	6–50 ha	2046	228	0.11	1628	2466
Dam	>50 ha	6808	738	0.11	5402	8137
Sewage pond	<6 ha	295	30	0.1	236	347
Sewage pond	6–50 ha	1363	80	0.06	1203	1501
Sewage pond	>50 ha	1452	105	0.07	1217	1602
River/stream	<6 ha	152907	5984	0.04	142093	163382
River/stream	6–50 ha	96642	4317	0.04	88773	104598
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	24278	2074	0.09	20634	28155
Wetland	6–50 ha	22391	1466	0.07	19602	25128
Wetland	>50 ha	44734	3038	0.07	39185	50195

Species: Chestnut Teal

Waterbody	Size class	*N*	SE	CV	LCL	UCL
Dam	<6 ha	423530	50637	0.12	333122	520085
Dam	6–50 ha	4372	695	0.16	3128	5686
Dam	>50 ha	12566	1822	0.15	9173	15888
Sewage pond	<6 ha	474	49	0.1	379	558
Sewage pond	6–50 ha	3986	273	0.07	3444	4451
Sewage pond	>50 ha	3079	261	0.08	2527	3424
River/stream	<6 ha	27702	3355	0.12	21616	34113
River/stream	6–50 ha	32268	5437	0.17	22801	43019
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	53155	4402	0.08	45122	61113
Wetland	6–50 ha	93566	5922	0.06	82612	104464
Wetland	>50 ha	150086	9127	0.06	132557	166806

Species: Hardhead

Waterbody	Size class	N	SE	CV	LCL	UCL
Dam	<6 ha	105856	24203	0.23	66993	156991
Dam	6–50 ha	1432	352	0.25	842	2124
Dam	>50 ha	4896	1068	0.22	3012	6929
Sewage pond	<6 ha	1028	158	0.15	728	1306
Sewage pond	6–50 ha	6416	380	0.06	5634	7031
Sewage pond	>50 ha	4631	274	0.06	4047	4977
River/stream	<6 ha	700	362	0.52	205	1537
River/stream	6–50 ha	1836	1033	0.56	510	4317
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	2058	509	0.25	1243	3116
Wetland	6–50 ha	6074	954	0.16	4451	7998
Wetland	>50 ha	14170	2054	0.14	10580	18107

Species: Pink-eared Duck

Waterbody	Size class	N	SE	CV	LCL	UCL
Dam	<6 ha	4206	2573	0.61	979	10464
Dam	6–50 ha	384	212	0.55	72	851
Dam	>50 ha	4477	1761	0.39	1713	8062
Sewage pond	<6 ha	346	119	0.35	147	585
Sewage pond	6–50 ha	10576	1044	0.1	8513	12308
Sewage pond	>50 ha	12892	801	0.06	11025	13810
River/stream	<6 ha	87	75	0.86	5	282
River/stream	6–50 ha	690	703	1.02	51	2736
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	50	30	0.6	10	120
Wetland	6–50 ha	977	340	0.35	436	1678
Wetland	>50 ha	7161	1628	0.23	4333	10317

Species: Australasian Shoveler

Waterbody	Size class	N	SE	CV	LCL	UCL
Dam	<6 ha	8321	3826	0.46	2990	17245
Dam	6–50 ha	86	41	0.47	25	174
Dam	>50 ha	317	141	0.44	97	614
Sewage pond	<6 ha	11	9	0.79	0	31
Sewage pond	6–50 ha	129	40	0.31	62	207
Sewage pond	>50 ha	155	59	0.38	52	269
River/stream	<6 ha	504	295	0.58	114	1210
River/stream	6–50 ha	976	689	0.71	169	2818
River/stream	>50 ha	0	0	0	0	0
Wetland	<6 ha	266	136	0.51	83	590
Wetland	6–50 ha	597	166	0.28	331	944
Wetland	>50 ha	1338	316	0.24	795	1960

Appendix C

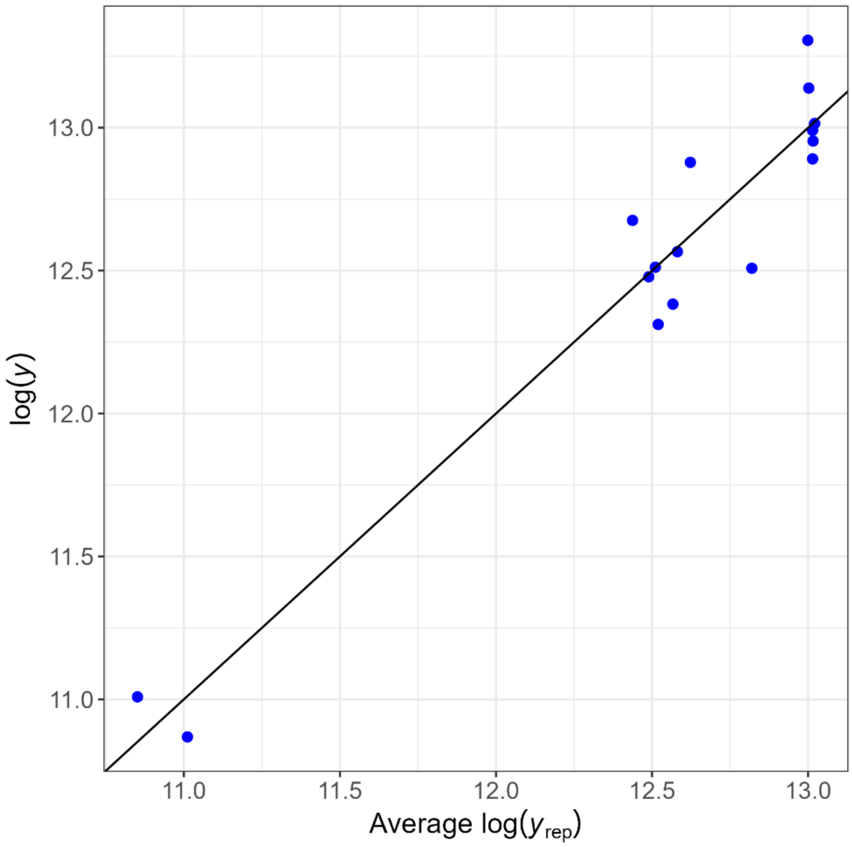


Figure C1. Posterior predictive distributions from the model fitted to the total game duck harvest from 2009 to 2024. $\log(y)$ **= observed (log) total harvest;** $\log(y_{rep})$ **= average predicted (log) total harvest from the fitted model. The black line shows a 1:1 relationship. The two points on the lower left of the plot represent the predicted and observed harvest during the years with COVID-19 restrictions (2020 and 2021).**

Appendix D

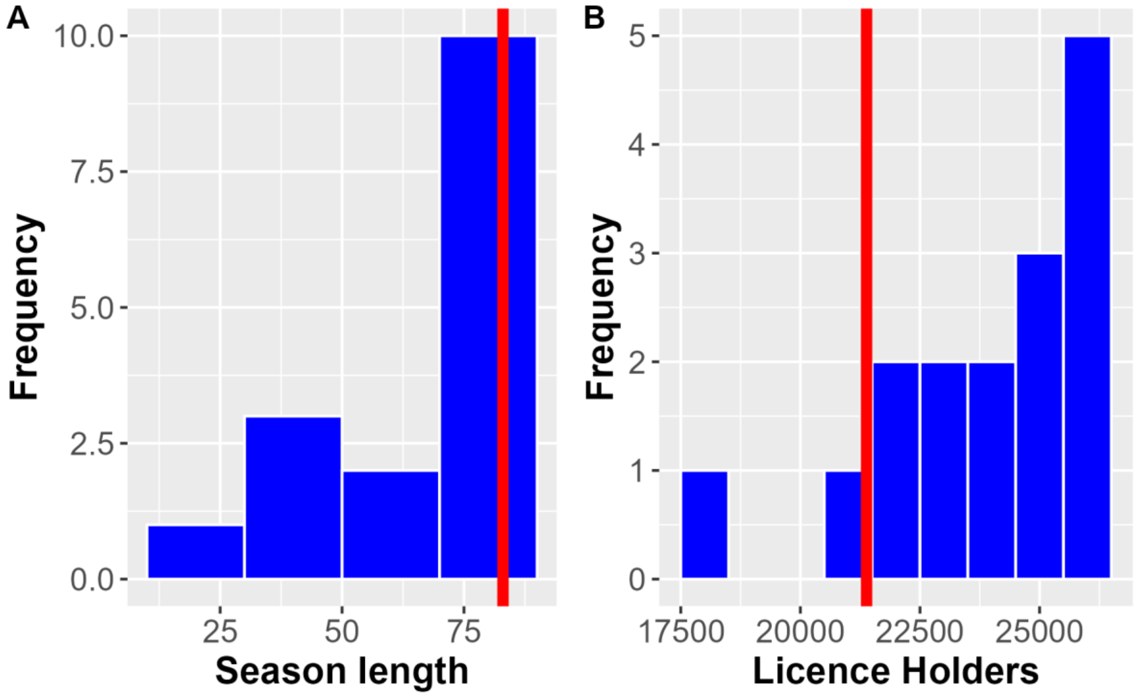


Figure D1. Frequencies of season lengths (days) and number of game licence holders recorded in the historical harvest data (2009 – 2024). Vertical red lines indicate the values used to predict the seasonal arrangements for 2025 (i.e. season length of 83 days and 21,383 licence holders).

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