Abundance estimates for game ducks in Victoria

Results from the 2022 aerial and ground surveys

D.S.L. Ramsey and B. Fanson

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Acknowledgement

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We are committed to genuinely partner, and meaningfully engage, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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Front cover photo: Pink-eared ducks, McDonalds Swamp (*Malacorhynchus membranaceus*) (source: Peter O'Toole)

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Abundance estimates for game ducks in Victoria: results from the 2022 aerial and ground surveys

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Summary

Context:

In Victoria, eight species of native duck 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*), Hardhead (*Aythya australis*), and Australasian Shoveler (*Anas rhynchotis*) (hereafter called game ducks), with the latter two species not able to be legally harvested in 2022. Comprehensive surveys of game ducks in Victoria are required to implement adaptive harvest management (Ramsey *et al.* 2017). A survey design suitable for estimating the statewide abundance of game duck species was recently developed (Ramsey 2020), with the initial pilot survey conducted in late 2020 (Ramsey and Fanson 2021). A revised survey design incorporating recommended improvements (Prowse and Kingsford 2021) was implemented in October 2021. This report details the results of the statewide aerial and ground survey of game ducks in Victoria conducted during 2022.

Aims:

The aims of this report were to (i) estimate 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, and (ii) conduct an analysis of the monitoring data from the aerial and ground surveys of game ducks to estimate the abundance of each game species within the main habitat types in Victoria.

Methods:

Waterbodies, selected using a stratified random sampling design, were subject to aerial surveys during mid-November to mid December 2022. At each waterbody, two observers on the left side of the aircraft (one forward and one rear) conducted counts of game ducks at each waterbody independently. 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 water bodies in Victoria (wetlands, dams, sewage treatment ponds, rivers and large streams) were derived from the most recent Landsat and Sentinel-2 satellite imagery at the time of the surveys to derive the number of waterbodies of each type in Victoria containing surface water. Design-based, finite sampling methods were then used to extrapolate estimates from sampled water bodies to the number of available waterbodies with surface water of each type to derive statewide estimates of abundance for each game duck species. Additionally, model-based procedures were also used to derive statewide abundance estimates for each species. Model-based estimates have the advantage of being able to use survey data collected using non-random sampling designs but have the disadvantage of relying on a stronger set of assumptions compared to design-based approaches.

Results:

A total of 883 waterbodies were subject to aerial (821) or ground surveys (62). Of these, 870 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. Counts of game duck species were sufficient to estimate the abundances for five species (Australian Shelduck, Australian Wood Duck, Grey Teal, Chestnut Teal and Pacific Black Duck). Counts for Hardhead, Pink-eared Duck and Australasian Shoveler were too few (< 50) for robust analysis.

Surface water estimates for Victoria revealed that the amount of surface water in dams, wetlands and sewage ponds increased by 58% compared with surface water estimates for 2021. Surface water estimates did not include temporary waterbodies (e.g., floodplains, paddocks) that contained water due to the floods experienced in Victoria during spring 2022. Design-based estimates of the total abundance of the five species indicated that the population of game ducks on dams, wetlands, sewage ponds, rivers and streams in Victoria was 2,410,000 (95% confidence interval: 1,873,500– 3,100,100).

Australian Wood Duck was the most numerous game species (c. 1,140,000), followed by Pacific Black Duck (c. 574,000), Grey Teal (c. 460,000), Australian Shelduck (c. 205,000) and Chestnut Teal (c. 30,000). Precision of the overall design-based estimate of abundance was good, with a 13% (0.13) coefficient of variation, within the target threshold of 15%. Model-based estimates of abundance were around 20% lower than the design-based estimates, giving an estimate of 1,900,300 game ducks. However, model-based estimates tended to be more precise than the corresponding design-based estimates.

Conclusions and implications:

The abundance estimates for some of the main game species, Grey Teal, Chestnut Teal and Australian Shelduck, have decreased compared with the 2021 survey while abundance for Pacific Black Duck has increased. Estimates for Australian Wood Duck were similar to those in 2021. The decreases noted for some species should be interpreted in light of the large increases in surface water experienced in the Murray Darling Basin during 2022, which provided an abundance of alternative habitat for game ducks, both in Victoria (e.g., floodplains) and interstate. As much of this habitat is outside the sampling frame used for the current survey, a more complete picture of game duck populations will need to incorporate surveys of key habitat outside Victoria. This could be undertaken by expanding the helicopter aerial surveys and/or incorporating data from the Eastern Australian Waterbird Survey.

Recommendations:

To strengthen the Victorian game duck survey to ensure robust estimates of abundance that will be suitable for use in Adaptive Harvest Management, it is recommended that:

- The current number and locations of surveyed waterbodies (~880) should be retained and used for future surveys. However, some adjustments to locations of some waterbodies will be required to align these with the latest satellite imagery collection (DEA 2.0).
- To provide more confidence in model-based predictions, undertake investigations to help remove any structural inadequacies in the model fitted to the counts of game ducks by investigating additional variables that might explain variation in counts.
- To investigate methods for expanding the current sampling frame to include key game duck habitat in New South Wales and South Australia (by expanding the current helicopter aerial survey) and investigate methods for calibrating data from the Eastern Australian Waterbird Survey.
- To improve the accuracy of surface water area estimates for farm dams by incorporating any updates to the spatial vector layer(s) recording farm dam locations.

1 Introduction

In Victoria, six species of native duck are currently subject to legal harvest: Grey Teal (*Anas gracilis*), Pacific Black Duck (*Anas superciliosa*), Australian Wood Duck (*Chenonetta jubata*), Australian Shelduck (*Tadorna tadornoides*), Pink-eared Duck (*Malacorhynchus membranaceus*) and Chestnut Teal (*Anas castanea*). Hardhead (*Aythya australis*) and Australasian Shoveler (*Anas rhynchotis*) are not able to be legally harvested in 2022. The Victorian Government manages recreational duck hunting sustainably by setting seasonal daily bag limits for each species, as well as the timing of the start and end of the hunting season (i.e., season length). These arrangements can change each year, depending on the information available about the status of populations and the prevailing environmental conditions. The main source of information used to inform the population status of game ducks is the Eastern Australian Waterbird Survey (EAWS) (Kingsford and Porter 2009). There is also some reliance on regional game duck surveys conducted in parts of South Australia (Anon 2016) and in the Riverina district of New South Wales (Vardanega *et al.* 2021). The Victorian Priority Waterbird Count (Menkhorst *et al.* 2019) includes annual surveys of up to 200 wetlands across Victoria. However, these surveys are conducted just before the start of the hunting season and are used primarily for identifying locations of threatened species or breeding colonies that may warrant site-specific management, including closure to hunting.

Comprehensive surveys for estimating the statewide abundance of game duck species are vital if an adaptive harvest management framework (e.g., Nichols *et al.* 2007) is to be adopted for managing the recreational harvest of game ducks (Ramsey *et al.* 2017). However, the Victorian Priority Waterbird Counts and EAWS have inadequate coverage and/or sampling designs for Victorian waterbodies to enable a robust estimation of duck abundances across the state. In addition to the undertaking of 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 can now be regularly determined by applying appropriate algorithms to satellite imagery (e.g., Pekel *et al.* 2016; Mueller *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, 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. Briefly, these included:

- increasing the sample size of the waterbodies, including large wetlands
- including waterways (rivers, large streams) as additional strata and adding large storage dams to the sampling design
- increasing the coverage of waterbodies throughout the state by including ground counts on waterbodies where it was not feasible to conduct aerial surveys
- including methods for obtaining separate abundance estimates for Grey and Chestnut Teal
- modification to the aerial survey methods involving partial counts of large waterbodies to ensure the main waterbody as well as edge is counted
- investigating alternative models for improving the detection probabilities of game ducks by observers

The revised survey design was then implemented during October/November 2021, sampling approximately 750 waterbodies across the state (Ramsey and Fanson 2022). The analysis of the 2021 game duck survey recommended some further improvements to the survey design including increasing the sample size of waterways (river and stream segments). Accordingly, the Victorian Game Management Authority implemented the revised survey design during mid-November to early-December 2022. This report summarises the results from the 2022 aerial and ground surveys of game ducks in Victoria.

1.1 Objectives

The aim of this study was to conduct an analysis of the aerial and ground survey data for game ducks, undertaken during 2022, to provide estimates of the abundance of each species of game duck. This was achieved through the following objectives:

- Estimate the current amount of surface water available for use by game ducks within Victoria, using the most recent satellite imagery (LandSat and Sentinel2) combined with vector layers of waterbodies (including farm dams and rivers/streams).
- Analyse the aerial and ground survey data in conjunction with the estimates of surface water availability, to estimate the abundance and distribution of each game duck species in Victoria.
- Identify modifications to the survey design that would lead to improvements in the statewide estimates, if required.

2 Methods

2.1 Estimates of surface water availability

To extrapolate the estimates of abundance of game ducks at sampled waterbodies to obtain regional or statewide estimates of abundance, an estimate is required of the surface water availability for the period within which the surveys were undertaken. 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 subject to sampling and is also the target of estimation. In other words, estimates of duck abundance obtained from each of the sampled waterbodies are then extrapolated to all waterbodies in the sampling frame to obtain an estimate of the total abundance. It follows that the sampling frame also delimits the total size of the regional duck population, which may exclude ducks residing in habitats that are outside the sampling frame and therefore not sampled. For the 2022 survey, 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 1). For wetlands and sewage ponds, we utilized 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. At this stage, this process excludes rivers and streams, which are dealt with separately.

As WOfS uses LandSat which has a ~30m pixel size, it uses an area threshold of 2700m^2 (0.27ha); detection of surface water for waterbody areas below this threshold area is 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) for the polygon to assess presence of water (Figure 1A). Sentinel 2 uses a Normalized Difference Water Index – NDWI for the detection of surface water (Mueller *et al.* 2016). For both WOfS and S2 imagery, we obtained the most recent estimate of surface water extent for each waterbody at the time of the aerial and ground surveys as well as the average of the three most recent observations.

Finally, for rivers and streams we used the Index of Stream Conditions (ISC) project to define the major river system (Figure 1B). This project mapped streambeds using LiDAR and hence has stream spatial 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 use flow gauge information to assess flowing conditions in the river/stream around the time of the survey, which was supplemented by satellite imagery from S2.

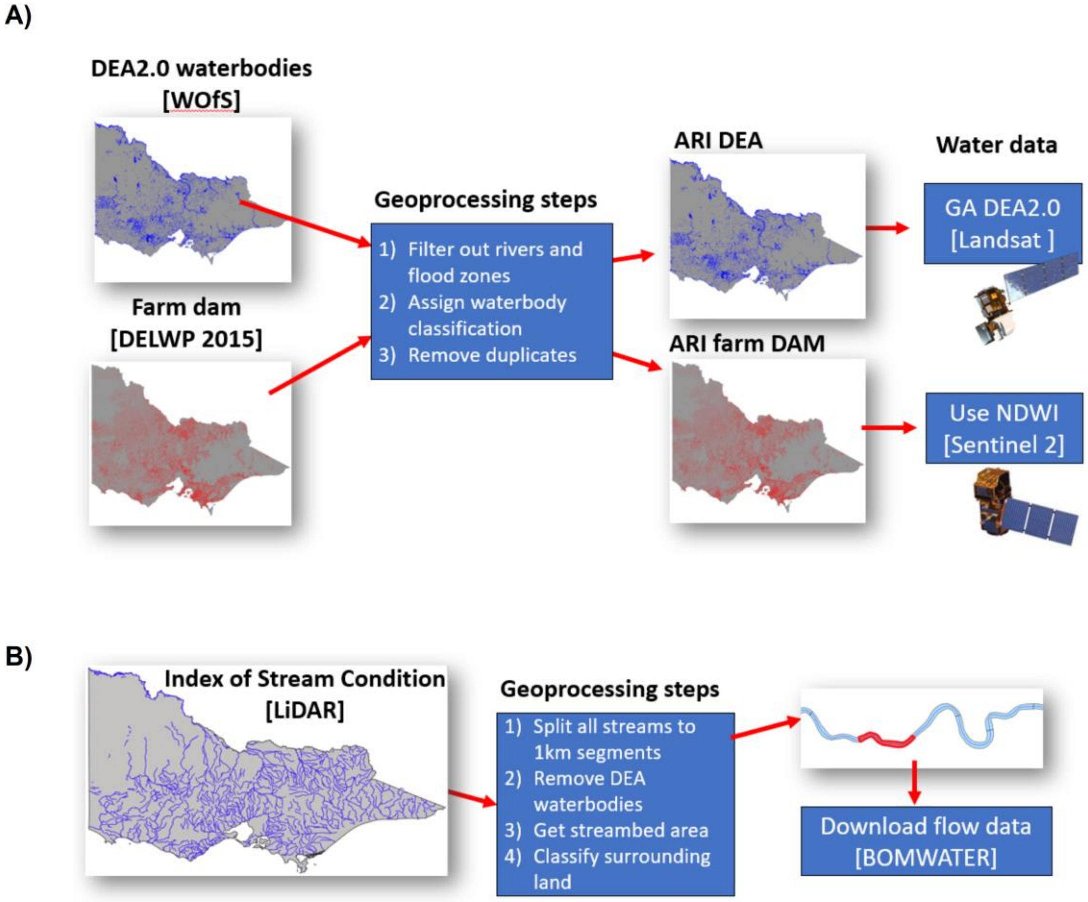

Figure 1. Overview of the waterbody (A) and river/stream (B) GIS layers and processing steps used to derive estimates of the number of waterbodies, rivers and streams with surface water in Victoria.

2.1.1 Updating the DEA waterbody layer to version 2.0

During the last year, the DEA waterbody Version 1.0 (Geosciences Australia) was updated to Version 2.0 (Krause *et al.* 2021). The main difference in versions is that the underlying Landsat data for delineating waterbodies changed (collection 3; see details “DEA Waterbodies v2” in (https://cmi.ga.gov.au/data-products/dea/693/dea-waterbodies-landsat#details) as well as the water classification algorithm (switched to *DEA Waterbody Observations*) that improved the water detection algorithm (e.g., dealing with terrain, solar incidence issues and shadowing).

This change resulted in pixel size changing from 25m to 30m and hence all waterbody polygons were redrawn in the new version. These revisions resulted in the following changes: 1) waterbodies having new boundaries; 2) the grouping of previously separate polygons into single waterbody; 3) splitting of waterbodies into multiple waterbodies; and 4) creation of new waterbodies and/or loss of waterbodies. Furthermore, the minimal polygon size decreased to 2700m^2 (3 pixels of 30m) from the previous 3,125m^2 (5 pixels of 25m) due to improved detection ability.

2.2 Selecting the sample of waterbodies

Following the recommendations in Ramsey and Fanson (2022), sample selection for the 2022 survey was modified by increasing the sample size of waterways (rivers/steams) to 100. Otherwise, most (99%) of the waterbodies sampled during the 2021 survey were sampled again in 2022. 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 (2021).

2.3 Aerial and ground sampling of game ducks

Aerial sampling of each waterbody was undertaken from a Squirrel AS-350 helicopter. 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 center. This addresses the propensity of ducks to concentrate on the shoreline, sometimes in clumped aggregations, and avoids under-estimating density by only counting the shoreline. The counts for each observer for the entire surface area were then imputed using the proportion of the waterbody surveyed.

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 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 using the same imputation method as used for aerial surveys.

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 and this ratio 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

2.4.1 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. Hence, this model includes a component that accounts for the probability that ducks are present on the waterbody at the time of 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 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 2.21.2) using RStan in R (Carpenter *et al.* 2017). Weakly informative prior distributions were used for all parameters in the model specified as $N(0, 5)$. A total of 3000 MCMC iterations were run for the model, using 5 chains, with the first 1000 iterations considered to be 'warmup' (tuning) iterations and discarded. This left a total of 10,000 samples for each parameter to form the inference.

2.4.2 Statewide abundance estimates

Predictions of game duck abundance for the entire sampling frame (i.e., waterbodies containing water within Victoria) were made using a design-based approach (Thompson 1992). Design-based estimates of total abundance were obtained by using predicted abundance for each sampled waterbody derived from the fitted model (section 2.4.1). The predicted abundance and associated variance were then used to produce design-based estimates of the total abundance and variance of game ducks for the entire sampling frame. To account for the unequal probability sampling designs used here, total abundance of ducks was estimated using a Horvitz–Thompson type estimator (Horvitz and Thompson 1952) with inclusion probabilities for waterbodies in each stratum calculated as inversely proportional to their availability in the sampling frame. This necessarily requires that inclusion probabilities be rescaled when the size of the sampling frame changes (i.e., due to drying and/or filling of waterbodies). Variance estimates were adjusted in a similar way (Hankin 1984; Skalski 1994). Further details of this sampling design and the estimators are provided in Appendix A.

In addition to design-based estimates, we also derived estimates of total abundance of game ducks using a model-based approach. The advantages of a model-based approach are that it can be used to predict abundance in areas outside the sampling frame and can use data collected from non-random sampling designs, which are properties that are not possible with design-based procedures. However, model-based approaches can produce biased estimates of abundance if a poor model is used for prediction. 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 2.4.1). The variance of the total abundance estimate was estimated using posterior predictive simulation based on the posterior distributions of the estimated parameters from the fitted model (Gelman and Hill 2007). A total of 1000 posterior estimates of total abundance were calculated for each species and used for inference.

3 Results

3.1 Survey summary

Aerial and ground surveys of game ducks were undertaken from 25 November – 13 December 2022. A total of 883 waterbodies were successfully surveyed, with 821 waterbodies surveyed from the air and a further 62 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 808 of the 821 waterbodies subjected to aerial survey were observed to have surface water (98%), with the remaining either being dry or not present at the identified location. No waterbody was observed to be completely dry during the ground surveys.

From the ground surveys, a total of 744 Chestnut teal were observed from 24 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 mean numbers of male and female Chestnut Teal observed were 12 and 18, respectively, giving a male:female sex ratio of 0.67 (SE = 0.085). This value was subsequently used to adjust the counts of Grey and Chestnut Teal from the aerial surveys.

Table 1. Waterbodies sampled by aerial and ground surveys during 2022. The numbers of these waterbodies observed with surface water are given in parentheses.

Waterbody type	Aerial	Ground	Totals
Dams	210 (205)	18 (18)	**228 (223)**
Sewage ponds	4 (4)	31 (31)	**35 (35)**
Wetlands	514 (506)	13 (13)	**527 (519)**
Rivers/Streams	93 (93)	0	**93 (93)**
Total	**821 (808)**	**62 (62)**	**883 (870)**

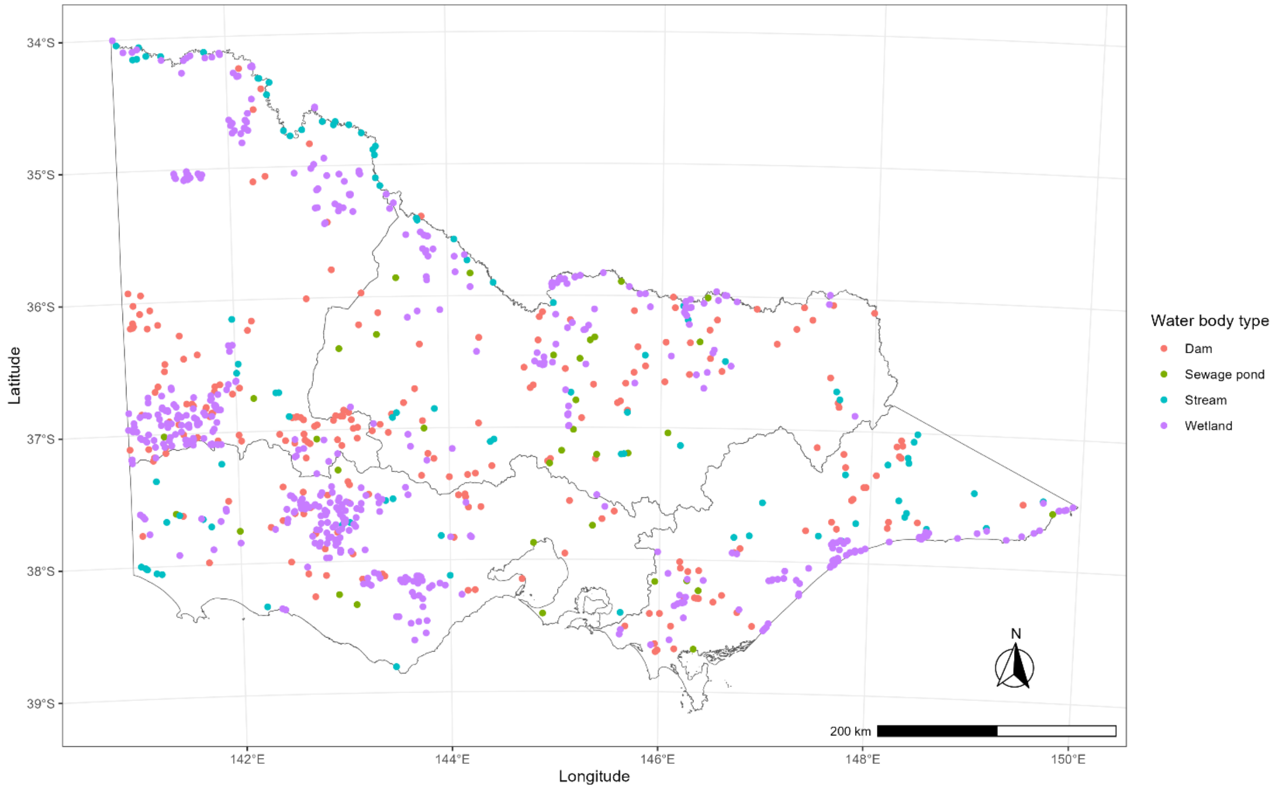

Figure 2. Locations of the 883 waterbodies (Dams, Sewage ponds, Wetlands and Rivers/Streams) that were subject to aerial and ground sampling during November-December 2022. Bioregion boundaries are (clockwise from top left), West, North, East and South.

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 251,734 (Table 2). This was 59% higher than estimated for the previous survey in 2021 (171,210), mainly due to the very wet conditions experienced in Victoria over the spring of 2022. Overall, surface water availability in 2022, especially in wetlands and dams, increased by 58% compared to 2021 resulting in a total surface water area of 245,737 ha (Figure 3).

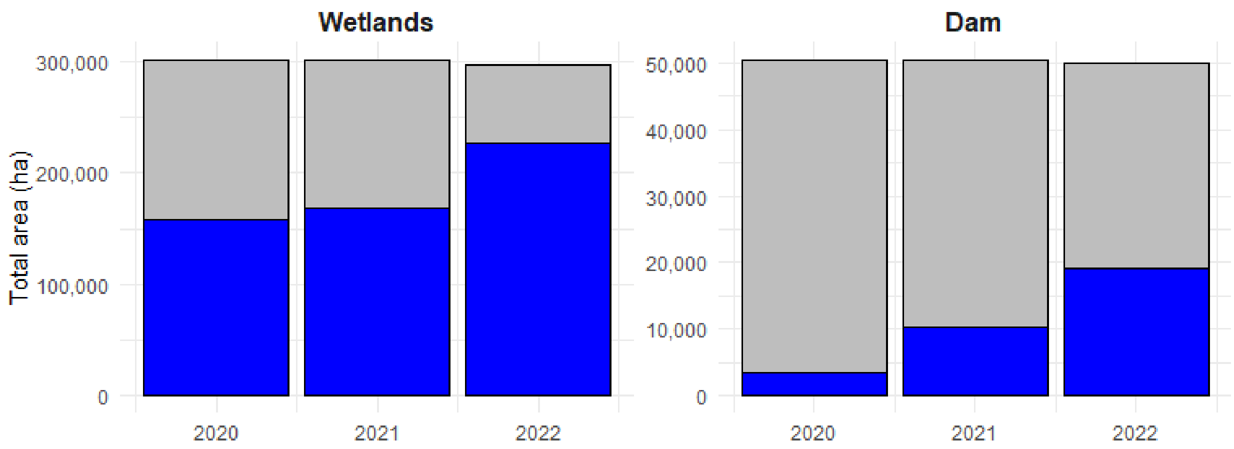

Figure 3. Temporal changes in surface water availability in wetlands and dams over the last 3 years.

Table 2. Number of mapped waterbodies determined as containing surface water during the spring 2022 period.

Waterbody type	Size class			
	<6 ha	**6–50 ha**	**>50 ha**	**Totals**
Dams	251,546	130	58	**251,734**
Sewage ponds	46	55	9	**110**
River/Streams	11,919	1,938	0	**13,857**
Wetlands	5,716	1,668	422	**7,806**
Totals	**269,227**	**3,791**	**489**	**273,507**

3.2.1 Calibration of surface water predictions

During the conversion from DEA1.0 to DEA2.0, there were 29 waterbodies that were present in DEA1.0 but completely missing in DEA2.0 (e.g., no overlap with DEA2.0 polygon). Hence, calibration results are presented only for waterbodies that were linked to DEA2.0 objects as these had estimates of surface water (Table 3). 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 wet waterbodies were high (>95%) for wetlands and sewage ponds and slightly lower for river/stream segments (92%) and dams (88%). Conversely, none of the dry wetlands and only 80% of dry dams were correctly predicted (Figure 4a). However, the latter result is difficult to interpret as the sample size of dry dams was very low (5) (Table 3). Examining the calibration results using the DEA2.0 surface water estimates showed that correct predictions of wet waterbodies were excellent (100%) for dams and sewage ponds and high (92%) for wetlands (Figure 4b). Correct predictions of dry wetlands were 67% accurate, but as for the Sentinel-2 results, the sample size of dry wetlands was very low (6) (Figure 4b).

Table 3. Summary of waterbody types with observations of surface water presence (Wet) or absence (Dry) from aerial surveys. Only DEA1.0 wetlands objects linked to a DEA2.0 objects are included.

Waterbody type	Wet	Dry
Dams	219	5
River/Stream	92	0
Sewage ponds	35	0
Wetlands	497	6
Total	**843**	**11**

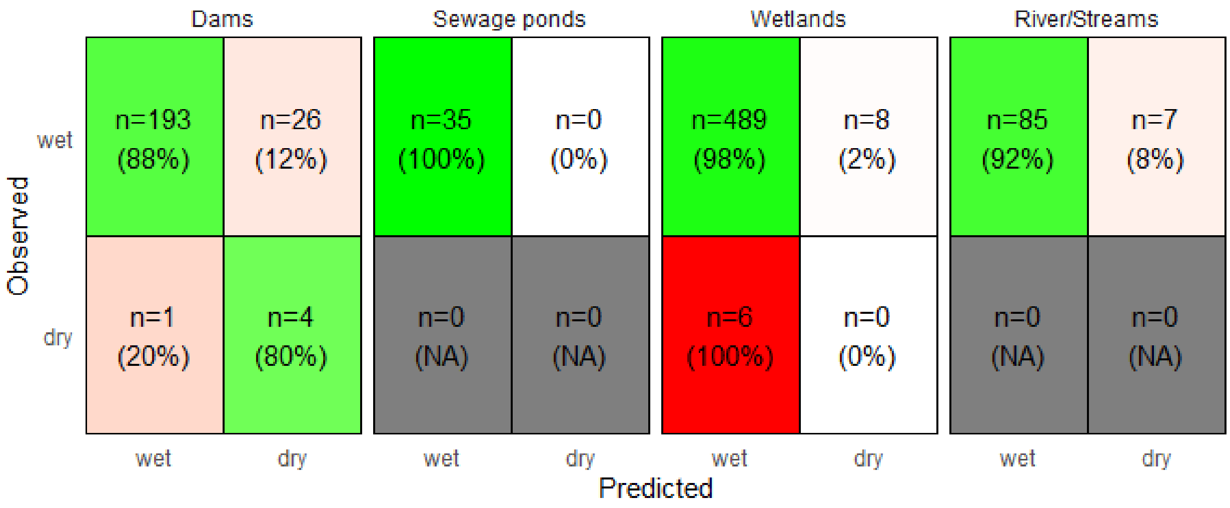

Figure 4a. Confusion table for observed (actual) vs predicted (Sentinel-2) surface water presence for (small) dams, sewage ponds, wetlands rivers/streams and storage dams. Red indicates incorrect predictions and green indicates correct predictions, with shading indicating relative (in)accuracy. White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

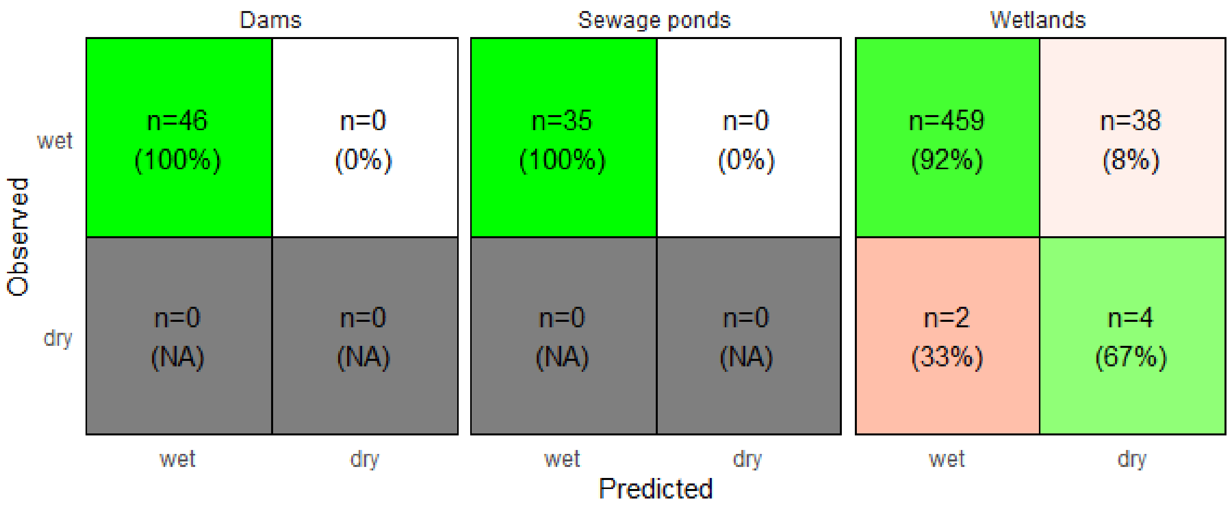

Figure 4b. Confusion table for observed (actual) vs predicted (DEA2.0) surface water presence for (large) dams, sewage ponds, wetlands, rivers/streams and storage dams. Red indicates incorrect predictions and green indicates correct predictions, with shading indicating relative (in)accuracy. White and 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 870 waterbodies with surface water are presented in Table 4. Australian Shelduck were the most numerous species counted, followed by Grey Teal and Pacific Black Duck. In contrast, the least numerous species counted were Australasian Shoveler, Hardhead and Pink-eared Duck, which all had less than 50 individuals counted (Table 4). Counts were higher within the South and West bioregions compared with the North and East (Table 5).

The monitoring data were adequate for estimating the abundance for five of the eight species of game duck; Grey Teal, Chestnut Teal, Australian Wood Duck, Australian Shelduck and Pacific Black Duck. The counts for the Australasian Shoveler, Pink-eared Duck and Hardhead were too low for robust analysis. The N-mixture ZIP model (section 2.4.1) 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). The Bayesian R^2 values (Gelman *et al.* 2019) were high for all species (GT = 0.91; WD = 0.90; AS = 0.94; PBD =

0.93; CT = 0.96). In particular, the fits indicated adequate prediction of the proportion of waterbodies with zero ducks, as well as of the mean duck abundance (Appendix B). 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 B). However, attempts to add additional structure to this model by adding random effects proved to be unsuccessful due to lack of convergence of the MCMC chains.

Table 4. Total counts of each species by waterbody type and size class. 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
Dams	<6 ha	178	90	347	71	138	1	0	0	0
	6–50 ha	26	113	116	48	37	68	1	0	0
	>50 ha	19	79	195	67	321	37	0	0	0
Sewage ponds	<6 ha	11	43	14	41	5	182	0	2	3
	6–50 ha	20	340	113	359	53	437	14	23	5
	>50 ha	4	57	62	191	0	64	7	12	1
Streams	<6 ha	62	203	304	0	172	35	0	0	0
	6–50 ha	31	102	76	20	49	4	0	0	0
Wetlands	<6 ha	167	402	364	133	277	155	0	0	0
	6–50 ha	189	780	508	630	719	258	2	3	0
	>50 ha	163	2541	450	6500	2957	986	17	7	0
Total		**870**	**4750**	**2549**	**8060**	**4728**	**2227**	**41**	**47**	**9**

Table 5: 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.

Bioregion	*n*	GT	WD	AS	PBD	CT	HH	PED	BWS	Total
East	147	774	480	772	697	938	1	0	7	**3669**
North	203	1252	739	842	1063	644	21	23	2	**4586**
South	226	1438	340	5011	1874	546	5	22	0	**9236**
West	294	1286	990	1435	1094	99	14	2	0	**4920**

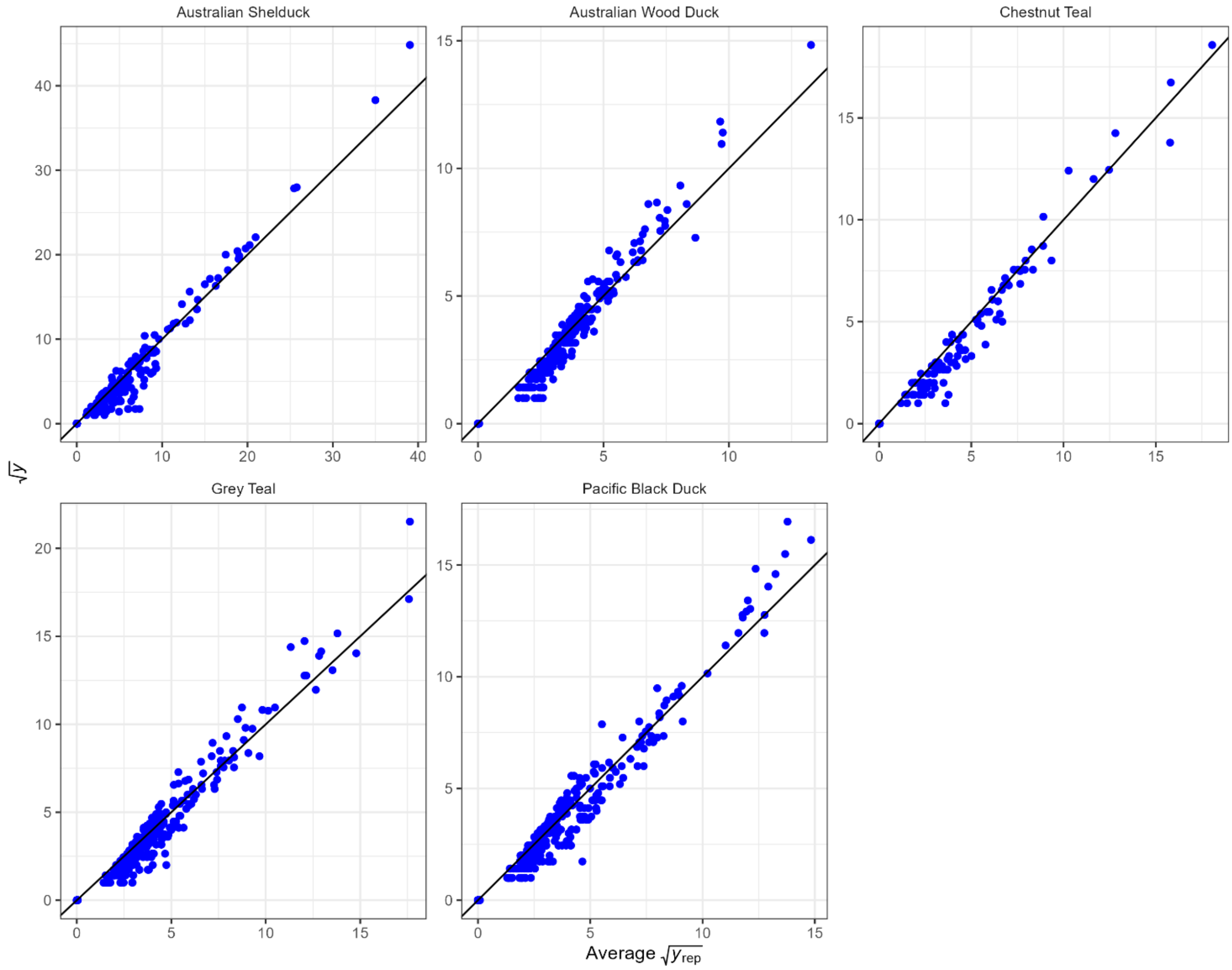

Figure 5: Posterior predictive distributions of the counts of five game duck species. y = observed counts (sum of both observers); y_{rep} = average predicted count from the fit of the zero-inflated N-mixture model. The predicted and observed counts were square root transformed to aid the visibility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

Detection probability of ducks was lower during aerial surveys compared with ground surveys with the magnitude of the difference dependent on habitat and waterbody size class (Figure 6). Aerial detection probability was highest on small (< 6 ha) and large (> 50 ha) waterbodies in open habitat (0.64 – 0.66) and was lowest on wooded habitat on mid-size (6-50 ha) waterbodies (0.30). In contrast, ground detection probability was highest on open and wooded habitat on small (< 6 ha) and medium (6-50 ha) waterbodies (0.82 – 0.87) and lowest on reed habitat on large (> 50 ha) waterbodies (0.43) (Figure 6). Compared with habitat or waterbody size class, the presence of glare on the water surface appeared to have a relatively minor influence on detection probabilities (Figure 6).

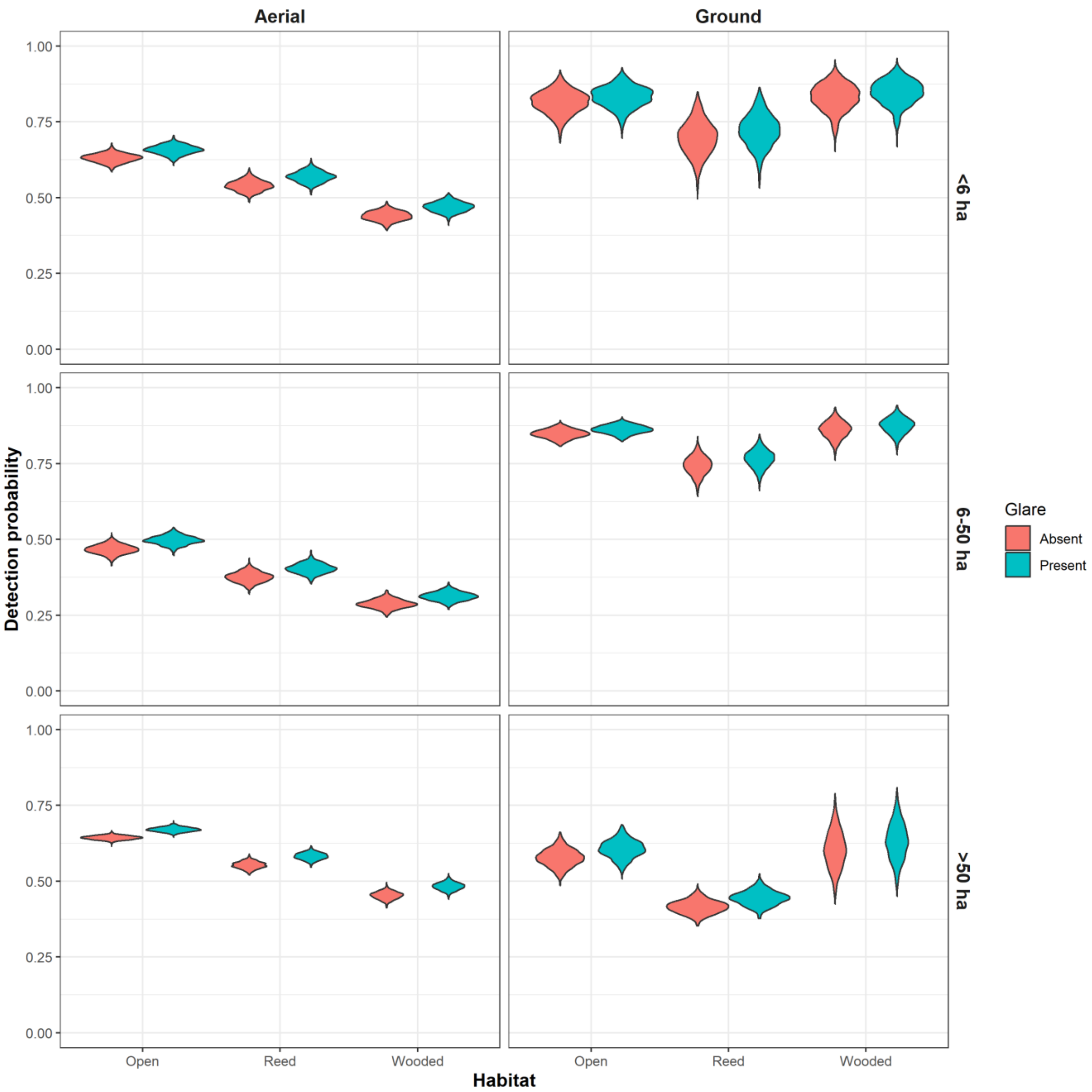

Figure 6. Detection probabilities of game ducks from aerial and ground surveys by habitat type and waterbody size class (<6 ha; 6–50 ha; >50 ha) in the presence or absence of glare from the water surface.

3.4 Statewide abundance estimates

3.4.1 Design-based estimates

Design-based estimates of total abundance indicated that the population of game ducks on dams, wetlands, sewage ponds and rivers/streams in Victoria was 2,410,000 (Table 6). Australian Wood Duck were the most numerous game species (1,140,100), followed by Pacific Black Duck (574,400) and Grey Teal (460,200) (Table 6). The precision of the overall estimate of abundance was good, with a 13% coefficient of variation, within the target threshold of 15% identified by Ramsey and Fanson (2021) as being of adequate precision. The precision of the estimates for the main individual game species, however, was variable. While the coefficients of variation for Pacific Black Duck and Chestnut Teal were close to the nominal target of 15%, those for Australian Shelduck, Australian Wood Duck and Grey Teal were higher than 20%. In particular, the estimate for Grey Teal was rather imprecise with a coefficient of variation of 30%.

3.4.2 Model-based estimates

The estimate of the total abundance of game ducks using the model-based approach was approximately 21% lower than the design-based estimate at 1,900,300 (Table 7). Estimates for all species, except for Chestnut Teal, were lower than the equivalent design-based estimates (Table 7). The precision of the overall model-based estimate of abundance was excellent, with a 6% coefficient of variation. The precision of the estimates for individual species was also good, with only the precision for Chestnut Teal exceeding 15% (Table 7).

Table 6: Summary of design-based estimates of total abundance of five game duck species in Victoria. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck; HH = Hardhead; PED = Pink-eared Duck; SE = standard error; CV = coefficient of variation; LCL = lower 90% confidence limit; UCL = upper 90% confidence limit.

Species	Estimate	SE	CV	LCL	UCL
AS	205,300	51,300	0.25	126,800	332,500
WD	1,140,100	255,700	0.22	738,500	1,759,900
CT	30,100	4,400	0.15	22,600	39,900
GT	460,200	138,600	0.30	258,300	819,800
PBD	574,400	97,300	0.17	413,100	798,600
Total	2,410,000	310,900	0.13	1,873,500	3,100,100

Table 7: Summary of model-based estimates of total abundance of five game duck species in Victoria. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck; HH = Hardhead; PED = Pink-eared Duck; SE = standard error; CV = coefficient of variation; LCL = lower 90% confidence limit; UCL = upper 90% confidence limit.

Species	Estimate	SE	CV	LCL	UCL
AS	173,100	17,500	0.10	141,800	207,800
WD	823,700	85,100	0.10	661,300	998,700
CT	88,900	18,700	0.21	58,200	129,000
GT	349,800	44,300	0.13	271,000	444,000
PBD	464,800	43,400	0.09	385,700	556,500
Total	1,900,300	108,400	0.06	1,699,500	2,124,900

The majority of game ducks occurred on small farm dams (<6 ha), especially Australian Wood Duck, Pacific Black Duck and Grey Teal (Figure 7). These species also occurred in large numbers on rivers and streams. In contrast, Chestnut Teal occurred predominantly on wetlands (Figure 7). Game ducks were far more numerous in the North bioregion and were least numerous in the East bioregion (Figure 8).

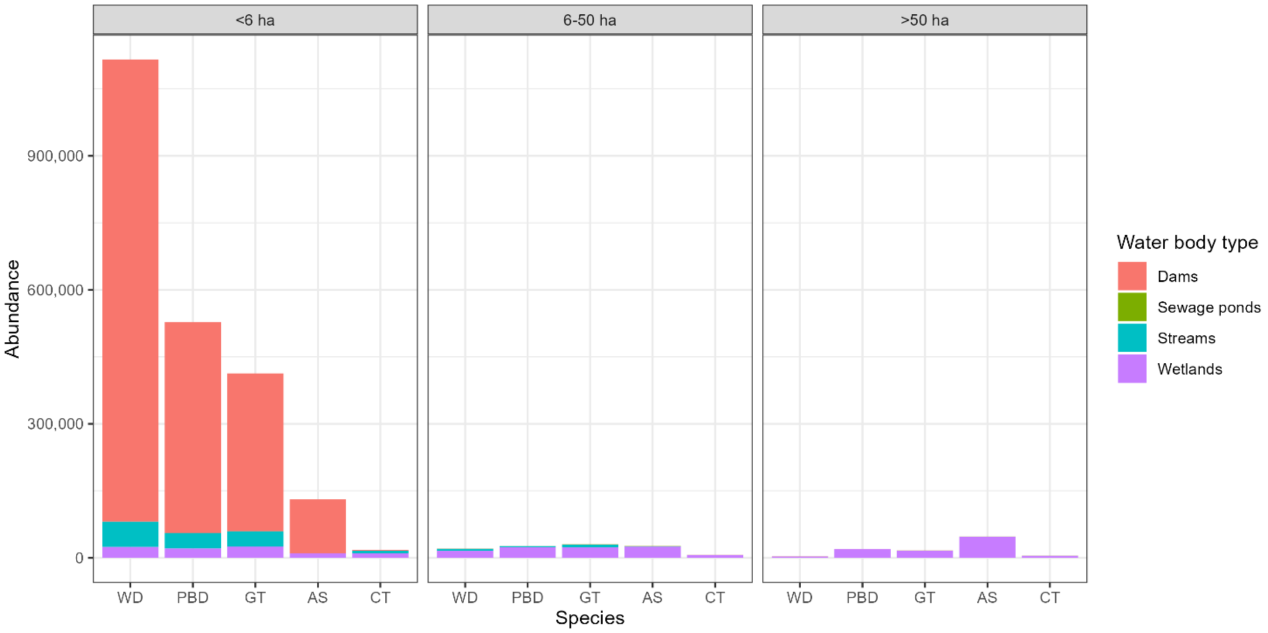

Figure 7. Abundance of game duck species by waterbody type and size class. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck.

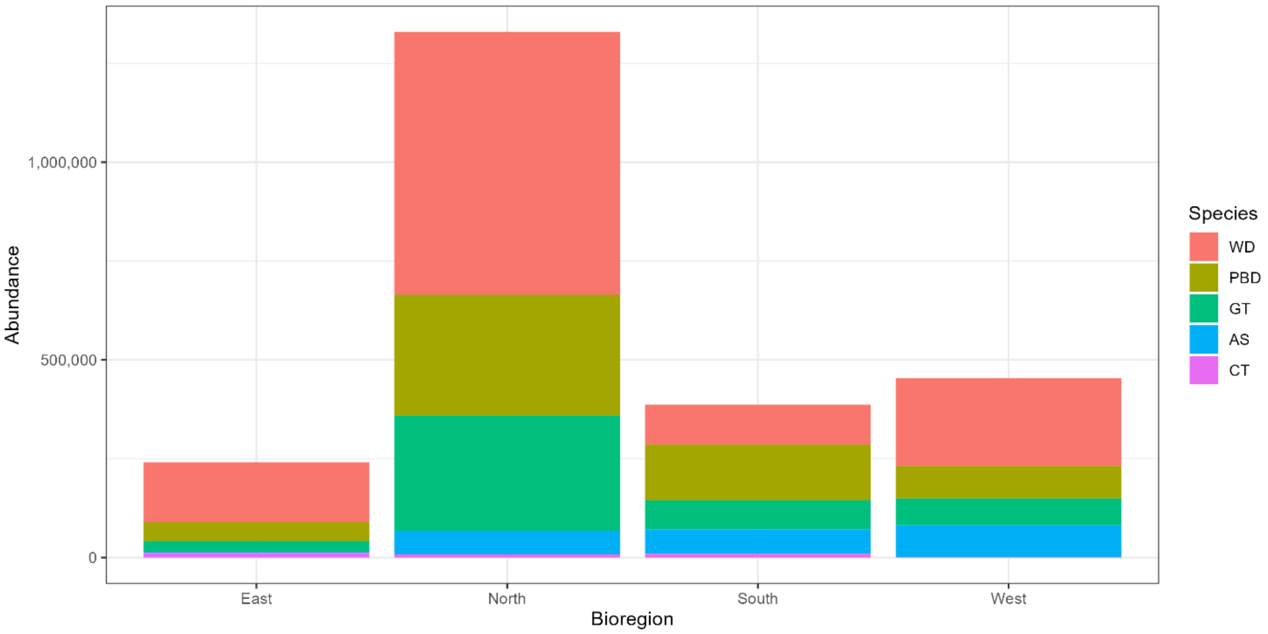

Figure 8. Abundance of game duck species by bioregion. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck.

4 Discussion

The abundance estimates for some of the main game species, Grey Teal, Chestnut Teal and Australian Shelduck, have decreased compared with the 2021 survey while abundance for Pacific Black Duck has increased. Estimates for Australian Wood Duck were similar to those in 2021 (Ramsey and Fanson 2021). No estimates for Hardhead, Pink-eared Duck and Australasian Shoveler were possible due to the low number of individuals of these species that were detected in Victoria. However, these three species have all been recorded in larger numbers in the northern Murray Darling Basin during the 2022 Eastern Australian Aerial Waterbird Survey (Porter *et al.* 2022). Rainfall in south-eastern Australia during Spring of 2022 was the highest on record and for all of 2022 was above average (in the highest 10% of historical observations) (Bureau of Meteorology 2022). Heavy flooding was also experienced in the northern parts of Victoria and southern NSW during spring 2022 (Bureau of Meteorology 2022). This was reflected in the higher estimates of surface water area over the spring period in Victoria in 2022, which were 58% higher than in 2021.

Although estimates of surface water availability for the spring period have shown dramatic increases compared with surface water area estimates for 2020 and 2021, the water detection algorithms used do not capture all occurrences of surface water. Hence, temporary flooding of low-lying areas, such as on floodplains and farm paddocks, which occurred extensively during spring 2022, were not included in surface water estimates. Ephemeral floodplains and other temporary waterbodies provide attractive habitat for many duck species as these areas are often highly productive when they contain water (Johnson *et al.* 1995; Roshier *et al.* 2008). Hence, it is probable that the lower estimates recorded for some of the game duck species could be due to the high availability of alternative habitat, both in Victoria and in the Murray Darling Basin more broadly. Game ducks occurring on floodplains and flooded paddocks would not have been captured as part of the current aerial or ground survey, which would lead to abundance being underestimated if these habitats were being used to any significant degree. In addition, increased water availability in the Murray Darling Basin may have resulted in some dispersal of ducks from Victoria, especially for species that have long-range and dispersive movements, such as Grey Teal and Pink-eared Duck (Roshier *et al.* 2008). Hence, a more complete picture of the abundance of game duck populations will need to incorporate surveys of key habitat outside Victoria. This could be undertaken by expanding the current helicopter aerial surveys and/or incorporating data from the Eastern Australian Waterbird Survey following suitable calibration with helicopter surveys.

Compared with the 2021 survey (Ramsey and Fanson 2021), the coefficient of variation (CV) of abundance estimates for some of the main game duck species were less precise, with CV's higher than 20%. The reason for the lower relative precision for these abundance estimates is due to larger than expected variation between counts among some waterbodies. For example, the precision of estimates for Grey Teal occurring on small farm dams was relatively low, with a CV of 39% (Appendix C). This indicates that counts of Grey Teal occurring on small dams were highly variable (i.e., lots of high and low (or zero) counts). Since there are many small farm dams, this variability leads to a relatively imprecise estimate for this species. The reasons for the variability in counts of Grey Teal as well as other game duck species, occurring on dams is unknown but may be due to the unusually high availability of alternative wetland habitats.

Model-based estimates of abundance were around 20% lower than design-based estimates for most species, with the discrepancy highest for Australian Wood Duck. The reason for this discrepancy is still unknown but may indicate some remaining structural inadequacies with the model. For example, posterior predictive tests indicated that the model fitted to the counts of game ducks tended to underestimate both the standard deviation and maximum counts of ducks. Hence, while the model was an excellent fit to the counts on sampled waterbodies, there may be some inadequacies when predicting to unsampled waterbodies. It should be noted that these issues do not affect design-based estimates as they do not rely on predictions for unsampled waterbodies. In general, if a random sampling design has been employed with adequate sample size, then design-based estimates are preferred over model-based estimates as the former are not based on any model assumptions about the distribution of the data. Hence, design-based estimators are relatively more robust than model-based estimators to modelling assumptions that could lead to bias in the estimates. However, design-based procedures often have high sampling variance leading to higher uncertainty in estimates compared with equivalent model-based procedures. Model-based procedures can also be used to predict abundance in areas outside the sampling frame and can use data collected from non-random sampling designs, which are properties that are not possible with design-based procedures. Further investigation of model-based estimates is therefore warranted to provide more confidence in model-based predictions of abundance of game ducks.

4.1 Recommendations

To strengthen the Victorian game duck survey to ensure robust estimates of abundance that will be suitable for use in Adaptive Harvest Management, it is recommended that:

- The current number and locations of surveyed waterbodies (~880) should be retained and used for future surveys. However, some adjustments to locations of some waterbodies will be required to align these with the latest satellite imagery collection (DEA 2.0).
- To provide more confidence in model-based predictions, undertake investigations to help remove any structural inadequacies in the model fitted to the counts of game ducks by investigating additional variables that might explain variation in counts.
- Investigate methods for expanding the current sampling frame to include key game duck habitat in New South Wales and South Australia (by expanding the current helicopter aerial survey) and investigate methods for calibrating data from the Eastern Australian Waterbird Survey.
- Improve the accuracy of surface water area estimates for farm dams by incorporating any updates to the spatial vector layer(s) recording farm dam locations.

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Appendix A

Design-based estimates of total abundance of game ducks

Stratified random design

For a stratified random design with unequal selection probabilities of sampling units, the total abundance of a game duck species in a particular stratum h $(h = 1, \dots, H)$ was given by the Horvitz–Thompson estimator (Horvitz and Thompson 1952)

$$\hat{\tau}_h = \sum_{i=1}^{m} \frac{\hat{n}_{ih}}{\pi_h} \qquad (Equation\ 1)$$

where $\hat{\tau}_h$ is total abundance of ducks in stratum h, $\hat{n}_{ih}$ is the best linear unbiased prediction (BLUP) estimate of the number of ducks in waterbody i and stratum h derived from the fitted N-mixture ZIP model (section 2.4.1), m is the number of sampled waterbodies in stratum h, and π_h is the inclusion probability for a waterbody in stratum h. The variance of $\hat{\tau}_h$ is then given by

$$\text{var}(\hat{\tau}_h) = \left(\frac{M - m}{M}\right)\frac{s_h^2}{m} + \sum_{i=1}^{m} \frac{\text{var}(\hat{n}_{ih})}{\pi_h}$$

where M is the total number of waterbodies in stratum h in the sampling frame, $\mathrm{var}\ n_{ih}$ is the variance of the BLUP estimate of $\hat{n}_{ih}$, and s_h^2 is given by

$$s_h^2 = \frac{\sum_{i=1}^{m}(\tau_{ih} - \hat{\tau}_h)^2}{m - 1}$$

where τ_{ih} is equal to $m\hat{n}_{ih}/\pi_h$ (Thompson 1992; section 6.2). The estimate of total abundance of ducks in the sampling frame is then

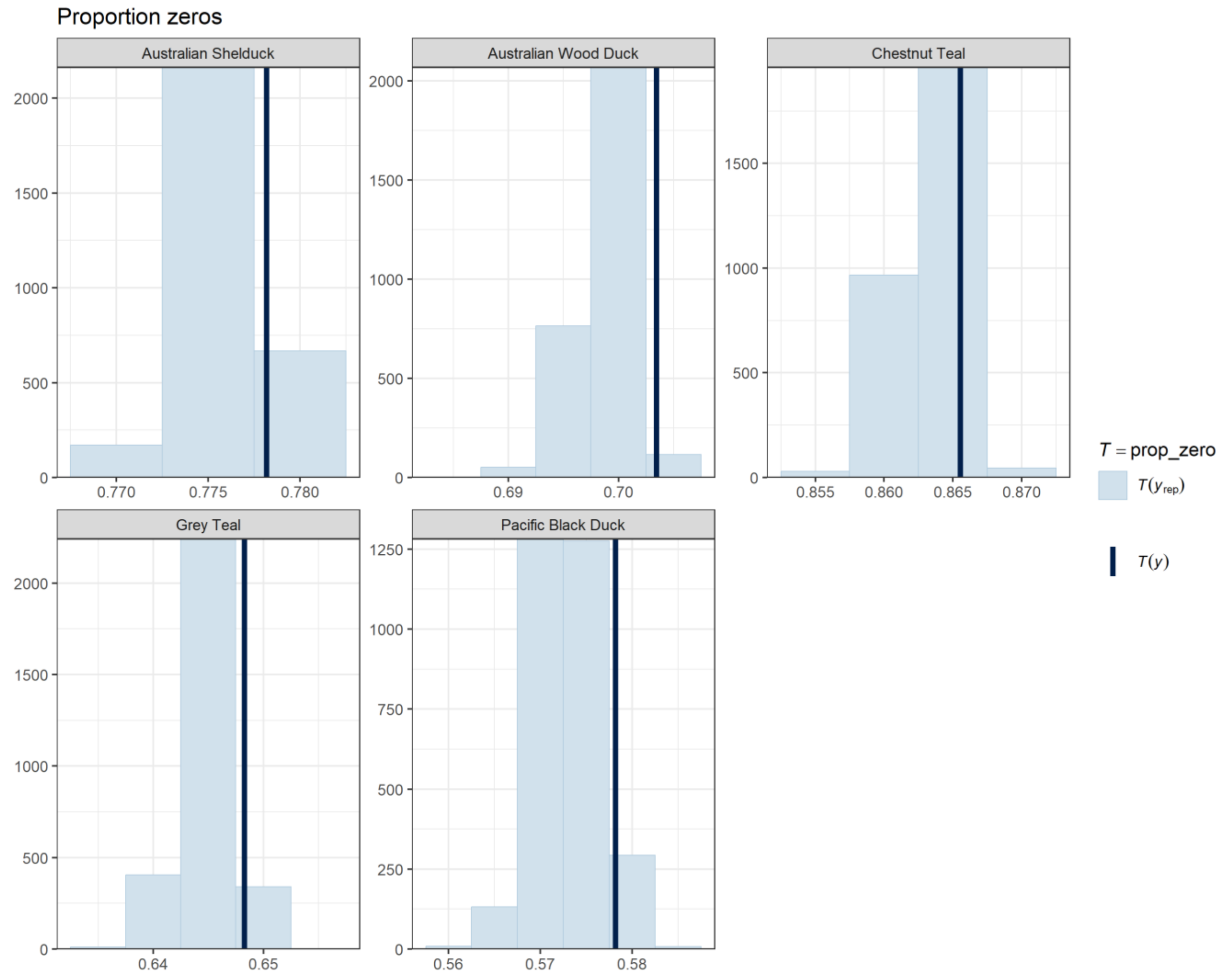
$$\hat{N}_T = \sum_{h=1}^{H} \hat{\tau}_h \qquad (Equation\ 2)$$

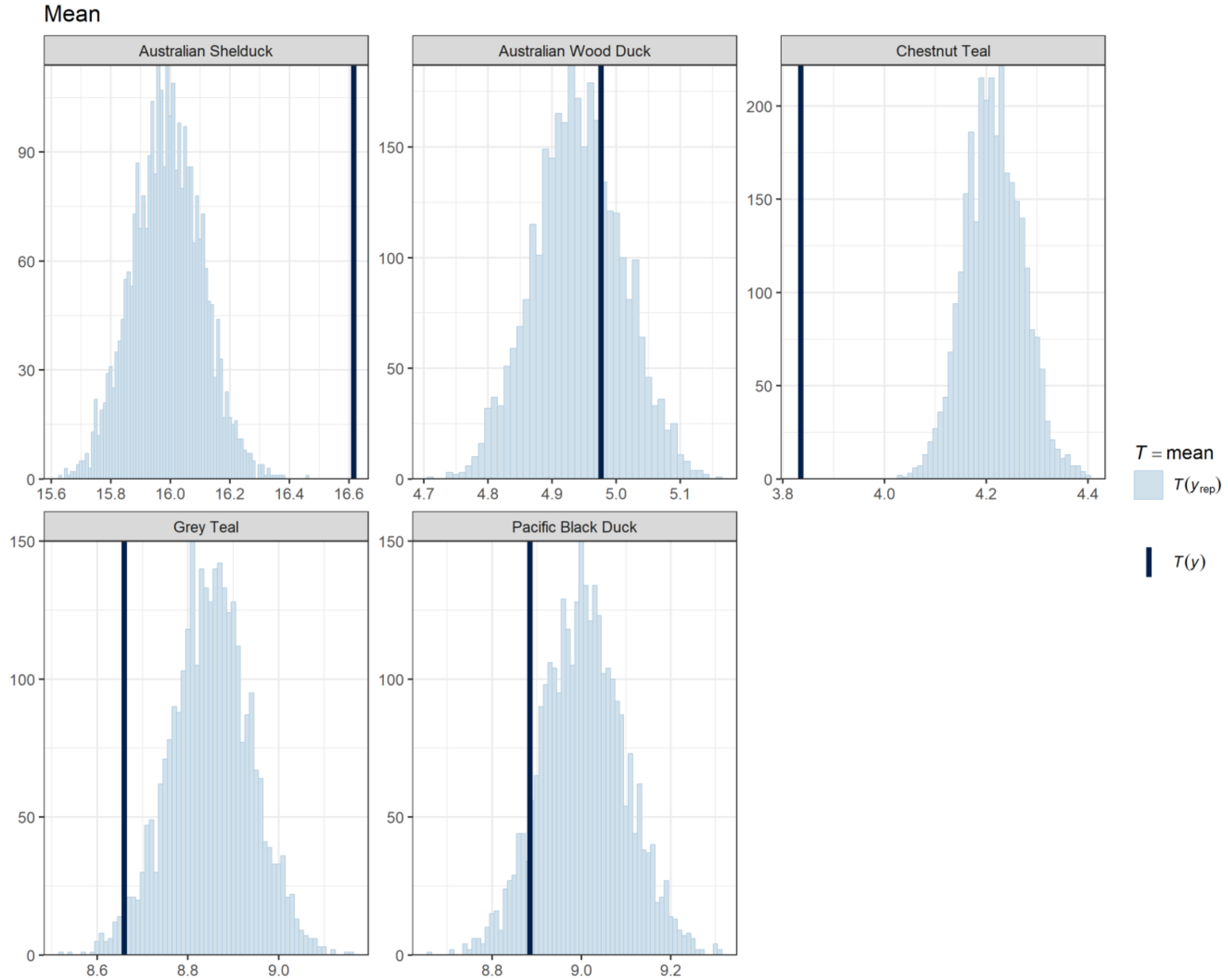
with variance

$$\text{var}(\hat{N}_T) = \sum_{h=1}^{H} \text{var}(\hat{\tau}_h) \qquad (Equation\ 3)$$

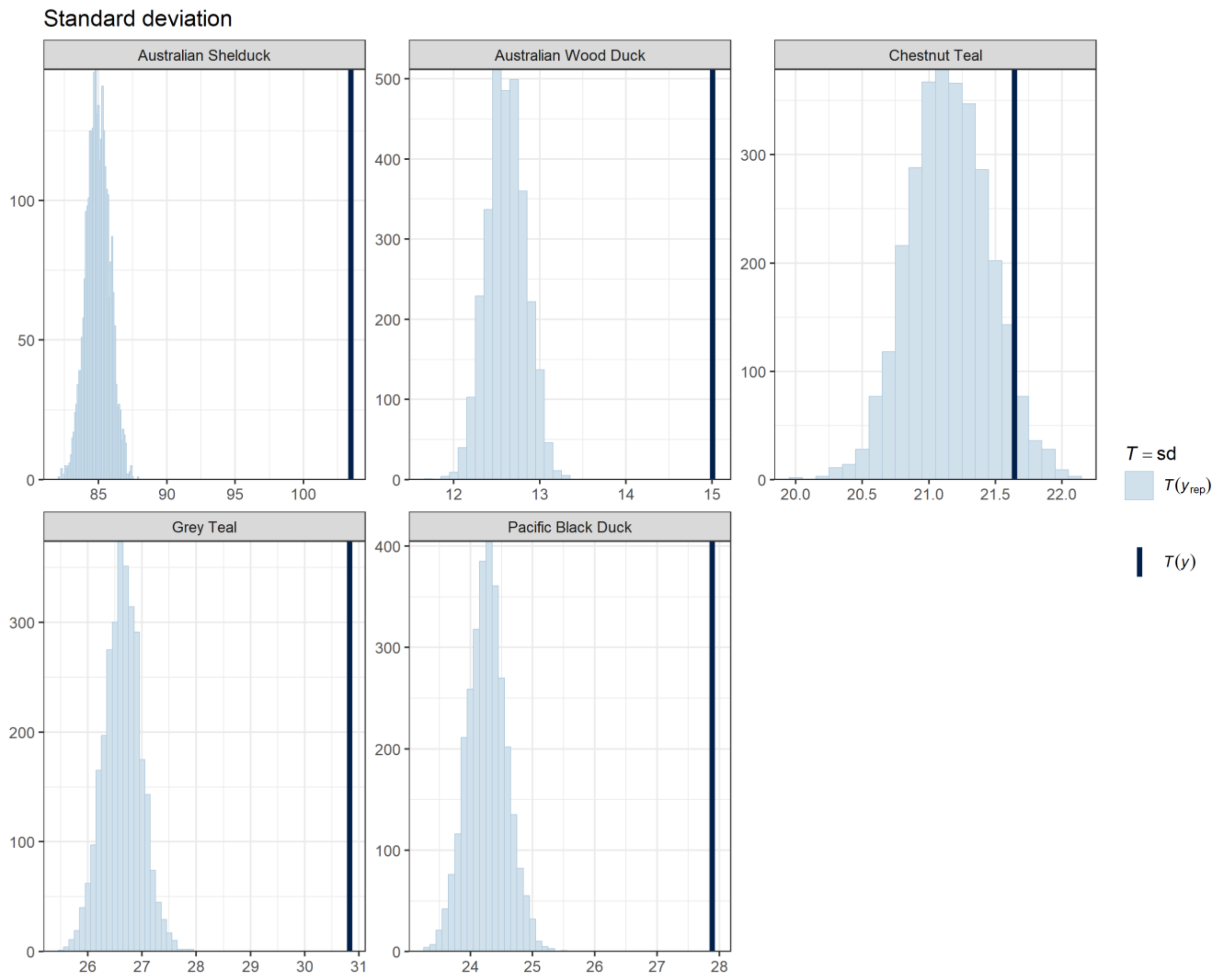
Appendix B

Posterior predictive checks 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 $\boldsymbol{T}(\boldsymbol{y})$.

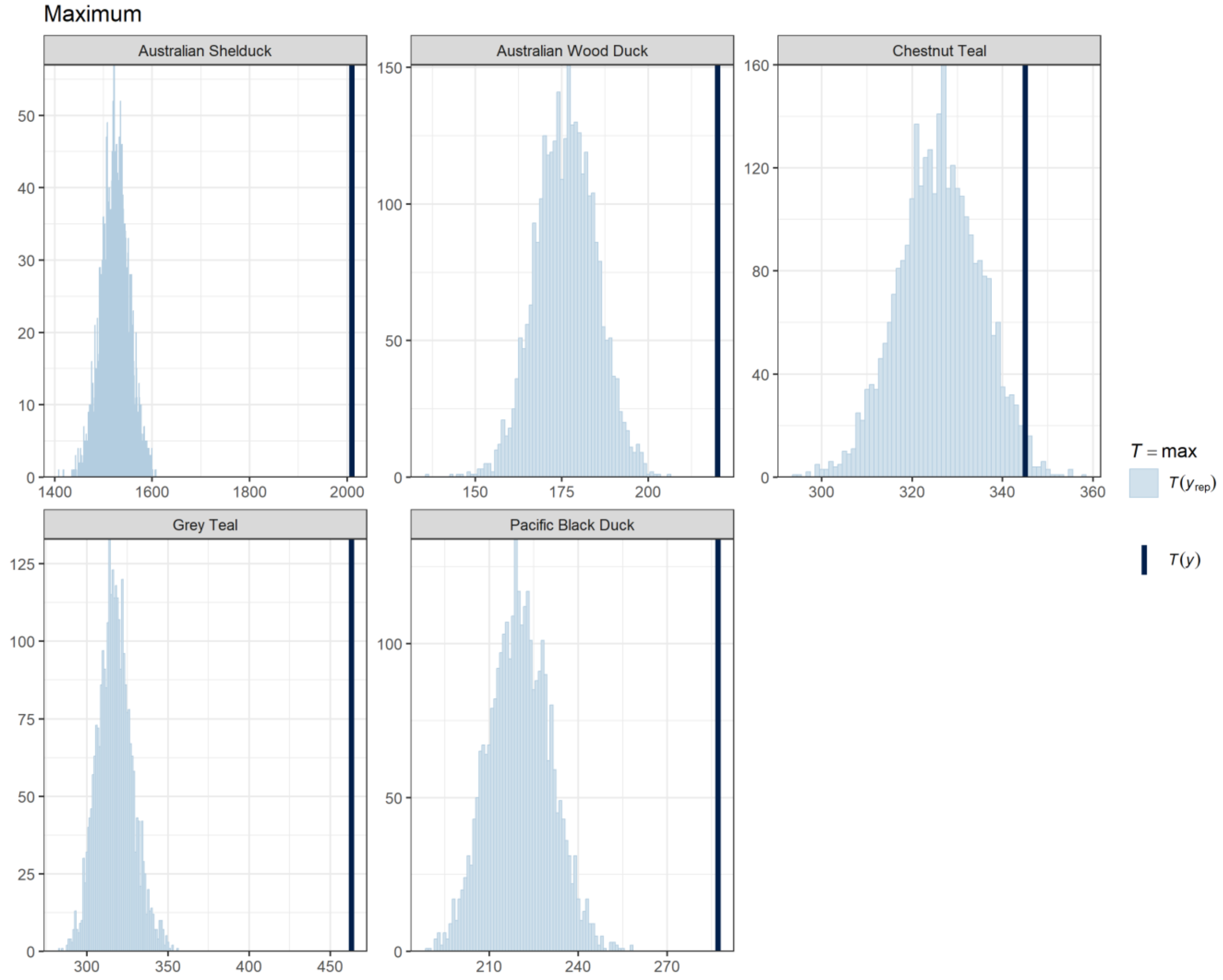




Mean
Australian Shelduck
Australian Wood Duck
Chestnut Teal
Grey Teal
Pacific Black Duck
T = mean
T(y_rep)
T(y)


Standard deviation
Australian Shelduck
Australian Wood Duck
Chestnut Teal
Grey Teal
Pacific Black Duck
T = sd
T(y_rep)
T(y)

OFFICIAL


Maximum
Australian Shelduck
Australian Wood Duck
Chestnut Teal
Grey Teal
Pacific Black Duck
T = max
T(y_rep)
T(y)

Appendix C

Table C1. Estimates of abundance for each species and stratum (*N*). SE = standard error; CV = coefficient of variation; LCL = lower 95% confidence limit; UCL = upper 95% confidence limit; *m* = number sampled; *M* = total number in the sampling frame.

Species	Waterbody	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Grey Teal	Dam	<6 ha	353349	138277	0.391	168614	740482	178	251546
	Dam	6–50 ha	268	113	0.422	121	592	26	130
	Dam	>50 ha	125	60	0.48	51	305	19	58
	Sewage ponds	<6 ha	54	16	0.296	31	94	11	39
	Sewage ponds	6–50 ha	394	86	0.218	258	602	20	55
	Sewage ponds	>50 ha	134	24	0.179	95	189	4	5
	Stream	<6 ha	34659	6556	0.189	24001	50051	62	11919
	Stream	6–50 ha	6394	1158	0.181	4497	9092	31	1938
	Stream	>50 ha	0	0	0	0	0	0	0
	Wetland	<6 ha	24978	5006	0.2	16929	36854	167	5716
	Wetland	6–50 ha	23385	2982	0.128	18232	29994	189	1668
	Wetland	>50 ha	16423	2254	0.137	12566	21464	163	422

Species	Waterbody	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Australian Wood Duck	Dam	<6 ha	1034776	255422	0.247	642446	1666695	178	251546
	Dam	6–50 ha	261	69	0.264	157	435	26	130
	Dam	>50 ha	296	66	0.223	192	456	19	58
	Sewage ponds	<6 ha	17	8	0.471	7	42	11	39
	Sewage ponds	6–50 ha	139	38	0.273	82	234	20	55
	Sewage ponds	>50 ha	105	13	0.124	82	134	4	5
	Stream	<6 ha	56576	8919	0.158	41617	76912	62	11919
	Stream	6–50 ha	4971	1393	0.28	2900	8521	31	1938
	Stream	>50 ha	0	0	0	0	0	0	0
	Wetland	<6 ha	24369	6188	0.254	14930	39775	167	5716
	Wetland	6–50 ha	15359	2589	0.169	11063	21323	189	1668
	Wetland	>50 ha	3189	549	0.172	2282	4457	163	422

Species	Waterbody	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Australian Shelduck	Dam	<6 ha	120592	50340	0.417	54974	264531	178	251546
	Dam	6–50 ha	113	46	0.407	52	243	26	130
	Dam	>50 ha	103	42	0.408	48	221	19	58
	Sewage ponds	<6 ha	53	11	0.208	35	80	11	39
	Sewage ponds	6–50 ha	445	69	0.155	329	602	20	55
	Sewage ponds	>50 ha	336	74	0.22	219	515	4	5
	Stream	<6 ha	0	0	0	0	0	62	11919
	Stream	6–50 ha	1044	963	0.922	224	4859	31	1938
	Stream	>50 ha	0	0	0	0	0	0	0
	Wetland	<6 ha	10507	2867	0.273	6214	17766	167	5716
	Wetland	6–50 ha	24911	4377	0.176	17699	35061	189	1668
	Wetland	>50 ha	47221	8129	0.172	33781	66007	163	422

Species	Waterbody	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Pacific Black Duck	Dam	<6 ha	472298	97031	0.205	317063	703536	178	251546
	Dam	6–50 ha	120	49	0.408	56	259	26	130
	Dam	>50 ha	495	123	0.248	306	800	19	58
	Sewage ponds	<6 ha	6	5	0.833	1	27	11	39
	Sewage ponds	6–50 ha	78	35	0.449	34	180	20	55
	Sewage ponds	>50 ha	0	0	0	0	0	4	5
	Stream	<6 ha	34902	5340	0.153	25904	47026	62	11919
	Stream	6–50 ha	2171	614	0.283	1260	3739	31	1938
	Stream	>50 ha	0	0	0	0	0	0	0
	Wetland	<6 ha	20838	2669	0.128	16228	26758	167	5716
	Wetland	6–50 ha	24061	2224	0.092	20081	28829	189	1668
	Wetland	>50 ha	19394	1725	0.089	16297	23079	163	422

Species	Waterbody	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Chestnut Teal	Dam	<6 ha	2190	2189	1	428	11193	178	251546
	Dam	6–50 ha	146	52	0.356	74	287	26	130
	Dam	>50 ha	53	27	0.509	21	136	19	58
	Sewage ponds	<6 ha	213	65	0.305	119	381	11	39
	Sewage ponds	6–50 ha	525	100	0.19	363	760	20	55
	Sewage ponds	>50 ha	159	36	0.226	103	245	4	5
	Stream	<6 ha	5850	1653	0.283	3398	10071	62	11919
	Stream	6–50 ha	71	52	0.732	20	256	31	1938
	Stream	>50 ha	0	0	0	0	0	0	0
	Wetland	<6 ha	9845	2825	0.287	5673	17085	167	5716
	Wetland	6–50 ha	6170	1543	0.25	3808	9998	189	1668
	Wetland	>50 ha	4839	1107	0.229	3108	7535	163	422

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