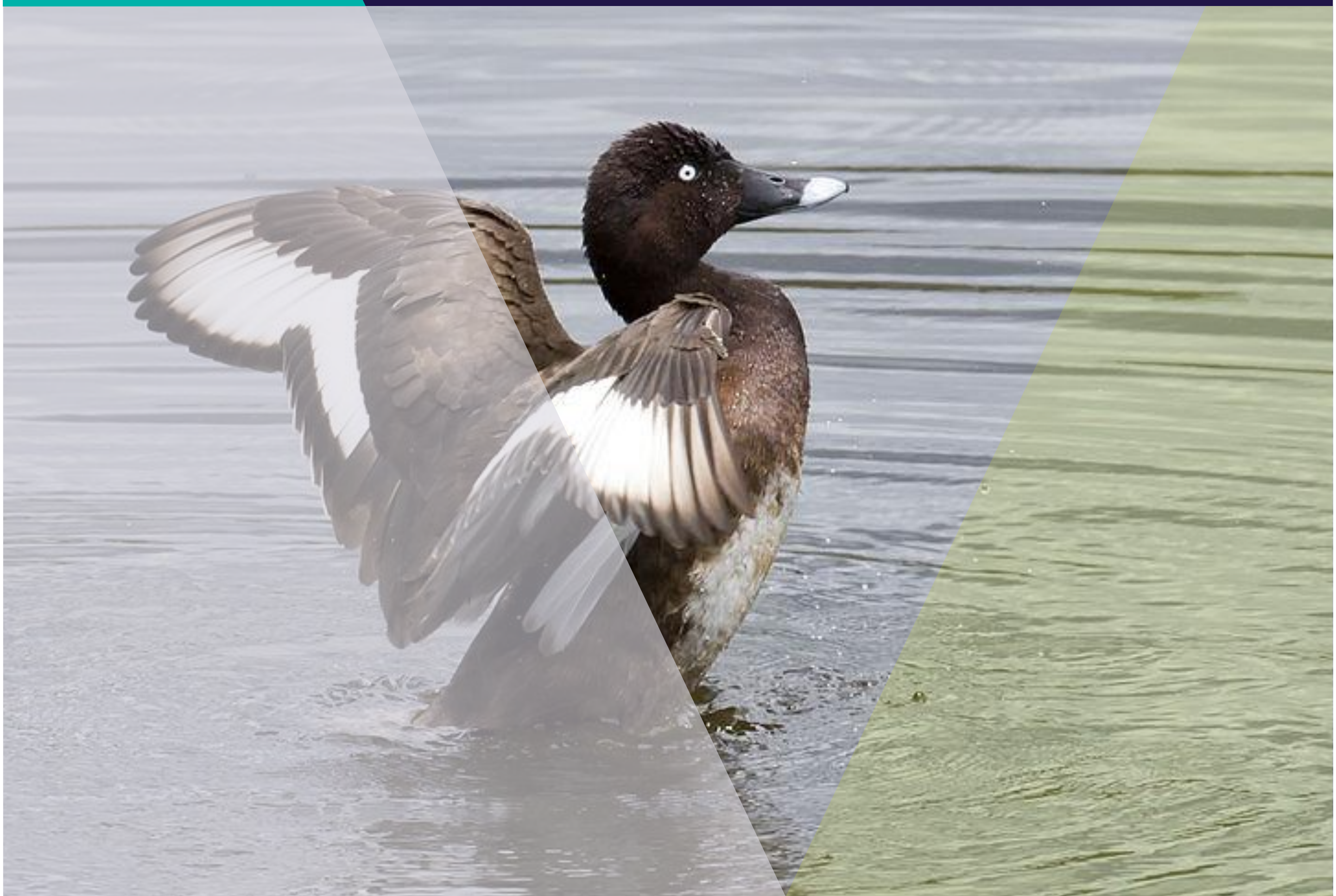
Abundance Estimates for Game Ducks in Victoria

Results from the 2020 Aerial Survey

D.S.L. Ramsey and B. Fanson

April 2021



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Game Management Authority

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Acknowledgment

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it. We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

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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Abundance Estimates of Game Ducks in Victoria: Results from the 2020 Aerial Survey

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Contents

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 (*Spatula rhynchotis*) (hereafter called game ducks). Comprehensive surveys in Victoria suitable for estimating the statewide abundance of game duck species are lacking, but are vital if an adaptive harvest management framework is to be adopted for managing recreational harvest. A recent study identified survey methods and a sampling design that would be suitable for estimating the abundance of game ducks on waterbodies in Victoria (Ramsey 2020). The survey design involved independent counts by two observers in a helicopter from at least 600 randomly selected waterbodies, including small farm dams, using a two-stage sampling design with the first stage consisting of hexagonal primary units with a 10 km minimal diameter (87 km^2). A pilot study was subsequently undertaken in November 2020 to assess the suitability of the survey design under actual conditions.

Aims:

The aim of this study was to conduct an analysis of the pilot aerial survey to determine whether the data were suitable for providing robust estimates of the abundance of game ducks. This included a detailed evaluation of the survey results to identify possible improvements to the sampling design to increase the confidence in the survey results. Investigation was also undertaken on the use of the abundance estimates for the setting of the annual seasonal duck hunting arrangements.

Methods:

Estimates of surface water on waterbodies in Victoria (wetlands, dams and sewage treatment ponds, but not watercourses) were derived from Landsat and Sentinel-2 raster imagery for the extended spring period to derive a sampling frame, which was then used to select a random sample of waterbodies for aerial survey. Aerial sampling of each waterbody was undertaken from a helicopter, with two observers on the left side of the aircraft (one forward and one rear) conducting counts of game ducks at each waterbody independently. The abundance of game duck species at each sampled waterbody was estimated using a zero-inflated N-mixture model with Bayesian inference. Design-based and model-based procedures were then used to estimate total abundance for the entire sampling frame to derive statewide estimates of abundance for each game duck species. Simulations were also undertaken to determine the improvement on the precision of abundance estimates when more waterbodies were added to the sample. The utility of the model-based approach was also tested by using it to predict the abundance of game ducks in the Riverina district of New South Wales, and then comparing these predictions to recent independent estimates from that region.

Data on the size of the total game duck harvest, estimated from telephone surveys of hunters from 2009 to 2019, was used to estimate the relationship between total duck harvest, seasonal arrangements (season length and daily bag limit) and number of licensed hunters. This relationship was then used to find combinations of season length and daily bag limit that would be consistent with a conservative recreational harvest rate of 10% of the estimated total game duck population.

Results:

A total of 653 waterbodies were subject to aerial survey including 540 dams, 2 sewage treatment ponds and 111 wetlands. Many of the waterbodies initially selected, but especially sewage ponds, could not be sampled due to the risks associated with the proximity of high-tension power lines, windfarms or built-up areas. Design-based estimates of total abundance indicated that the population of game ducks on dams and wetlands in Victoria was 2 452 100 (95% confidence interval: 1 840 400 – 3 267 000). Teal (Grey and Chestnut Teal combined) were the most numerous game species (c. 981 000), followed by Wood Duck (c. 690 000), Australian Shelduck (c. 407 000), Pacific Black Duck (c. 328 000) and Hardhead (c. 55 000). The relative precision of estimates for individual species varied, being most precise for Pacific Black Duck (0.2), and least precise for Hardhead (0.51). Model-based estimates were similar to the design-based ones, with a total estimate of 2 348 100 game ducks. However, model-based estimates tended to be more precise than

the corresponding design-based estimates. The majority of game ducks occurred on small farm dams (up to 6 ha), especially Wood Duck and teal. Teal and Australian Shelduck were also found in substantial numbers in larger wetlands.

Using the model-based approach to predict game duck abundances to the Riverina produced mixed results. Estimates for teal and Wood Duck were comparable to independently derived estimates having a relative bias of < 20%. However, results for Pacific Black Duck, Australian Shelduck and Hardhead were highly biased, indicating that the model was inadequate for predicting the abundance of these species outside Victoria.

For the desired harvest quota of 10% of the estimated total game duck abundance (i.e., 245 200), the corresponding estimates of bag limit and season length suggests that a season length of 75 days and a bag limit of 5 would be consistent with this harvest quota. However, other combinations of season length and bag limit were also compatible with this level of offtake.

Conclusions and implications:

The pilot aerial survey has provided the first robust estimates of the abundance of game ducks across Victoria. Although the estimates presented here account for the major sources of variation in duck abundances, such as habitat availability (surface water estimates) and observer error (detection probability), some adjustment to the sample sizes of each type of waterbody is warranted to increase the precision of the abundance estimates for individual species. These are detailed in the recommendations.

Estimates of statewide abundance of game ducks, such as those detailed here, would be suitable as a basis for setting more rigorous and transparent recreational harvest arrangements. Moreover, regular estimates of statewide abundance will be essential if Victoria is to adopt adaptive harvest management as the basis for maintaining the sustainability of recreational duck hunting.

Recommendations

To improve the Victorian game duck survey to provide more robust estimates of abundance that will be suitable for setting the annual seasonal arrangements for recreational duck hunting, the following changes are recommended:

- Increase the number of sampled waterbodies in the two-stage sampling design to 1300 by sampling 90 primary units and 15 waterbodies per primary unit.
- Alternatively, sample 800 waterbodies using single-stage stratified random sampling, as this should lead to more precise abundance estimates than two-stage sampling. However, only adopt this option if logistically and financially feasible.
- Following sample selection, implement alternative sampling methods for waterbodies where it is not feasible to conduct aerial surveys from a helicopter. Smaller waterbodies (up to 6 ha) should be sampled simultaneously by two ground observers recording independently with the aid of a spotting scope, while larger waterbodies (more than 6 ha) should be sampled by an unmanned aerial vehicle (UAV) recording high resolution video (i.e., 4K at 60 fps).
- Modify the survey design to include waterways (i.e. rivers, large streams and irrigation channels). This can be achieved by including waterways in either the two-stage or single-stage sampling design.
- To provide separate estimates for Grey and Chestnut Teal from aerial surveys, conduct ground surveys targeting teal at sites around the coast as well as north of the Princess Highway/Freeway to obtain an estimate of the sex ratio for both teal species.
- To improve model-based estimates of duck abundance, investigate additional variables, such as landuse, waterbody proximity or climate variables, that may better describe variation in duck abundance to provide more confidence in model-based predictions.
- To improve the model of the relationship between total duck harvest and annual seasonal arrangements, investigate additional variables that more accurately reflect hunting effort, which should lead to improved estimates of daily bag limits and season length to achieve the desired harvest quota.

1 Introduction

In Victoria, eight species of native duck are 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*), Chestnut Teal (*Anas castanea*), Hardhead (*Aythya australis*) and Australasian Shoveler (*Spatula rhynchotis*). 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 (DEWNR 2016) and the Riverina district of New South Wales (Dundas *et al.* 2019). The Victorian Priority Waterbird Count (Menkhorst and Purdey 2016) 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 more careful 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 Count and EAWS surveys have inadequate coverage and/or sampling designs for Victorian waterbodies to enable a robust estimation of duck abundances. In addition, these surveys also have other drawbacks including being unable to account for birds missed by observers (imperfect detection) and being unsuitable for the detection of species inhabiting smaller waterbodies such as farm dams. 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 around the period when the surveys were undertaken. Surface water can now be routinely detected using appropriate algorithms applied to satellite imagery (e.g. Pekel *et al.* 2016; Mueller *et al.* 2016).

A recent study identified survey methods and a sampling design that would be suitable for estimating the abundances of games ducks on waterbodies in Victoria (Ramsey 2020). The survey design involves double observer counts from a helicopter from at least 600 randomly selected waterbodies, including small farm dams. Waterbodies were stratified into type (wetlands, dams, sewage treatment ponds) and size classes (< 6 ha, 6–50 ha, > 50 ha). A two-stage sampling design was recommended, with waterbodies partitioned into primary units on a hexagonal grid with a cell size of 10 km minimal diameter (area 87 km^2), with both primary units and waterbodies within selected primary units subject to random sampling (see Ramsey 2020 for more details on the sampling design). That study further recommended that a pilot study be undertaken to assess the performance of the survey design and observation methods in order to refine the recommended survey design. The Victorian Game Management Authority carried out a pilot study of this methodology, covering 650 waterbodies, in November 2020.

1.1 Objectives

The aim of this study was to conduct an analysis of the pilot study data to determine whether the data could provide robust estimates of the abundance for each species of game duck. This was to be 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).
- Conduct an analysis of the aerial survey data from the pilot study 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 aerial survey design that would lead to improvements in the statewide estimates, if required.
- Evaluate the predictive ability of model-based estimates of game duck abundances using additional monitoring data on game ducks collected in the Riverina district of New South Wales.

2 Methods

2.1 Estimates of surface water availability

To extrapolate estimates of abundance of game ducks obtained at sampled waterbodies to obtain regional or statewide estimates of abundance, an estimate is required of surface water availability for the period when the aerial 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 resident in habitats that are outside the sampling frame and therefore not sampled. In the present study, surface water estimates included only wetlands, dams and sewage treatment ponds; rivers, streams, irrigation canals and estuaries were excluded. Hence the regional abundance estimates produced here do not include ducks resident in these habitats. Since estimates of surface water are likely to change each year due to prevailing environmental conditions and rainfall patterns, the sampling frame will also change each year and must be re-estimated.

Estimates of surface water on wetlands, dams and sewage treatment ponds were derived from two sources. The first was the `DEA_waterbody` layer from Geosciences Australia (Mueller *et al.* 2016) (available from https://www.ga.gov.au/dea/products/dea-waterbodies) derived from `LandSat` imagery taken every 16 days (dependent on cloud cover). These satellite images provide a timeseries of wet surface area for waterbodies that are present more than 10% of the time and which were larger than 3125 m^2 (i.e. five `LandSat` pixels). The resulting derived image of surface water extent has a pixel resolution of 25 m, which was classified as surface water if the majority of the pixel contained water. These images are suitable for detecting surface water in waterbodies larger than 1 ha and are 97% accurate (true positivity rate) for detecting open surface water (Mueller *et al.* 2016). The second source was the European Space Agency `Sentinel-2` satellite imagery (available from https://www.sentinel-hub.com/explore/sentinelplayground/), which provides multi-spectral images at 10 m resolution suitable for detecting surface water in small waterbodies such as farm dams. These raster images of surface water locations were intersected with digitised waterbody objects in the vector layers `vic_hydro` and `wetland_current` (available from http://services.land.vic.gov.au/SpatialDatamart/), which contains digitised boundaries of wetlands, sewage treatment ponds and some farm dams, and `farm_dams`, which contains boundaries of most small farm dams. Intersecting the raster layers with the digitised vector layers allowed estimates of surface water for each mapped waterbody classification. These data sources are summarised in Table 1.

Table 1. Summary of datasets used to create surface water estimates for Victoria.

Layer name	Type	Source	Method	Notes
vic_hydro	Vector	DEWLP	satellite and aerial	Digitised boundaries of all artificial waterbodies (including farm dams) in southern Victoria and all larger artificial waterbodies in northern Victoria using a combination of satellite and aerial imagery. Last updated in January 2019.
wetland_current	Vector	DELWP	Aerial	Polygons showing the extent and types of wetlands in Victoria. Wetland Current was created in 2013 and updated in 2014. Wetlands were classified (according to the new classification framework) into primary categories based on wetland system type, salinity regime, water regime, water source, dominant vegetation and wetland origin.
farm_dams	Vector	DELWP	Satellite and aerial	Digitised boundaries of all man-made farm dams (< 6 ha) in Victoria
DEA waterbody	Raster	Geosciences Australia	Landsat imagery every 16 days, depending on cloud cover; if >10% cloud, then missing	Wet surface area for waterbodies that are present more than 10% of the time and are larger than 3125 m^2 (5 Landsat pixels). Water classification is based on the Tasseled Cap Wetness metric (Jin and Sader 2005).
Sentinel-2	Raster	ESA	Satellite imagery every 5 days (depending on cloud cover)	Green and near-infrared bands used to construct Normalised Difference Water Index (NDWI) (Mueller *et al.* 2016) indicating surface water at 10 m resolution. Used to indicate the presence of surface water in small farm dams (less than 1 ha).

2.1.1 Creating the farm dam layer

Farm dams were abundant and their mapped locations were contained in the `farm_dam` and `vicmap_hydro` vector layers. We estimated the concordance between these layers by calculating the overlap of dams between the two layers (Figure 1). Overall, concordance was moderate (~65%). It should also be noted that the documentation for `vicmap_hydro` states that 70% of the farm dams in Victoria are included (Vicmap Hydro product data description, 2018). Assuming this 70% estimate is correct, the estimated number of farm dams in Victoria is 555 764, or 166 729 extra dams not mapped. The `farm_dam` layer had an extra 127 299, which could account for 76% of those extra farm dams. The final combined layer contained 509 737 farm dams, which together accounted for 93% of farm dams. (Table 2).

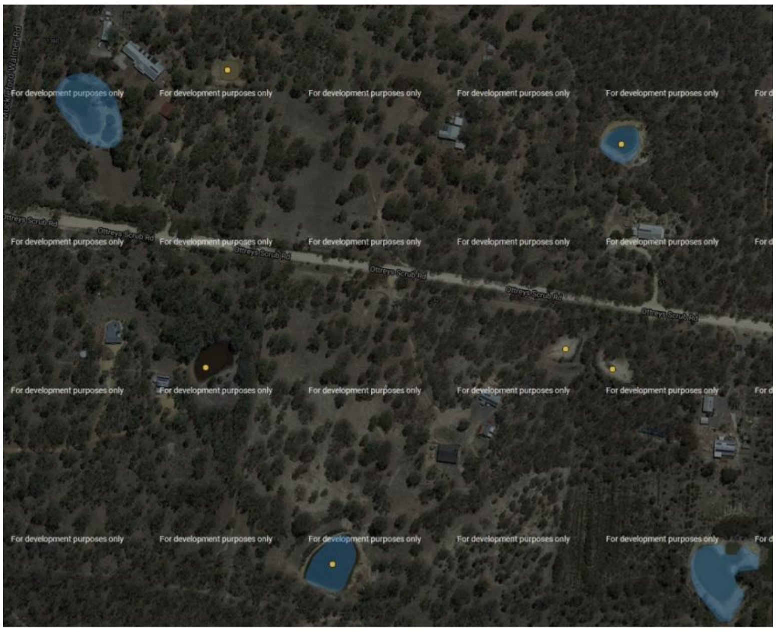

Figure 1. Example of `farm_dam` layer (blue polygons) and `vicmap_hydro_point` layer (yellow dots) showing partial overlap.

2.1.2 Creating the waterbody surface water layer

The `DEA_waterbody` raster layer of surface water presence was first clipped, keeping only spatial objects in Victoria. This resulted in 19 740 objects. As the `DEA_waterbody` layer did not have waterbody classifications, we intersected the other vector layers `wetland_current`, `vicmap_hydro` and `farm_dam` and used the appropriate attributes to classify each waterbody based on the type (wetland, dam or sewage treatment pond) as well as a size class (< 6 ha, 6–50 ha, > 50 ha) (Figure 2). Objects classified as watercourses (i.e. rivers, streams, estuaries, irrigation channels) were not included. Sewage treatment plants containing multiple polygons (representing separate ponds) were combined into a single object. This final layer contained 9 715 waterbody objects (Table 2).

Using this layer, we obtained the most recent wet proportion for each object as well as the average of the three most recent observations. Additionally, for every object we calculated the proportion of times in the 'extended spring' period (October to January) that the object had water in the past 30 years.

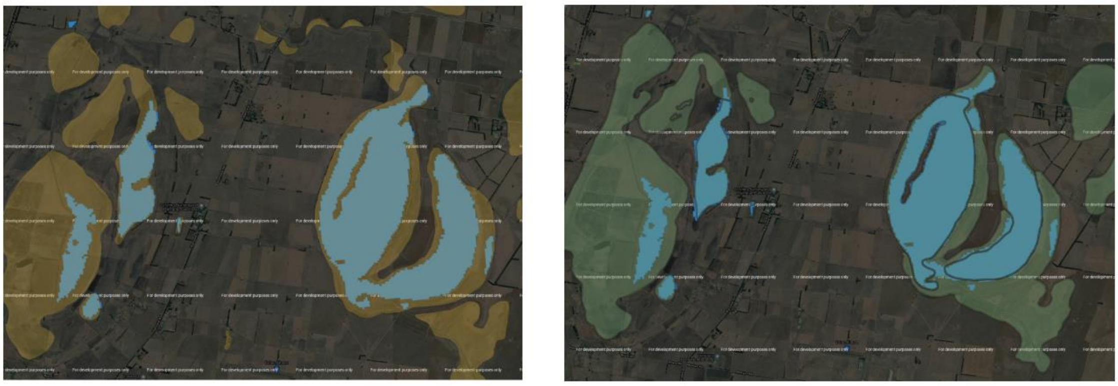

Figure 2: Example of DEA layer (blue polygons) compared to vicmap_hydro_point (yellow polygons in the left figure) and current_wetland layer (green polygons in the right figure).

Table 2: Number of waterbodies within each waterbody type and size class from the combined vector layers listed in Table 1.

Waterbody type	Size class (max)	n
Dam	< 6 ha	509 737
	6–50 ha	52
Sewage ponds	< 6 ha	31
	6–50 ha	31
	> 50 ha	7
Wetlands	< 6 ha	7 098
	6–50 ha	1 978
	> 50 ha	518
Total		519 452

2.2 Selecting the sample of waterbodies

2.2.1 Assigning waterbody objects to primary sampling units

Primary sampling units were created across Victoria using a hexagonal grid (hexagon minimal diameter = 10 km, area = 87 km^2) across the state. Each waterbody object was then assigned to a primary unit. If an object overlapped multiple hexagons, the object was assigned to the hexagon that encompassed the highest percentage of the objects area (if tied, then the first hexagon was picked for the assignment). It should be noted that this method used the maximum water extent of the object (the DEA polygon) to calculate polygon area and it was also possible that during drier periods no surface water was in the chosen hexagon.

2.2.2 Selecting the sampling frame

To help determine whether objects in the waterbody layer contained surface water during spring, just prior to the aerial surveys, we selected the DEA waterbodies that historically held water more than 40% of the time in the extended spring period or had more than 10% water based on the last `Landsat` image. All farm dams were initially included in the initial sampling frame. Following the aerial survey we observed the presence or absence of surface water in each of the sampled waterbodies. We used this information to refine the sampling frame by calibrating the Normalised Difference Water Index (NDWI) calculated from the imagery for both the DEA waterbody layer (larger waterbodies) and Sentinel-2 layer (small farm dams) by using the observed presence or absence of water as a training set. The NDWI threshold was then set for both the DEA and Sentinel-2 derived NDWI that maximised the training accuracy (proportion of both observed wet and dry waterbodies that were correctly predicted).

2.2.3 Selecting the sample

Sample selection was as described in Ramsey (2020), using the estimate of the sampling frame described above. An initial sample of 110 primary units were selected from the sampling frame with inclusion probabilities proportional to the number of waterbodies larger than 50 ha within the unit. Within each selected primary unit, up to 10 secondary units were selected using proportional representation based on waterbody type and size class. A total of 1259 waterbodies were initially selected for sampling (Table 3, Figure 3), which was more than the nominal amount required (about 600) due to the fact that some waterbodies would not be available for aerial sampling due to airspace restrictions (e.g. proximity to built-up areas) or the need to avoid areas with high-tension power lines.

Table 3: Summary of initial random sample of waterbodies within each selected primary unit by waterbody type and size class.

Waterbody type	Size class	Number
Dams	< 6 ha	972
	6–50 ha	1
Sewage ponds	< 6 ha	1
	6–50 ha	8
Wetlands	< 6 ha	203
	6–50 ha	40
	> 50 ha	34
Total		1259

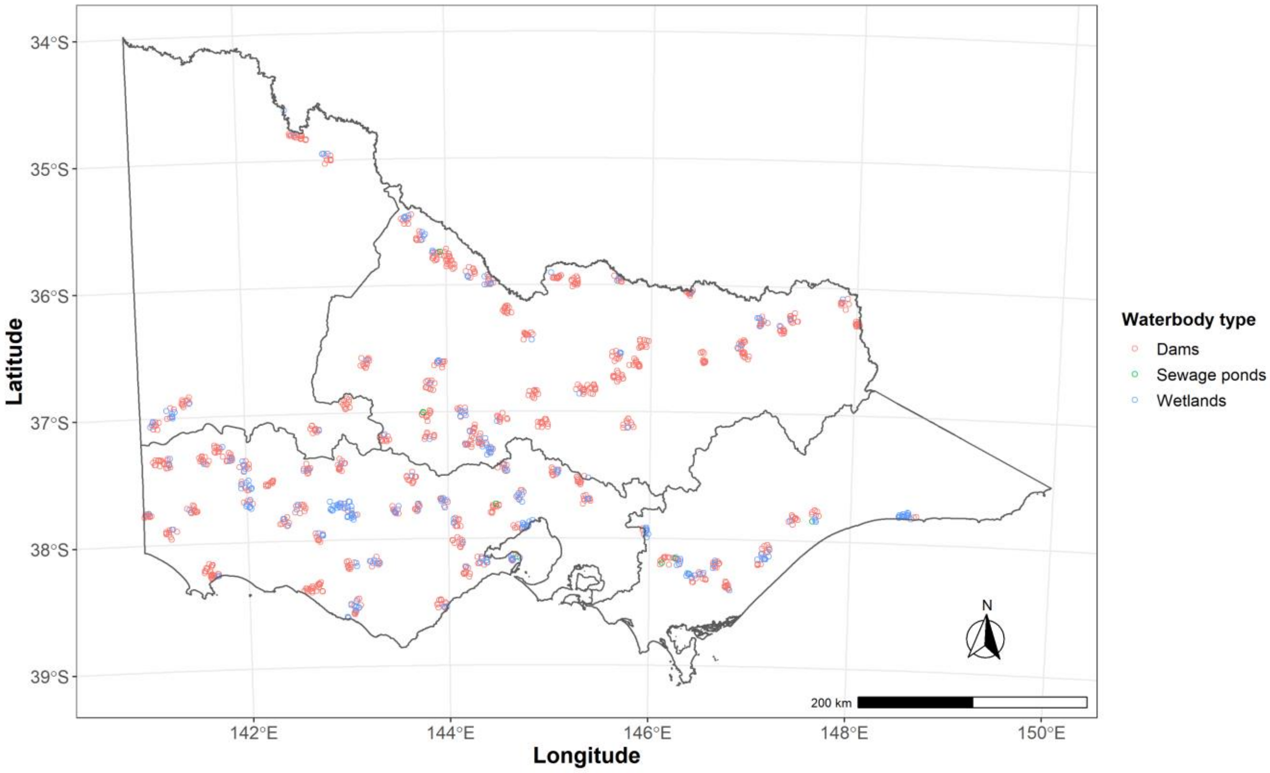

Figure 3. Locations of the initial sample of waterbodies selected for aerial surveys. Waterbodies were selected from 110 primary units with an unequal probability selection design. Bioregion boundaries are (clockwise from top left), West, North, East and South.

2.3 Aerial 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 conducted while the aircraft completed a low circuit around the waterbody circumference at a height of around 30–50 m. For eight of the larger waterbodies (> 50 ha), only a portion of the waterbody (selected at random) was surveyed, and the proportion of the surface area searched was recorded using GPS. The counts for each observer for the entire surface area were then imputed using the proportion of the waterbody surveyed.

2.4 Abundance estimation

2.4.1 Waterbody level estimates

The two independent replicate counts of game ducks at each sampled waterbody can be used to estimate the abundance of ducks at each waterbody, corrected for imperfect detection (birds missed by the observers) using an N-mixture model (Royle 2004). The 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 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 can also be extended to account for extra spatial heterogeneity such as the presence of excess zeros in the count data, caused by some waterbodies being unsuitable for ducks at the time of the survey. Here, adopting a zero-inflated distribution such as a zero-inflated Poisson (ZIP) enables the N-mixture model to account for excess zeros by modelling the probability of duck presence on each waterbody. Hence, the count data (containing excess zeros) are now modelled as being subject to three random processes, the probability that ducks were present on the waterbody, the abundance of ducks, given that ducks were present and the probability of being observed, given ducks were present. Like the abundance and detection probability parameters, the probability of presence can also be modelled with covariate values.

To account for all these potential sources of variation in the aerial counts of game ducks, we fitted an N-mixture ZIP model to the data on each sampled waterbody using the following model definition:

$$
\begin{aligned}
y_{sit} &\sim \mathrm{Binomial}(n_{si}, p_{it}) \qquad (Equation\ 1)\\
n_{si} &\sim \mathrm{Poisson}(\lambda_{si}\ P_{si})\\
P_{si} &\sim \mathrm{Bernoulli}(\psi_{si})\\
\log(\lambda_{si}) &= \beta_{0,s} + \zeta_{k,s} T_i + \theta_{l,s} S_i + \delta_{r,s} R_i\\
\mathrm{logit}(\psi_{si}) &= \gamma_{0,s} + \eta_{k,s} T_i + \varsigma_{l,s} S_i + \tau_{r,s} R_i\\
\mathrm{logit}(p_{it}) &= \alpha_0 + \upsilon_g G_i + \rho_h H_i
\end{aligned}
$$

Where y_{sit} is the aerial count for duck species s at waterbody i for observer t, which was a binomial random variable given the true abundance n_{si} for species s on waterbody i and detection probability p_{it}. The latent abundance (n_{si}) was assumed to be Poisson distributed with rate λ_{si} if P_{si} was equal to 1 with probability ψ_{si} and zero otherwise with probability $(1-\psi_{si})$. Covariates affecting abundance were waterbody type T, size class S and bioregion R.

The probability of presence was considered to depend on the same set of attributes, while the detection probability was modelled as a function of the presence of glare from the water surface G and habitat type H (open, reeds or woodland). The parameters β_0, α_0, γ_0 were the intercepts while $\zeta, \theta, \delta, \eta, \varsigma, \tau, \upsilon$ and ρ were the parameters for the respective covariates in the linear models. The parameters for the covariates on abundance and presence probability were estimated separately for each duck species, indicated by the subscript s and had levels subscripted by k, l, or r as indicated in Equation 1. The model in Equation 1 was estimated in a Bayesian framework using Hamiltonian Markov Chain Monte Carlo methods in `Stan` (version 2.21.2) from within `R` using `RStan` (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 remaining for each parameter to form 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 proceeded by using predicted abundance $\hat{n}_i$ for each sampled waterbody ($i = 1, \dots, w_s$) derived from the fitted model (Equation 1). The predicted $\hat{n}_i$ and associated variance $\mathrm{var}(\hat{n}_i)$ were then used to produce design-based estimates of total abundance $\hat{N}_T$ and variance $\mathrm{var}(\hat{N}_T)$ 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). Variance estimates were adjusted in a similar way (Hankin 1984; Skalski 1994). Further details of this sampling design and 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, conditional on their covariate values (waterbody attributes and region) using the fitted model relationship for each species:

$$\hat{\lambda}_{si} = \exp\left(\beta_{0,s} + \zeta_{k,s}T_i + \theta_{l,s}S_i + \delta_{r,s}R_i\right) \qquad (Equation\ 2)$$

$$\hat{\psi}_{si} = \left(1 + \exp\left(-\left(\gamma_{0,s} + \eta_{k,s}T_i + \varsigma_{l,s}S_i + \tau_{r,s}R_i\right)\right)\right)^{-1}$$

$$\hat{n}_{si} = \begin{cases} \mathrm{Poisson}(\lambda_{si}) & \text{, with probability } \psi_{si} \\ 0 & \text{, with probability } (1 - \psi_{si}) \end{cases}$$

$$\hat{N}_T = \sum_{i=1}^{w} \hat{n}_i$$

where i indexes each waterbody, s indexes species, w is the total number of waterbodies in the sampling frame ($i = 1, \dots, w$), T_i, S_i and R_i are the vectors of covariate values for waterbody type, size class and bioregion respectively, and $\beta_{0,s}, \gamma_{0,s}, \zeta_k, \theta_l, \delta_r, \eta_k, \varsigma_l, \tau_r$ are the parameter estimates from the fitted model. Hence, the expected value for duck abundance at each waterbody was

$$E(n_{si}) = \lambda_{si}\,\psi_{si},$$

which is the product of expected abundance and expected probability of presence. Note that a prediction of zero game ducks for a particular waterbody can arise from both the abundance process (λ_{si}) as well as through the probability of presence ($1 - \psi_{si}$) and has probability equal to.

$$P(n_{si} = 0) = (1 - \psi_{si}) + \psi_{si} \exp(-\lambda_{si})$$

The variance of $\hat{N}_T$ was estimated using posterior predictive simulation of Equation 2 based on the posterior distributions of the estimated parameters from the fitted model (Gelman and Hill 2007). A total of 1000 posterior estimates of $\hat{N}_T$ were calculated for each species and used for inference.

2.4.3 Predicting abundance outside Victoria

As an additional test of the utility of the model-based approach, we used Equation 2 to predict abundance for the Riverina district of southern New South Wales and compared our estimates to the independent estimates derived for the region based on sampling conducted by the NSW Department of Primary Industries in May 2020 (Dundas *et al.* 2020). This was undertaken to determine the utility of the models developed here at extrapolating predictions of abundance to areas outside Victoria. The independent estimates from Dundas *et al*. (2020) were based on a similar survey methodology to that used for Victoria (i.e., double observer counts from a helicopter). However, larger (> 10 ha) waterbodies were surveyed with an unmanned aerial vehicle (UAV) instead of a helicopter. To undertake this assessment, we obtained the inventory of dams of different size classes collated for the Riverina and derived a sampling frame by correcting for the presence of surface water using information given in Dundas *et al*. (2020). We then used Equation 2 to predict to this sampling frame by using the parameter estimate for dams restricted to the Northern bioregion only (see Figure 3). Estimates for the Northern bioregion were considered the most appropriate due to the proximity of this region to the Riverina district of NSW.

2.5 Adjustments to the sampling design

Following abundance calculations, we examined the precision of the design-based abundance estimates for each species and considered possible adjustments to the sampling design that might result in improved precision for future surveys. This was undertaken by estimating the improvement in precision resulting from increases in the sample size of surveyed waterbodies. Sample size increases were considered at two levels; an increase in the number of sampled primary units and an increase in the number of waterbodies sampled per primary unit. Additional primary units were drawn from the East and West bioregions as these areas had a lower sampling coverage than the North and South bioregions (see Figure 3 for bioregion boundaries). Waterbody abundance estimates used for these analyses consisted of the those estimated from the initial survey data ($\hat{n}_i$), for each sampled waterbody ($i = 1, \ldots, w_s$), with abundance for additional (unsampled) waterbodies inferred using a single draw from the posterior predictive distribution from the fitted model (Equation 2) with the corresponding variance estimated from 100 draws of the posterior predictive distribution. We simulated 200 replicate surveys for each combination of sample size parameters calculating the coefficient of variation of the resulting abundance estimate from each survey.

As a contrast to the sample size adjustments for the two-stage sampling design detailed above, we also examined sample size requirements for a single stage, stratified random design, where the strata were waterbody type and size class. We examined samples sizes from 600 to 1200 total waterbodies where the selection probabilities for each stratum were based on their relative abundance in the sampling frame. For these analyses, abundance estimates for each species were predicted for each selected waterbody using a single random draw from the posterior predictive distribution of the fitted model (Equation 2).

2.6 Estimates of seasonal harvest arrangements

Data on the size of the total game duck harvest, estimated from telephone surveys of hunters from 2009 to 2019 (e.g. Moloney and Turnbull 2016), were recently analysed to estimate the relationship between total duck harvest, seasonal arrangements (season length and daily bag limit) and number of licensed hunters (Ramsey 2020). That study fitted a simple linear model to the log harvest of the form,

$$\log(H_i) \sim N(\mu_i, \sigma) \qquad (Equation\ 3)$$

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

Where $\log(H_i)$ was the natural log of the total game duck harvest during year i, which was assumed to be normally distributed with mean μ_i and standard deviation σ. B, D and L were the daily bag limit, season length (days) and number of licensed hunters, respectively and $\beta_0, \beta_1, \beta_2, \beta_3$ and σ were parameters to be estimated. Both L and D were standardized before analysis by subtracting the mean and dividing by one standard deviation while a log transform was used on B to ensure estimates were positive following transformation. The model was fitted in a Bayesian framework to obtain posterior distributions of the parameters (Ramsey 2020). The fitted model in equation 3 was also used to find combinations of seasonal arrangements (season length and daily bag limit) that would be consistent with a recreational harvest rate of 10% of the estimated total game duck population. A 10% harvest for game ducks is consistent with sustainable harvest offtake rates estimated for waterfowl in North America (Hauser *et al.* 2007; Mattsson *et al.* 2012) and mirrors the offtake rate recommended for duck control in the Riverina district of NSW (Dundas *et al.* 2019). Estimates of the combination of season length and daily bag limit that resulted in a total harvest rate of 10% for a given number of licensed duck hunters were estimated using a missing data imputation approach. This was undertaken by adding an additional row of data to those analysed above with values given for the desired total harvest and the number of licensed hunters for the 2021 season and specifying the season length and bag limit as missing values to be estimated. The prior distributions for the two estimated values were given as $N(\mu_j, \sigma_j)$, $j = 1{,}2$, with the posterior estimates of the parameters subject to estimation through the fitted relationship in Equation 3.

3 Results

3.1 Aerial survey summary

Helicopter aerial surveys of game ducks were undertaken from the 6th to the 18th of November 2020. From the 1259 randomly selected waterbodies provided for the initial sample, 653 were eventually sampled from a total of 120 primary units. Many waterbodies were judged to be unavailable due to the risks associated with the proximity of high-tension power lines, windfarms or built-up areas. These risks were especially apparent in the East bioregion, which had a lower sampling coverage than expected from the initial sample (Figure 4). In addition, many of the farm dams on the list were also excluded due to their proximity to residential housing or the presence of horses or stock. In these cases, the next nearest farm dam within the primary unit was substituted. This led to the number of primary units (120) being greater than the nominal 80 required due to some of the substituted dams being outside the boundaries of the focal primary unit. This had implications for Horvitz–Thompson estimates of total abundance. Hence, a ratio estimator was subsequently found to be more robust and was used for the design-based estimates detailed below.

3.2 Surface water availability

From the 653 sampled waterbodies, 635 were observed to contain water, with 15 farm dams and 3 wetlands observed to be dry. Observations of the wet/dry status of waterbodies thus allows a validation of the estimates of surface water by comparing these observations to the predicted presence of surface water from the satellite imagery. Results of this comparison revealed that Sentinel-2 estimates performed rather poorly for small farm dams, with 74% of dams and 41% of wetlands incorrectly predicted to be dry (false negatives) (Figure 5). Hence, the Sentinel-2 water detection algorithm was adjusted with the following changes. The NDWI threshold was reduced to –0.1 to detect more wetlands with vegetation as well as small dams, causing the 10 m × 10 m pixels to be a mix of land and water and hence decreasing NDWI values. The date range was also expanded to 15 December to account for waterbodies being obscured by cloud cover. Following these revisions classification accuracy improved with the false negative rate for small dams decreasing from 74% to 26%. However, this also resulted in an increase in the false positive rate (dams incorrectly predicted to be wet). Overall, surface water presence was correctly predicted for approximately 74% of dams and 97% of wetlands.

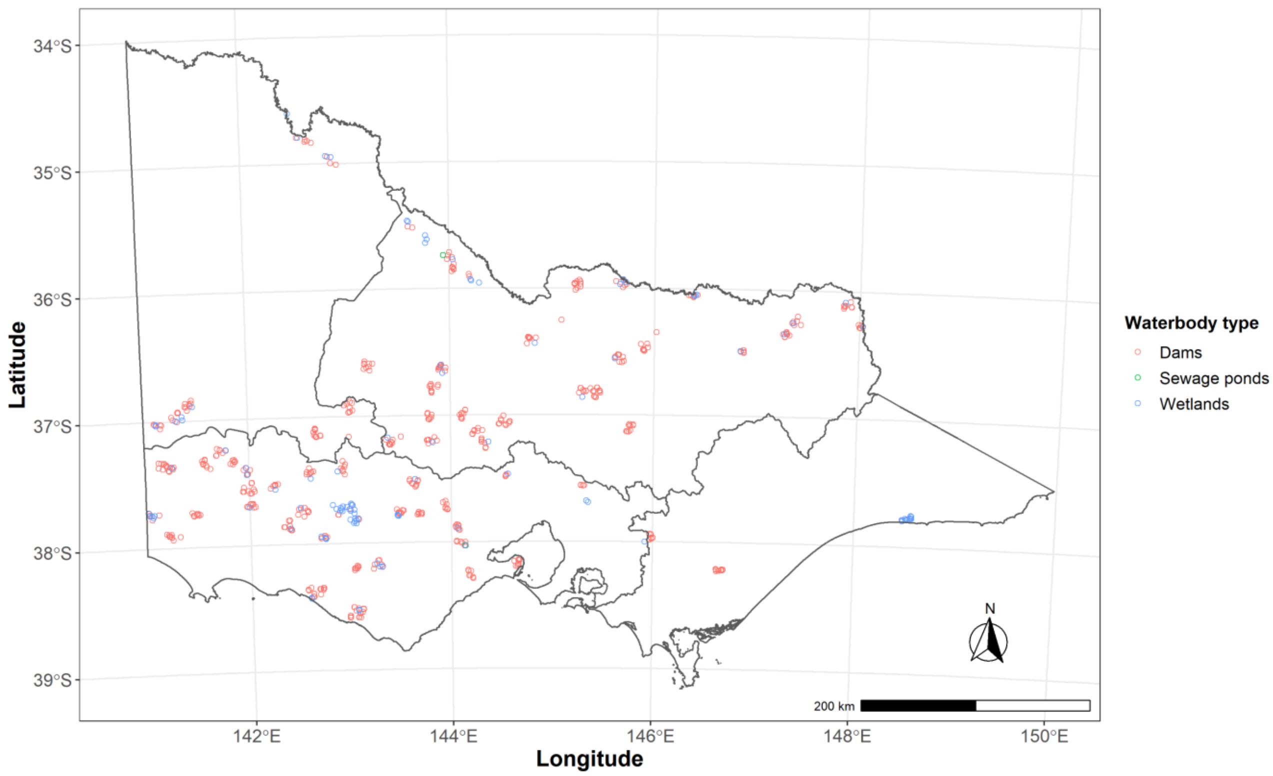

Figure 4. Locations of 653 waterbodies that were subject to aerial sampling during November 2020. Bioregion boundaries are (clockwise from top left), West, North, East and South.

Following revision of the surface water layer, from a total of 519 452 waterbodies that were mapped across Victoria, a total of 187 285 were estimated to have surface water after training the satellite imagery to the presence/absence of surface water from the 653 sampled waterbodies. Approximately 35% of the mapped small farm dams were judged to have water, compared to approximately 70% of wetlands (Table 4).

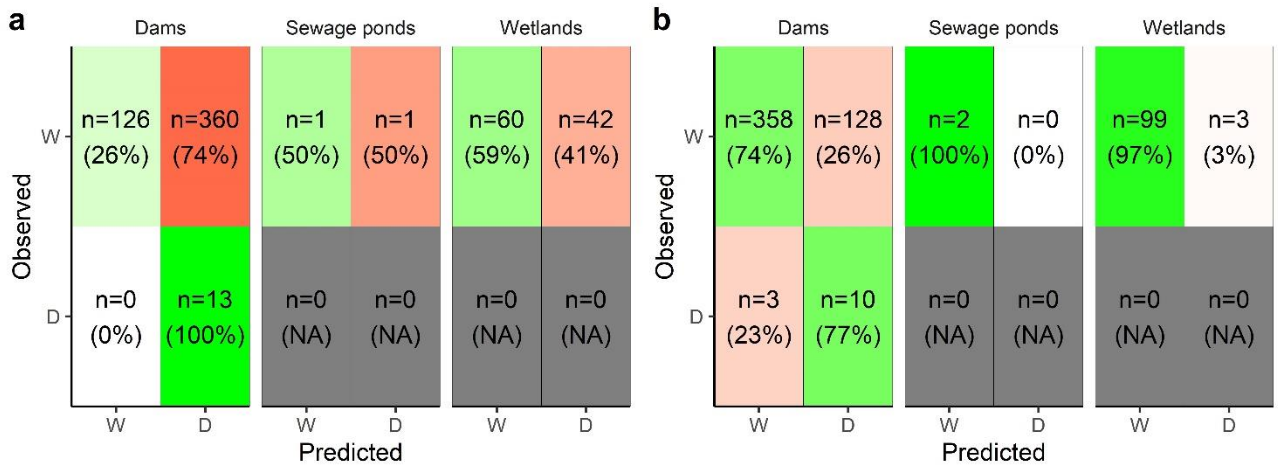

Figure 5. Confusion table for observed (Actual) vs predicted (Sentinel-2) surface water presence for dams, sewage ponds and wetlands. (a) Classifications before training. (b) Classifications following training. Red indicates incorrect predictions and green indicates correct predictions. Grey indicates no data. W – surface water present; D – surface water absent.

Table 4. Number (and percentage) of mapped waterbodies estimated to contain surface water during the spring 2020 period.

Waterbody type	Size Class		
	< 6 ha	6–50 ha	> 50 ha
Dams	180 497 (35%)	39 (75%)	–
Sewage pond	30 (97%)	28 (90%)	7 (100%)
Wetland	4909 (69%)	1377 (70%)	398 (78%)

3.3 Waterbody level abundance estimates

Total counts of game ducks on the 635 waterbodies with surface water based on the maximum count are presented in Table 5. Due to the risk that female Chestnut Teal could be misidentified as Grey Teal, we combined the two teal species for further analysis. Teal were the most numerous species counted, followed by Australian Shelduck, Australian Wood Duck and Pacific Black Duck (Table 5). In contrast, the least numerous species counted were Australasian Shoveler and Pink-eared Duck (Table 5). Counts were also much higher within the North and South bioregions due to the much higher numbers of waterbodies sampled in those two regions (Table 6).

Aerial survey data were adequate to estimate abundance for five species of game duck, including teal (Grey and Chestnut), Australian Wood Duck, Australian Shelduck, Pacific Black Duck and Hardhead. Counts for Pink-eared Duck and Australasian Shoveler were too low for robust analysis. The zero-inflated N-mixture model appeared to be an adequate fit to the aerial survey data for each species with posterior predictive distributions indicating strong positive relationships (Figure 6). Bayesian R^2 values (Gelman *et al.* 2019) were high for all species (teal – 0.89; WD – 0.87; AS – 0.96; PBD – 0.93; HH – 0.97). In particular, the fits indicated adequate prediction of the proportion of waterbodies with zero ducks, as well as the mean duck abundance (Appendix B). However, models for some species 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. Detection probability of the aerial observers was negatively related to the presence of glare on the water surface as well as the presence of vegetation (reeds or woodland) and averaged 0.59 for waterbodies in open habitat and no glare compared with 0.27 for waterbodies in woodland habitat in the presence of glare (Figure 7).

Estimates of the probability of presence for different waterbody types indicated that teal and Wood Duck were more likely to be found on small farm dams (<6 ha) than other game species (Appendix C). These species also had higher average abundances on small farm dams compared with other game species. Wetlands generally had higher probabilities of duck presence as well as average duck abundance, given presence compared with dams with both presence probabilities and average abundance increasing with the size of the wetland for all species except Wood Duck (Appendix C). Highest average abundances (i.e. > 200 ducks) occurred for teal and Australian Shelduck on large (>50 ha) wetlands (Appendix C).

Table 5. Summary of the aerial survey counts of game ducks (n) by waterbody type and size class. The maximum count for each waterbody was used for the summary. Species codes are: Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; PBD – Pacific Black Duck; AS – Australian Shelduck; H – Hardhead; PED – Pink-eared Duck; BWS – Australasian Shoveler.

Waterbody type	Size class	n	Teal	WD	PBD	AS	H	PED	BWS
Dams	<6 ha	516	1443	1666	455	457	91	5	5
	6-50 ha	9	176	3	28	2	0	1	0
	>50 ha	0	0	0	0	0	0	0	0
Sewage ponds	<6 ha	1	90	0	10	3	0	0	0
	6-50 ha	1	60	0	0	10	2	0	0
	>50 ha	0	0	0	0	0	0	0	0
Wetlands	<6 ha	60	346	200	144	37	31	0	0
	6-50 ha	30	1444	132	113	539	75	0	0
	>50 ha	18	2587	39	466	2481	242	10	1
Total		**635**	**6146**	**2040**	**1216**	**3529**	**441**	**16**	**6**

Table 6: Summary of the aerial survey counts of game ducks (n) by bioregion. The maximum count for each waterbody was used for the summary. Species codes are: Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; PBD – Pacific Black Duck; AS – Australian Shelduck; H – Hardhead; PED – Pink-eared Duck; BWS – Australasian Shoveler.

Bioregion	n	Teal	WD	PBD	AS	H	PED	BWS
North	238	1428	785	246	1378	59	0	2
South	305	3654	973	744	1901	370	14	3
East	32	270	33	26	105	5	0	0
West	60	794	249	200	145	7	2	1
Total	**635**	**6146**	**2040**	**1216**	**3529**	**441**	**16**	**6**

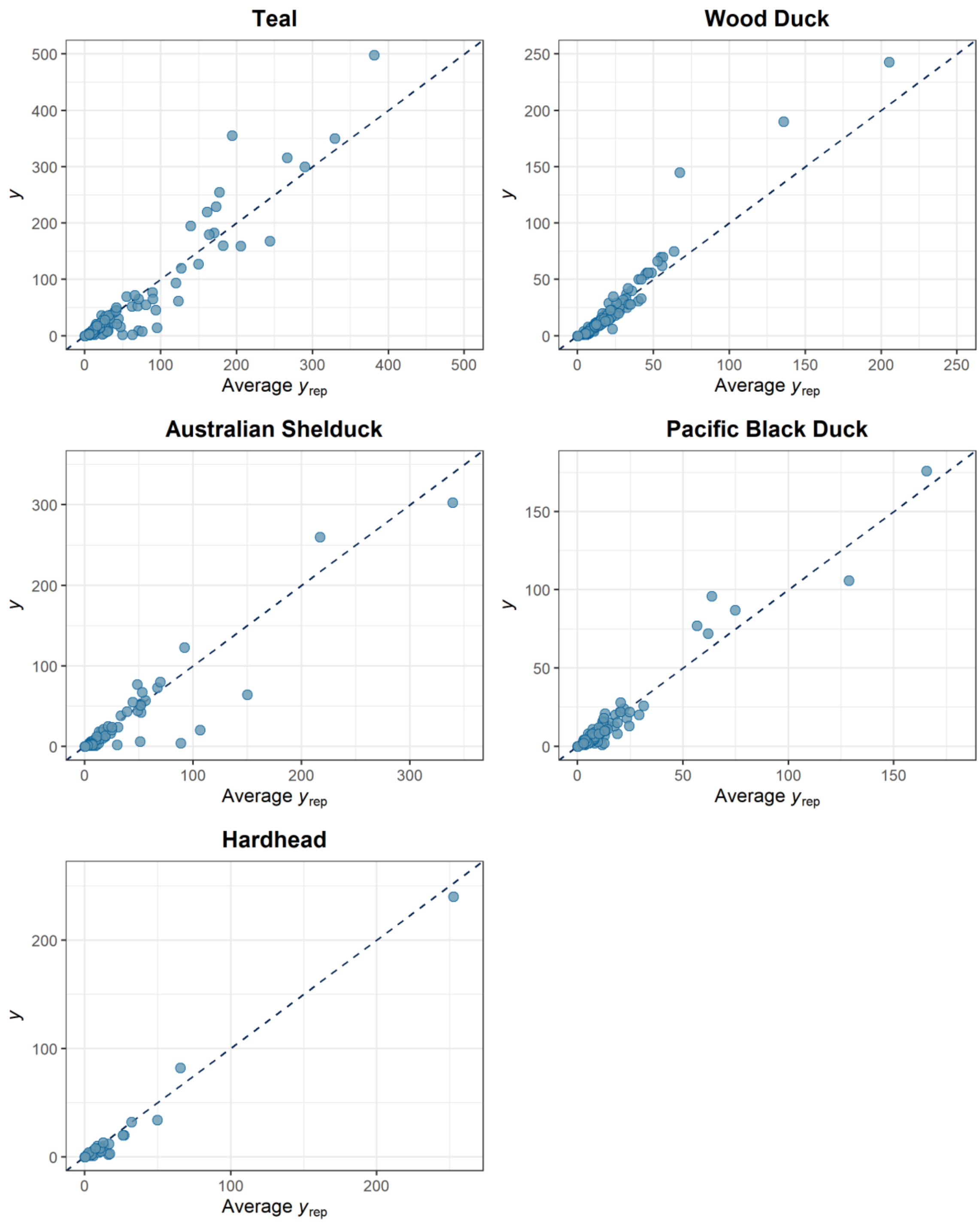

Figure 6: Posterior predictive distributions of the counts of five game duck species. y – observed counts (sum of both observers); y_{rep}– average predicted count from the fit of the zero-inflated N-mixture model.

3.4 Statewide abundance estimates

3.4.1 Design-based estimates

Design-based estimates of total abundance using the two-stage estimator (Appendix A) indicated that the population of game ducks on dams and wetlands in Victoria was 2 452 100 (Table 7). Teal (Grey and Chestnut Teal) were the most numerous game species (c. 981 000), followed by Australian Wood Duck (c. 690 000), Australian Shelduck (c. 407 000), Pacific Black Duck (c. 328 000) and Hardhead (c. 55 000) (Table 7). Precision of the overall estimate of abundance was adequate, with a 14% (0.14) coefficient of variation. However, precision of estimates for individual species varied, being most precise for teal and Pacific Black Duck, and least precise for Hardhead. Generally, precision (coefficient of variation) of 15% (0.15) or less would be considered adequate for management purposes and equates to the estimate being within 25% of the true abundance, 90% of the time (Skalski and Millspaugh 2002). None of the precision estimates for the individual species met this criterion (Table 7).

3.4.2 Model-based estimates

The estimate of the total abundance of game ducks using the model-based approach (Equation 2) was similar to the design-based estimate at 2 348 100 (Table 8). Teal were the most numerous game species (c. 907 000), followed by Australian Wood Duck (c. 807 000), Australian Shelduck (c. 313 000), Pacific Black Duck (c. 267 000) and Hardhead (c. 54 000) (Table 8). Precision of the overall estimate of abundance was very good at 6% (0.06) coefficient of variation. Precision of estimates for individual species was also good with only the precision for Hardhead exceeding 15% (0.15) (Table 8).

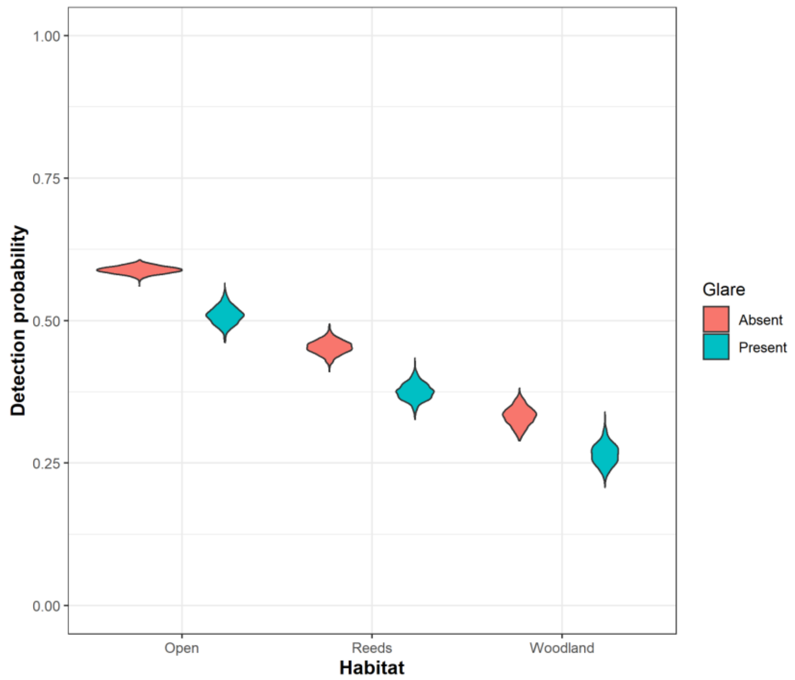

Figure 7. Detection probabilities of game ducks from aerial surveys in the presence of glare from the water surface and habitat type in the vicinity of the waterbody.

Table 7: Summary of design-based estimates of total abundance of five game duck species in Victoria. Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead; SE – standard error; CV – coefficient of variation; L95 – lower 95% confidence interval; U95 – upper 95% confidence interval.

Species	Estimate	SE	CV	L95	U95
Teal	981 600	241 000	0.25	610 900	1 577 100
WD	680 900	204 200	0.30	383 100	1 210 200
AS	406 700	159 200	0.39	194 000	852 600
PBD	327 600	65 900	0.20	221 700	484 000
H	55 300	28 200	0.51	21 600	141 900
Total	**2 452 100**	**360 900**	**0.14**	**1 840 400**	**3 267 000**

Table 8: Summary of model-based estimates of total abundance of five game duck species in Victoria. Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead. Estimate is the mean of the posterior predictive distribution calculated from Equation 2. SE – standard error; CV – coefficient of variation; L95 – lower 95% confidence interval; U95 – upper 95% confidence interval.

Species	Estimate	SE	CV	L95	U95
Teal	906,500	55,900	0.06	801,200	1,018,600
WD	807,000	56,500	0.07	698,700	913,800
AS	313,400	41,000	0.13	240,000	397,000
PBD	266,800	23,500	0.09	221,700	315,300
H	54,400	11,900	0.22	33,500	80,100
Total	**2,348,100**	**92,500**	**0.04**	**2,176,900**	**2,539,800**

The majority of game ducks occurred on small farm dams (< 6 ha), especially Australian Wood Duck and teal. Both teal and Australian Shelduck were also found in substantial numbers in larger wetlands (Figure 8). Game ducks were far more numerous in the North and South bioregions and were least numerous in the East bioregion (Figure 9). This was mostly due to the greater relative abundance of waterbodies in the North and South bioregions. However, as the East bioregion was comparatively under sampled compared with the other regions, there remains a larger uncertainty about the abundance of game ducks in this area.

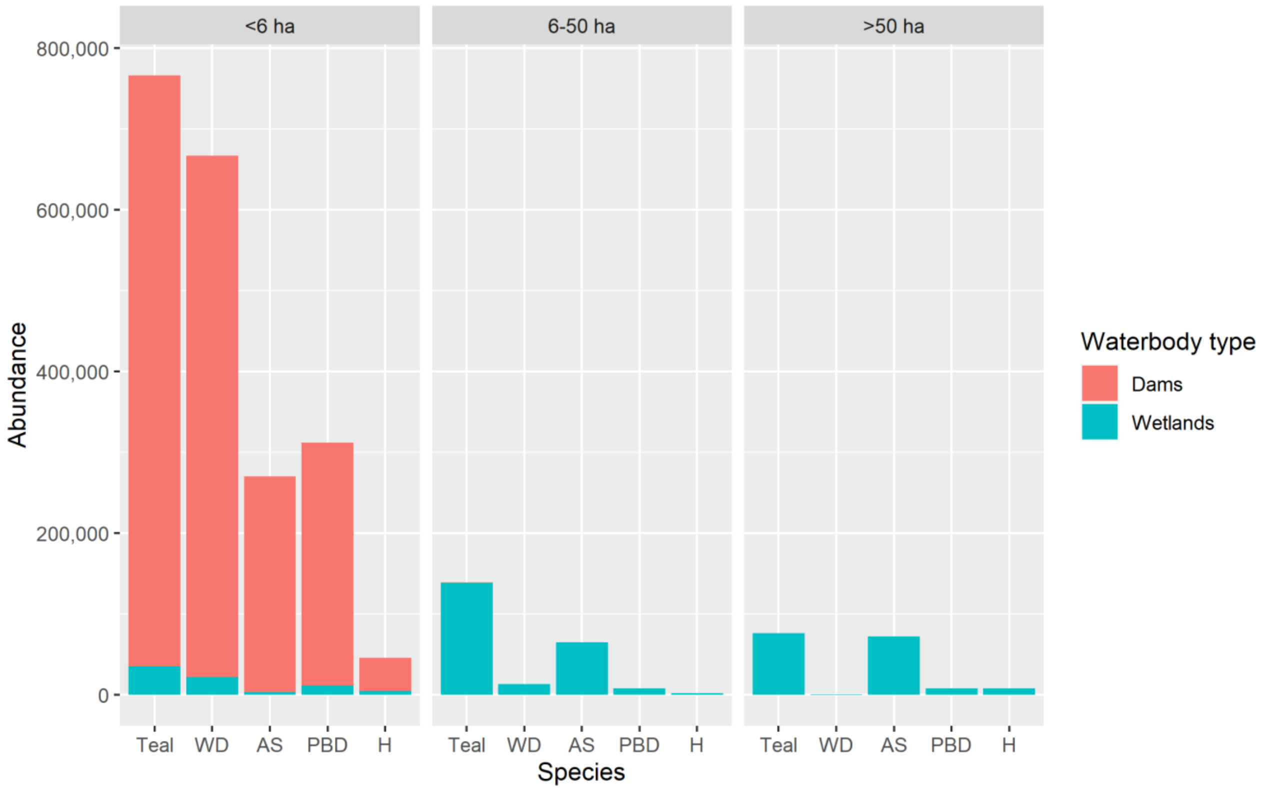

Figure 8. Abundance of game duck species by waterbody type and size class. Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead.

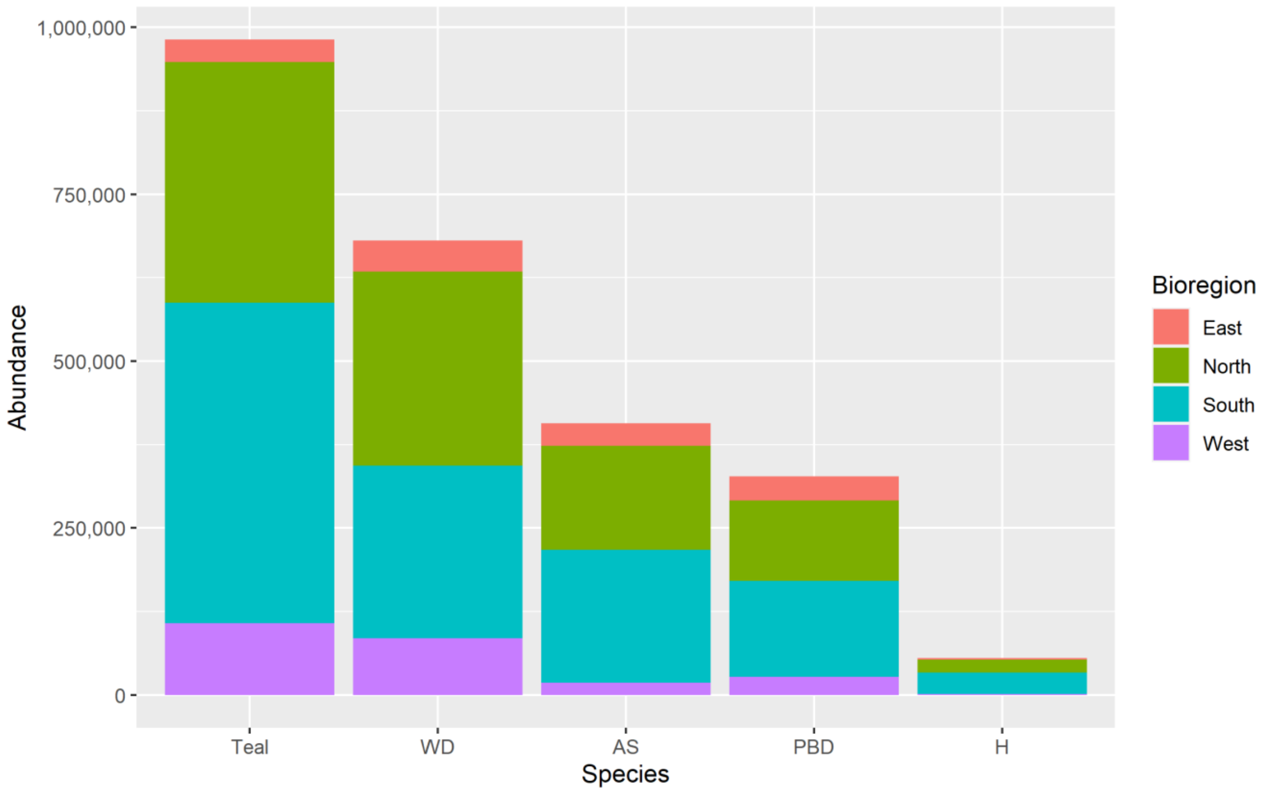

Figure 9. Abundance of game duck species by bioregion. Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead.

3.4.3 Predicting abundance outside Victoria

Predictions of the abundance of the five game duck species in the Riverina district, using model-based inference (Equation 2) and the number of dams with surface water in the Riverina in each size class, produced mixed results when compared with the independently derived estimates in Dundas *et al*. (2020) (Table 9). Estimates for teal and Australian Wood Duck were comparable to the corresponding independent estimates having a relative bias of < 20% (Table 9). However, estimates for Pacific Black Duck, Australian Shelduck and Hardhead were highly biased, with the estimate for Australian Shelduck being over 20 times greater and Pacific Black duck around 5 times smaller than the estimates derived by Dundas *et al*. (2020) (Table 9).

Table 9. Predictions of the abundance of game ducks in the Riverina district, based on the fitted model (Equation 2). Predictions were based on the numbers of dams in the Riverina of different size classes containing water. Riverina – Independent estimate based on aerial surveys undertaken by Dundas et al. (2020) during May 2020. Teal – Grey and Chestnut Teal; WD – Australian Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead.

Type	Size Class	Teal	WD	AS	PBD	HH
Dams	< 6 ha	118400	154500	45700	27150	5700
	6–50 ha	2500	500	1900	110	50
	> 50 ha	500	10	900	70	20
Total (predicted)		121400	155000	48500	27300	5770
Riverina (actual)		147400	145250	2400	116800	3250
Relative bias		–17%	+6.7%	+1 921%	–76%	+77%

3.5 Adjustments to the sampling design

The increase in the precision (coefficient of variation, CV) of the design-based estimates of total abundance for each species following increases in sample size are given in Figure 10. Increasing the number of waterbodies sampled per primary unit from 10 to 20 in at least 80 primary units resulted in precision for estimates of teal, Wood Duck and Pacific Black Duck being around the nominal target CV of 0.15. This resulted in a total sample size of around 1550 waterbodies. Increasing the number of primary units to 90 and sampling at least 15 waterbodies per primary unit gave similar increases in precision but required a smaller sample size of 1280 waterbodies. The total estimated sample size was always less than the nominal size due to some selected primary units having less than the desired number of waterbodies. None of the adjustments to sample size resulted in precision estimates for the abundance of Australian Shelduck or Hardhead that were within the target CV range.

The analyses of the single-stage stratified random design suggest that a total sample size of 800 waterbodies would result in CVs within the target range of 0.15 in abundance estimates for the major games species (Grey Teal, Chestnut Teal, Wood Duck and Pacific Black Duck) (Figure 11).

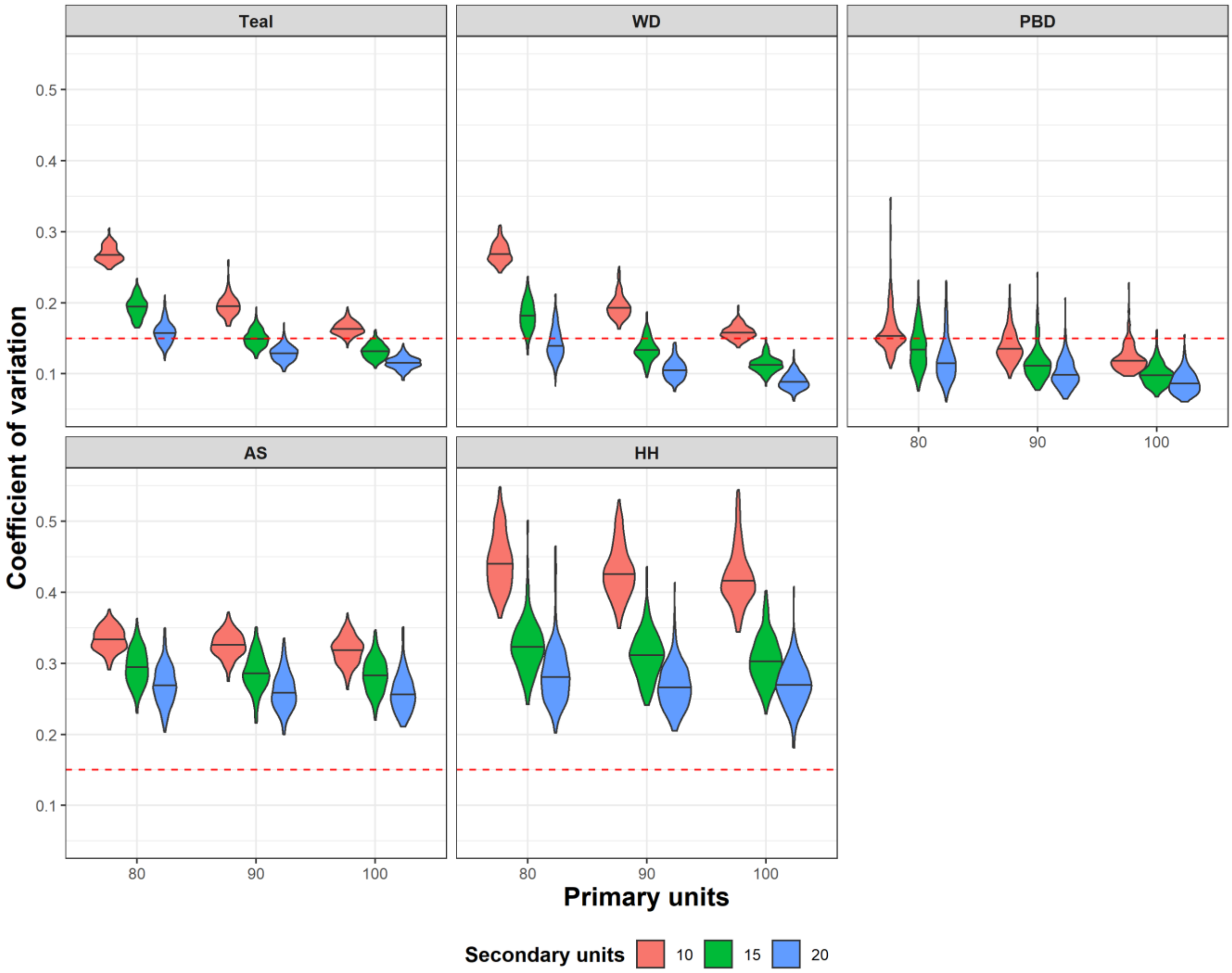

Figure 10. Coefficients of variation for estimates of total abundance for the five species of game duck following augmentation of the sampled waterbodies by increasing the number of primary units and/or the number of secondary units (waterbodies per primary unit). Teal – Grey and Chestnut Teal; WD – Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead. Dashed line – target coefficient of variation.

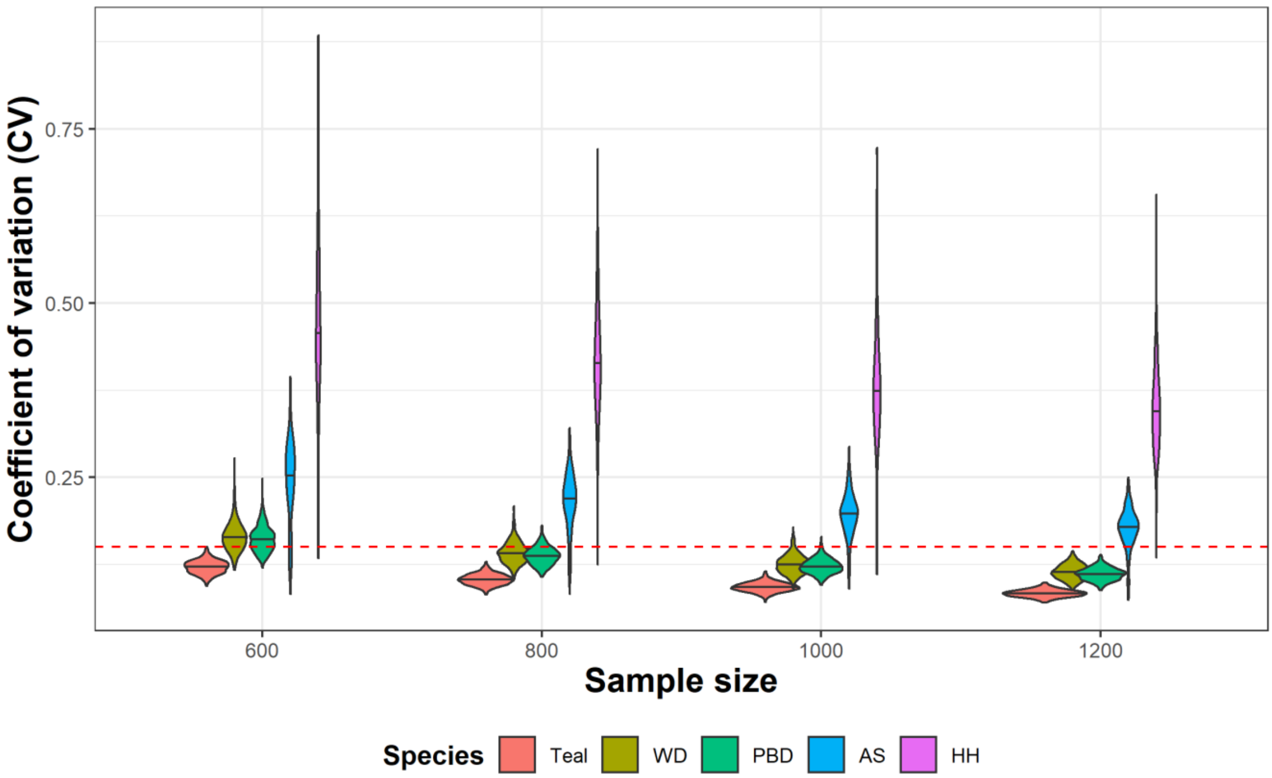

Figure 11. Coefficient of variation for estimates of total abundance for the five species of game duck under a single stage, stratified random design for various sample sizes. Abundance for individual waterbodies in the sample were predicted using Equation 2. Teal – Grey and Chestnut Teal; WD – Wood Duck; AS – Australian Shelduck; PBD – Pacific Black Duck; H – Hardhead. Dashed line – target coefficient of variation

3.6 Seasonal harvest regulations

From the design-based estimate of total statewide abundance for the five game species analysed here (2 452 100), a 10% total maximum offtake amounts to a quota of 245 200 birds. In addition, the total number of licensed duck hunters that could potentially participate in the 2021 season was estimated to be 25 500 (Game Management Authority unpublished data). Using these as inputs in Equation 3, the corresponding estimates of bag limit and season length suggests that a season length of 75 days and a daily bag limit of 5 would be consistent with a total harvest of 245 200 birds (Figure 12a). Alternatively, if a set season length is required, for example 65 days, then a bag limit of 6 would be consistent with the desired harvest quota (Figure 12b). Other combinations of season length and daily bag limit that were compatible with the harvest quota are presented in Table 10.

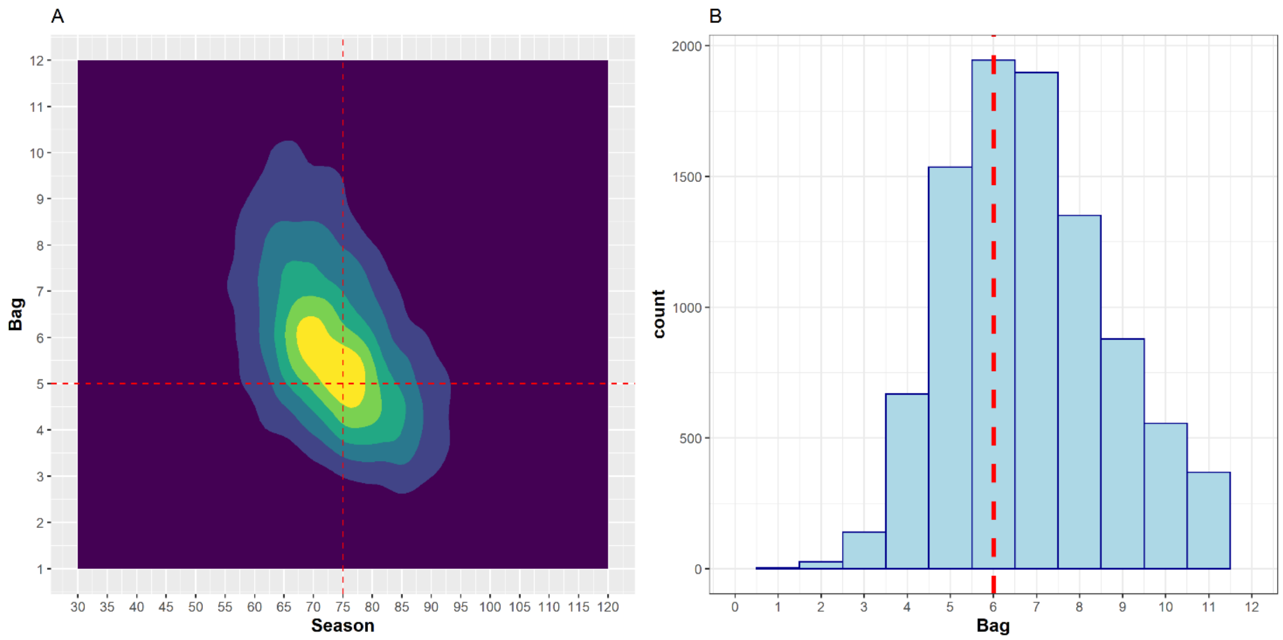

Figure 12. Estimates of (a) the joint distribution of season length (days) and daily bag limit that were consistent with a desired total harvest of 245 200 birds, assuming 25 500 licensed hunters or (b) the estimate of the bag limit consistent with the above but assuming a set season length of 65 days.

Table 10. Combinations of season length (days) and daily bag limit (maximum birds per day) that were compatible with a total harvest quota of 245 200 birds, assuming 25 500 licensed hunters. SE – standard error; Lower – lower 90% credible interval; Upper – upper 90% credible interval.

Season length	Bag limit	SE	Lower	Upper
30 – 50	8	3.2	5	13
50 – 70	6	2.2	5	11
70 – 90	5	1.7	4	8
90 – 120	4	1.5	3	7

4 Discussion

The pilot aerial survey undertaken in November 2020 has provided the first robust estimates of the abundance of game ducks across Victoria. To meet most harvest management objectives, estimates of absolute abundance are preferable to an index of abundance (i.e., an uncorrected count), because they allow a more direct assessment of the impact of harvesting from associated estimates of total harvest offtake. The setting of harvest management objectives, in terms of a maximum proportional offtake or minimum population size threshold, can also be directly assessed using absolute abundance. Such assessments are difficult (proportional offtake) or impossible (minimum population size threshold) to undertake using an index of abundance.

Although the estimates presented here account for the major sources of variation in duck abundances, such as habitat availability (surface water estimates for waterbodies including small dams) and observer error (detection probability), there is still room for improvement. For example, sampling coverage in the East bioregion was inadequate because many selected waterbodies were unavailable for aerial survey due to airspace restrictions. Coverage of sewage treatment ponds was also inadequate for similar reasons. Hence, to increase coverage for strata where aerial surveys are problematic, alternative survey methods should be investigated. Ground surveys should be suitable for smaller waterbodies (up to 6 ha), while UAVs recording high-resolution video (e.g. 4K at 60 fps) should be suitable for larger waterbodies (Dundas *et al.* 2020). Ground counts of waterbodies should be undertaken by two observers counting independently and simultaneously with the aid of spotting scopes. This will enable easy calibration of helicopter counts with ground counts. In addition, the pilot survey did not include waterways (rivers, large streams and irrigation channels) in the sampling frame. Since waterways are used by game ducks (Dundas *et al.* 2020), these should be included in future surveys to get a more complete picture of duck abundance in Victoria.

Estimates of total abundance for individual species had varying levels of precision. To be useful for most management objectives, abundance estimates should have a level of precision (coefficient of variation) of 15% or less (Skalski and Millspaugh 2002). None of the design-based estimates for the individual species (Table 7) currently meet this target. Increasing the number of sampled waterbodies per primary unit from 10 to 20 would be likely to result in abundance estimates with precision within the desired range for the major game species (Grey Teal, Chestnut Teal, Wood Duck, Pacific Black Duck). This would require an increase in the number of sampled waterbodies to at least 1550, but they would be sampled on the same number of primary units as used currently (80), so it may not greatly increase survey costs. Alternatively, acceptable precision could be obtained by increasing the number of primary units to 90 and increasing the number of sampled waterbodies per primary unit to 15, for a total sample size of around 1300 waterbodies. Another attractive alternative would be to use single-stage sampling (i.e. no primary units) and select a stratified sample of waterbodies across the state. Such a design should produce acceptable levels of precision for all four major game species from a sample of 800 waterbodies. However, removing the use of primary units as the basis for sampling may be logistically challenging, resulting in increased survey costs. Hence the feasibility of this option should be examined more closely in concert with the aerial survey provider.

The estimates of statewide abundance were also heavily influenced by the corresponding estimates of surface water availability in waterbodies. Our initial investigations revealed that the use of Sentinel-2 imagery for detecting surface water in smaller waterbodies can result in a very high rate of false negatives where waterbodies were incorrectly assessed to be dry. Classification accuracy was greatly improved by using the observed status of waterbodies from the aerial survey data for calibration, but a misclassification rate of about 25% was still evident for small farm dams. Hence ongoing calibration of the Sentinel-2 imagery will be required following each aerial survey to maximise classification accuracy until improved surface water detection algorithms are developed.

Model-based estimates of total abundance were similar to, and had higher precision than, the corresponding design-based estimates. However, the precision for model-based estimates was likely to have been slightly overestimated as the fitted model (Equation 1) tended to underestimate the variation in the observed counts, especially for teal and Wood Duck. However, in other respects model-based estimates appeared to give a reasonable fit to the observed counts and offer a promising alternative to the design-based approach. 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. A limited test of the ability of the model developed here to predict outside the sampling frame was undertaken by using it to predict game duck abundance in the Riverina district using an assessment of the number of waterbodies with surface water. However, comparisons of the predicted abundances with the independent estimates obtained from surveys in the Riverina by Dundas *et al*. (2020), gave mixed results. While predictions for teal and Wood Duck were comparable to those in Dundas *et al*. (2020), the results for the other three game duck species were highly biased. This suggests that there are factors driving abundance for these species other than those used to build the model used here. Hence, further investigation of factors driving variation in abundance of game ducks, such as land use, waterbody proximity (i.e. waterbody clustering) or climate variables are therefore needed to build more confidence in model-based estimates before they could be used to reliably estimate statewide duck abundance, or to estimate duck abundance outside Victoria.

Proportional harvest strategies, involving the setting of maximum harvest offtake as a fixed proportion of total population size, are currently used for managing the commercial harvest of kangaroos in Australia (McLeod *et al.* 2004; Pople 2008; Scroggie and Ramsey 2019) as well as for the setting of control targets for ducks in the Riverina (Dundas *et al.* 2020). The use of proportional harvest thresholds have been shown to be safe and effective for populations inhabiting fluctuating environments (Engen *et al.* 1997) with the threshold most commonly used for kangaroos (15%) based on an analysis of long-term datasets. In the absence of long-term data for game ducks, a conservative proportional harvest threshold of 10% has been suggested as suitable target for recreational offtake quotas. A 10% harvest threshold for game ducks is consistent with sustainable harvest offtake rates estimated for waterfowl in North America (Hauser *et al.* 2007; Mattsson *et al.* 2012) and therefore, should be suitable in the interim until enough data have accumulated to develop a full adaptive harvest management approach (e.g. Ramsey *et al.* 2017).

Implementing the 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 maximum 10% harvest quota. For the harvest quota estimated here of 245 200 birds, the daily bag limit and season length that were most compatible was a bag limit of 5 birds per day and a season length of 75 days. However, there was considerable uncertainty around these estimates, which was a consequence of the limited amount of historical data on seasonal arrangements and harvest offtake that has accumulated to date. An additional investigation into relationships between harvest offtake estimates and concurrent seasonal regulations is warranted to reduce uncertainty in these predictions. Incorporating more relevant variables, such as estimates of the number of active hunters or number of days hunted per season (e.g., Moloney and Turnbull 2016) could provide fruitful avenues to improve this relationship.

In conclusion, the analysis of the data from the first Victorian game duck survey has indicated that aerial survey of game ducks could provide more robust estimates of abundance across the state. These estimates in turn would be suitable as a basis for setting more rigorous and transparent recreational harvest arrangements. Moreover, estimates of statewide abundance will be essential if Victoria is to adopt adaptive harvest management as the basis for maintaining the sustainability of recreational duck hunting.

4.1 Recommendations

To improve the Victorian game duck survey to provide more robust estimates of abundance that will be suitable for setting the annual seasonal arrangements for recreational duck hunting, the following changes are recommended:

- Increase the number of sampled waterbodies in the two-stage sampling design to 1300 by sampling 90 primary units and 15 waterbodies per primary unit.

- Alternatively, sample 800 waterbodies using single-stage stratified random sampling, as this should lead to more precise abundance estimates than two-stage sampling. However, only adopt this option if it is logistically and financially feasible.
- Following sample selection, implement alternative sampling methods for waterbodies where it is not feasible to conduct aerial surveys from a helicopter. Smaller waterbodies (up to 6 ha) should be sampled simultaneously by two ground observers recording independently with the aid of a spotting scope, while larger waterbodies (more than 6 ha) should be sampled by an unmanned aerial vehicle (UAV) recording high-resolution video (i.e., 4K at 60 fps).
- Modify the survey design to include waterways (i.e. rivers, large streams and irrigation channels). This can be achieved by including waterways in either the two-stage or single-stage sampling design.
- To provide separate estimates for Grey and Chestnut Teal from aerial surveys, conduct ground surveys targeting teal at sites around the coast as well as north of the Princess Highway/Freeway to obtain an estimate of the sex ratio for both teal species.
- To improve model-based estimates of duck abundance, investigate additional habitat variables, such as landuse, waterbody proximity or climate variables, that may better describe variation in duck abundance to provide more confidence in model-based predictions.
- To improve the model of the relationship between total duck harvest and annual seasonal arrangements, investigate additional variables that more accurately reflect hunting effort, which should lead to improved estimates of daily bag limits and season length to achieve the desired harvest quota.

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Appendix A

Two-stage, design-based estimates of total abundance of game ducks

Following Skalski (1994) and Hankin (1984), design-based estimates of total population size for a multistage sampling design under unequal selection probabilities at the primary stage used a Horvitz–Thompson estimator of the form

$$\widehat{N}_T = \sum_{i=1}^{k} \frac{\widehat{N}_i}{\pi_i} \qquad (Equation\ 4)$$

where $\widehat{N}_T$ is total abundance, $\widehat{N}_i$ is the estimated abundance of ducks in primary unit i, and π_i is the probability of selection for primary unit i for the k sampled primary units selected among K total primary units.[1]

From Skalski (1994), the Horvitz–Thompson version of the variance of Equation 4 is then given by

$$\mathrm{var}(\widehat{N}_T) = \sum_{i=1}^{k} \frac{(1-\pi_i)\widehat{N}_i^2}{\pi_i^2} + 2\sum_{i=1}^{k}\sum_{j>i}^{k} \frac{(\pi_{ij}-\pi_i\pi_j)\widehat{N}_i\widehat{N}_j}{\pi_{ij}\pi_i\pi_j} + \sum_{i=1}^{k} \frac{\mathrm{var}(\widehat{N}_i)}{\pi_i} \qquad (Equation\ 5)$$

where π_{ij} is the probability that primary units i and j are both in the sample. Since the calculation of the π_{ij} is a non-trivial exercise, this were estimated using the `UPmaxentropypi2()` function in the `sampling` package (Tillé and Matei 2016) in `R` version 3.6.3 (R Development Core Team 2020). The estimate of the primary unit variance $\mathrm{var}(\widehat{N}_i)$ needed to account for the fact that m waterbodies were selected from a total of M_i within each primary unit, as well as the variance of the estimates of abundance of ducks for each waterbody. Because the sample of waterbodies at the secondary stage was selected with simple random sampling, this was calculated as

$$\mathrm{var}(\widehat{N}_i) = M_i^2 \left[\frac{\left(1-\frac{m}{M_i}\right) S_i^2}{m} + \frac{\overline{\mathrm{var}(\hat{n}_i)}}{M_i} \right] \qquad (Equation\ 6)$$

where

$$S_i^2 = \frac{\sum_{j=1}^{m} (\hat{n}_{ij} - \bar{n}_i)^2}{(m-1)}$$

and

$$\bar{n}_i = \frac{\sum_{j=1}^{m} \hat{n}_{ij}}{m}$$

$$\overline{\mathrm{var}(\hat{n}_i)} = \frac{\sum_{j=1}^{m} \mathrm{var}(\hat{n}_{ij})}{m}$$

where $\hat{n}_{ij}$ is the estimate of abundance of ducks (Equation 1) for waterbody j from the sample of m waterbodies ($j = 1, \ldots, m$) from among the total of M_i waterbodies in primary unit i, $\bar{n}_i$ is the average abundance estimate of ducks for the m sampled waterbodies in primary unit i, and $\mathrm{var}(\hat{n}_{ij})$ and $\overline{\mathrm{var}(\hat{n}_i)}$ are the variances of the estimates of abundance for each waterbody j and the average variance (within primary

[1] Equation numbers continue from the main text.

unit i), respectively. Given waterbodies at the secondary stage were selected at random, it follows that ($\hat{N}_i$), the estimate of the total abundance of ducks for primary unit i, was given by

$$\hat{N}_i = \bar{n}_i \times M_i$$

Which is simply the average abundance within primary unit i multiplied by the number of waterbodies within primary unit i. The above calculations (Equations 4–6) were undertaken separately for each stratum. Total abundance (and its variance) were then calculated as the sum of the strata abundances (and variances).

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. 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 $\boldsymbol{T}(\boldsymbol{y})$.

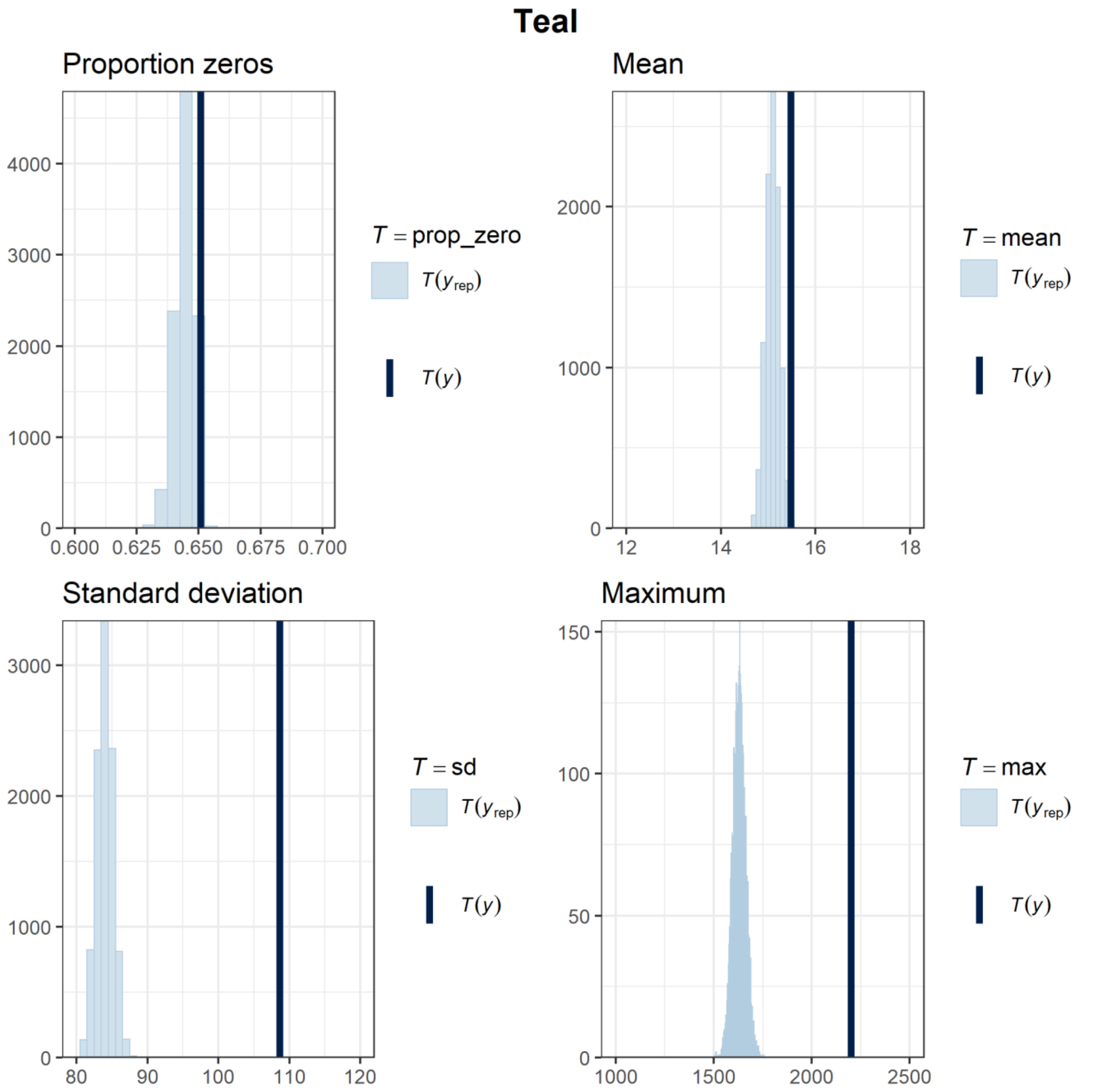

Figure B1: Posterior predictive checks for Teal (Grey and Chestnut Teal).

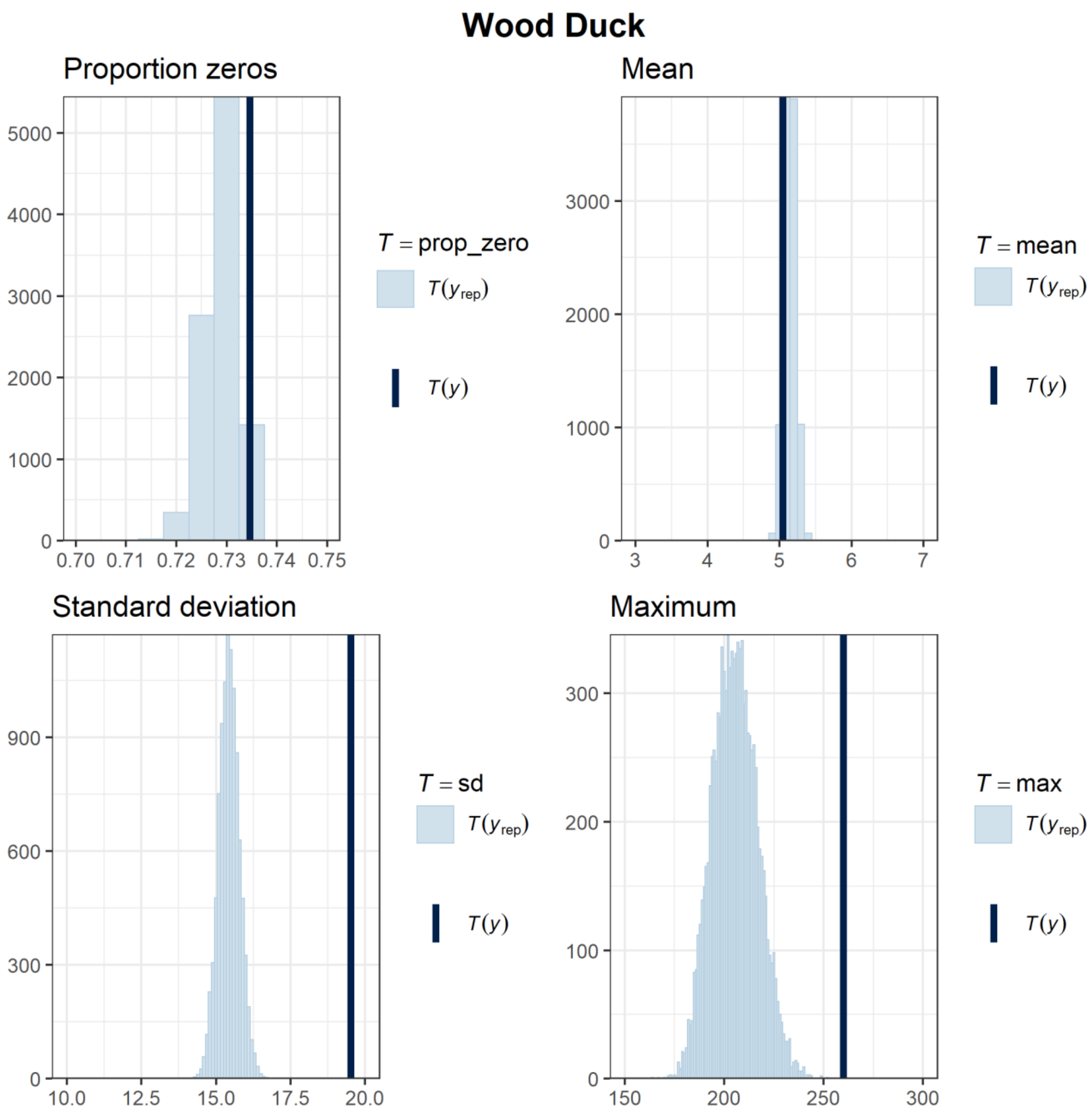

Figure B2: Posterior predictive checks for Wood Duck.

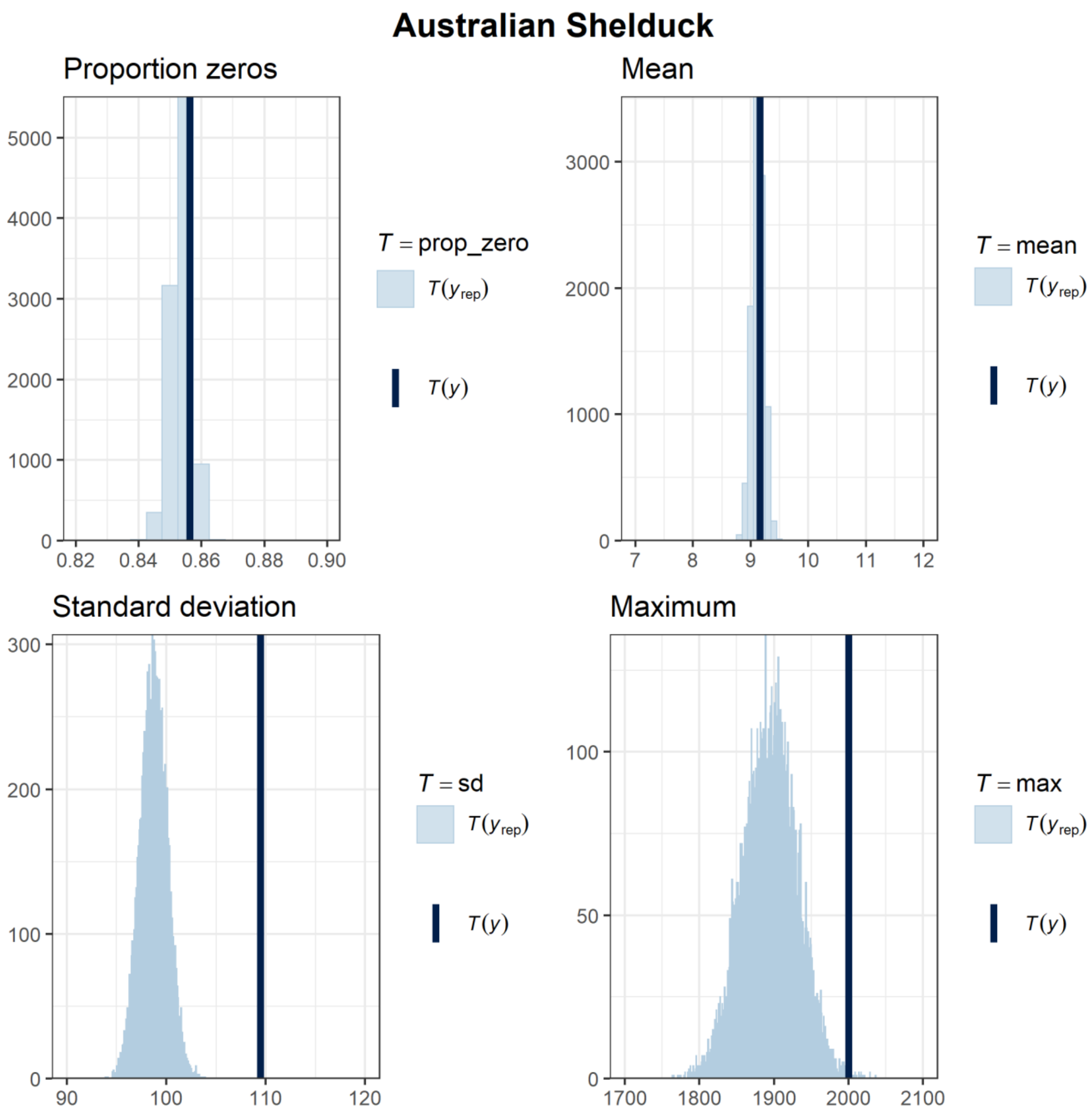

Figure B3: Posterior predictive checks for Australian Shelduck.

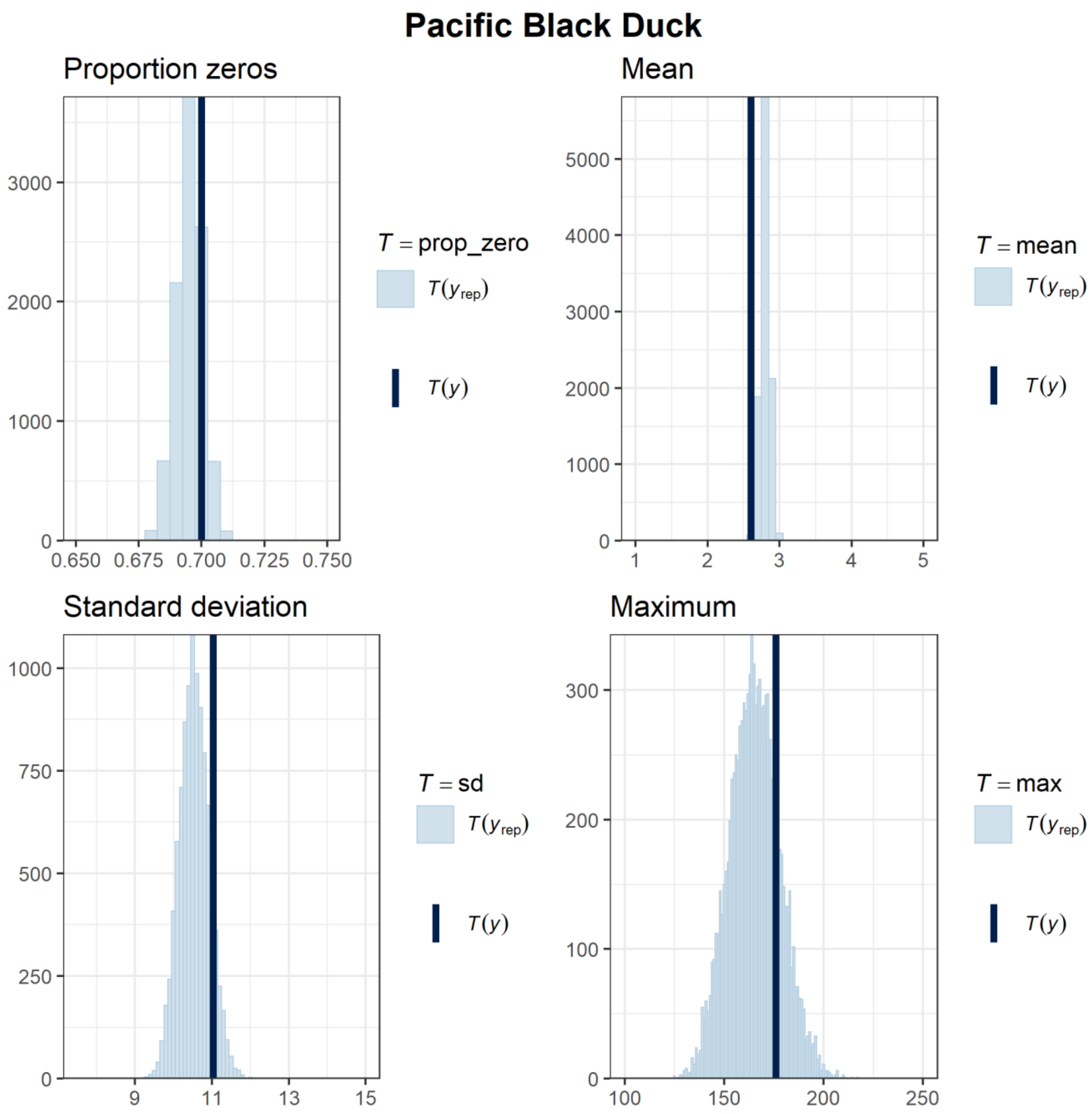

Figure B4: Posterior predictive checks for Pacific Black Duck.

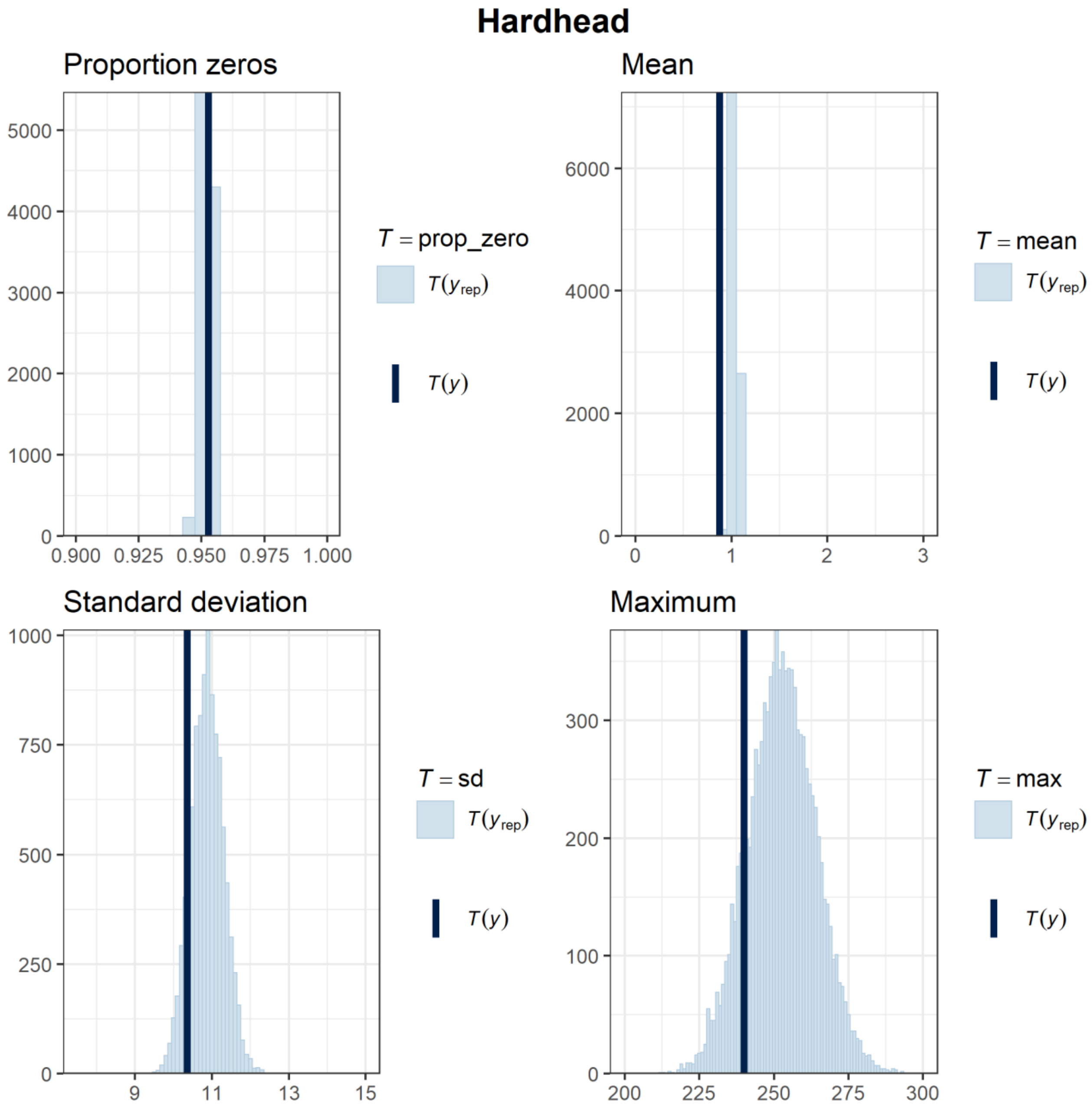

Figure B5: Posterior predictive checks for Hardhead.

Appendix C

Estimates of abundance and probability of presence for each waterbody

Table C1. Average probability of presence per waterbody type and size class for each game species predicted by the model (equation 1). Values in brackets are the standard error. NA – stratum not sampled.

Type	Size Class	Teal	WD	AS	PBD	HH
Dams	<6 ha	0.27 (0.06)	0.26 (0.07)	0.16 (0.1)	0.2 (0.09)	0.06 (0.11)
	6-50 ha	0.46 (0.11)	0.06 (0.04)	0.45 (0.19)	0.2 (0.11)	0.12 (0.16)
	>50 ha	NA	NA	NA	NA	NA
Wetlands	<6 ha	0.47 (0.09)	0.31 (0.1)	0.2 (0.12)	0.45 (0.15)	0.1 (0.14)
	6-50 ha	0.67 (0.1)	0.08 (0.05)	0.52 (0.18)	0.43 (0.16)	0.17 (0.18)
	>50 ha	0.75 (0.11)	0.27 (0.12)	0.46 (0.2)	0.7 (0.16)	0.35 (0.35)

Table C2. Average abundance given presence per waterbody type and size class for each game species predicted by the model (equation 1). Values in brackets are the standard error. NA – stratum not sampled.

Type	Size Class	Teal	WD	AS	PBD	HH
Dams	<6 ha	12.9 (5.9)	14.1 (7.3)	9.4 (8.5)	7 (5.3)	7 (5.9)
	6-50 ha	69.2 (27.1)	65.6 (30.8)	37.4 (32.9)	12.8 (9.3)	11.5 (9.6)
	>50 ha	NA	NA	NA	NA	NA
Wetlands	<6 ha	17.7 (7.8)	19 (9.5)	14.3 (13.1)	7.9 (5.9)	9.9 (8.2)
	6-50 ha	95 (36.5)	89.5 (41.8)	56 (48.7)	14.3 (10.2)	15.4 (12.1)
	>50 ha	281.8 (106.1)	9.3 (5.3)	562.9 (484.3)	69 (46.1)	40.1 (30.1)

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