Abundance estimates for game ducks in Victoria

Results from the 2021 aerial and ground surveys

D.S.L. Ramsey and B. Fanson

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Acknowledgement

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 their 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 for game ducks in Victoria: results from the 2021 aerial and ground surveys

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Summary

Context:

In Victoria, eight species of native duck are currently 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). 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). Modifications to the initial survey design were recommended, and the revised survey of around 800 water bodies was implemented in October 2021.

Aims:

The aims of this report were (i) to conduct an analysis of the monitoring data from the revised aerial and ground surveys of game ducks to estimate the abundance of each game species within the main habitat types in Victoria; (ii) to recommend possible modifications to the survey design to improve the robustness of the population estimates.

Methods:

Estimates of surface water area for water bodies in Victoria (wetlands, dams, sewage treatment ponds, rivers, large streams and irrigation channels) were derived from Landsat and Sentinel-2 raster imagery for the late winter – spring period to derive a sampling frame, which was then used to select a stratified random sample of around 850 water bodies. The selection probabilities of water bodies in each stratum were calculated to be inversely proportional to the number available. Water bodies were subject to aerial surveys during late-October to early-November 2021, 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 water body independently. Ground surveys were conducted for those water bodies 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 water body was estimated using a zero-inflated N-mixture model and Bayesian inference. Design-based and model-based procedures were then used to extrapolate estimates from sampled water bodies to the entire sampling frame to derive statewide estimates of abundance for each game duck species. The utility of the model-based approach was tested by using it to predict the abundance of game ducks in the Riverina district of New South Wales, and then comparing the predictions with recent independent estimates from that region.

Results:

A total of 853 water bodies were subject to aerial (787) or ground surveys (66). Of these, 765 were observed to contain surface water, and the counts of game duck species on these were used to estimate their abundance on each water body using the zero-inflated N-mixture model. However, an insufficient number of irrigation channels were surveyed, so estimates were not available for this water body stratum. The majority of game ducks occurred on small farm dams (up to 6 ha) and on rivers and streams, especially Wood Duck, Grey Teal, Australian Shelduck and Pacific Black Duck. Design-based estimates of the total abundance indicated that the population of game ducks on dams, wetlands, sewage ponds, rivers and streams in Victoria was 2,938,800 (95% confidence interval: 2,414,200–3,576,600).

Australian Wood Duck was the most numerous game species (c. 1,247,000), followed by Grey Teal (c. 616,000), Australian Shelduck (c. 510,000) and Pacific Black Duck (c. 447,000). Abundances of Chestnut Teal, Pink-eared Duck and Hardhead were each less than 100,000, and counts for Australasian Shoveler were insufficient for analysis. Precision of the overall design-based estimate of abundance was good, with a 10% (0.10) coefficient of variation, well within the target threshold of 15%. Model-based estimates were similar to the design-based estimates, and generated a total estimate of 2,820,800 game ducks. However, model-based estimates tended to be more precise than the corresponding design-based estimates.

Using the model-based approach to predict game duck abundances for the Riverina district produced mixed results. While predictions were broadly comparable with independent estimates for some species, for other species, predicted abundances varied greatly from the independent estimates.

Conclusions and implications:

Although the estimates presented here take into account the major sources of variation in duck abundance estimates, such as habitat availability (surface water area estimates) and observer error (detection probability), some adjustment to the sample sizes of some strata are warranted, especially waterways (river and large streams), to increase the precision of the abundance estimates in these strata. Irrigation channels should be an additional stratum. However, only major irrigation channels should be subject to sampling.

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 so as to provide more 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 water bodies (825, excluding irrigation channels) should be retained and used for future surveys. However, minor adjustments to sample sizes for some strata will be required, and these are detailed below.
- The number of sampled waterways (rivers and large streams) in the sampling design be increased to at least 100 (i.e. 25 per region).
- The spatial layers for irrigation channels be revised to only include large channels; resample the revised layers to obtain a sample size of at least 50.
- To improve model-based estimates of duck abundance, investigate additional habitat variables, such as land use, water body proximity, and climate variables, in order to better describe variation in duck abundance (to provide more confidence in model-based predictions).
- 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. Review key changes to algorithms for detecting surface water from satellite imagery and incorporate relevant changes to improve surface water area estimates in future surveys.

1 Introduction

In Victoria, eight 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*), Chestnut Teal (*Anas castanea*), Hardhead (*Aythya australis*) and Australasian Shoveler (*Anas 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 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 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 (see 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 EAWSs have inadequate coverage and/or sampling designs for Victorian water bodies to enable a robust estimation of duck abundances across the state. In addition to the undertaking of surveys at a sample of water bodies, 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 water body types 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).

A recent study identified survey methods and a sampling design that would be suitable for estimating the abundances of games ducks on water bodies in Victoria (Ramsey 2020). Water bodies were stratified into types (wetlands, dams, sewage treatment ponds), size classes (<6 ha, 6–50 ha, >50 ha) and bioregions (North, South, East, West). After a pilot study of the survey design, involving aerial counts of game ducks from 635 randomly selected water bodies, a revised survey design was recommended (Ramsey and Fanson 2021). The revised survey design incorporated moving to a simpler stratified random design from the two-stage design, increasing the sample size of the water bodies to at least 800, and including waterways (rivers, large streams and irrigation channels) as additional strata. In addition, the survey design was modified to include ground counts on water bodies where it was not feasible to conduct aerial surveys, and to include methods for obtaining separate estimates for Grey and Chestnut Teal (Ramsey and Fanson 2021). Following an independent review of the pilot study (Prowse and Kingsford 2021), further modifications to the survey design were made, including a modification to the aerial survey methods involving partial counts of large water bodies, and investigating alternative models for improving the detection probabilities of game ducks by observers. Accordingly, the Victorian Game Management Authority implemented the revised survey design during mid-October to early-November 2021. This report summarises the results from the 2021 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 2021, 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 water bodies (including farm dams).

- 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.
- 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 the estimates of abundance of game ducks obtained at sampled water bodies 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. Water bodies in Victoria were stratified according to water body type and size class, with the number of water bodies 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 water bodies are then extrapolated to all water bodies 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. For the 2021 survey, surface water types estimated included wetlands, dams, sewage treatment ponds, rivers, streams and irrigation channels. Estuaries were excluded from the surface water estimates. 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 area in wetlands, dams, sewage treatment ponds, rivers, streams and irrigation channels were derived from the DEA_water body layer from Geosciences Australia (Mueller et al. 2016) as well as from Sentinel-2 satellite imagery (available from https://www.sentinel-hub.com/explore/sentinelplayground/), which provides multispectral images at 10-m resolution. Imagery from DEA_waterbody was suitable for water bodies larger than 1 ha, while imagery from Sentinel-2 was suitable for detecting surface water in small water bodies such as farm dams. The methods for deriving surface water area estimates from each of these sources and the resultant mapped water body layers are described in Ramsey and Fanson (2021), with calibration of Sentinel-2 images being undertaken to improve classification accuracy. Calibration used the actual observations of surface water for each sampled water body that were obtained during the aerial and ground surveys.

2.1.1 Surface water changes between 2020 and 2021

The surface water area estimates for 2020 and 2021 were compared using the predictions from both the Landsat and Sentinel-2 sources. The 210 (mainly large storage) water bodies classified as 'wetlands' in the 2020 estimates that were reclassified as 'dams' in 2021 were not included in the comparison. Hence, the surface water area estimates for 'dams' refer mainly to small farm dams. Also, note that the large Gippsland Lakes (i.e. Lake Wellington and Lake Victoria) are classified as estuaries due to the level of salt-water intrusion. Hence, the surface water of these lakes is not included in the surface water area estimates.

2.2 Selecting the sample of water bodies

Following the recommendations in Ramsey and Fanson (2021), sample selection for the 2021 survey was modified from the two-stage design to a single-stage, stratified random design, as the latter was predicted to result in abundance estimates with better precision. Selection probabilities for water bodies in each stratum were calculated as inversely proportional to their availability in the sampling frame. Strata consisted of water bodies of different types, including wetlands, dams, sewage treatment ponds, rivers, streams, and irrigation channels, which were also categorised according to size class (<6 ha, 6–50 ha, >50 ha). Size classes for waterways (rivers, streams and irrigation channels) were calculated by multiplying the segment length (2 km) by the width of the segment. Water bodies were further stratified into four broad geographic regions in the state (North, South, East and West). Further details of the stratification of water bodies across Victoria can be found in Ramsey and Fanson (2021).

2.3 Aerial and ground sampling of game ducks

Aerial sampling of each water body 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 water body independently. For smaller water bodies and farm dams, each water body was approached and counts were conducted while the aircraft completed a low circuit around the water body circumference at a height of around 30–50 m. For the larger water bodies (>50 ha), only a portion of the water body, usually 50% (selected at random), was surveyed by flying inside the perimeter of the water body and counting towards the water body edge and then towards the water body center. The counts for each observer for the entire surface area were then imputed using the proportion of the water body surveyed.

Ground surveys of water bodies that could not be sampled from the air 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.

Counts of Chestnut Teal on water bodies surveyed from the ground were partitioned separately into adult male and females. These counts were then 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. This adjustment was undertaken because female Chestnut Teal are very similar in appearance to Grey Teal, and hence aerial observations are likely to confuse female Chestnut Teal with Grey Teal. Only water bodies 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 Water body level estimates

The two independent replicate counts of game ducks at each sampled water body were used to estimate the abundance of ducks at each water body, 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 water body 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 water bodies, such as water body 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 water bodies 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 water body 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 water body 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), water body 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. water bodies 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 water body 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). 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 water body in the sampling frame (i.e. both sampled and unsampled), conditional on their covariate values (water body 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.

2.4.3 Predicting abundance outside Victoria

As an additional test of the utility of the model-based approach, we used the fitted N-mixture ZIP model (section 2.4.1) to predict game duck species abundance for the Riverina district of southern New South Wales and compared our estimates with the independent estimates derived for the region based on sampling conducted by the NSW Department of Primary Industries in April/May 2021 (Vardanega et al. 2021). This was undertaken to determine the utility of the models developed here for extrapolating predictions of abundance to areas outside Victoria. The independent estimates from Vardanega et al. (2021) were based on a similar survey methodology to that used for Victoria (i.e. double-observer counts from a helicopter). However, larger (>10 ha) water bodies 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 Vardanega et al. (2021). We then used the fitted N-mixture ZIP model (section 2.4.1) to predict this sampling frame by using the parameter estimate for dams restricted to the Northern bioregion only. Estimates for the Northern bioregion were considered the most appropriate due to the proximity of this region to the Riverina district of New South Wales.

3 Results

3.1 Survey summary

Aerial and ground surveys of game ducks were undertaken 19 October – 7 November 2021. A total of 853 water bodies were surveyed, with 787 water bodies surveyed from the air and a further 66 surveyed from the ground (Table 1, Figure 1). A total of 704 of the 787 water bodies subjected to aerial survey were observed to have surface water (89%), with the remaining either being dry or not present at the identified location. Only a single water body was observed to be completely dry during the ground surveys. Only four of the irrigation channels that were sampled contained water at the time of the survey. Since this was considered insufficient for analysis, the data from irrigation channels were not analysed further; hence, no estimates were obtained for ducks on irrigation channels.

From the ground surveys, there were 30 water bodies where at least one male Chestnut Teal was observed, and the maximum counts of male and female Chestnut Teal on these water bodies were used to estimate the male:female sex ratio. The mean numbers of male and female Chestnut Teal observed were 15.4 and 19.5, respectively, giving a male:female sex ratio of 0.79 (SE = 0.097). This value was subsequently used to adjust the counts of Grey and Chestnut Teal from the aerial surveys.

Table 1. Water bodies sampled by aerial and ground surveys during 2021. The numbers of these water bodies observed with surface water are given in parentheses.

Water body type	Aerial	Ground	Totals
Dams	195 (180)	17 (16)	**212 (196)**
Sewage ponds	5 (5)	34 (34)	**39 (39)**
Wetlands	533 (489)	15 (15)	**548 (504)**
Streams	26 (26)	0	**26 (26)**
Channels	28 (4)	0	**28 (4)**
Total	**787 (704)**	**66 (65)**	**853 (769)**

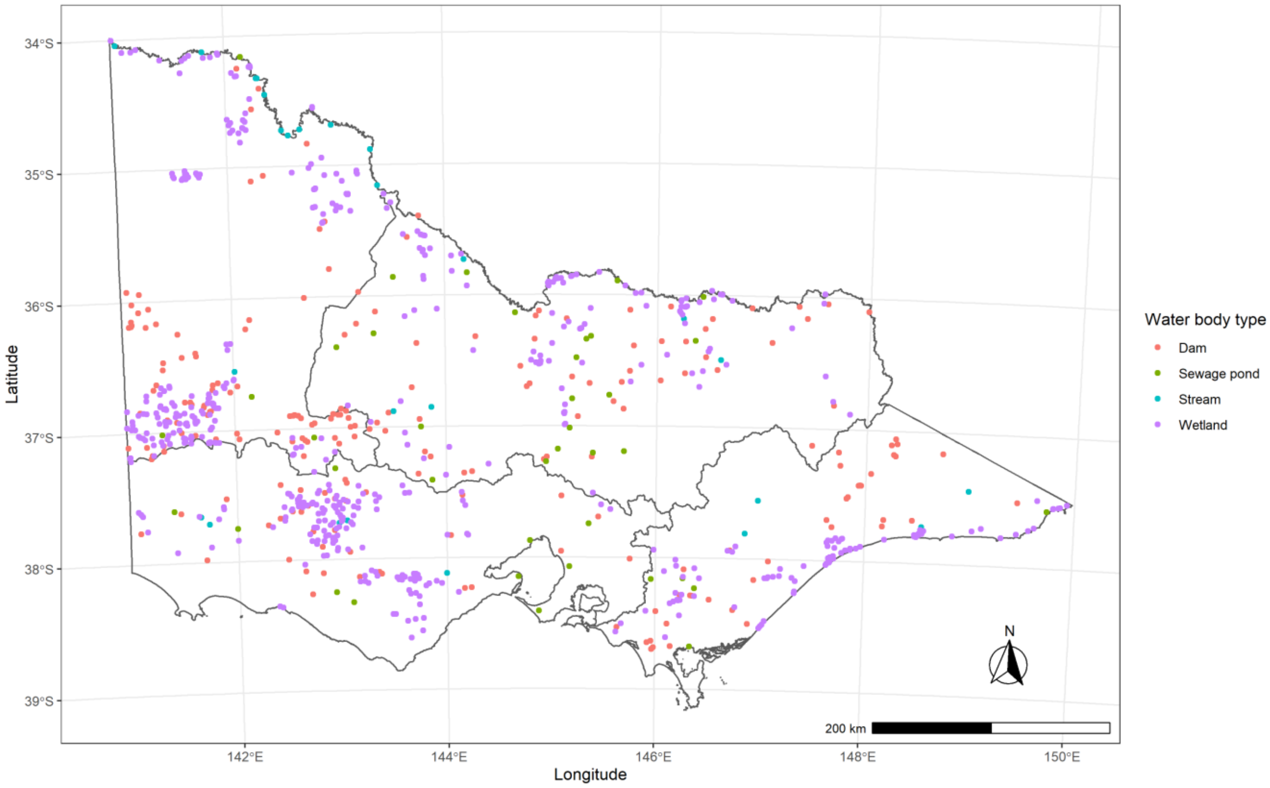


Figure 1. Locations of the 825 water bodies (Dams, Sewage ponds, Wetlands and Streams) that were subject to aerial and ground sampling during October–November 2021. Irrigation channels were excluded from the current analysis. Bioregion boundaries are (clockwise from top left), West, North, East and South.

3.2 Surface water availability

The number of water bodies (dams, sewage ponds, wetlands and rivers/streams) categorised as containing surface water following calibration of the satellite imagery was estimated at 171,210 (Table 2). Excluding stream segments, the total number of water bodies with surface water was 158,607. This was lower than estimated for the previous survey in 2020 (187,285), mainly due to the lower number of dams estimated with surface water compared with the previous year. However, the number of wetlands determined as containing surface water was higher than in the previous year. The results from the calibration of the Sentinel-2 satellite imagery with the observations of surface water for each sampled water body suggested that the true positive rates were high for dams, with 79% of wet dams and 82% of dry dams correctly predicted (Figure 2). For wetlands, 92% of wetlands with surface water were correctly predicted. Conversely, only 41% of dry wetlands were correctly predicted by Sentinel-2; hence, the false negative rate for wetlands (dry wetlands predicted to be wet) was 51% (Figure 2). However, it should be noted that the majority of wetlands used surface water predictions derived from Landsat, rather than Sentinel-2.

3.2.1 Surface water changes between 2020 and 2021

Total surface water area estimates for dams decreased between 2020 and 2021 in all four regions, while total surface water area for wetlands increased in all regions except the West (Table 3). The largest increases were in the East and South regions, where surface water area increased by 28% and 33%, respectively. Total surface water area (combined dams and wetlands) increased by 13% between 2020 and 2021 (Table 3).

Table 2. Number of mapped water bodies determined as containing surface water during the spring 2021 period.

Water body type	Size class			
	<6 ha	6–50 ha	>50 ha	Totals
Dams	151,435	113	56	**151,604**
Sewage ponds	47	49	8	**104**
Wetlands	5,166	1,379	354	**6,899**
Streams	10,440	962	1,201	**12,603**
Totals	**167,088**	**2,503**	**1,619**	**171,210**

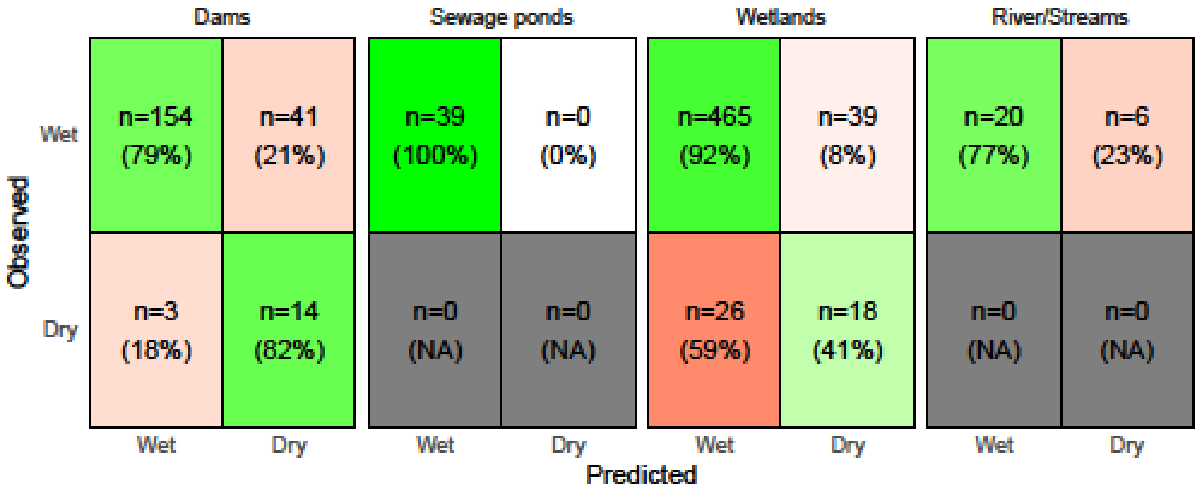


Figure 2. Confusion table for observed (actual) vs predicted (Sentinel-2) surface water presence for dams, sewage ponds, wetlands and rivers/streams. Red indicates incorrect predictions and green indicates correct predictions, with shading indicating relative (in)accuracy. White and grey indicates no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

Table 3. Surface water area estimates (total, mean and maximum in hectares) for the combined water bodies containing surface water for dams (mainly farm dams) and wetlands for the late winter – spring periods in 2020 and 2021 in each of four regions.

		2020				2021			
Water body type	Region	Total	Mean	Max	*n*	Total	Mean	Max	*n*
Dams	East	1,499	0.09	10	17,485	1,300	0.08	23	16,341
	North	7,643	0.09	33	85,161	6,087	0.08	36	71,878
	South	5,390	0.09	12	58,821	4,473	0.09	12	49,493
	West	1,361	0.07	10	19,066	907	0.07	12	13,682
Wetlands	East	11,753	9.88	1,706	1,190	15,043	12.05	1,879	1,248
	North	13,779	9.30	2,309	1,481	14,372	8.72	2,207	1,648
	South	48,086	14.75	14,472	3,261	63,720	18.70	24,000	3,407
	West	18,859	32.24	9,280	585	16,794	28.18	3,609	596
	Total	108,370				122,696			

3.3 Water body level abundance estimates

The total counts of game ducks (based on the maximum observed in each waterbody) on the 765 water bodies with surface water (excluding irrigation channels) are presented in Table 4. Grey Teal were the most numerous species counted, followed by Australian Shelduck, Pink-eared Duck and Pacific Black Duck. In contrast, the least numerous species counted were Australasian Shoveler and Hardhead (Table 4). Counts were higher within the North and South bioregions compared with the East and West bioregions (Table 5).

The monitoring data were adequate for estimating the abundance for seven of the eight species of game duck, including Grey Teal, Chestnut Teal, Australian Wood Duck, Australian Shelduck, Pacific Black Duck, Pink-eared Duck and Hardhead. The counts for the Australasian Shoveler were too low for robust analysis. The N-mixture ZIP model (section 2.4.1) appeared to be an adequate fit to the aerial and ground survey data for each species, with posterior predictive distributions indicating strong positive relationships (Figure 3). The Bayesian R^2 values (Gelman et al. 2019) were high for all species (GT = 0.95; WD = 0.98; AS = 0.92; PBD = 0.70; CT = 0.86; PED = 0.96; HH = 0.97). In particular, the fits indicated adequate prediction of the proportion of water bodies 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.

Detection probability of ducks was lower during aerial surveys compared with ground surveys with the magnitude of the difference dependent on habitat and water body size class (Figure 4). Aerial detection probability was highest on small (< 6 ha) water bodies in open or reed habitat (0.70 – 0.72) and was lowest on wooded habitat on mid-size (6-50 ha) water bodies (0.10). In contrast, ground detection probability declined with increasing water body size class but was highest in wooded habitat. Highest detection probabilities were achieved by ground surveys of small and mid-size wetlands in wooded habitat (0.91 – 0.92) and were lowest on large (> 50 ha) water bodies in reed habitat (0.31) (Figure 4). Compared with habitat or water body size class, the presence of glare on the water surface appeared to have a relatively minor influence on detection probabilities (Figure 4).

Table 4. Total counts of each species by water body type and size class. The maximum of the two counts for each water body 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 water bodies with surface water.

Water body type	Size class	*n*	GT	WD	AS	PBD	CT	HH	PED	BWS
Dams	<6 ha	173	132	455	147	141	7	1	0	3
	6–50 ha	23	419	876	97	46	20	67	23	3
	>50 ha	0	0	0	0	0	0	0	0	0
Sewage ponds	<6 ha	17	554	67	155	14	236	89	84	0
	6–50 ha	17	2094	92	167	106	338	249	316	6
	>50 ha	5	891	32	98	0	192	73	629	0
Streams	<6 ha	16	55	129	2	65	16	2	0	2
	6–50 ha	0	0	0	0	0	0	0	0	0
	>50 ha	10	85	147	94	21	0	0	0	0
Wetlands	<6 ha	156	861	553	374	318	120	4	18	0
	6–50 ha	182	1667	344	1246	785	307	143	603	20
	>50 ha	166	10743	642	10883	1968	1565	642	7080	32
Total		**765**	**17501**	**3337**	**13263**	**3464**	**2801**	**1270**	**8753**	**66**

Table 5: Total counts of each species by bioregion. The maximum of the two counts for each water body 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 water bodies with surface water.

Bioregion	*n*	GT	WD	AS	PBD	CT	HH	PED	BWS	Total
East	135	807	275	2,223	137	1,895	88	28	0	**5,586**
North	176	7,986	1,504	770	865	418	189	787	15	**12,713**
South	209	5,926	508	7,257	1,668	444	853	7,843	42	**24,761**
West	245	2,782	1,050	3,013	794	44	140	95	9	**8,172**
Total	**765**	**17,501**	**3,337**	**13,263**	**3,464**	**2,801**	**1,270**	**8,753**	**66**	**51,232**

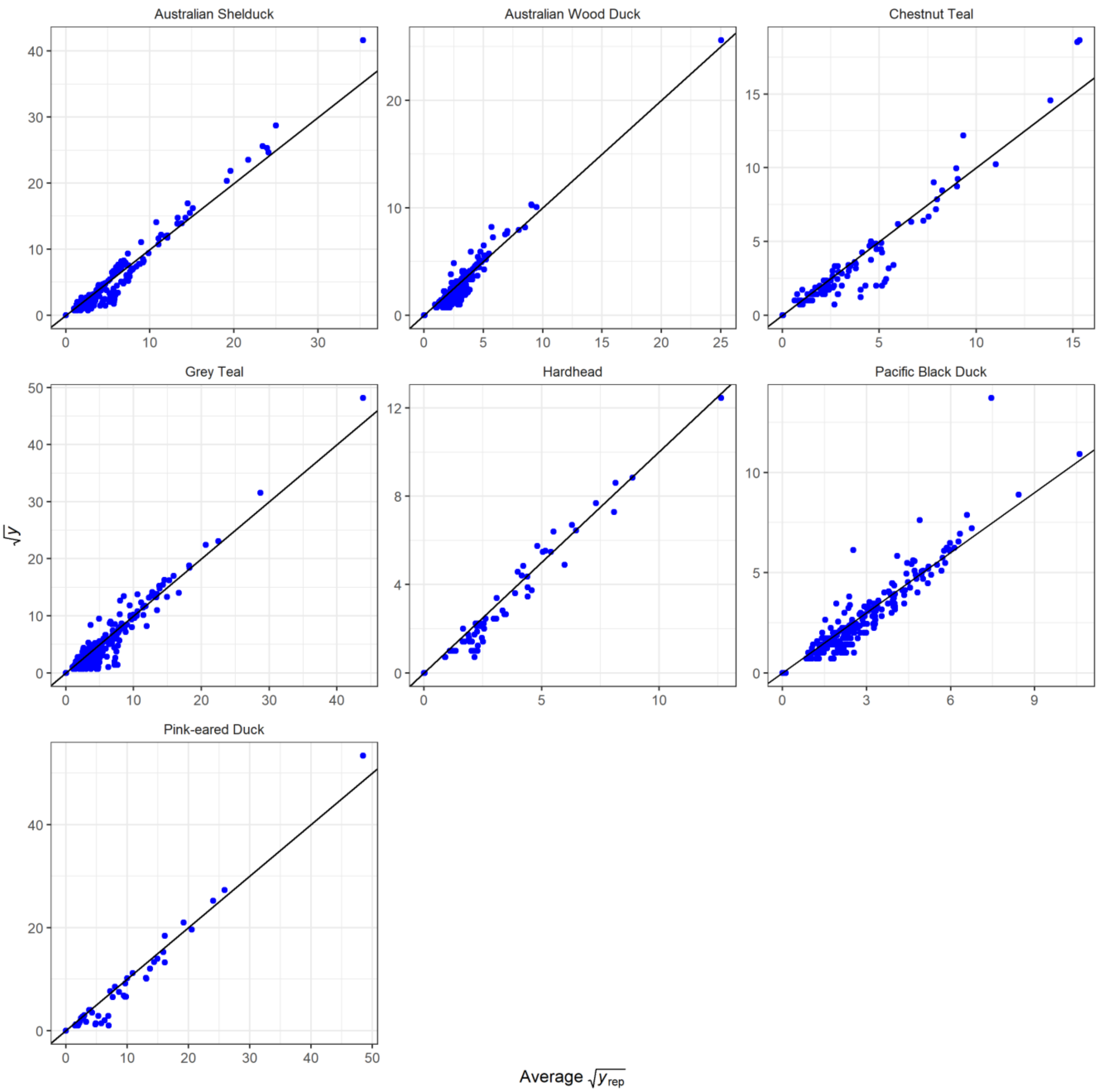


Figure 3: Posterior predictive distributions of the counts of seven game duck species. y = observed counts (sum of both observers); y_{rep} = average predicted count from the fit of the zero-inflated N-mixture model. The predicted and observed counts were square root transformed to aid the visibility of the small counts. The black line shows a 1:1 relationship.

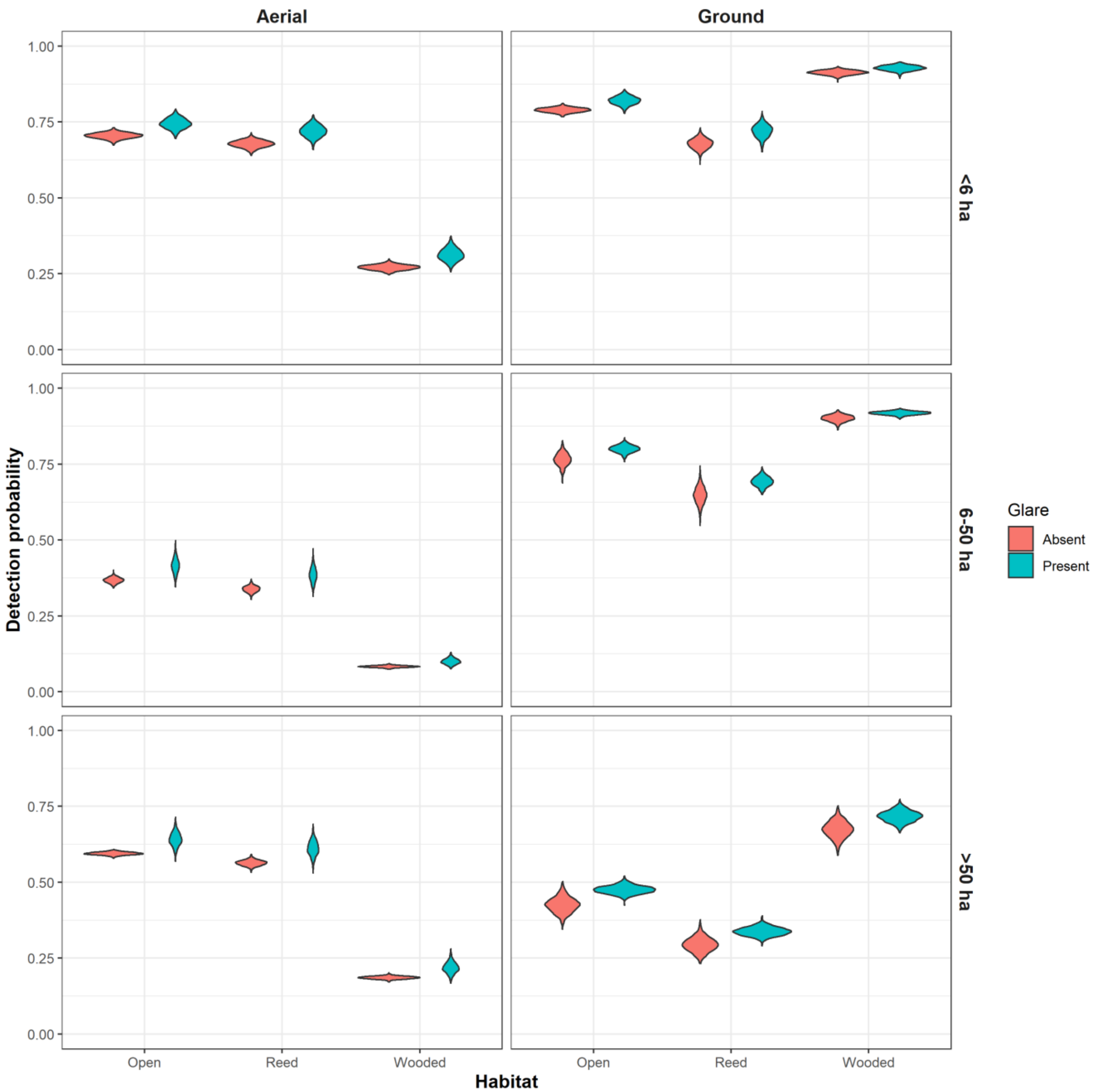


Figure 4. Detection probabilities of game ducks from aerial and ground surveys by habitat type and water body size class (<6 ha; 6–50 ha; >50 ha) in the presence or absence of glare from the water surface.

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 2,958,700 (Table 6). Australian Wood Duck were the most numerous game species (c. 1,248,000), followed by Grey Teal (c. 616,000), Australian Shelduck (c. 510,000) and Pacific Black Duck (c. 447,000) (Table 6). Abundances of Chestnut Teal, Pink-eared Duck and Hardhead were each less than 100,000 (Table 6). The precision of the overall estimate of abundance was good, with a 10% coefficient of variation, well 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 has also improved compared with the previous survey, with coefficients of variation for Grey Teal, Wood Duck and Pacific Black Duck being at, or close to, the nominal target of 15% coefficient of variation

(Table 6). However, the estimates for Australian Shelduck, Chestnut Teal, Hardhead and Pink-eared Duck had low precision, with a coefficient of variation of >25%.

3.4.2 Model-based estimates

The estimate of the total abundance of game ducks using the model-based approach was similar to the design-based estimate at 2,820,800 (Table 7). Estimates for Australian Wood Duck, Grey and Chestnut Teal, Pacific Black Duck and Pink-eared Duck were broadly similar to the design-based estimates, with estimates for Australian Shelduck and Hardhead showing the most discrepancy from the design-based estimates (Table 7). The precision of the overall estimate of abundance was excellent, with a 5% coefficient of variation. The precision of the estimates for individual species was also good, with only the precision for Hardhead, Chestnut Teal and Pink-eared Duck exceeding 15% (Table 7).

Table 6: Summary of design-based estimates of total abundance of seven 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 interval; UCL = upper 90% confidence interval.

Species	Estimate	SE	CV	LCL	UCL
AS	509,900	189,900	0.37	281,800	922,600
WD	1,248,200	197,400	0.16	963,800	1,616,400
CT	62,700	21,500	0.34	36,200	108,600
GT	616,000	84,900	0.14	491,500	771,900
HH	13,300	4,000	0.30	8,200	21,500
PBD	446,600	69,700	0.16	346,100	576,400
PED	62,000	17,500	0.28	39,400	97,700
Total	**2,958,700**	**296,500**	**0.10**	**2,510,200**	**3,487,400**

Table 7: Summary of model-based estimates of total abundance of seven 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 interval; UCL = upper 90% confidence interval.

Species	Estimate	SE	CV	LCL	UCL
AS	265,800	39,100	0.15	210,500	334,300
WD	1,410,400	113,100	0.08	1,232,100	1,589,900
CT	90,300	21,900	0.24	58,300	132,400
GT	655,500	68,000	0.10	553,300	768,000
HH	28,300	10,000	0.35	15,800	51,900
PBD	326,000	31,900	0.10	273,500	379,100
PED	44,500	9,400	0.21	31,100	219,600
Total	**2,820,800**	**143,700**	**0.05**	**2,594,200**	**3,067,100**

The majority of game ducks occurred on small farm dams (<6 ha), especially Australian Wood Duck, Grey Teal, Australian Shelduck and Pacific Black Duck (Figure 5). These species, along with Chestnut Teal, also occurred in large numbers on rivers and streams. In contrast, Pink-eared Duck and Hardhead occurred predominantly on wetlands (Figure 5). Game ducks were more numerous in the North and South bioregions and were least numerous in the East bioregion (Figure 6).

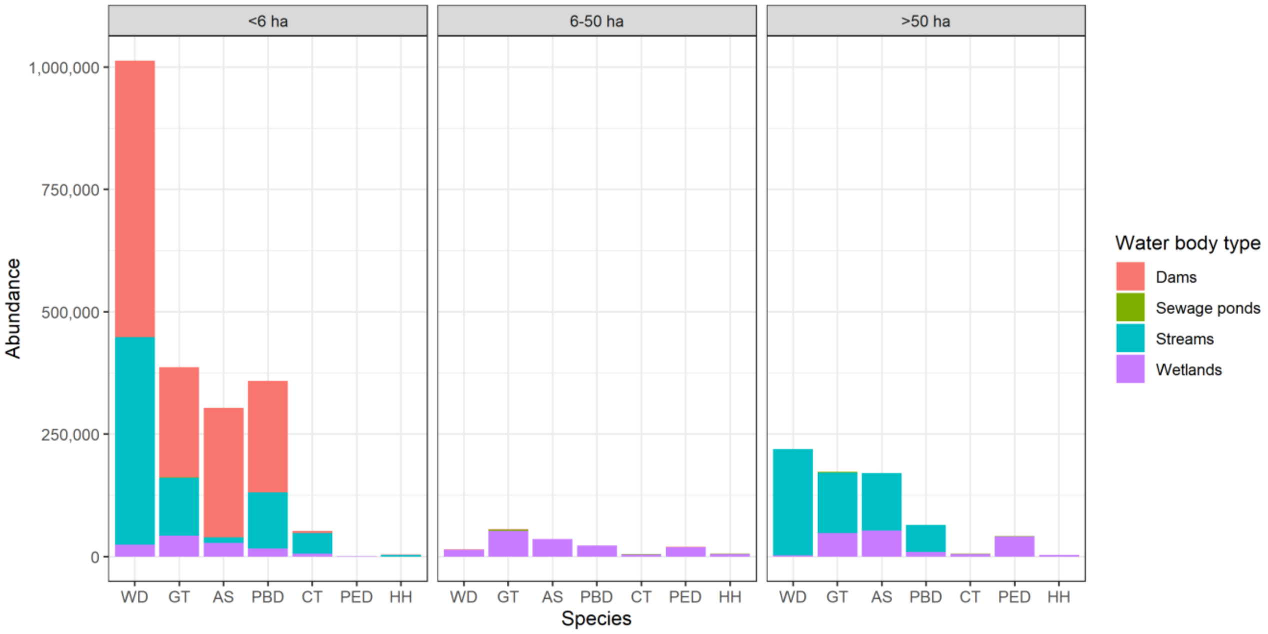


Figure 5. Abundance of game duck species by water body type and size class. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck; HH = Hardhead; PED = Pink-eared Duck.

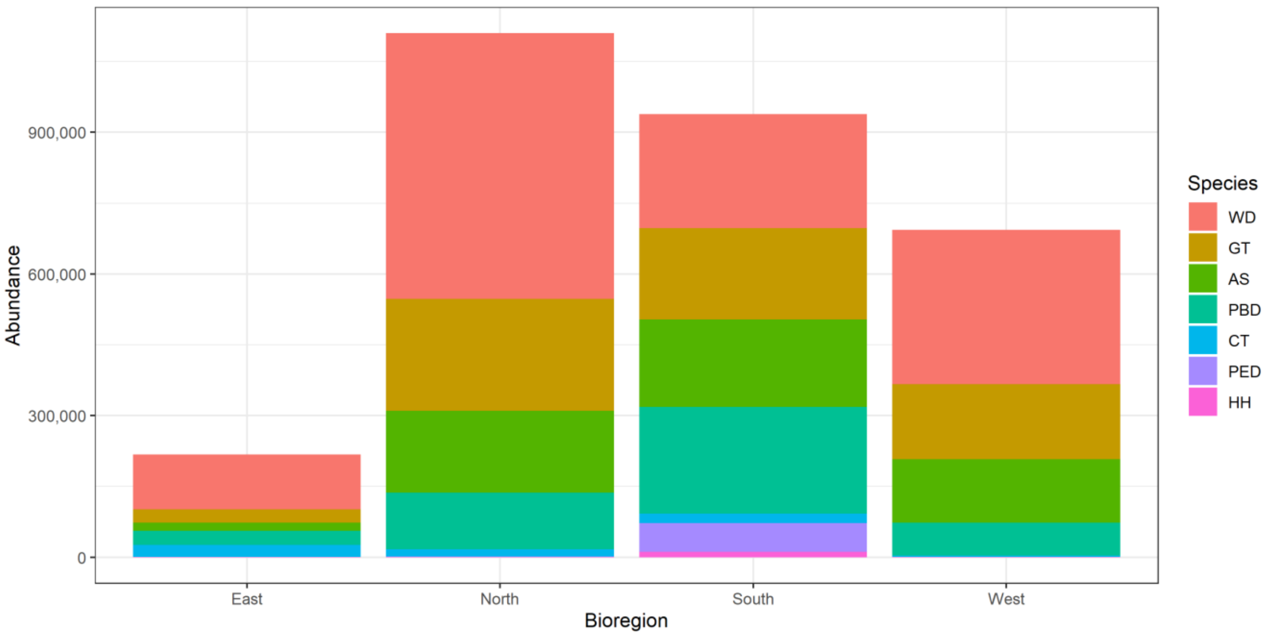


Figure 6. Abundance of game duck species by bioregion. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck; HH = Hardhead; PED = Pink-eared Duck.

3.4.3 Predicting abundance outside Victoria

Predictions of the abundance of seven of the eight game duck species (excluding Australasian Shoveler) in the Riverina district, using model-based inference 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 given in Vardanega et al. (2021) (Table 8). Predictions underestimated the number of Grey Teal, Australian Wood Duck, Pacific Black Duck, Pink-eared Duck and Hardhead in the Riverina by between 34% and 86%, while predictions overestimated the number of Chestnut Teal and Australian Shelduck (Table 8). However, despite these errors, predictions were generally around the correct order of magnitude.

Table 8. 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 – the independent estimate was based on aerial surveys undertaken by Vardanega et al. (2021) during April/May 2021. GT = Grey Teal; CT = Chestnut Teal; WD = Australian Wood Duck; AS = Australian Shelduck; PBD = Pacific Black Duck; HH = Hardhead; PED = Pink-eared Duck.

Type	Size class	GT	CT	WD	AS	PBD	PED	HH
Dams	<6 ha	129,780	768	354,459	9,234	53,092	178	758
	6–50 ha	3,082	19	6,826	210	875	26	43
	>50 ha	1,072	0	539	143	139	27	13
Total (predicted)		133,934	787	361,824	9,587	54,106	231	814
Riverina (actual)		322,796	513	551,729	4,589	145,493	1,731	1,411
Relative bias		–59%	+53%	–34%	+109%	–62%	–86%	–42%

4 Discussion

Compared with the pilot survey conducted in 2020, the 2021 aerial and ground surveys of game ducks has provided estimates of abundance with improved precision for the main game species, Grey Teal, Wood Duck and Pacific Black Duck. In addition, the 2021 survey was also able to obtain separate estimates for Grey and Chestnut Teal and included additional water body types, with duck abundances being estimated for the first time in both sewage treatment ponds and waterways (rivers/streams), in addition to dams and wetlands. However, inadequate sampling coverage was obtained for irrigation channels due to many of the channels selected for sampling being either dry or not present at the recorded location. Future surveys should modify the sampling scheme for irrigation channels to only include the major channels.

Abundance estimates for some of the main game species, Australian Wood Duck, Pacific Black Duck and Australian Shelduck, have increased compared with the 2020 survey (Ramsey and Fanson 2021), especially Australian Wood Duck, which was around twice as abundant (1.2 M cf. 0.68 M birds). However, this increase was due primarily to the inclusion of estimates for rivers and streams in the 2021 survey, in which Wood Duck were abundant. In contrast, Grey Teal and Hardhead have declined in abundance compared with the 2020 survey. The rainfall in south-eastern Australia during spring of 2021 was the highest since 2010, with rainfall in NSW reaching 60% and Victoria 24% above the long-term average (Bureau of Meteorology 2021). This was reflected in the higher estimates of surface water area over the late winter – spring period in Victoria in 2021 compared with in 2020. Increased water availability in the wider landscape may result in dispersal of ducks, especially for species that have long-range and dispersive movements, such as Grey Teal (Roshier et al. 2008). This dispersive behaviour may manifest as reductions in abundance more locally. In contrast, species known to be relatively sedentary, such as Australian Wood Ducks, may exhibit increases in local abundance in response to increased water availability.

The increase in the estimate of the area of surface water in 2021 was a result of increases recorded in wetlands, with surface water in dams estimated to have declined. The reasons for this apparent anomaly are unknown, but it could be due to classification errors and/or errors in the underlying spatial layer recording farm dam locations. This should be subject to further investigation. In particular, the spatial layer recording farm dam locations is likely to be dynamic, as farm dams are added and/or removed by landholders. Hence, this layer should incorporate any updates as they become available. As the detection of surface water from satellite imagery is an active research area, it is possible that the algorithms used to classify surface water will be subject to improvements. It will be important to review the key changes to algorithms for detecting surface water from satellite imagery and to incorporate relevant improvements in surface water area estimates into future surveys.

The inclusion of ground surveys in the 2021 survey allowed sampling of water bodies that could not be monitored by aerial surveys, due to the presence of hazards or other airspace restrictions. (For example, ground surveys were necessary for most sewage ponds due to the airspace restrictions near towns, where most sewage ponds are located.) Ground surveys by two observers had higher detection probabilities than comparable aerial surveys. Averaged over all attributes affecting detection rates (habitat, water body size, and surface glare), detection probabilities were 0.70 for ground surveys and 0.44 for aerial surveys. However, the magnitude of the difference was dependent on water body attributes, with the largest difference occurring for larger water bodies in wooded habitat, which had high detection probabilities for ground surveys (0.7–0.9) but low detection probabilities for aerial surveys (0.1–0.3). This may have been due to the greater disturbance of ducks by the helicopter, compared with ground surveys, resulting in more birds escaping detection in more complex, wooded habitat. In addition, ground surveys on larger waterbodies monitored ducks from multiple vantage points to increase coverage. This search strategy likely improved detection rates for ground surveys in wooded habitat compared with aerial surveys. In contrast, detection probabilities for small water bodies in open habitat were relatively similar between aerial and ground surveys (aerial 0.72, ground 0.80).

Compared with the 2020 survey (Ramsey and Fanson 2021), the simpler stratified random design for the 2021 survey has resulted in a more balanced sample size among the different strata. This has resulted in a higher proportion of the sample now comprising wetlands (64%) compared with the 2020 survey (17%).

However, the sample size of waterways was still relatively low for their availability in the landscape, with only 26 rivers/streams being subject to monitoring. This was due to waterways being a recently added stratum, with sampling undertaken principally for evaluation purposes. Subsequently, monitoring data has revealed that waterways are important habitat for game ducks, especially Australian Wood Duck, Grey and Chestnut Teal, and Pacific Black Duck. Hence, it is recommended that waterways are subject to increased sampling effort, to improve the precision of abundance estimates for this stratum.

Model-based estimates used to predict the abundance of game duck species in the Riverina district of NSW showed mixed results when compared with the independent estimates in Vardanega et al. (2021). While predictions were broadly comparable, some species (e.g. Australian Shelduck) had predicted abundances that varied greatly from the independent estimates in Vardanega et al. (2021). The majority of this variance is likely to be attributable to the differences in time of year at which the respective surveys were conducted (the Riverina surveys were conducted in May 2021). However, there is also likely to be other regional factors driving the abundance of game duck species in the Riverina district that are not captured by the models used here. Further investigation of the factors driving variation in abundance of game ducks is, therefore, required in order to improve the reliability of model-based estimates.

In conclusion, analysis of the 2021 aerial and ground surveys of game ducks in Victoria has indicated that aerial surveying of game ducks could provide more robust estimates of abundance across the state. Such estimates in turn would be a suitable 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 so as to provide more 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 water bodies (825, excluding irrigation channels) should be retained and used for future surveys. However, minor adjustments to the sample sizes for some strata will be required, and these are detailed below.
- The number of sampled waterways (rivers and large streams) in the sampling design be increased to at least 100 (i.e. 25 per region).
- The spatial layers for irrigation channels be revised to only include large channels; resample the revised layers to obtain a sample size of at least 50.
- To improve the model-based estimates of duck abundance, investigate additional habitat variables, such as land use, water body proximity, and climate variables, in order to better describe variation in duck abundance (to provide more confidence in model-based predictions).
- 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. Review key changes to algorithms for detecting surface water from satellite imagery and incorporate relevant changes to improve surface water estimates area in future surveys.

References

Bureau of Meteorology. (2021). *Seasonal Summary for Australia – 2021*. Available at: http://www.bom.gov.au/climate/current/season/aus/summary.shtml (accessed 28 January 2022).

Carpenter, B., Gelman, A., Hoffman, M.D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P. and Riddell, A. (2017). Stan : a probabilistic programming language. *Journal of Statistical Software* **76**, 1–32. doi:10.18637/jss.v076.i01

DEWNR. (2016). *Assessment of waterfowl abundance and wetland condition in south-eastern South Australia*. Department of Environment, Water and Natural Resources, Adelaide, South Australia.

Gelman, A., Goodrich, B., Gabry, J., and Vehtari, A. (2019). R-squared for Bayesian regression models. *The American Statistician* **73**, 307–309. doi:10.1080/00031305.2018.1549100

Gelman, A. and Hill, J. (2007). *Data Analysis Using Regression and Multilevel/Hierarchical Models*, 1st edn. Cambridge University Press, New York, USA.

Hankin, D.G. (1984). Multistage sampling designs in fisheries research: applications in small streams. *Canadian Journal of Fisheries and Aquatic Sciences* **41**, 1575–1591.

Horvitz, D.G. and Thompson, D.J. (1952). A generalization of sampling without replacement from a finite universe. *Journal of the American Statistical Association* **47**, 663–685.

Kingsford, R.T. and Porter, J.L. (2009). Monitoring waterbird populations with aerial surveys – what have we learnt? *Wildlife Research* **36**, 29.

Menkhorst, P., Stamation, K. and Brown, G. (2019). *Victorian Summer Waterbird Count 2019.* Unpublished Client Report, Arthur Rylah Institute for Environmental Research, Heidelberg, Victoria.

Mueller, N., Lewis, A., Roberts, D., Ring, S., Melrose, R., Sixsmith, J., Lymburner, L., McIntyre, A., Tan, P., Curnow, S. and Ip, A. (2016). Water observations from space: mapping surface water from 25y ears of Landsat imagery across Australia. *Remote Sensing of Environment* **174**, 341–352. doi:10.1016/j.rse.2015.11.003

Nichols, J.D., Runge, M.C., Johnson, F.A. and Williams, B.K. (2007). Adaptive harvest management of North American waterfowl populations: a brief history and future prospects. *Journal of Ornithology* **148**, 343–349.

Pekel, J.-F., Cottam, A., Gorelick, N. and Belward, A.S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature* **540**, 418–422.

Prowse, T.A.A. and Kingsford, R.T. (2021). Review of Ramsey and Fanson (2021) Abundance estimates for games ducks in Victoria. Unpublished report to the Game Management Authority. Available at: https://www.gma.vic.gov.au/__data/assets/pdf_file/0003/819282/Game-duck-review-Kingsford-Prowse.pdf

Ramsey, D.S.L. (2020). Design of a monitoring program for game ducks in Victoria. Arthur Rylah Institute for Environmental Research Technical Report Series No. 314. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Ramsey, D.S.L. and Fanson, B. (2021). Abundance estimates of game ducks in Victoria: results from the 2020 aerial survey. Arthur Rylah Institute for Environmental Research Technical Report Series No. 325, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Ramsey, D.S.L., Pacioni, C., Mcleod, S. and Dundas, S. (2017). Towards the implementation of adaptive harvest management of waterfowl in south-eastern Australia. Arthur Rylah Institute for Environmental Research Technical Report Series No. 284, Heidelberg, Victoria.

Roshier, D., Asmus, M. and Klaassen, M. (2008). What drives long-distance movements in the nomadic Grey Teal *Anas gracilis* in Australia? *Ibis* **150**, 474–484.

Royle, J.A. (2004). N-Mixture models for estimating population size from spatially replicated counts. *Biometrics* **60**, 108–115. doi:doi:10.1111/j.0006-341X.2004.00142.x

Skalski, J.R. (1994). Estimating wildlife populations based on incomplete area surveys. *Wildlife Society Bulletin* **22**, 192–203.

Thompson, S.K. (1992). *Sampling*. John Wiley & Sons, New York, USA.

Vardanega, M., Dundas, S.J. and McLeod, S.R. (2021). *2021–2022 annual waterfowl quota report to DPI Hunting*, NSW Department of Primary Industries. NSW Department of Primary Industries, Orange, NSW.

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 water body i and stratum h derived from the fitted N-mixture ZIP model (section 2.4.1), m is the number of sampled water bodies in stratum h, and π_h is the inclusion probability for a water body 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 water bodies 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

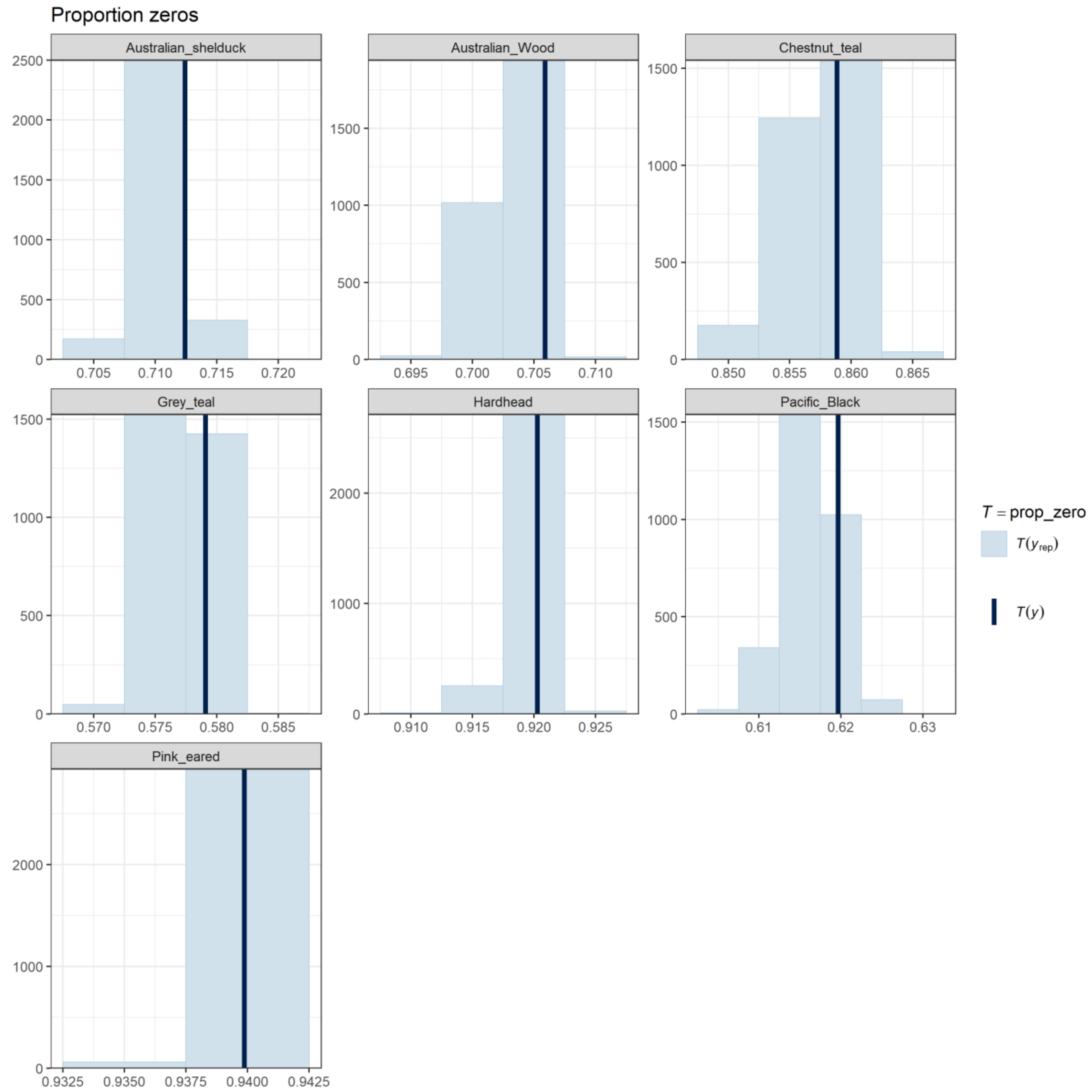
$$\hat{N}_T = \sum_{h=1}^{H} \hat{\tau}_h \qquad (Equation\ 2)$$

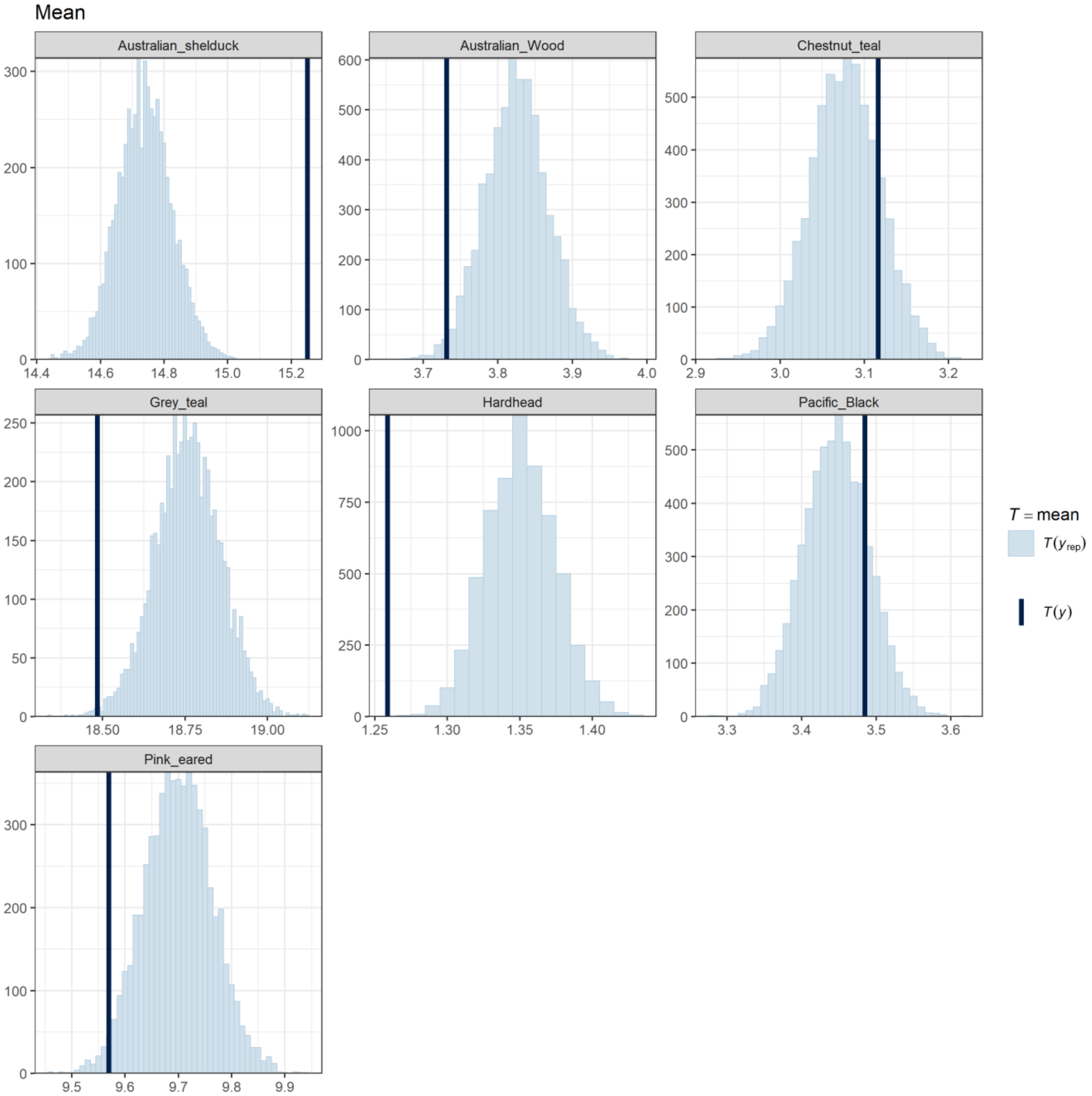
with variance

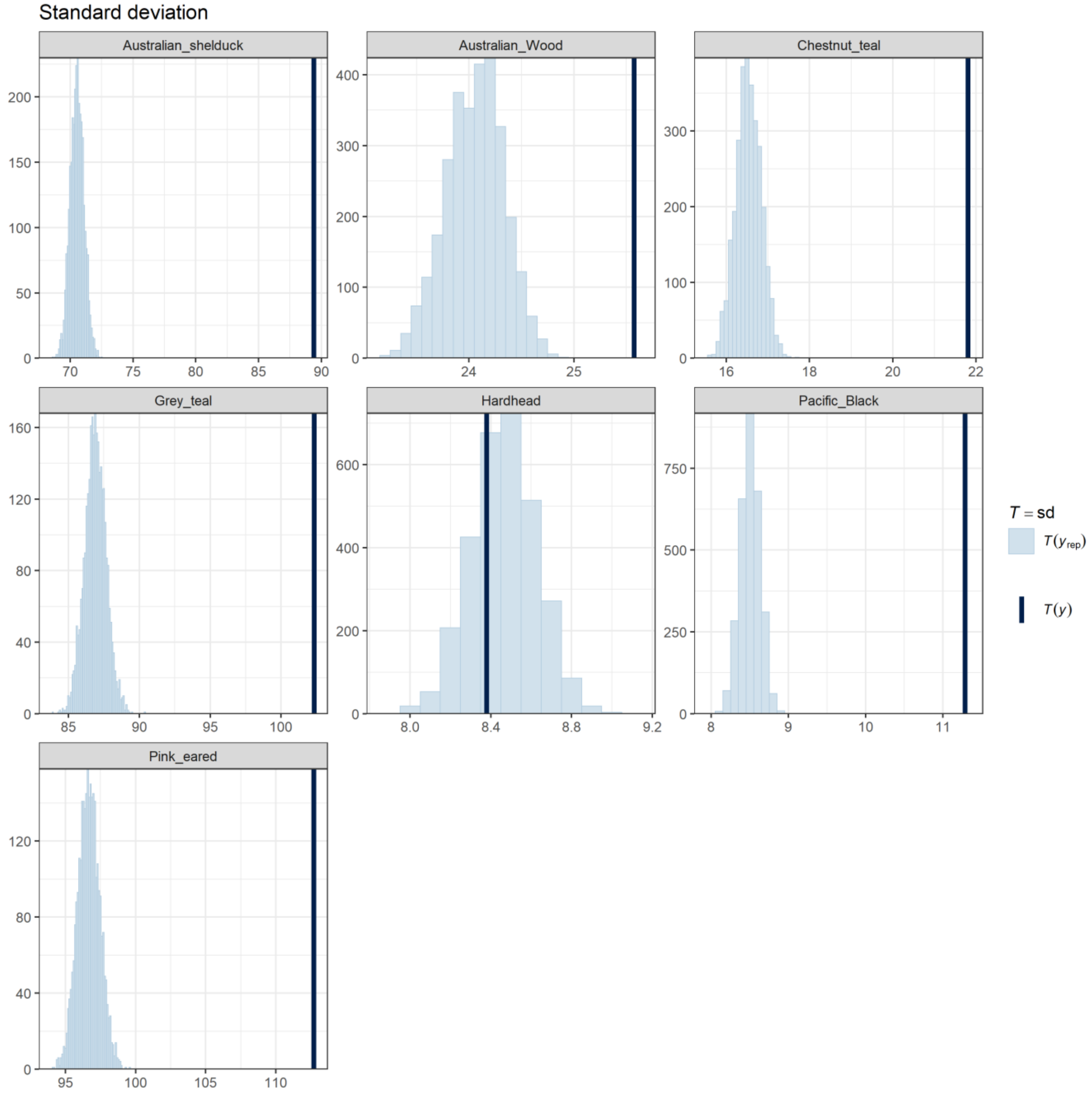
$$\text{var}(\hat{N}_T) = \sum_{h=1}^{H} \text{var}(\hat{\tau}_h) \qquad (Equation\ 3)$$

Appendix B

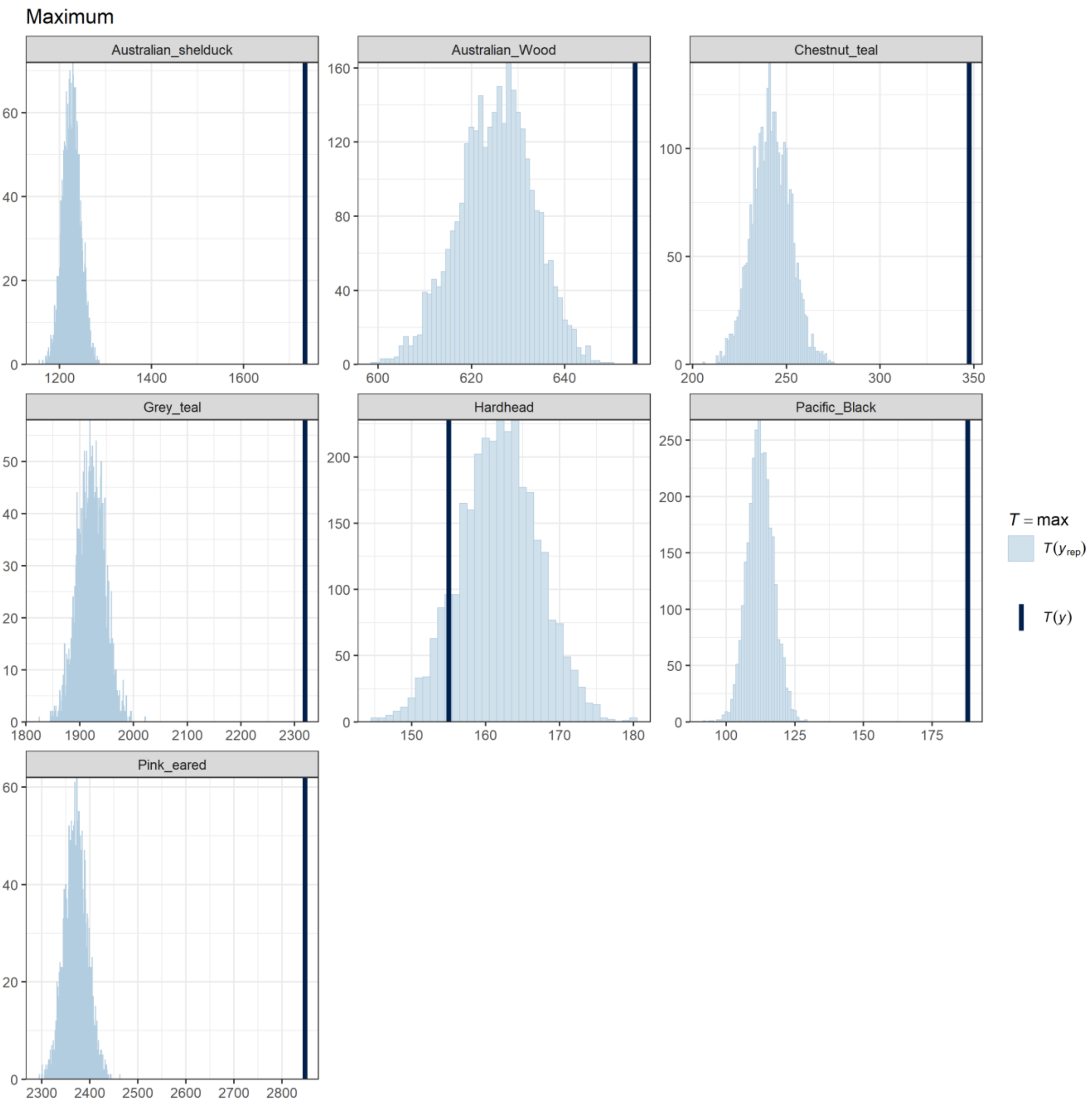
Posterior predictive checks comparing summary statistics $\boldsymbol{T}$ of the predicted counts for each game duck species under the model (equation 1), with the observed counts on each water body. The summary statistics are the proportion of water bodies with zero counts, the mean total count, the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




Mean
Australian_shelduck
Australian_Wood
Chestnut_teal
Grey_teal
Hardhead
Pacific_Black
Pink_eared
T = mean
T(y_rep)
T(y)



Standard deviation
Australian_shelduck
Australian_Wood
Chestnut_teal
Grey_teal
Hardhead
Pacific_Black
Pink_eared
T = sd
T(y_rep)
T(y)


Maximum
Australian_shelduck
Australian_Wood
Chestnut_teal
Grey_teal
Hardhead
Pacific_Black
Pink_eared
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	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Grey Teal	Dam	<6 ha	225,048	68,045	0.302	126,042	401,824	173	151,435
	Dam	6–50 ha	624	351	0.562	224	1,742	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	687	143	0.208	459	1,028	16	42
	Sewage ponds	6–50 ha	2,745	399	0.145	2,067	3,645	16	44
	Sewage ponds	>50 ha	2,059	44	0.021	1,975	2,146	5	5
	Stream	<6 ha	118,444	44,938	0.379	57,725	243,033	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	12,3559	20,474	0.166	89,492	170,595	10	712
	Wetland	<6 ha	43,002	8,134	0.189	29,777	62,100	156	5,166
	Wetland	6–50 ha	52,178	6,067	0.116	41,576	65,484	182	1,379
	Wetland	>50 ha	48,075	5,868	0.122	37,879	61,015	166	354

Species	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Australian Wood Duck	Dam	<6 ha	567,447	89,709	0.158	417,048	772,084	173	151,435
	Dam	6–50 ha	1,250	701	0.561	448	3,485	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	77	23	0.299	43	137	16	42
	Sewage ponds	6–50 ha	128	36	0.281	74	220	16	44
	Sewage ponds	>50 ha	58	4	0.069	50	67	5	5
	Stream	<6 ha	423,385	170,360	0.402	198,152	904,632	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	217,215	43,078	0.198	147,810	319,209	10	712
	Wetland	<6 ha	24,658	5,787	0.235	15,662	38,821	156	5,166
	Wetland	6–50 ha	13,609	2,378	0.175	9,688	19,117	182	1,379
	Wetland	>50 ha	2,697	423	0.157	1,987	3,661	166	354

Species	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Australian Shelduck	Dam	<6 ha	264,249	170,294	0.644	83,243	838,842	173	151,435
	Dam	6–50 ha	173	44	0.254	105	284	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	182	39	0.214	120	277	16	42
	Sewage ponds	6–50 ha	210	61	0.29	120	367	16	44
	Sewage ponds	>50 ha	201	9	0.045	183	220	5	5
	Stream	<6 ha	11,465	11,459	0.999	2,244	58,585	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	117,644	82,504	0.701	34,058	406,367	10	712
	Wetland	<6 ha	27,524	7,271	0.264	16,544	45,792	156	5,166
	Wetland	6–50 ha	35,697	5,635	0.158	26,248	48,548	182	1,379
	Wetland	>50 ha	52,888	8,766	0.166	38,302	73,028	166	354

Species	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Pacific Black Duck	Dam	<6 ha	227,898	61,038	0.268	136,051	381,751	173	151,435
	Dam	6–50 ha	104	38	0.365	52	208	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	27	16	0.593	9	80	16	42
	Sewage ponds	6–50 ha	201	100	0.498	80	506	16	44
	Sewage ponds	>50 ha	0	0	0	0	0	5	5
	Stream	<6 ha	114,479	31,064	0.271	67,896	193,024	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	55,207	12,180	0.221	36,010	84,638	10	712
	Wetland	<6 ha	16,527	2,682	0.162	12,050	22,668	156	5,166
	Wetland	6–50 ha	22,356	2,282	0.102	18,311	27,294	182	1,379
	Wetland	>50 ha	9,825	891	0.091	8,229	11,731	166	354

Species	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Chestnut Teal	Dam	<6 ha	4,003	2,339	0.584	1,384	11,578	173	151,435
	Dam	6–50 ha	35	18	0.514	14	89	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	279	77	0.276	164	476	16	42
	Sewage ponds	6–50 ha	246	80	0.325	132	457	16	44
	Sewage ponds	>50 ha	394	14	0.036	367	423	5	5
	Stream	<6 ha	45,762	23,614	0.516	17,657	118,602	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	0	10	–	0	0	10	712
	Wetland	<6 ha	5,869	1,592	0.271	3,481	9,894	156	5,166
	Wetland	6–50 ha	4,599	1,090	0.237	2,908	7,273	182	1,379
	Wetland	>50 ha	5,531	898	0.162	4,032	7,588	166	354

Species	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Hardhead	Dam	<6 ha	480	480	1	94	2,452	173	151,435
	Dam	6–50 ha	152	101	0.664	46	498	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	116	44	0.379	57	237	16	42
	Sewage ponds	6–50 ha	253	82	0.324	136	469	16	44
	Sewage ponds	>50 ha	133	7	0.053	120	147	5	5
	Stream	<6 ha	3,260	3,258	0.999	638	16,657	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	0	22	–	0	0	10	712
	Wetland	<6 ha	237	221	0.932	50	1,117	156	5,166
	Wetland	6–50 ha	5,326	1,991	0.374	2,622	10,820	182	1,379
	Wetland	>50 ha	3,354	989	0.295	1,904	5,907	166	354

Species	Water body	Size class	*N*	SE	CV	LCL	UCL	*m*	*M*
Pink-eared Duck	Dam	<6 ha	0	6	–	0	0	173	151,435
	Dam	6–50 ha	45	23	0.511	17	116	23	114
	Dam	>50 ha	0	0	0	0	0	0	0
	Sewage ponds	<6 ha	109	58	0.532	41	292	16	42
	Sewage ponds	6–50 ha	380	155	0.408	176	821	16	44
	Sewage ponds	>50 ha	1,110	25	0.023	1,062	1,160	5	5
	Stream	<6 ha	0	3	–	0	0	16	10,440
	Stream	6–50 ha	0	0	0	0	0	0	0
	Stream	>50 ha	0	5	–	0	0	10	712
	Wetland	<6 ha	609	521	0.856	143	2,601	156	5,166
	Wetland	6–50 ha	19,165	11,894	0.621	6,261	58,666	182	1,379
	Wetland	>50 ha	40,603	12,772	0.315	22,238	74,134	166	354

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