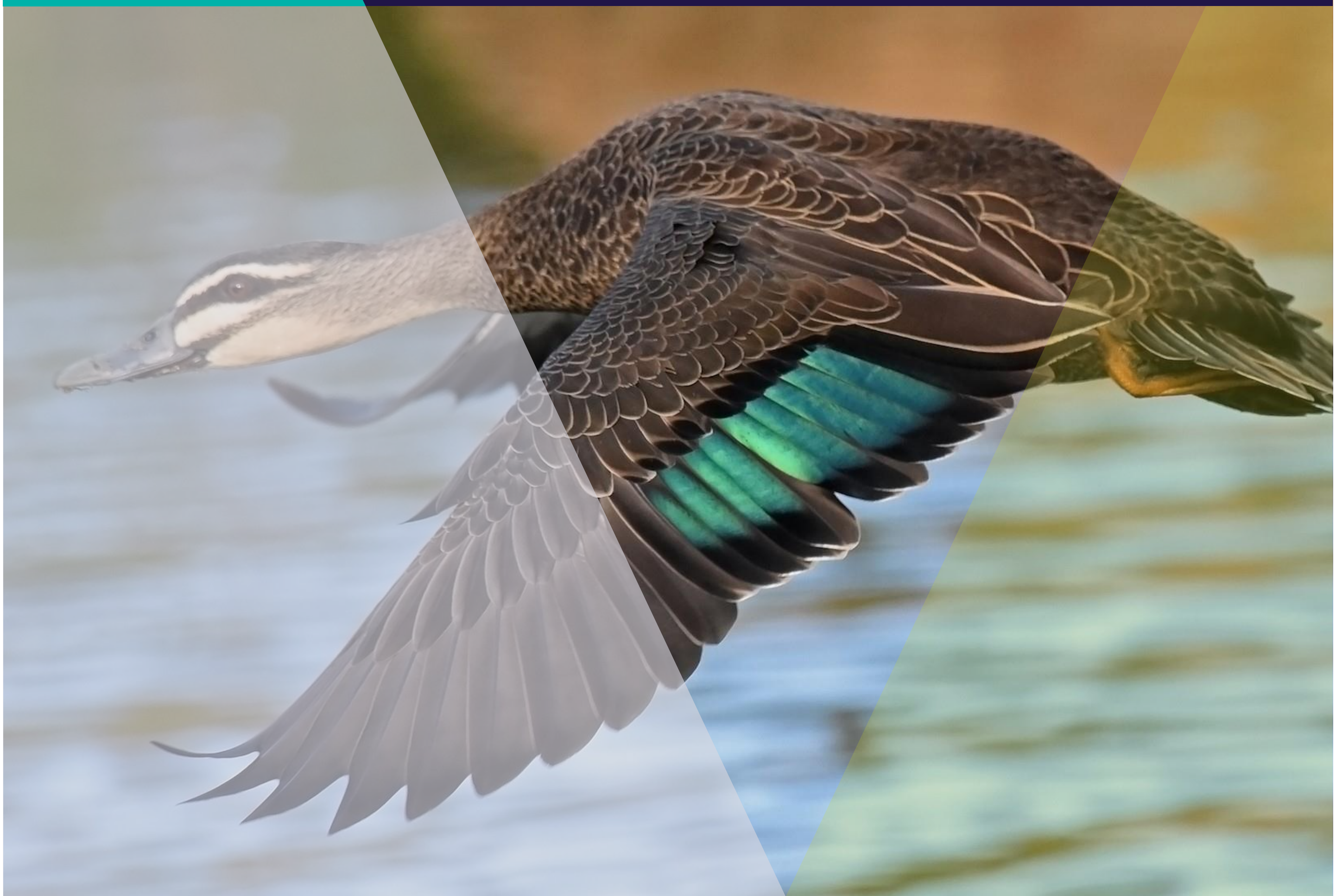
Design of a Monitoring Program for Game Ducks in Victoria

D.S.L. Ramsey

June 2020



Arthur Rylah Institute for Environmental Research
Technical Report Series No. 314

Arthur Rylah Institute for environmental research
Game Management Authority
VICTORIA State Government
Environment, Land, Water and Planning

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.

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
PO Box 137
Heidelberg, Victoria 3084
Phone (03) 9450 8600
Website: www.ari.vic.gov.au

Citation: 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.

Front cover photo: Pacific Black Duck (*Anas superciliosa*) (Dan Forster. Available at https://ebird.org/).

Printed by Melbourne Polytechnic, Preston

Edited by David Meagher, Zymurgy SPS

ISSN 1835-3827 (print)
ISSN 1835-3835 (pdf))
ISBN 978-1-76105-208-8 (Print)
ISBN 978-1-76105-209-5 (pdf/online/MS word)

Accessibility

If you would like to receive this publication in an alternative format, please telephone the DELWP Customer Service Centre on 136 186, email customer.service@delwp.vic.gov.au or contact us via the National Relay Service on 133 677 or www.relayservice.com.au. This document is also available on the internet at www.delwp.vic.gov.au

Design of a Monitoring Program for Game Ducks in Victoria

David S.L. Ramsey

Arthur Rylah Institute for Environmental Research
123 Brown Street, Heidelberg, Victoria 3084

Arthur Rylah Institute for Environmental Research
Technical Report Series No. 314

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
Heidelberg, Victoria

Acknowledgements

The author would like to thank Simon Toop, Jordan Hampton, Ben Fanson and Peter Menkhorst for providing comments on a draft of this report.

Contents

Tables

Figures

Summary

Context:

The Victorian Government is seeking to adopt a more defensible and rigorous method for regulating the recreational harvest of game ducks in Victoria, such as Adaptive Harvest Management (AHM). In order to implement AHM, robust estimates of the total abundances of game ducks in Victoria are required. In addition, AHM also requires the establishment of a relationship between seasonal harvest regulations (i.e. bag limits and season length) and either the harvesting rate or total harvest size.

Aims:

- To determine the optimal number of waterbodies for aerial survey needed to estimate the abundance of game duck species in Victoria for use in AHM.
- Conduct an analysis of historical game duck harvests in Victoria to determine whether a suitable relationship between the size of the recreational harvest and seasonal arrangements (i.e. bag limits and season length) can be identified.

Methods:

Various sampling designs for aerial surveys of waterbodies in Victoria were investigated using Monte Carlo simulation techniques, to identify designs with an optimal balance between the competing criteria of survey accuracy (i.e. bias and precision) and total cost. An inventory of waterbodies in Victoria (natural wetlands and impoundments, but excluding rivers and streams) was assembled from spatial data sources and used to construct sampling designs. Two scenarios were derived to define the sampling frame to assess each survey design: a 'wet' scenario representing waterbodies likely to contain water during high rainfall or low flow years and a 'dry' scenario representing waterbodies likely to contain water during low rainfall or low flow years. Each waterbody was classified into three types (natural wetlands, dams and sewage treatment ponds) and three size classes (< 6 ha, 6–50 ha, > 50 ha), which were used as separate strata in the sampling designs. Counts of game duck species collected between 1970 and 2009 during the Victorian summer waterfowl count were analysed to provide estimates of the likely numbers of game ducks on waterbodies for each stratum. Two main sampling designs were investigated: a stratified random sampling design and a multistage (cluster) sampling design. For each of these designs, various sample sizes were selected using an unequal probability selection strategy to ensure sufficient samples for each stratum were analysed. For each waterbody selected for sampling, game duck numbers were simulated and then sampled by simulating aerial counts from a helicopter using the point-count removal technique. Total abundance of each game duck species for Victoria was then estimated using model-based as well as design-based inference procedures that accounted for imperfect detection as well as the unequal probabilities of sample unit selection. Total costs of each survey design were also estimated, based on the travel costs between sampled waterbodies as well as personnel costs incurred over the estimated duration of sampling.

The analysis of historical game duck harvest offtake in Victoria between 2009 and 2019 to determine the relationship between seasonal harvest regulations and the size of the recreational harvest, was undertaken using a Bayesian generalised linear model. The fitted model was then used to estimate the size of the total recreational harvest of game ducks predicted by changes in the bag limit and season length, conditional on the total number of licensed hunters.

Results:

Stratified random sampling designs were the most efficient (low bias and high precision for a fixed cost) under design-based inference but were inefficient under model-based inference, having high bias when the fitted model was mildly misspecified. Multistage sampling designs were generally slightly less efficient but were more robust to model misspecification. For a given sample size, multistage sampling designs generally had lower costs than the equivalent stratified random design as the former had lower travel costs due to the sampling of waterbodies in clusters. A multistage sampling design that sampled 80 primary units (clusters) of 10 km with up to 10 waterbodies sampled per unit (total of 500–600 waterbodies) had acceptable

accuracy (mean relative bias of 5% and mean coefficient of variation of 15%) and should be suitable for either model-based or design-based estimates of game duck abundance in Victoria in both 'dry' and 'wet' years. The estimated cost of implementing this sampling design was around $280,000. However, this does not include costs associated with project planning and management, logistics and data analysis.

Results from the generalised linear model of the relationship between total game duck harvest and seasonal arrangements indicated that both bag limit and season length were positively related to harvest size. Predictions from the model were a reasonable fit to the data, explaining around 78% of the variation in the total game duck harvest. The model predicted that a change in the bag limit by one standard deviation (i.e. ± 2.6 ducks) resulted in a change in the total harvest by 21% and a similar change to the season length (i.e. ±12.6 days) resulted in a change in the total harvest by 22%.

Conclusions and implications:

The regulation of recreational game duck harvesting using AHM requires the development of a population model, which requires the assessment of population abundance and harvesting rates over several years in order to estimate critical parameters and calibrate the model. In the interim, a proportional harvest strategy can be adopted for regulating game duck harvests which only requires an assessment of population size and total harvest. Such proportional harvest strategies have been used successfully to set sustainable harvest quotas for ducks in New South Wales.

The simulation approach used here to assess sampling designs was based on a number of simplifying assumptions and is likely to under-represent the amount of natural variation in real monitoring data. Hence, the actual performance of the survey design could differ substantially from its theoretical performance and thus should be refined following collection of an initial set of monitoring data. We suggest that a pilot survey is undertaken, designed using the principles and recommended survey effort identified in this report. The collection of monitoring data through a pilot study would be invaluable for refining the survey design and updating the likely amount of monitoring effort and associated costs required to achieve the desired survey accuracy. Another advantage of collecting data through an initial pilot survey would be that the resulting model could be tested against similar survey data collected in other jurisdictions, such as the NSW Riverina (Dundas *et al.* 2019), to determine whether the model could potentially be used to predict game duck abundances outside Victoria.

Recommendations

- Consider implementing a proportional harvest scheme as a more robust method for regulating game duck harvest in Victoria as it transitions to Adaptive Harvest Management.
- If a proportional harvest scheme was adopted, cap the maximum quotas for recreational offtake of game ducks under a proportional harvest scheme at 10% of the total population size until sufficient data accumulates to make a more informative quota assessment.
- Estimate the total population size of game ducks in Victoria in summer each year, just prior to the recreational hunting season, to facilitate the implementation of the proportional harvest scheme if it was adopted.
- Conduct aerial surveys to estimate the population size of game ducks, using a multistage random sampling design to sample 500–600 waterbodies. The implementation of this survey design would be likely to cost around $280,000, which does not include additional costs associated with survey planning, project management, logistics and data analysis.
- Undertake a pilot study to collect aerial survey data, in order to assess the performance of the recommended survey design under actual conditions. The monitoring data collected should then be used to refine the recommended survey design.
- Following refinement of the survey design and estimators using the pilot survey data, undertake further testing on similar monitoring data collected in the Riverina to determine the suitability of the methods for predicting game duck abundances outside Victoria.
- If a move to a proportional harvest scheme was adopted, use the statistical relationship between total recreational harvest, bag limits, season length and numbers of licensed hunters identified in this report to set the annual seasonal arrangements (bag limits and season length).

1 Introduction

Adaptive Harvest Management (AHM) is a scientific approach to the management of wild population harvests. It seeks to understand the potential of wild populations to support harvesting, the ability of managers to regulate harvesting, and the influence of environmental, social and economic factors on management decisions (Nichols *et al.* 2007; Johnson 2011; Johnson *et al.* 2015). AHM has been successfully applied to the management of waterfowl harvest in North America for mid-continental Mallards (*Anas platyrhynchos*) (Johnson *et al.* 1997) and Northern Europe for pink-footed goose (*Anser brachyrhynchus*) (Madsen *et al.* 2017).

Recent reviews of AHM for the management of game duck harvesting in south-eastern Australia (Ramsey *et al.* 2010; Ramsey *et al.* 2017) identified the annual collection of reliable waterfowl monitoring data as being essential for the successful implementation of AHM. Currently, the Eastern Australian Aerial Waterbird Count (EAAWC) is the only spatially and temporally extensive source of monitoring data for waterbirds in Australia (Kingsford and Porter 2009). However, EAAWC coverage of Victorian wetlands is relatively poor and the survey methods have several 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. Hence, the review by Ramsey *et al*. (2017) recommended investigating alternative monitoring designs that would be suitable for estimating the abundance of both mobile and sedentary game duck species at both a state and regional level.

Monitoring design principles

An important goal of any monitoring or survey designed to estimate the abundance of a wildlife population is to determine the appropriate level of effort required to conduct the survey; that is, the amount of effort that results in an unbiased estimate with a level of precision (confidence) that is useful for deciding among management alternatives. Hence, the goal of a survey design is to allocate the appropriate resources (effort and cost) to each of the components of the survey, the number and size of sampling units, and the amount of monitoring effort to allocate to each unit.

The first step in planning a survey is to decide on the objectives. In the context of providing information to inform AHM, the objectives of the survey are to provide estimates of absolute abundance (i.e. corrected for imperfect detection) of each game duck species so that the harvest rate of each species can be estimated with minimal error (i.e. low bias and adequate precision) for a given cost. Estimates of the harvest rate are a crucial element of AHM (Ramsey *et al.* 2010; Ramsey *et al.* 2017). Currently, telephone surveys of hunters are undertaken each year to estimate the total numbers of each species of game duck harvested in Victoria (Gormley and Turnbull 2011). An unbiased estimate of the harvest rate of each species is then simply the number estimated to have been harvested divided by the total abundance.

The second step in survey design is to decide on the target population and sampling frame. This process entails deciding on the size of the area to survey and hence how much of the species range to sample. If multiple species are to be sampled, the target population should include the total range of all the species. Once the target population has been identified, the sampling frame ideally should include the entire target population. Hence, the sampling frame establishes the total area from which we can draw units that would be subject to sampling and defines the population from which we can make statistical inference (Skalski 1994; Thompson *et al.* 1998).

In this study the target population is defined as the game duck population resident in Victoria during spring–summer in a particular year. Although AHM is likely to be applied eventually to the game duck population in southern Australia, to allow for the long-distance movements of some species (e.g. Grey Teal), the sampling frame for the present study was confined to Victoria because this is the only region where robust estimates of harvest offtake are calculated (Moloney and Turnbull 2016). The seasonal arrangements for regulating recreational harvest apply only to Victoria, although the survey principles and design used here should be transferable to other jurisdictions, which will be required to transition to AHM.

The third step entails decisions on the size of sampling units and the technique used for sampling. Sampling unit size should take into consideration the spatial arrangement of waterbodies in the landscape, as these are the principle units subject to sampling. Riverine or floodplain wetlands are fed by inundations from river systems, and occur on a linear network. However, even non-floodplain wetlands do not occur randomly across Victoria, showing high levels of spatial clustering (Smith *et al.* 2007). Hence, a sampling design that takes advantage of the non-random distribution of waterbodies across the landscape may be more efficient, in terms of both precision and cost, than one that ignores these attributes.

Step four entails selecting the number of units to sample (sample size) and the amount of monitoring effort required in each unit. Unit selection should consist of a random sample from the total number of available units. Non-random unit selection will result in biased estimates of abundance with measures of precision with unknown reliability. On the other hand, choosing a simple random sample of units will provide unbiased estimates, but could result in inflated estimates of variance if spatial heterogeneity across the sampling frame is not taken into account (Thompson *et al.* 1998). Conversely, a sampling design that stratifies unit selection to sample more intensely in areas where spatial variability is highest will result in unbiased estimates with higher precision (Thompson 1992).

The number of units to sample, and the amount of effort to expend in each unit, should be driven primarily by the precision of abundance estimates required, but will also be influenced by the cost involved. This requires some estimate of the precision needed to achieve management objectives. For example, we may need abundance estimates with a relative precision (coefficient of variation) of 25% or less in order to decide between management alternatives (i.e. harvest regulations) (Robson and Regier 1964). In the absence of any baseline data, a useful technique to determine the optimal amount of sampling effort is a Monte Carlo simulation in which the performance of various survey designs is assessed against simulated populations with known characteristics (i.e. density and spatial variation).

Relationship between harvest offtake and harvest regulations

A cornerstone of AHM is the ability to predict how changing seasonal regulations for game duck harvesting, notably the bag limits for each species and season length (i.e. opening and closing dates), will ultimately result in a change to the size of the harvest during that season. Hence, models used for AHM will require some statistical relationship between seasonal arrangements and the harvest rate (Conroy *et al.* 2005). As discussed above, the harvest rate depends on estimates of both the total population of game ducks and the estimated size of the harvest. In the past the harvest rate was estimated using analysis of band recoveries (e.g. Williams *et al.* 2002; Fonnesbeck and Conroy 2004), and then a statistical relationship between seasonal arrangements and the harvest rate was established directly. Unfortunately, the lack of recent banding studies on game ducks in Victoria makes this approach to estimating the harvest rate unfeasible. However, an alternative approach is possible through exploring statistical relationships between seasonal arrangements and the estimated size of the harvest, because of the availability of total harvest size estimates for game ducks in Victoria since 2009 (Gormley and Turnbull 2011).

The purpose of this study was to assess the precision of different survey designs to estimate the abundance of the major game duck species in Victoria. To achieve this goal, simulated aerial surveys of ducks on waterbodies (natural wetlands and impoundments) were undertaken across the state. Each survey design differed in the sampling effort by varying both the number and size of sampled sites and the survey effort within each site, and assessing the accuracy (bias and precision) of abundance estimates for each scenario. The expected cost of each survey design was also estimated to determine which design would generate the most precise abundance estimates for a given expenditure.

Statistical relationships between the total harvest and bag limits, season length and licensed hunter numbers were also explored, using data on the estimated size of game duck harvests and seasonal arrangements.

2 Methods

2.1 Designing surveys of game ducks

The approach taken to designing surveys for estimating the abundance of game ducks in Victoria was based on simulated monitoring. This involved constructing a sampling frame, consisting of the number of waterbodies that could be sampled in Victoria. Waterbodies were classified into different strata, based on attributes likely to influence numbers of game ducks. Water occurrence in each waterbody was then determined, based on some defined criteria (i.e. under high or low rainfall conditions), and then numbers of game ducks were simulated for each waterbody containing water, with expected numbers dependent on waterbody attributes. Simulated sampling of these waterbodies was then undertaken using a chosen survey design, to produce a simulated sample of ducks. This sample was then analysed to estimate the total numbers of ducks on all waterbodies containing water within Victoria. Either model-based or design-based estimation can be used to extrapolate the numbers of ducks from the sample to the total population. Different survey designs were then simulated by varying survey design parameters such as sample size and sample unit size. Results from different designs were compared using different criteria such as bias, precision and cost. Using these criteria, an optimal sampling design was chosen, based on the relative importance of each of criteria. The following sections outline each of these steps in turn.

2.1.1 Sampling frame

An inventory of waterbodies in Victoria was compiled from spatial layers available from VicMap spatial data sources (available at http://services.land.vic.gov.au/SpatialDatamart/). These included vector maps of farm dams (`farm_dams`) containing digitised boundaries of man-made waterbodies, mainly smaller farm dams less than 6 ha in area. Only features labelled 'farm dams' were selected from this layer. Digitised polygons of natural wetlands, lakes and other impoundments were also obtained from the layer `wetlands_current`, which included all naturally occurring wetlands as well as larger dams and sewage treatment ponds. The features from both these sources were then combined to construct a combined waterbody layer for Victoria. The total number of waterbodies in this layer was almost 411 000.

One issue with designing surveys of game ducks is that many waterbodies are ephemeral, because of the highly variable rainfall, runoff and groundwater flows in many parts of Australia. This means that surveys using the same simple random sample of waterbodies every year could encounter many dry waterbodies during a particularly dry year, which would be inefficient. Hence, in designing a survey of waterbodies in Victoria, it is envisaged that the sampling frame (i.e. all waterbodies potentially subject to sampling) would be defined as those waterbodies containing water during a particular year. This could be ascertained using satellite imagery (e.g. Landsat/MODIS) during some period prior to conducting surveys. To account for this sort of dynamic sampling universe in the simulated sampling design, water availability in Victoria was examined using historical satellite imagery from the Global Surface Water project available through the Google Earth Engine website https://earthengine.google.com/. This spatial resource is a raster image of the occurrence of water over the period 1984–2015, at a spatial resolution (one pixel) of 30 metres (Pekel *et al.* 2016). To reduce the size of the downloaded file, the spatial resolution was decreased to approximately 500 m. The occurrence of water for each pixel was summarised as the percentage of times over the 32-year period that the pixel contained surface water. The raster image was then further classified into two possible states: all pixels with a probability of containing water of 20% or greater ('wet' conditions) and all pixels with a probability of containing water of 50% or greater ('dry' conditions). Hence, 'wet' conditions contained all pixels with water in 6 or greater of the 32 sampled years and 'dry' conditions contained all pixels having water in 16 or greater of the 32 years (Figure 1).

Each of these raster layers was then intersected with the vector layer of waterbodies. This resulted in a selection of waterbodies likely to contain water under each of the selected conditions. This resulted in 23 836 and 4372 waterbodies under 'wet' and 'dry' conditions, respectively, which consisted of our two hypothetical sampling frames (Figure 1).

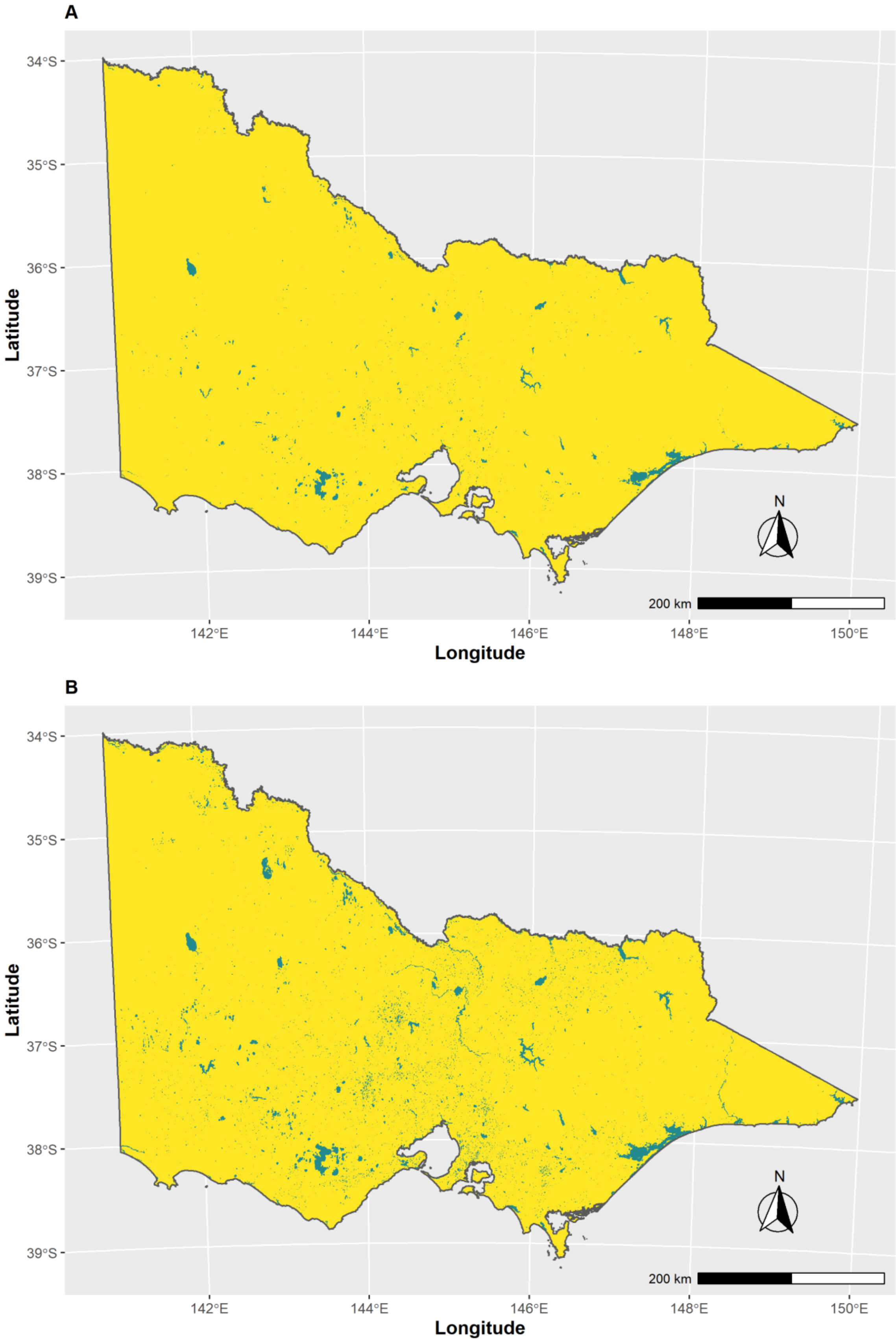


Figure 1. Waterbodies (wetlands, dams and sewage ponds) used to represent (A) 'dry' and (B) 'wet' sampling conditions based on the presence of water between 1984 and 2015, estimated from LandSat imagery from the Global Surface Water project (Pekel *et al.* 2016).

2.1.2 Simulating game duck numbers

Game duck species use a wide variety of aquatic habitats including naturally occurring wetlands, impoundments (dams) and sewage treatment ponds (hereafter 'waterbodies'). Numbers of ducks within these different types of waterbody can vary widely. To determine the likely numbers of game ducks on waterbodies of different types and sizes, records of game duck numbers collected during ground counts undertaken during the Victorian Summer Waterfowl Count (SWC) were collated for the period 1970–2009. The majority of the waterbodies included in these counts were classified by type and estimated size. These were then reduced to the following classifications to facilitate further modelling (Table 1).

Table 1. Classification of waterbody attributes (Type, Size) and sample size of observations (*n*) from the SWC, used to model variation in game duck abundance.

Type	Size	*n*
Dam	< 6 ha	795
	6–50 ha	1648
	> 50 ha	4053
Natural wetland	< 6 ha	368
	6–50 ha	1248
	> 50 ha	2311
Sewage treatment pond	< 6 ha	561
	6–50 ha	689
	> 50 ha	244

Counts of game duck species, including Grey Teal (*Anas gracilis*), Pacific Black Duck (*Anas superciliosa*), Australian Wood Duck (*Chenonetta jubata*), Australian Shelduck (*Tadorna tadornoides*), Pink-eared Duck (*Malacorhynchus membranaceus*) and Chestnut Teal (*Anas castanea*) were extracted from the SWC data for each waterbody. There were insufficient data for Hardhead (*Aythya australis*) and Australasian Shoveler (*Spatula rhynchotis*) for analysis. For each species, generalised linear models were then fitted to these counts to determine relationships between duck numbers and waterbody type and size class, separately for each species. Because of the highly skewed nature of these counts, a gamma distribution was used to model the counts, with both the shape and scale of the gamma distribution a function of the covariate values. Hence the following model was fitted.

$$\log(\mu_i) = \beta_0 + \beta_{j(i)}T_i + \gamma_{k(i)}S_i + \delta_{jk(i)}T_iS_i \qquad (Equation\ 1)$$
$$\log(\sigma_i) = \alpha_0 + \eta_{k(i)}S_i$$

where μ and σ were the mean and standard deviation of the gamma distribution, T_i was the waterbody type category (wetland, dam, sewage pond), S_i the waterbody size category (< 6 ha, 6 – 50 ha, > 50 ha) and β_0, β_j, γ_k, δ_{jk}, α_0 and η_k were parameters to be estimated.

Equation 1 is therefore equivalent to a two-way analysis of variance in which the mean depends on the factors T_i (j levels) and S_i(k levels) and their interaction and the standard deviation depends on the main effect S_i. Under this parameterisation the shape parameter of the gamma distribution was given by $\mu^2/(\mu^2\sigma^2)$ and the dispersion parameter is given by $(\mu^2\sigma^2)/\mu$. The model definition in Equation 1 was fitted separately for each species, using parameters from the fitted models to simulate numbers of ducks for each species, conditional on waterbodies attributes.

2.1.3 Sampling designs

Two types of sampling design were used to sample waterbodies across Victoria. The first was a stratified random sampling design where the strata comprised the waterbody attributes size and type (Table 1), giving a total of nine strata. Under this sampling design, the main design variable was the total sample size (S), which was varied from 200 to 4000 total waterbodies (Table 2). However, as the total number of waterbodies within each stratum varied considerably, using proportional allocation to select samples within each stratum resulted in too few samples in some strata. Hence, a disproportionate allocation was used by constructing selection probabilities for each stratum based on their relative abundance in the sampling frame. This ensured that the less numerous waterbody strata (e.g. sewage ponds > 50 ha) were adequately represented in each sample. Spatial representativeness was also accounted for by drawing a spatially-balanced sample (Foster *et al.* 2017), based on the locations for each waterbody. An example of a spatially balanced stratified sample of waterbodies is given in Figure 2.

The second type of design was a multistage sampling design (Thompson 1992), which involved partitioning the sampling frame into a number of primary units (i.e. clusters). From each selected primary unit, secondary units (waterbodies) were then selected for sampling. Primary units were constructed by overlaying a hexagonal grid on the waterbody locations (Figure 3a). This recognised the fact that waterbody locations were often aggregated, which can be exploited by the sampling design. Hence, by concentrating sampling within selected spatial locations, the total travel time (and cost) for a given sample size should be lower than the equivalent stratified random sample. Different sizes of primary units were examined by varying the cell diameter from 10 to 50 km (e.g. Figure 3a). Similar to the stratified random design, selection probabilities for primary units were based on the less numerous waterbody strata within each primary unit (Figure 3a). An example of a multistage sampling design using 10 km primary units is given in Figure 3b.

Under the multistage design, the design variables of interest were the number and size of primary units (cells) and the number of secondary units (waterbodies) within each primary unit selected for sampling. If the number of primary units is denoted as P and the number of secondary units in primary unit i is denoted as M_i, then the total sample size $S = \sum_{i=1}^{P} M_i$. Ranges for each of these design parameters were varied according to the values given in Table 2. All combinations of these design parameters for each type of survey design were then evaluated using Monte Carlo simulation.

Table 2. Values of the design parameters that were explored in simulated game duck surveys across Victoria.

Survey Design	Design variable	Values
Stratified random design	Total sample size (S)	200, 500, 1000, 1500, 2500, 4000
Multistage design	Primary unit sample size (P)	20, 40, 60, 80
	Primary unit size (km)	10, 25, 50
	Secondary unit sample size (M_i)	10, 25, 50

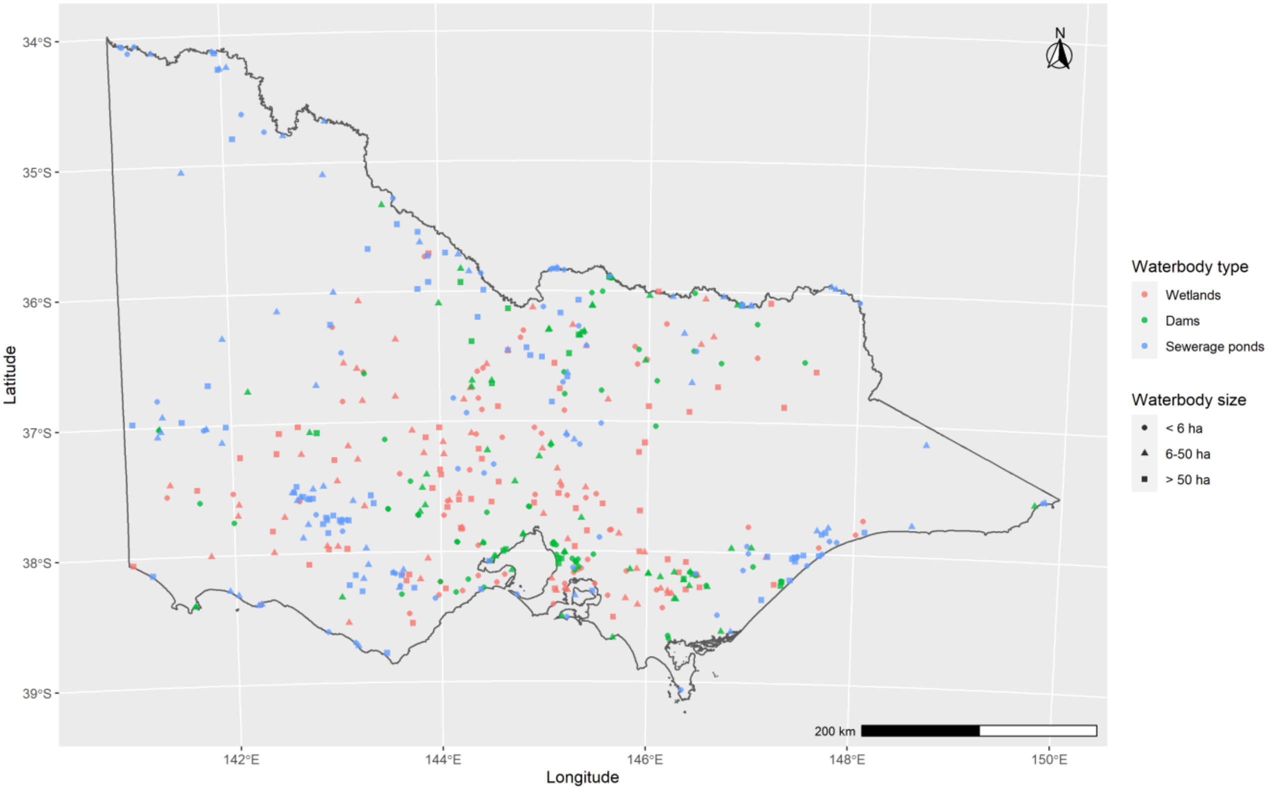


Figure 2. An example of a spatially balanced stratified random sample of waterbodies under 'wet' conditions. Total number of sampled waterbodies is 500 with the number in each stratum selected using probabilities inversely proportional to the total number in each stratum within the sampling frame. Locations are waterbody centroids.

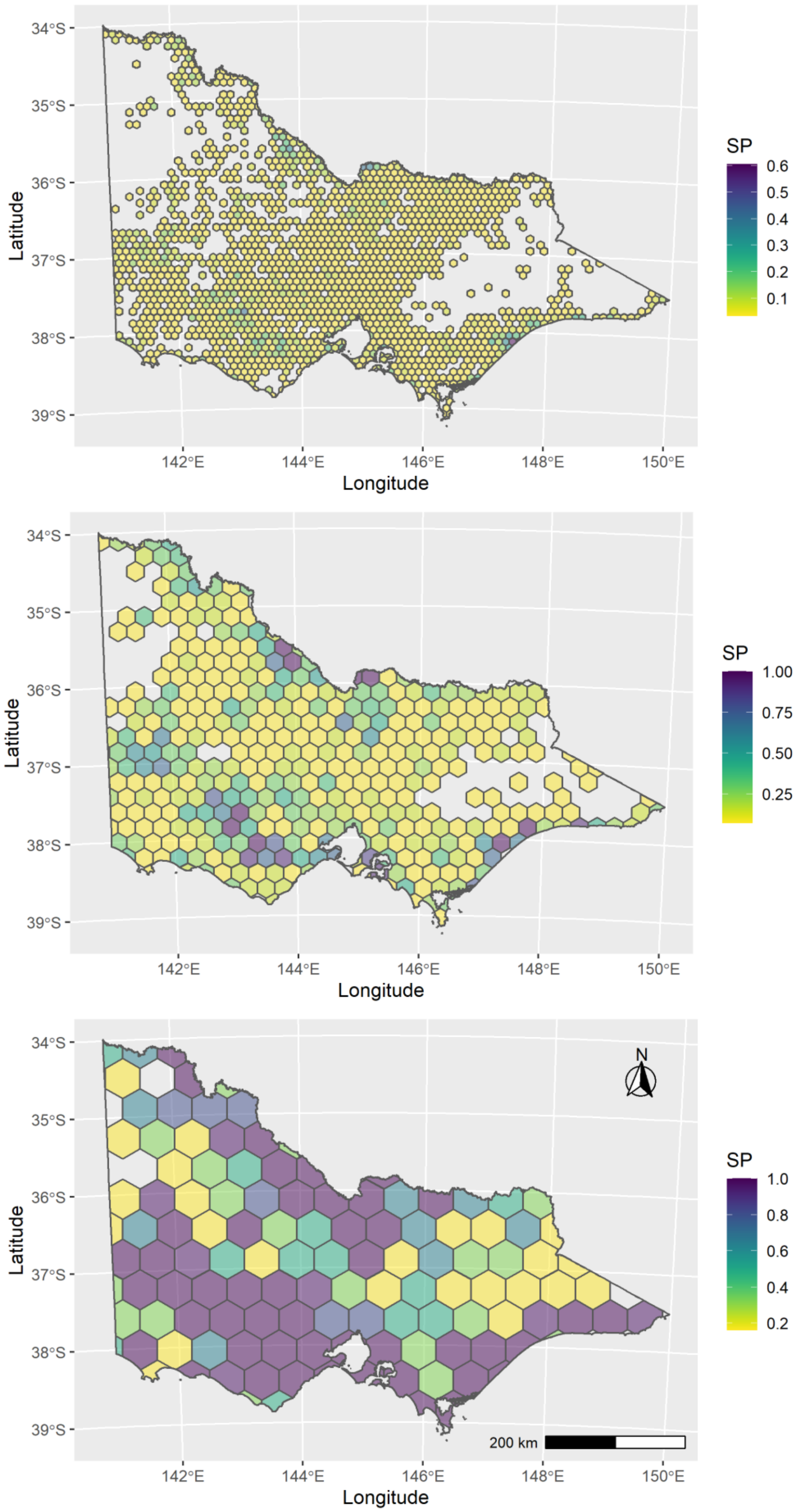


Figure 3a. Hexagonal grids used to delineate waterbodies into primary sampling units (*P*) for the multistage sampling design. Unit sizes are (from top to bottom) 10 km, 25 km and 50 km in diameter. Colours indicate the selection probabilities (SP) for a sample size of 80, based on the number of large (> 50 ha) waterbodies within each hexagon.

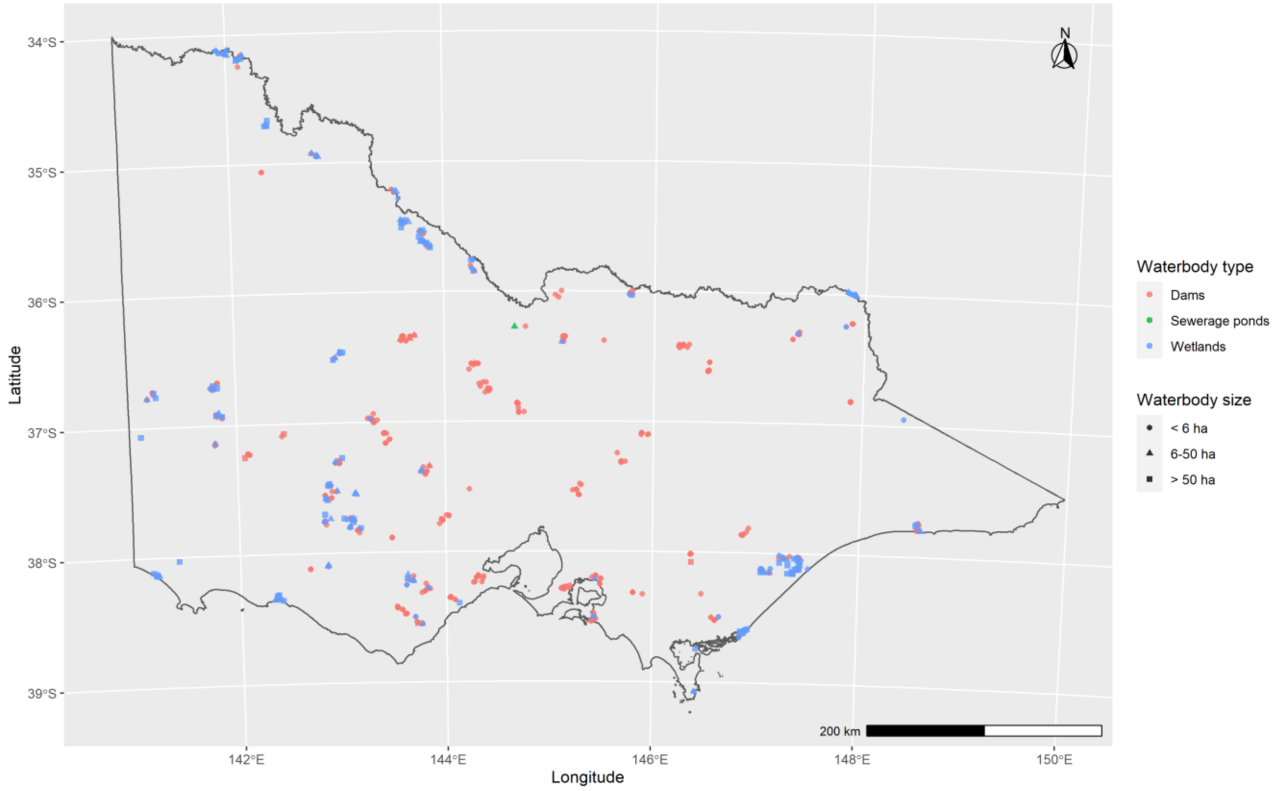


Figure 3b. An example of a spatially balanced multistage sample of waterbodies under 'wet' conditions selected using a random sample of 80 primary units of 10 km, with a maximum of 10 secondary units per primary unit. Primary unit selection probabilities were based on the number of large (> 50 ha) waterbodies within each unit. Total number of sampled waterbodies is 595. Locations are waterbody centroids.

2.1.4 Simulated surveys

Duck counts were simulated for waterbodies in each sampling frame using random draws from a gamma distribution conditional on waterbody attributes and game duck species (i.e. section 2.1.2). Since the gamma distribution does not allow for zero counts, the simulated counts on each waterbody were further conditioned on an occurrence probability (ψ), which was dependent on waterbody attribute and conditions. The occurrence probability was assumed to be < 1 for smaller wetlands and dams and equal to 1 for sewage treatment ponds and large dams and wetlands (Table 3). Probabilities of occurrence were derived from game duck surveys undertaken in the Riverina during 2019 (Dundas *et al.* 2019). The distribution of counts for each waterbody was therefore

$$C_{ijk} = \psi_{jk}\mathrm{Ga}\left(\mu_{ijk}, \sigma_{ik}\right) + \left(1 - \psi_{jk}\right)(0) \qquad (Equation\ 2)$$

where C_{ijk} was the count for duck species i for waterbody type j and size class k.

Thus, the count for a species and waterbody attribute was gamma distributed with mean μ_{ijk} and standard deviation σ_{ik} with probability ψ_{jk}, and equal to zero with probability $\left(1 - \psi_{jk}\right)$. Detection probability of observers averaged 0.5, which was the average detection probability estimated for helicopter surveys of game ducks in the Riverina (Dundas *et al.* 2019). During simulations, detection probability varied by drawing random deviates from a Beta distribution with shape and scale parameter equal to 50.

Table 3. The probability of occurrence (ψ) of game ducks according to conditions ('dry' or 'wet') and waterbody attributes (type and size). Attributes not appearing in the table were assumed to have an occurrence probability of 1.0.

Conditions	Type	Size	ψ
Dry	Wetland, Dam	< 6 ha	0.5
Dry	Wetland, Dam	6 – 50 ha	0.8
Dry	Wetland, Dam	> 50 ha	1.0
Wet	Wetland, Dam	< 6 ha	0.9
Wet	Wetland, Dam	6 – 50 ha	1.0
Wet	Wetland, Dam	> 50 ha	1.0

Simulated aerial surveys were undertaken for waterbodies in the sampling frames 'wet' and 'dry' conditions for both types of sampling design (stratified random and multistage) for each unique combination of the design parameters for each survey design (Table 2). For the stratified random design, samples of waterbodies in each stratum were selected at random, without replacement. However, the sample size within each stratum was based on the abundance of waterbodies within that stratum relative to the total number of waterbodies in the sampling frame by calculating selection probabilities based on the inverse of their relative abundance. This ensured that less numerous strata were always represented in each sample and hence, was an unequal probability sample in that the numbers of waterbodies sampled in each stratum did not reflect their relative proportions in the sampling frame. Spatial representativeness was also ensured by drawing a spatially-balanced sample based on waterbody location (Foster *et al.* 2017).

For the multistage design, primary units were also selected using an unequal probability random sample, without replacement. For each selected primary unit, a simple random sample of secondary units (waterbodies) were then selected, again without replacement. Selection probabilities for primary units were based on the number of large (> 50 ha) waterbodies within each primary unit to ensure that adequate numbers of large water bodies entered the sample (e.g. Figure 3a,b).

Following selection of the sample of waterbodies, simulated aerial surveys from a helicopter were undertaken for each waterbody. During each survey, the observers were assumed to sample the entire waterbody and that all ducks present within the waterbody could potentially be detected. However, in practice, only a selected portion of larger waterbodies may be sampled, which is then extrapolated to the entire waterbody (Dundas *et al.* 2019). For each simulated survey of a waterbody, birds were counted using the point-count removal technique (Farnsworth *et al.* 2002). This method requires that birds are counted during a set period of time with the time of detection recorded for each bird (or group of birds). The total period of the survey is then divided into t equal time intervals with birds assigned to an interval based on their time of first detection. The counts of birds within each time interval $y_t (t = 1, \dots, T)$ thus represent a multinomial sample $\mathbf{y} \sim Multinomial(n, \boldsymbol{\pi})$ with cell probabilities for each interval t (π_t) equal to

$$\pi_t = (1 - p)^{t-1} p$$

Where p is the probability of detection and n is the abundance of birds within the waterbody. Since n is unobserved, multinomial *N*-mixture models (Dorazio *et al.* 2005) were used to estimate n within a maximum likelihood framework by numerically integrating over plausible values for n. Counts of ducks y_{it} for each of the i waterbodies $(i = 1, \dots, S)$ during time interval t were analysed using multinomial *N*-mixture models fitted by maximum likelihood using the following model specification.

$$y_{it} \sim Multinomial\big(n_i, \pi_t(p)\big) \qquad (Equation\ 3)$$

$$n_i \sim Poisson(\lambda_i)$$

$$\log(\lambda_i) = \beta_0 + \zeta_{k(i)} T_i + \theta_{l(i)} S_i$$

$$logit(p) \sim \alpha_0$$

Where β_0 is the intercept, ζ_k is the parameter for the k^{th} level of the covariate T_i, representing waterbody type (i.e. wetland, dam, sewage pond), θ_l is the parameter for the l^{th} level of the covariate S_i, representing waterbody size class (i.e. < 6 ha, 6 – 50 ha, > 50 ha), and α_0 is the parameter representing the logit-scale detection probability. Equation (3) outlines a model for the sampled waterbodies. Note that this model is misspecified compared with the true model used to simulate game duck abundances (Equation 2), which contains an interaction term between T_i and S_i, and additionally, models the counts with a Poisson distribution compared with the gamma distribution used to simulate true duck abundance. Hence, the performance of each survey design was examined under realistic sorts of model misspecification, which will usually be the case in practice as the true generating model will always be unknown.

2.1.5 Estimate of total abundance

Prediction of game duck abundance for the entire sampling frame (i.e. waterbodies containing water within Victoria) were estimated using a model-based approach and a design-based approach (Thompson 1992). 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) using the fitted model relationship

$$\hat{n}_i = exp\left(\beta_0 + \zeta_{k(i)} T_i + \theta_{l(i)} S_i\right) \qquad (Equation\ 4)$$

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

where i indexes each waterbody, w is the total number of waterbodies in the sampling frame ($i = 1, \dots, w$), T_i and S_i are the vectors of covariate values for waterbody type and size class respectively, and $\beta_0, \zeta_k, \theta_l$ are the parameter estimates from the fitted model.

The variance of $\hat{N}_T$ was estimated using the delta method (e.g. Bravington *et al.* 2018). In a model-based approach, inferences do not rely on how the samples were drawn (i.e. probabilistic random sampling is not an assumption of model-based inference. Instead the focus is on the strength of the causal relationship between duck abundance and covariates, and on satisfying other assumptions of the model. In a model-based approach, extrapolating the model to predict values outside the covariate space where observations are sparse or absent could lead to biased estimates (Ramsey *et al.* 2018). An additional source of bias is model misspecification, caused by an omitted variable that is important in the causal relationship (Morgan and Winship 2007; Ramsey *et al.* 2018).

An alternative to model-based inference is design-based inference (Thompson 1992). Unlike the model-based approach where the causal model is unknown and the focus of discovery, the design-based approach assumes that the model is known and is specified by the sampling design. Hence, the design-based approach is based on the probability distribution of the sampling design and the principles of random sampling, where the selection probabilities of sampling units is known. Design-based estimates of total abundance proceeded by using Equation 4 to predict abundance for each sampled waterbody ($i = 1, \dots, S$). However, in contrast to the model-based approach, empirical Bayes methods were used to estimate random-effects estimates of $\hat{n}_i$, using best linear unbiased prediction (BLUP) for each $\hat{n}_i$ conditional on the observed data y_{it} (Robinson 1991). The predicted $\hat{n}_i$ and associated variance $\mathrm{var}\ n_i$ 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.

2.1.6 Optimal survey design

Since the true population of ducks for each species was known, the estimated population size for each species $(\hat{N}_T)$ could be compared to the true population size (N) to estimate the relative bias. Another measure of performance of the survey was the relative precision or coefficient of variation (CV). A useful metric that combines both bias and precision is the relative root mean square error (rRMSE), which is given by

$$\text{rRMSE} = \frac{\sqrt{\left(\widehat{N}_T - N\right)^2}}{\widehat{N}_T} \qquad (Equation\ 5)$$

and is also sometimes called the coefficient of variation (CV) of RMSE. Hence, surveys with smaller values of rRMSE are more accurate (lower bias and higher precision) and would generally be preferred. However, surveys with low rRMSE are likely to entail higher costs as these measures usually scale proportionally with sample size. Increasing sample size would require larger aerial survey effort conducted at more sampling units. To investigate the trade-off between rRMSE with survey cost, a measure of cost was derived based on the likely travel costs for conducting aerial surveys.

2.1.7 Survey costs

The approximate travel costs for conducting aerial surveys across an arbitrary number of waterbodies was calculated, based on the minimum distance required to travel between every waterbody within the selected sample. The minimum travel distance that visited every waterbody within the selected sample once was calculated by solving the Travelling Salesman Problem (TSP) (Lenstra and Kan 1975). The TSP is a well-known problem in operations research that has a goal of finding the shortest route that visits every destination on a list exactly once, before returning to the starting point. For the route distances calculated here, the starting and ending destination was always Melbourne. Calculations of the shortest route were undertaken using the `TSP` package (Hahsler and Hornik 2020) in `R` (R Development Core Team 2018).

Distances travelled along each route were converted to a dollar cost based on the unit costs of the operation of the helicopter. Helicopter operation costs are usually quoted as $/per hour of operation. Hence, distances can be converted to costs using average flight speeds (knots). Based on helicopter aerial surveys of kangaroos using a Bell JetRanger 206 (Moloney *et al.* 2017), it was assumed that average flight speed whilst actively travelling between waterbodies averaged 90 knots and that time spent undertaking monitoring at a waterbody averaged 5 minutes. This translated to the unit costs below (Table 4). The total cost was then calculated as the cost for undertaking surveys, which included an allowance for refuelling stops based on an assumed range of 600 km (Table 4) and the likely salary costs, including accommodation and meals required to undertake the survey, based on a 4 person crew (two pilots and two observers) and a working day of 8 hours. Other costs associated with survey planning, project management, logistics and data analysis were not included in the calculation of survey costs.

Table 4. Costs associated with aerial surveys of waterfowl using a Bell JetRanger 206 helicopter.

Cost type	Unit cost
Base cost	$3000/hour
Travel between waterbodies	$18/km
Monitoring cost per waterbody	$250
Range	600 km
Salary costs	$1500/person/day
Persons	4

The performance of alternative sampling designs was measured by examining the tradeoff between rRMSE and survey cost, based on the unit costs in Table 4. For each sampling frame (‘wet’/’dry’), survey design type, survey effort and game duck species, 500 simulated surveys were conducted with total population abundance, rRMSE and total cost calculated for each simulated survey.

2.2 Relationship between harvest offtake and harvest regulations

Data on the size of the total game duck harvest, estimated from telephone surveys of hunters (e.g. Gormley and Turnbull 2011; Moloney and Turnbull 2012; Moloney and Turnbull 2016), was collated for the period 2009 to 2019. In addition to the total duck harvest, estimates were also available for the number of licensed duck hunters as well as the seasonal arrangements (daily bag limit and season length) that were in place during that year (Appendix C). Other variations to the arrangements were also recorded such as modifications to the bag limit during opening weekend or limits placed on particular species. However, these variations were not analysed here. To determine whether there was any relationship between the size of the total duck harvest and seasonal arrangements, a generalized linear model was fitted to the data of the form

$$\log(H_i) \sim N(\mu_i, \sigma) \qquad (Equation\ 6)$$

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

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 $\beta_0, \beta_{1,2,3}$ and σ were parameters to be estimated. An additional model examined the interaction between the daily bag limit and season length to determine whether these regulatory variables were multiplicative in their relationship with total harvest. Equation 6 was fitted to the data in a Bayesian framework using the `stan_glm()` function in the `rstanarm` package (Goodrich *et al.* 2020) within `R`. All covariates values for B, D and L were standardised before analysis by subtracting their respective means and dividing by their standard deviations. Vague normal prior distributions were used for all unconstrained parameters while a vague exponential prior was used for the standard deviation parameter. Five MCMC chains were run with diffuse initial values and checked for convergence by using the Brooks–Gelman–Rubin convergence statistic $\hat{R}$ (Brooks and Gelman 1998). Thereafter, sampling continued for 1000 samples for each chain, giving 5000 samples for posterior summaries. Posterior predictive checks (Gelman *et al.* 1996) were undertaken to check adherence to model assumptions.

3 Results

3.1 Game duck abundance

Counts of game ducks collected as part of the summer waterfowl count between 1970 and 2009 indicated a general trend for duck numbers to be higher on larger waterbodies. However, patterns varied among species (Figure 4). Grey Teal and Pink-Eared Duck were observed in higher numbers on sewage ponds compared with wetlands or dams, while Australian Wood Duck did not show a strong preference for waterbody type or size (Figure 4). From these results two species were selected as exemplars of these general patterns: Grey Teal (high abundance varying with waterbody size and type) and Australian Wood Duck (lower abundance with little variation between waterbody size or type). These exemplar species were used in all further simulations of survey designs.

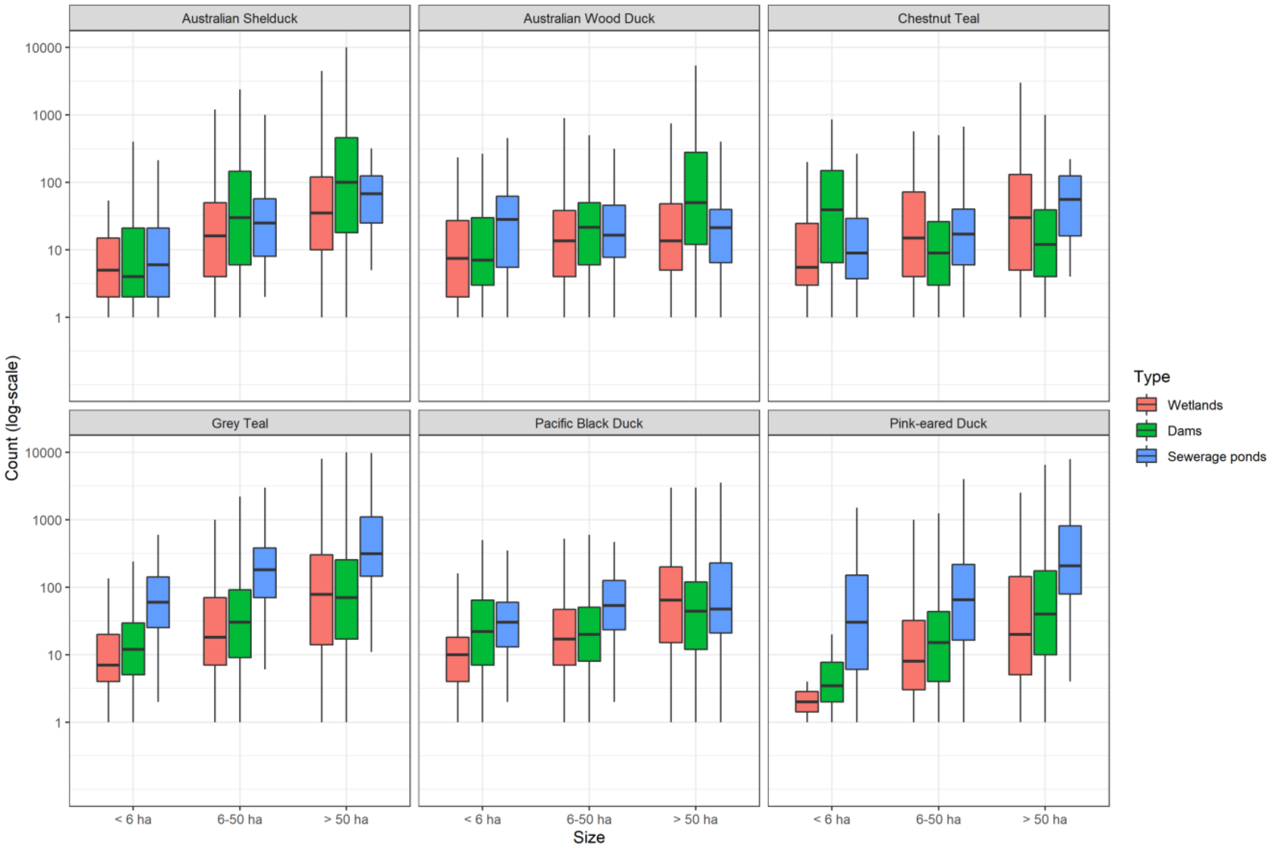


Figure 4. Counts of game duck species on different waterbody types and size classes collected in Victoria as part of the summer waterfowl count between 1970 and 2009. Y-axis is $\log_{10}$ transformed.

Models fitted to the counts of Grey Teal and Australian Wood Duck showed that both the mean and variance of the gamma distribution were dependent on waterbody size and type (and their interaction) and that the standard deviation was dependent on size (Appendix B). However, using the resulting estimates of the standard deviation parameter (range 1.3 – 1.6) gave unrealistic predicted counts, especially for Grey Teal. Reducing the standard deviation to 1.0 resulted in more realistic predictions (Figure 5), so this value was used for both species in all further simulations.

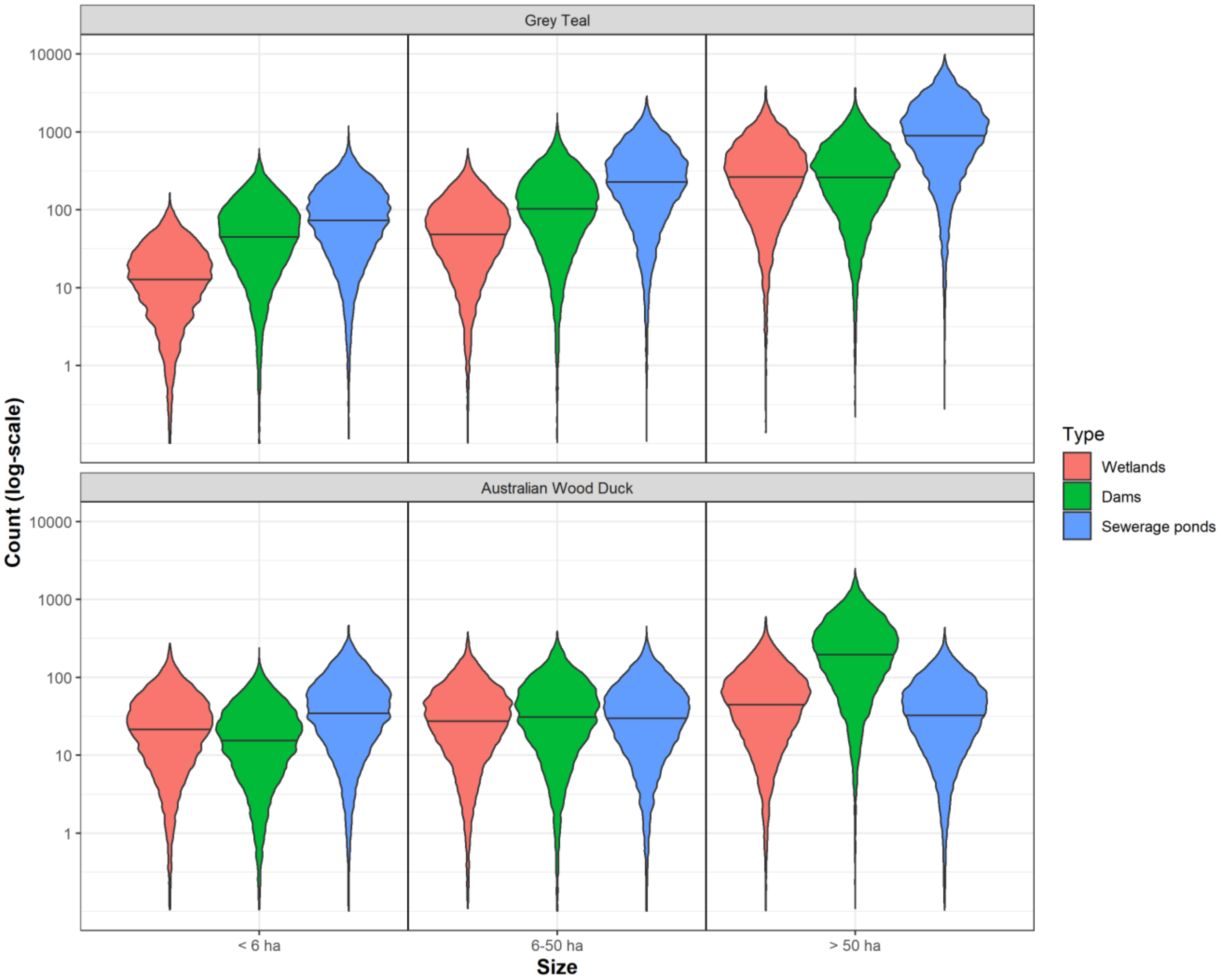


Figure 5. Simulated counts of Grey Teal and Australian Wood Duck in waterbodies varying by type and size, based on the fitted parameters from the gamma regression with standard deviation constrained to 1.0. Predicted counts are on the $\log_{10}$ scale.

3.2 Optimal survey design

3.2.1 Stratified random design

Model-based estimates

The relationship between the relative root mean square error (rRMSE) (Equation 5) and total cost for the model-based estimates of total abundance under the stratified random sampling design exhibited different patterns for each species under both ‘dry’ and ‘wet’ conditions (Figure 6a). Average rRMSE was high for Australian Wood Duck compared with Grey Teal, especially under ‘wet’ conditions. This was largely driven by a high amount of bias in the estimates of total abundance compared with the true abundance, a consequence of the misspecification of the model used for prediction (Equation 4). While bias was not as apparent in the estimates for Grey Teal, variation in the rRMSE was higher for this species compared with the Australian Wood Duck (Figure 6a). If an arbitrary threshold for the rRMSE of 0.2 was taken to be the minimal acceptable survey accuracy suitable for management purposes (e.g. Robson and Regier 1964) then acceptable survey designs could not be achieved for Australian Wood Duck under ‘wet’ conditions for the sample sizes simulated. For Grey Teal a sample size of at least 500 was required costing approximately $333,000, which took around 11 days to complete (Figure 6a).

Design-based estimates

The relationship between rRMSE and total cost for the design-based estimates under the stratified random sampling design exhibited similar patterns under both 'dry' and 'wet' conditions but was more variable under 'wet' conditions (Figure 6b). Average rRMSE was less than 15% (0.15) under all sample sizes with variation in rRMSE estimates higher for sample sizes of 200 compared with larger sample sizes (Figure 6b). In contrast to the model-based estimates, the design-based estimates were relatively robust to the misspecification of the model, exhibiting much lower levels of bias. Using the arbitrary threshold of 0.2 for the rRMSE of 0.2 as the minimal acceptable survey accuracy, then acceptable survey designs required at least 200 waterbodies to be sampled, for a cost of approximately $184,000 taking around 6 days to complete (Figure 6b).

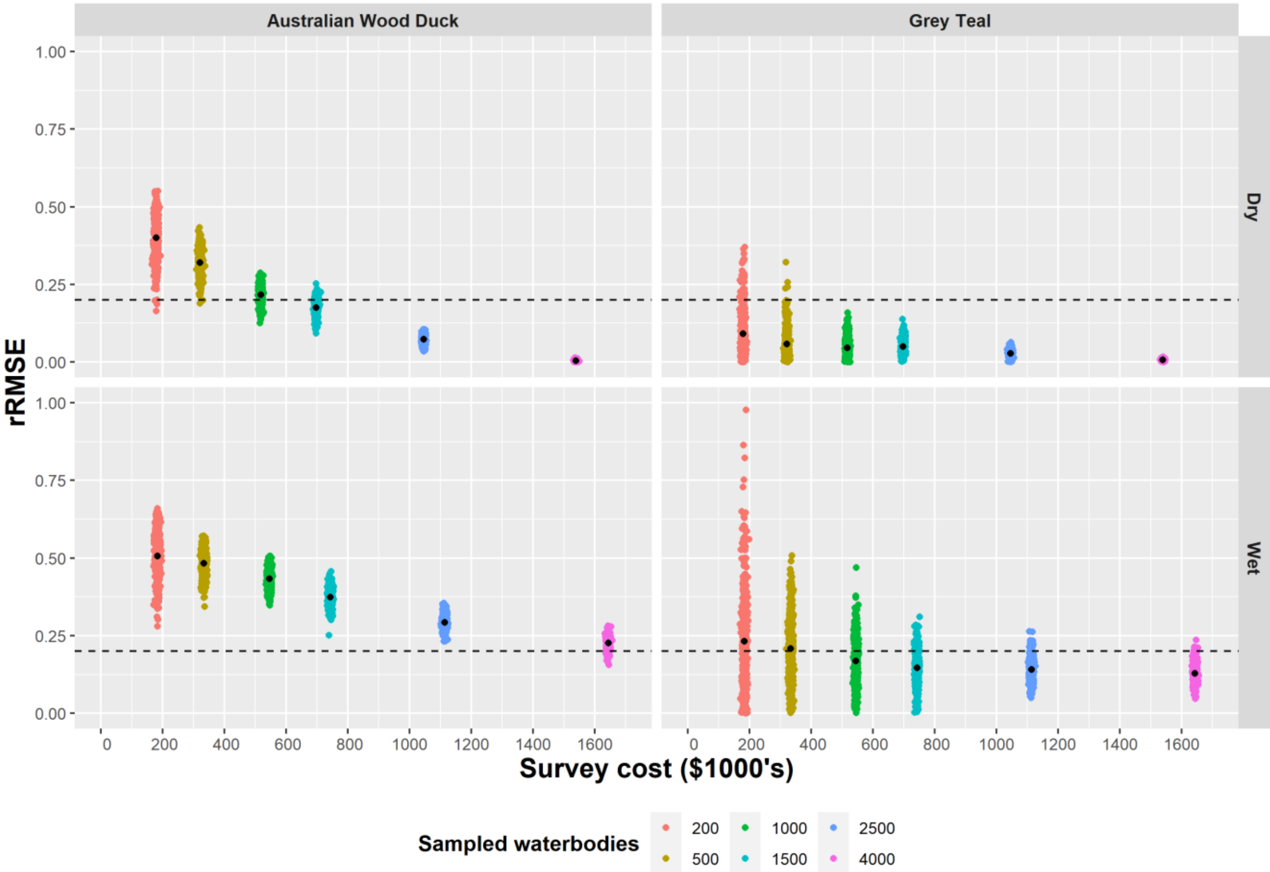


Figure 6a. The relationship between the relative root mean square error (rRMSE) of the model-based estimates of total abundance and survey cost for the stratified random sampling design under various sample sizes (total sampled waterbodies). Columns give results for each duck species and rows give results under varying conditions ('dry' or 'wet'). Black circles indicate the mean of each distribution.

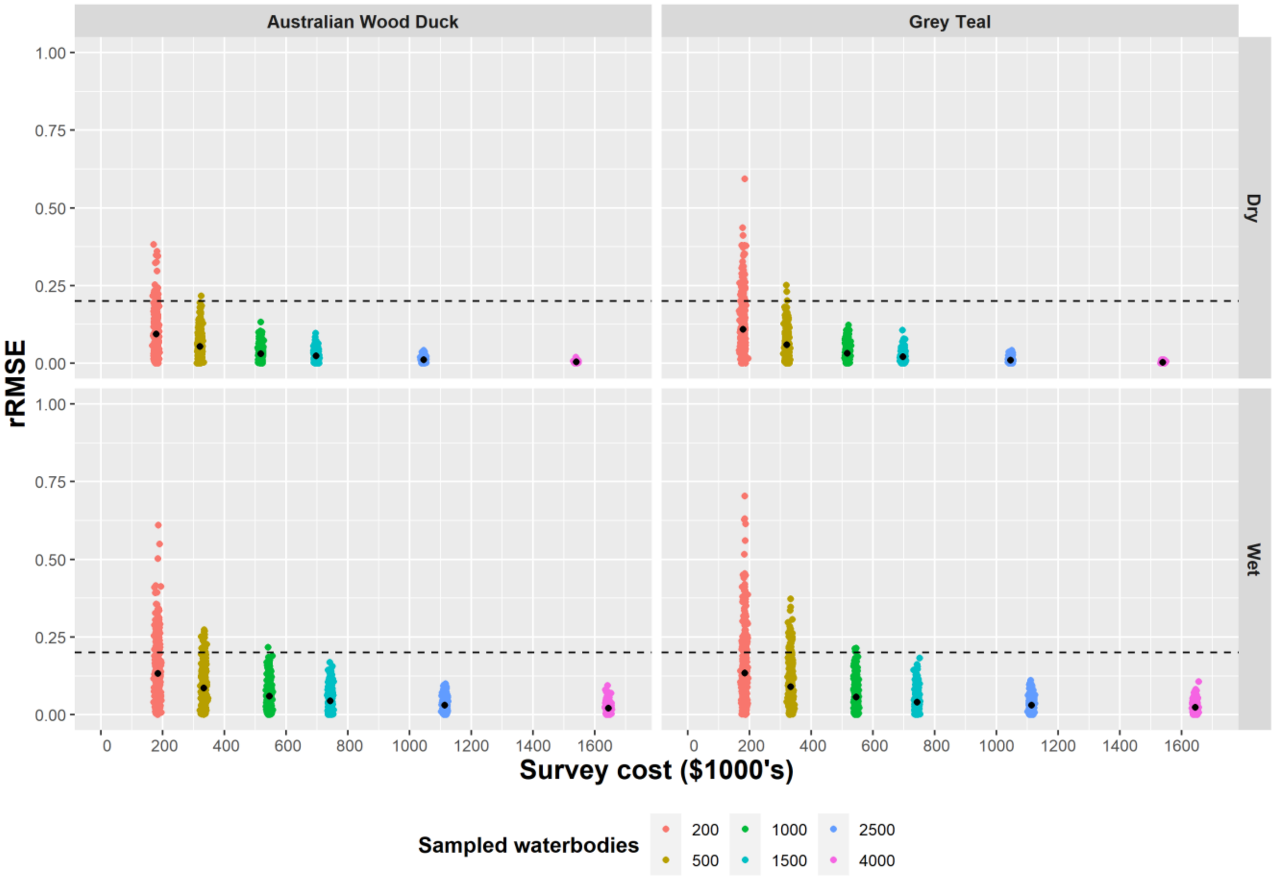


Figure 6b. The relationship between the relative root mean square error (rRMSE) of the design-based estimates of total abundance and survey cost for the stratified random sampling design under various sample sizes (total sampled waterbodies). Columns give results for each duck species and rows give results under varying conditions (‘dry’ or ‘wet’). Black circles indicate the mean of each distribution.

3.2.2 Multistage sampling design

Model-based estimates

The relationship between the rRMSE of model-based estimates of abundance and total survey cost under the multistage sampling design was similar for both duck species so results are presented for both species combined (Figures 7a & b). In general, the rRMSE of abundance estimates under the multistage design were lower than under the stratified random design, exhibiting lower levels of bias and hence, were more robust to model misspecification. However, the variability in rRMSE with survey cost was higher than for the stratified random design with higher variation under ‘dry’ compared with ‘wet’ conditions. This was a consequence of the smaller number of waterbodies sampled under ‘dry’ compared with ‘wet’ conditions (Appendix E).

In general, the rRMSE was much more sensitive to the number of sampled primary units than to the number of sampled secondary units with little variation apparent when greater than 10 secondary units per primary unit were sampled (Figures 7a & b). Using the arbitrary threshold of 0.2 for the rRMSE as the minimal acceptable survey accuracy, then acceptable survey designs only required the 20, 10 km primary units with 10 secondary units per primary unit. However, lower variability in rRMSE was obtained for 60, 10 km primary units with 10 secondary units per primary unit with 90% of rRMSE values being < 0.2 for this design. The total cost for this design was estimated to be $211,000 and would take around 7 days to complete.

Actual total sample sizes (i.e. total numbers of sampled waterbodies) varied from the nominal value of S (section 2.1.3) because some primary units had less than the nominal number of secondary units available to be sampled. This was especially apparent when using the smaller (10 km) primary unit sizes (Appendix E). The multistage designs with 60 primary units of 10 km, with 10 secondary units per primary unit, which had a nominal value of S of 600, sampled an average of 270 and 400 waterbodies under 'dry' and 'wet' conditions, respectively.

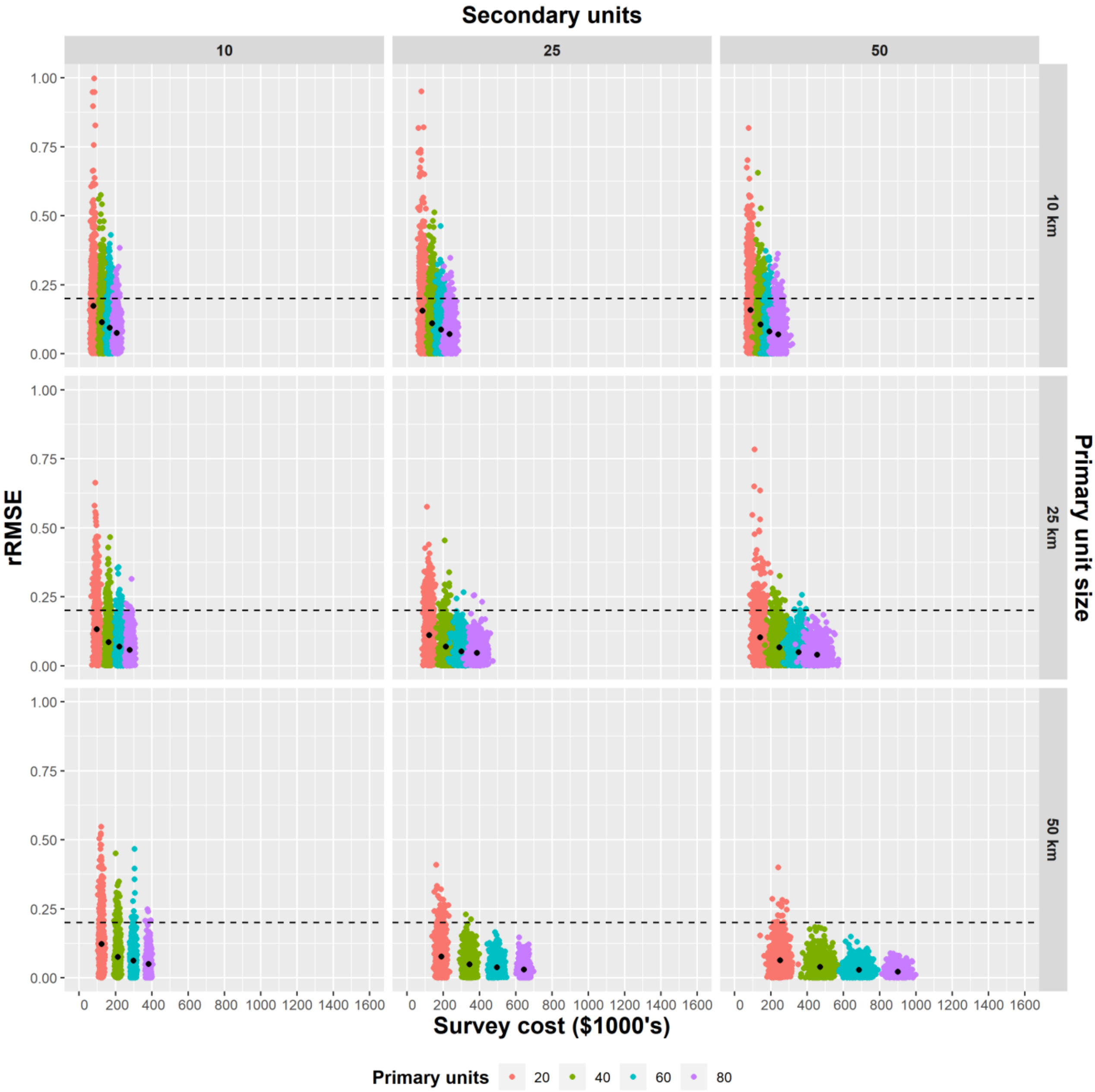


Figure 7a. Relationship between relative root mean square error (rRMSE) of model-based estimates of total abundance for both duck species combined and total survey cost for multistage sampling designs under 'dry' conditions, varying by the number of sampled primary units (colours) and secondary units (columns) for different primary unit sizes (rows). Black circles indicate the mean of each distribution.

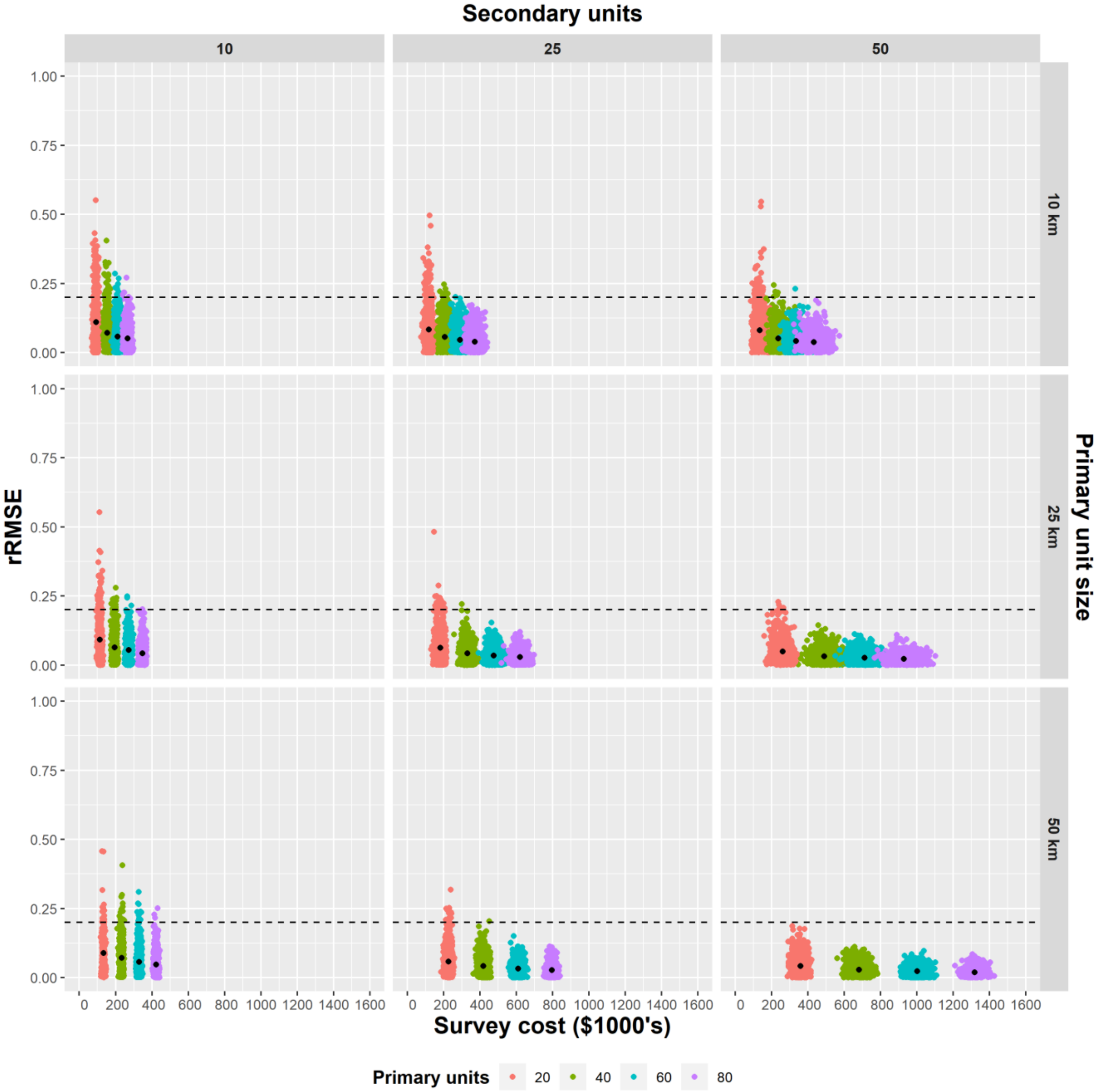


Figure 7b. Relationship between relative root mean square error (rRMSE) of model-based estimates of total abundance for both duck species combined and total survey cost for multistage sampling designs under 'wet' conditions, varying by the number of sampled primary units (colours) and secondary units (columns) for different primary unit sizes (rows). Black circles indicate the mean of each distribution

Design-based estimates

The relationship between the rRMSE of the design-based estimates of abundance and total survey cost under the multistage sampling design were similar for both duck species, so results are presented for both species combined (Figures 8a, b). Unlike the corresponding model-based estimates, the variability in rRMSE with survey cost was much greater under 'wet' compared with 'dry' conditions. Using the arbitrary threshold of 0.2 for the rRMSE as the minimal acceptable survey accuracy, acceptable survey designs under 'dry' conditions required at least 40 primary units of 10 km with 10 secondary units per primary unit, or 40 primary units of 10 km with 25 secondary units per primary unit under 'wet' conditions. However, only 75% and 64% of the rRMSE values for these designs were less than the 0.2 threshold under 'dry' and 'wet' conditions, respectively (Appendix D). Designs with 80, 10 km primary units each with 10 secondary units had 92% and 75% of rRMSE values less than the 0.2 threshold under 'dry' and 'wet' conditions, respectively and may be preferred for their lower variability (Appendix D). This design sampled 410 and 580 total waterbodies, costing around $223,000 and $282,000, taking around 7 and 10 days to complete under ‘dry’ and ‘wet’ conditions respectively.

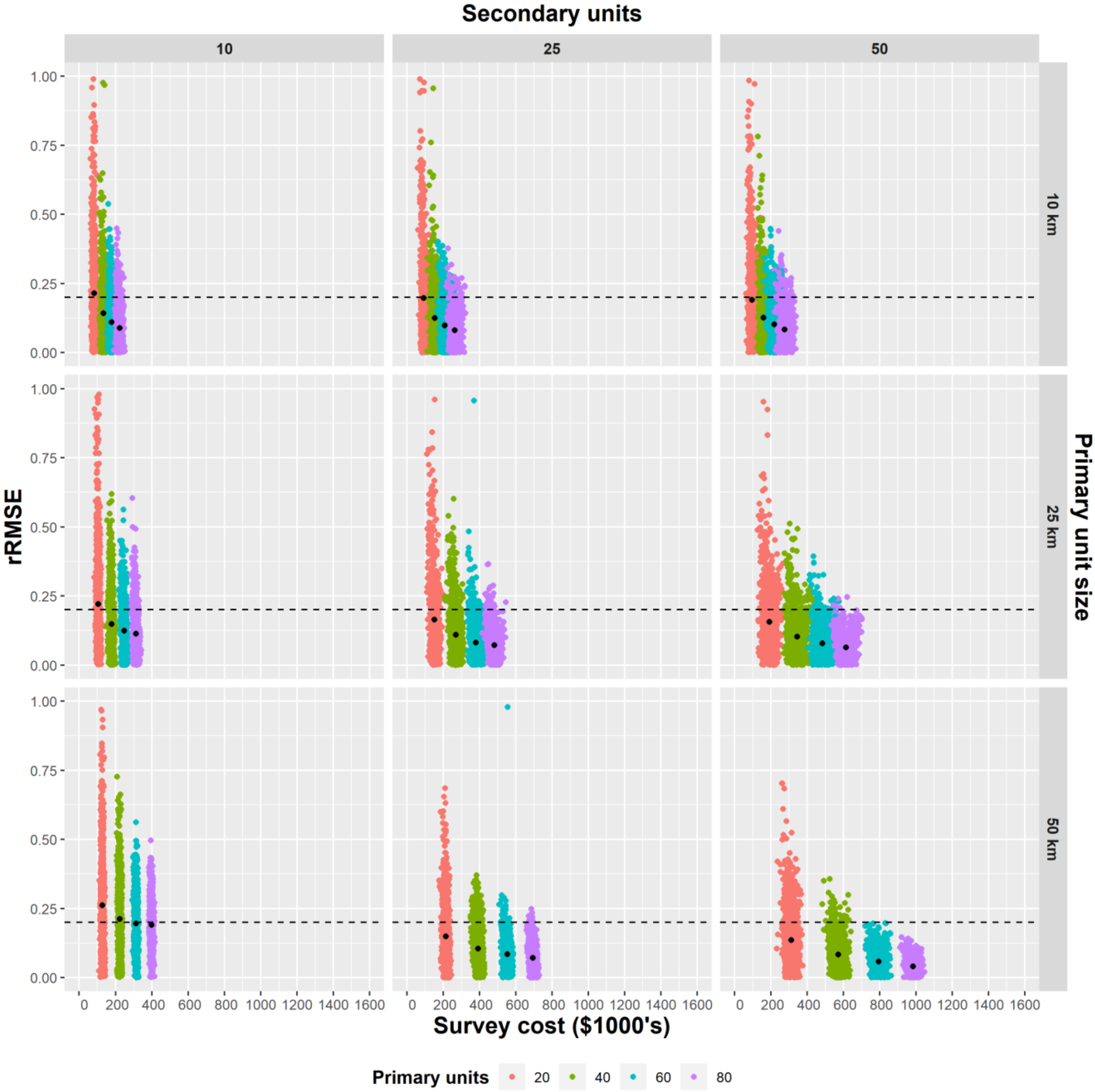


Figure 8a. Relationship between relative root mean square error (rRMSE) of design-based estimates of total abundance for both duck species combined and total survey cost for multistage sampling designs under ‘dry’ conditions, varying by the number of sampled primary units (colours) and secondary units (columns) for different primary unit sizes (rows). Black circles indicate the mean of each distribution.

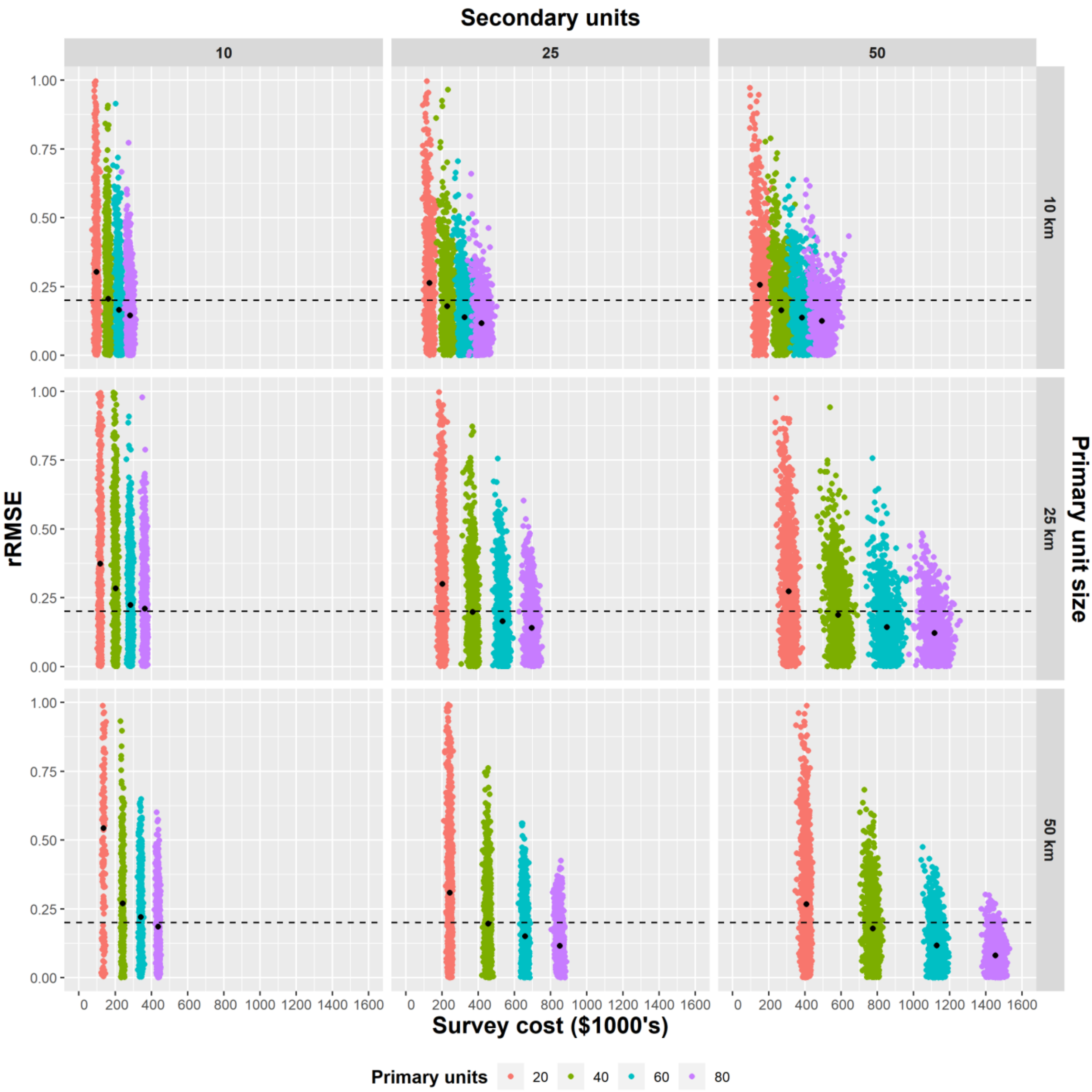


Figure 8b. Relationship between relative root mean square error (rRMSE) of design-based estimates of total abundance for both duck species combined and total survey cost for multistage sampling designs under 'wet' conditions, varying by the number of sampled primary units (colours) and secondary units (columns) for different primary unit sizes (rows). Black circles indicate the mean of each distribution.

3.3 Relationship between harvest offtake and harvest regulations

Results from the generalised linear model for the relationship between total game duck harvest and seasonal arrangements indicated that both bag limit and season length were positively related to harvest size, while the number of licensed hunters was negatively related (Table 5). However, only the estimate for bag limit did not include zero in the 90% credible interval. Hence, there remains some uncertainty around the true effects of season length and number of licensed hunters on the total game duck harvest. This uncertainty was a consequence of the small sample size (11 years) available for analysis. Increasing the model complexity by including an interaction between bag limit and season length led to higher uncertainty in the estimated effects, so this model was not used for further inference. Despite this, predictions from the additive model were a reasonable fit to the data, explaining around 78% of the variation in total game duck harvest (Bayesian R^2 = 0.78) (Figure 9). The model parameter estimates indicated that a change in the bag limit by one standard deviation (i.e. $\pm$ 2.6 ducks) resulted in a change in the total harvest by 21% and a similar change to the season length (i.e. $\pm$12.6 days) resulted in a change in the total harvest by 22% (Table 5).

The model (Equation 6) was also used to predict the likely size of the game duck harvest for different combinations of bag limit and season length, conditional on the number of licensed hunters. Predictions under different seasonal arrangements, assuming 24 460 licensed hunters, indicate that the predicted harvest ranged from 117 000 for a bag limit of 2 and a season of 30 days to 496 000 for a bag limit of 10 and a season length of 90 days (Figure 10).

Table 5. Parameter estimates from the model fitted to the relationship between the total game duck harvest (on the natural log scale) and seasonal regulations. Season – season length (days), Bag limit – daily bag limit, Hunters – number of licensed hunters, σ – residual standard deviation. $\hat{R}$ – convergence statistic.

Term	Mean	SE	5%	95%	$\hat{R}$
(Intercept)	12.78	0.056	12.69	12.86	1.00
Season	0.20	0.124	0.00	0.40	1.00
Bag limit	0.19	0.076	0.07	0.32	1.00
Hunters	-0.07	0.104	-0.24	0.10	1.00
σ	0.17	0.056	0.11	0.28	1.00

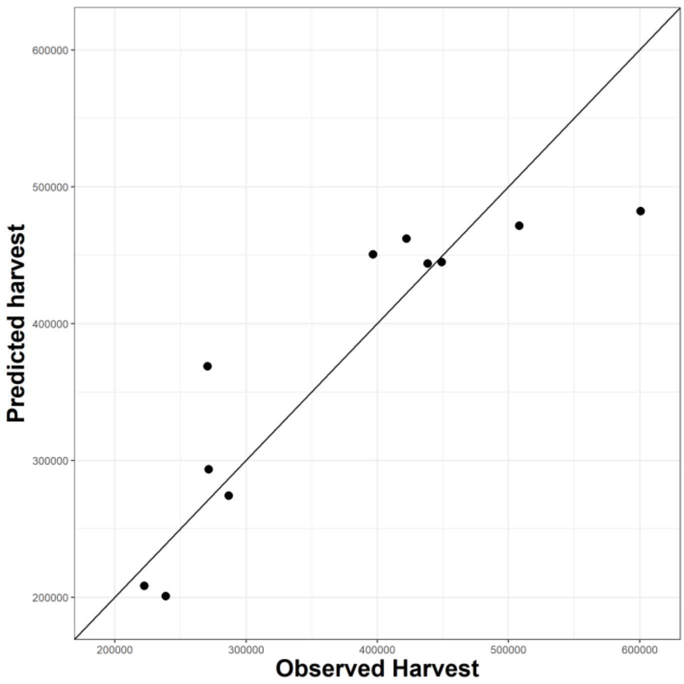


Figure 9. Plot of the observed total game duck harvest from 2009 to 2019 and the predicted duck harvest from the model relating harvest to seasonal regulations and number of licensed hunters.

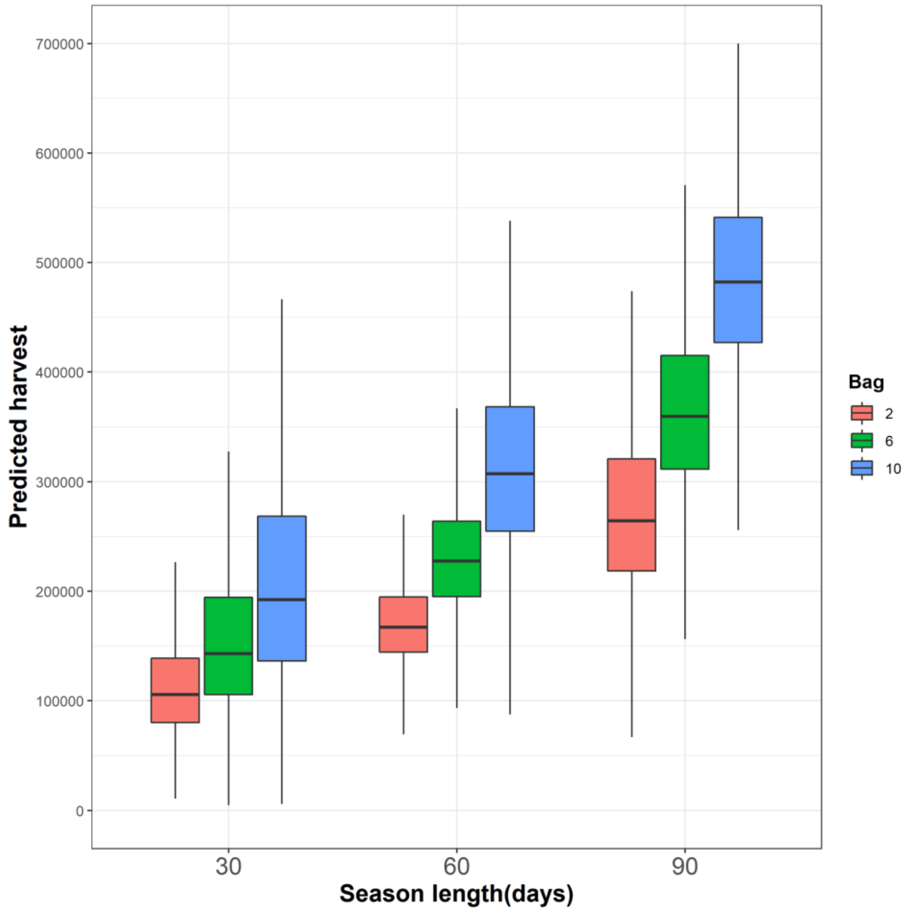


Figure 10. Predicted total harvest of game ducks for different bag limits and season length assuming 24 460 licensed hunters. The horizontal line is the median and the box size indicates the interquartile range, with the length of the lines indicating the 95% credible interval.

4 Discussion

In a recent review of Adaptive Harvest Management for Victorian waterfowl, Ramsey *et al*. (2017) recommended that survey designs be investigated to determine the amount of monitoring data that is likely to be required to estimate the abundance of game duck species within several bioclimatic regions in Victoria. This recommendation was made on the basis that monitoring data would be used to develop a population model for predicting the impact of harvest on game duck species, which would then be used to set sustainable harvest regulations (bag limits and season length) over the long term (i.e. AHM). However, the current seasonal arrangements in New South Wales for the setting of annual quotas for waterfowl use a proportional harvest strategy, whereby a proportion of the estimate of total population abundance of a species, capped at a maximum of 10%, is set as the annual quota (Dundas *et al.* 2016). Expressing the quota as a proportion of the current population size implicitly results in reducing quotas when abundances are low, and vice versa. Such proportional harvest strategies have been used successfully to set sustainable quotas for kangaroo populations in various Australian states (McLeod *et al.* 2004; Hacker *et al.* 2004; Pople *et al.* 2006), and can be further modified or made conditional on prevailing environmental conditions to safeguard against over-exploitation. As the data requirements for implementing a proportional harvest strategy are not as onerous as that required for developing a credible population/harvest model, there is some interest in adopting a proportional harvest strategy to manage recreational harvesting of game ducks in Victoria as an interim measure until sufficient data accumulates to move to full AHM. A proportional harvest strategy would be a more robust method for setting recreational harvest regulations compared to current methods, and is likely to be required for at least five years while transitioning to full AHM. However, the monitoring data accumulated during this interim process would make a valuable contribution to our understanding of Victorian waterfowl populations and would form the basis for developing the population model necessary to implement AHM.

Since seasonal arrangements for recreational duck hunting involve the setting of bag limits and season length for the entire state of Victoria, it makes sense that population abundance and total harvest offtake are also estimated over the same spatial scale. Hence, the results in this report relate to sampling designs for the estimation of game duck abundance for the whole state, rather than the bioclimatic regions identified in Ramsey *et al*. (2017). However, given that spatially balanced sampling designs were investigated in this study (e.g. Figure 2), it should be relatively simple to derive separate estimates for each bioclimatic region using post-stratification (Thompson 1992).

4.1.1 Optimal survey design for game duck monitoring

Pivotal to the implementation of a proportional harvest strategy is an estimate of the current population abundance of each game duck species just prior to harvesting. Here, abundance estimators that correct sample counts for imperfect detection (Dorazio *et al.* 2005), were combined with model-based and classic design-based finite population inference (Thompson 1992) to investigate sampling designs that resulted in population estimates for Victoria that had minimal bias and high precision, for a reasonable cost.

The reason for investigating two different methods of inference (i.e. model-based and design-based) was to explore the possibility of achieving two different objectives with the survey data. In design-based inference procedures, the sampling frame (i.e. the population of interest) must be specified in advance. This means that it is not possible to use design-based procedures for making inferences about population abundance to areas outside the sampling frame (i.e. outside Victoria), because waterbodies outside the sampling frame have no chance of being selected in the sample. However, model-based inference may be suitable for predicting game duck abundances in areas outside Victoria, if it can be demonstrated that a good causative model of game duck abundances can be constructed from measured covariates and that these covariate values are available for areas outside the sampling frame. One issue with model-based inference is the possibility of bias in the estimate of abundance due to model misspecification (e.g. omitting an important variable from the model), which was a scenario simulated in this study. This issue is less of a problem in design-based inference, which is why it may be preferred for predicting abundance within the sampling frame.

Of the two types of sampling designs examined, the results for the stratified random designs differed the most between model-based and design-based inference. Design-based estimates were acceptably accurate, and the corresponding model-based estimates were inaccurate by comparison. This was a consequence of bias caused by the misspecification of the model used for predicting the abundance at each waterbody. This bias differed for the two duck species examined here. Counts of Australian Wood Duck were mostly unrelated to waterbody size or type, so the additive model used for estimation predicted poorly for this species compared with Grey Teal. Hence, under a model-based approach, it is likely that separate models would need be fitted to each duck species, with care taken to ensure an adequate fit to the data. In contrast, results for the multistage sampling designs were more robust to model misspecification. However, the estimates of survey accuracy (rRMSE) were more variable under the multistage design.

Multistage designs were also generally less expensive than the equivalent stratified random design, because of the lower travel costs. Of the stratified random designs examined, designs with a sample size of 500 waterbodies had design-based estimates with consistently low rRMSE (mean rRMSE of 0.09 with 90% of estimates < 0.2) and cost around $333,000. The total sample consisted of around 60 samples per stratum, with complete coverage of the stratum with the least number of waterbodies. For the multistage designs examined, survey designs that sampled 80 primary units of 10 km diameter, sampling up to 10 waterbodies per unit, had the highest accuracy for the minimum cost under both model-based and design-based inference, for both duck species and under 'dry' and 'wet' conditions. This design sampled around 410 to 580 total waterbodies, costing around $223,000 to $282,000, and taking around 7 and 10 days to complete under 'dry' and 'wet' conditions respectively. However, it should be noted that there would be additional costs for survey planning, project management, logistics, data analysis, and determining seasonal arrangements. The overall conclusion is that the multistage sampling design appears to be a robust and fairly efficient survey design, in terms of maximising accuracy for a given cost while giving the flexibility to apply either model-based or design-based inference to estimate total duck abundance. Thus it is recommended that a multistage sampling design be used for monitoring game duck abundance across Victoria, conditional on the assumptions underpinning the simulated sampling designs examined in this study.

4.1.2 Relationship between harvest offtake and seasonal arrangements

The fitted model describing the relationship between total harvest and seasonal arrangements (bag limit and season length), while being a relatively good fit to the available data, had some limitations. The main limitation was that it was necessary to assume that the marginal effect of manipulating either the bag limit or season length on the total harvest was additive. Although a model with an interaction between the bag limit and season length was explored, the interaction effect had high uncertainty (CV of 57%) and predictions from this model were counterintuitive. This was a consequence of the limited amount of data available and the fact that, when seasonal arrangements are set, both the bag limit and season length tend to be decreased or increased together rather than set independently. Despite this, the predictions from the additive model appear to be plausible, and hence should be a reasonable basis for managers to predict the likely total harvest for a given bag limit, season length and number of licensed hunters. Further development of this model should continue as future data are collected and the model revised accordingly.

4.2 Conclusion

Although the simulation approach to designing a Victoria-wide survey of game ducks used in this report is useful for identifying candidate survey designs and the likely required effort and cost, it is no substitute for the collection of real monitoring data. The Monte Carlo simulation procedure used here was based on a number of simplifying assumptions, which imposed certain limitations and is therefore likely to under-represent the amount of natural variation in real monitoring data. Hence, the actual performance of the survey design could differ substantially from its theoretical performance and should be refined following collection of an initial set of monitoring data. For example, analysis of initial monitoring data used to estimate the Victorian kangaroo population led to a substantial increase in the required sampling effort due to the presence of significant clustering in kangaroo populations, an effect which was underestimated in the initial survey design (Moloney *et al.* 2018). Thus, it is suggested that a pilot survey be undertaken, designed using the principles and recommended survey effort identified in this report. The collection of monitoring data through a pilot study would be invaluable for refining the survey design and updating the likely amount of monitoring effort and associated costs required to achieve the desired survey accuracy. Another advantage of collecting data through an initial pilot survey would be that the resulting model could be tested against similar survey data collected in other jurisdictions, such as the NSW Riverina (Dundas *et al.* 2019), to determine whether model-based inferences could potentially be used to predict game duck abundances outside Victoria. Such a feature would be useful to predict the abundances of those species of game ducks that are highly mobile (e.g. Grey Teal), for areas which potentially could influence the number of birds in Victoria (Roshier *et al.* 2008).

4.3 Recommendations

- Consider implementing a proportional harvest scheme as a more robust method for regulating game duck harvest in Victoria as it transitions to Adaptive Harvest Management.
- If a proportional harvest scheme was adopted, cap the maximum quotas for recreational offtake of game ducks under a proportional harvest scheme at 10% of the total population size until sufficient data accumulates to make a more informative quota assessment.
- Estimate the total population size of game ducks in Victoria in summer each year, just prior to the recreational hunting season, to facilitate the implementation of the proportional harvest scheme if it was adopted.
- Conduct aerial surveys to estimate the population size of game ducks, using a multistage random sampling design to sample 500–600 waterbodies. The implementation of this survey design would be likely to cost around $280,000, which does not include additional costs associated with survey planning, project management, logistics and data analysis.
- Undertake a pilot study to collect aerial survey data, in order to assess the performance of the recommended survey design under actual conditions. The monitoring data collected should then be used to refine the recommended survey design.
- Following refinement of the survey design and estimators using the pilot survey data, undertake further testing on similar monitoring data collected in the Riverina to determine the suitability of the methods for predicting game duck abundances outside Victoria.
- If a move to a proportional harvest scheme was adopted, use the statistical relationship between total recreational harvest, bag limits, season length and numbers of licensed hunters identified in this report to set the annual seasonal arrangements (bag limits and season length).

References

Bravington, M. V, Miller, D. L., and Hedley, S. L. (2018). Reliable variance propagation for spatial density surface models. , 1–23. Available at: http://arxiv.org/abs/1807.07996

Brooks, S., and Gelman, A. (1998). General methods for monitoring convergence of iterative simulations. *Journal of Computational and Graphical Statistics* **7**, 434–455.

Conroy, M. J., Fonnesbeck, C. J., and Zimpfer, N. L. (2005). Modeling regional waterfowl harvest rates using Markov Chain Monte Carlo. *Journal of Wildlife Management* **69**, 77–90.

Dorazio, R. M., Jelks, H. L., and Jordan, F. (2005). Improving removal-based estimates of abundance by sampling a population of spatially distinct subpopulations. *Biometrics* **61**, 1093–1101.

Dundas, S., McLeod, S., and Tracey, J. (2016). Background information for the estimation of the 2016-2017 waterfowl quota for NSW. Orange, Australia.

Dundas, S., Vardanega, M., and McLeod, S. R. (2019). 2019-2020 annual waterfowl quota report to the game licensing unit, NSW Department of Primary Industries. NSW Department of Primary Industries, Orange, NSW.

Farnsworth, G. L., Pollock, K. H., Nichols, J. D., Simons, T. R., Hines, J. E., and Sauer, J. R. (2002). A removal model for estimating detection probabilities from point-count surveys. *The Auk* **119**, 414–425.

Fonnesbeck, C. J., and Conroy, M. J. (2004). Application of integrated Bayesian modeling and Markov chain Monte Carlo methods to the conservation of a harvested species. *Animal Biodiversity and Conservation* **27**, 267–281.

Foster, S. D., Hosack, G. R., Lawrence, E., Przeslawski, R., Hedge, P., Caley, M. J., Barrett, N. S., Williams, A., Li, J., Lynch, T., Dambacher, J. M., Sweatman, H. P. A., and Hayes, K. R. (2017). Spatially-balanced designs that incorporate legacy sites. *Methods in Ecology and Evolution* **8**, 1433–1442.

Gelman, A., Meng, X. L., and Stern, H. (1996). Posterior predictive assessment of model fitness via realized discrepancies. *Statistica Sinica* **6**, 733–807.

Goodrich, B., Gabry, J., Ali, I., and Brilleman, S. (2020). rstanarm: Bayesian applied regression modeling via Stan. Available at: https://CRAN.R-project.org/package=rstanarm

Gormley, A. M., and Turnbull, J. D. (2011). Estimates of harvest for deer, duck and quail in Victoria: Results from surveys of Victorian game licence holders in 2011. Arthur Rylah Institute for Environmental Research Technical Report Series No. 224, of Sustainability and Environment, Heidelberg, Victoria.

Hacker, R., Mcleod, S., Druhan, J., Tenhumberg, B., and Pradhan, U. (2004). Kangaroo management options in the Murray-Darling Basin. Murray-Darling Basin Commission, Canberra, Australia.

Hahsler, M., and Hornik, K. (2020). Traveling Salesperson Problem (TSP). Available at: https://cran.r-project.org/package=TSP

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.

Johnson, F. A. (2011). Learning and adaptation in the management of waterfowl harvests. *Journal of Environmental Management* **92**, 1385–1394. doi:10.1016/j.jenvman.2010.10.064

Johnson, F. A., Boomer, G. S., Williams, B. K., Nichols, J. D., and Case, D. J. (2015). Multilevel learning in the adaptive management of waterfowl harvests: 20 years and counting. *Wildlife Society Bulletin* **39**, 9–19.

Johnson, F. A., Moore, C. T., Kendall, W. L., Dubovsky, J. A., Caithamer, D. F., Kelley, J. R., and Williams, B. K. (1997). Uncertainty and the management of mallard harvests. *Source: The Journal of Wildlife Management* **61**, 202–216.

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

Lenstra, J. K., and Kan, A. R. (1975). Some simple applications of the travelling salesman problem. *Operational Research Quarterly* **26**, 717–733.

Madsen, J., Williams, J. H., Johnson, F. A., Tombre, I. M., Dereliev, S., and Kuijken, E. (2017). Implementation of the first adaptive management plan for a European migratory waterbird population: The case of the Svalbard pink-footed goose *Anser brachyrhynchus*. *Ambio* **46**, 275–289.

McLeod, S. R., Hacker, R. B., and Druhan, J. P. (2004). Managing the commercial harvest of kangaroos in the Murray-Darling Basin. *Australian Mammalogy* **26**, 9–22.

Moloney, P. D., Ramsey, D. S. L., and Scroggie, M. P. (2017). A state-wide aerial survey of kangaroos in Victoria. Arthur Rylah Institute for Environmental Research Technical Report Series No. 286, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Moloney, P. D., Scroggie, M. P., and Ramsey, D. S. L. (2018). Revisiting the Victorian kangaroo aerial survey design. Unpublished Client Report. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Moloney, P. D., and Turnbull, J. D. (2012). Estimates of harvest for deer, duck and quail in Victoria: Results from surveys of Victorian Game Licence holders in 2012. Arthur Rylah Institute for Environmental Research Technical Repoort Series No. 239, Department of Sustainability and Environment, Heidelberg, Victoria.

Moloney, P. D., and Turnbull, J. D. (2016). Estimates of harvest for duck and quail in Victoria. Unpublished client report, Arthur Rylah Institute of Evironmental Research, Heidelberg, Victoria.

Morgan, S. L., and Winship, C. (2007). *Counterfactuals and causal inference: Methods and principles for social research*. (Cambridge University Press: Cambridge, UK.)

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.

Pople, A. R., Cairns, S. C., Menke, N., and Payne, N. (2006). Estimating the abundance of eastern grey kangaroos (Macropus giganteus) in south-eastern New South Wales, Australia. *Wildlife Research* **33**, 93–102.

R Development Core Team (2018). R: A language and environment for statistical computing. Available at: http://www.r-project.org

Ramsey, D. S. L., Forsyth, D. M., Conroy, M. J., Hall, G. P., Kingsford, R. T., Mitchell, G., Roshier, D. A., Veltman, C. J., Webb, G., and Wintle, B. A. (2010). Developing a sustainable harvest model for Victorian waterfowl. Arthur Rylah Institute for Environmental Research Technical Repoort Series No. 195, Department of Sustainability and Environment, Heidelberg, Victoria.

Ramsey, D. S. L., Forsyth, D. M., Wright, E. F., McKay, M., and Westbrooke, I. (2018). Using propensity scores for causal inference in ecology: options, considerations and a case study. *Methods in Ecology and Evolution* **10**, 320–331.

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, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Robinson, G. K. (1991). That BLUP is a good thing: the estimation of random effects. *Statistical Science* **6**, 15–51.

Robson, D. S., and Regier, H. A. (1964). Sample size in Petersen mark-recapture experiments. *Transactions of the American Fisheries Society* **93**, 215–226.

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.

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

Smith, M. J., Schreiber, E. S. G., Kohout, M., Ough, K., Lennie, R., Turnbull, D., Jin, C., and Clancy, T. (2007). Wetlands as landscape units: Spatial patterns in salinity and water chemistry. *Wetlands Ecology and Management* **15**, 95–103.

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

Thompson, W. L., White, G. C., and Gowan, C. (1998). *Monitoring Vertebrate Populations*.. (Academic Press.)

Tillé, Y., and Matei, A. (2016). Sampling: survey sampling. Available at: https://cran.r-project.org/package=sampling

Williams, B. K., Nichols, J. D., and Conroy, M. J. (2002). *Analysis and management of animal populations*. (Academic Press: San Diego.)

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)

$$\hat{\tau}_h = \sum_{i=1}^{m} \frac{\hat{n}_{ih}}{\pi_h} \qquad (Equation\ 7)$$

where $\hat{\tau}_h$ is total abundance of ducks in stratum h, $\hat{n}_{ih}$ is the BLUP estimate of the number of ducks (Equation 3) in waterbody i and stratum h, m is the number of sampled waterbodies in stratum h, and π_h is the inclusion probability for a waterbody in stratum h. The variance of $\hat{\tau}_h$ is then given by

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

where M is the total number of waterbodies in stratum h in the sampling frame, $\text{var}\ n_{ih}$ 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 given by $m\hat{n}_{ih}/\pi_h$ (Thompson 1992; section 6.2). The estimate of total abundance of ducks in the sampling frame is then

$$\hat{N}_T = \sum_{h=1}^{H} \hat{\tau}_h \qquad (Equation\ 8)$$

with variance

$$\text{var}(\hat{N}_T) = \sum_{h=1}^{H} \text{var}(\hat{\tau}_h) \qquad (Equation\ 9)$$

Multistage design

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

$$\hat{N}_T = \sum_{i=1}^{k} \frac{\hat{N}_i}{\pi_i} \qquad (Equation\ 10)$$

where $\hat{N}_T$ is total abundance, $\hat{N}_i$ 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.

From Skalski (1994), the Horvitz–Thompson version of the variance of Equation 10 is then given by

$$\mathrm{var}(\hat{N}_T) = \sum_{i=1}^{k} \frac{(1-\pi_i)\hat{N}_i^2}{\pi_i^2} + 2\sum_{i=1}^{k}\sum_{j>i}^{k} \frac{(\pi_{ij}-\pi_i\pi_j)\hat{N}_i\hat{N}_j}{\pi_{ij}\pi_i\pi_j} + \sum_{i=1}^{k} \frac{\mathrm{var}(\hat{N}_i)}{\pi_i} \qquad (Equation\ 11)$$

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 2018). The estimate of the primary unit variance $\mathrm{var}(\hat{N}_i)$ 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 BLUP estimates of abundance of ducks for each waterbody. Since the sample of waterbodies at the secondary stage was selected with simple random sampling, this was calculated as

$$\mathrm{var}(\hat{N}_i) = M_i^2 \left[\frac{\left(1-\frac{m}{M_i}\right)S_i^2}{m} + \frac{\overline{\mathrm{var}(\hat{n}_i)}}{M_i} \right] \qquad (Equation\ 12)$$

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 BLUP estimate of abundance of ducks (Equation 3) 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 BLUP abundance estimate of ducks for the m sampled waterbodies in primary unit i, and $\mathrm{var}(n_{ij})$ and $\overline{var(\hat{n}_i)}$ are the variances of the BLUP estimates of abundance for each waterbody j and the average variance (within primary unit i), respectively. Given waterbodies at the secondary stage were selected at random, it follows that the estimate of the total abundance of ducks for primary unit i ($\hat{N}_i$) 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 10–12) were undertaken separately for each stratum. Total abundance (and its variance) were then calculated as the sum of the strata abundances (and variances) (Equations 8 and 9).

Appendix B

Models fitted to counts of game ducks from the Victorian summer waterfowl count.

The generalised linear model fitted to the counts of Grey Teal and Australian Wood Duck (Equation 1) assumed counts followed a Gamma distribution with parameters mean (μ) and standard deviation (σ).

$$\log(\mu_i) = \beta_0 + \beta_{j(i)} T_i + \gamma_{k(i)} S_i + \delta_{jk(i)} T_i S_i$$

$$\log(\sigma_i) = \alpha_0 + \eta_{k(i)} S_i$$

Where μ and σ were the mean and standard deviation of the gamma distribution, T_i was the waterbody type category (wetland, dam, sewage pond), S_i the waterbody size category (< 6 ha, 6–50 ha, > 50 ha) and β_0, β_j, γ_k, δ_{jk}, α_0 and η_k are parameters to be estimated. The parameter estimates for this model for the two species are given in Tables B1 and B2 with the predicted means and standard deviations given in Tables B3 and B4.

Table B1. Parameter estimates from the generalised linear model fitted to the counts of Grey Teal collected during the summer waterfowl count. The distribution for the count response was gamma with parameters mean (μ) and standard deviation (σ).

Parameter	Term	Estimate	S.E.	Statistic	P value
μ	(Intercept)	4.19	0.106	39.4	0.000
	Size (6–50 ha)	0.83	0.128	6.5	0.000
	Size (> 50 ha)	1.74	0.118	14.7	0.000
	Type (Sewage pond)	0.47	0.158	3.0	0.003
	Type (Wetlands)	–1.28	0.181	–7.1	0.000
	Size (6–50ha) × Type (Sewage pond)	0.32	0.211	1.5	0.132
–	Size (> 50 ha) × Type (Sewage pond)	0.74	0.285	2.6	0.009
	Size (6–50 ha) × Type (Wetlands)	0.50	0.210	2.4	0.018
	Size (> 50 ha) ×Type (Wetlands)	1.29	0.199	6.5	0.000
σ	(Intercept)	0.27	0.031	8.7	0.000
	Size (6–50 ha)	0.09	0.037	2.3	0.020
	Size (> 50 ha)	0.21	0.034	6.1	0.000

Table B2. Parameter estimates from the generalised linear model fitted to the counts of Australian Wood Duck collected during the summer waterfowl count. The distribution for the count response was gamma with parameters mean (μ) and standard deviation (σ).

Parameter	Term	Estimate	S.E.	Statistic	P value
μ	(Intercept)	3.11	0.103	30.2	0.000
	Size (6-50 ha)	0.71	0.136	5.2	0.000
	Size (> 50 ha)	2.53	0.122	20.8	0.000
	Type (Sewage pond)	0.83	0.179	4.6	0.000
–	Type (Wetlands)	0.31	0.210	1.5	0.140
–	Size (6–50ha) × Type (Sewage pond)	–0.88	0.243	–3.6	0.000
–	Size (> 50 ha) × Type (Sewage pond)	–2.62	0.369	–7.1	0.000
	Size (6-50 ha) × Type (Wetlands)	–0.45	0.252	–1.8	0.072
	Size (> 50 ha) × Type (Wetlands)	–1.78	0.249	–7.2	0.000
σ	(Intercept)	0.23	0.036	6.5	0.000
	Size (6–50 ha)	–0.02	0.047	–0.3	0.734
	Size (> 50 ha)	0.20	0.042	4.9	0.000

Table B3. Estimated means (Mean) and standard deviations (SD) of fitted gamma distributions for each waterbody type and size class predicted from the generalised linear model for Grey Teal.

Size class	Type	Mean	SD
< 6 ha	Dams	66.2	1.31
6–50 ha	Dams	152.1	1.43
> 50 ha	Dams	378.0	1.62
< 6 ha	Sewage pond	105.8	1.31
6–50 ha	Sewage pond	334.1	1.43
> 50 ha	Sewage pond	1270.1	1.62
< 6 ha	Wetlands	18.3	1.31
6–50 ha	Wetlands	69.2	1.43
> 50 ha	Wetlands	381.7	1.62

Table B4. Estimated means (Mean) and standard deviations (SD) of fitted gamma distributions for each waterbody type and size class predicted from the generalised linear model for Australian Wood Duck.

Size	Type	Mean	SD
< 6 ha	Dams	22.5	1.26
6–50 ha	Dams	45.8	1.24
> 50 ha	Dams	282.1	1.55
< 6 ha	Sewage pond	51.5	1.26
6–50 ha	Sewage pond	43.5	1.24
> 50 ha	Sewage pond	46.8	1.55
< 6 ha	Wetlands	30.7	1.26
6–50 ha	Wetlands	39.7	1.24
> 50 ha	Wetlands	64.8	1.55

Appendix C

Table C1. Estimates of the size of the game duck harvest, seasonal arrangements (bag limit and season length), and number of licensed hunters for the years 2009–2019.

Year	Season length (days)	Bag limit	Licensed Hunters	Total Harvest
2009	49	5	18348	222 302
2010	72	8	21967	270 574
2011	87	10	23835	600 739
2012	87	10	24539	508 256
2013	87	10	25160	422 294
2014	87	10	26296	449 032
2015	80	5	25989	286 729
2016	87	4	25646	271 576
2017	87	10	26357	438 353
2018	87	10	25918	396 708
2019	65	5	25022	238 666

Appendix D

Table D1. Summary of simulation results for model-based estimates of game duck abundance sampled using a stratified random sampling design.
Size – sample size; CV – coefficient of variation; Bias – relative bias; RMSE – relative root mean square error; Cost – survey cost; P – proportion of RMSE values < 0.2; Work days – number of days to complete survey.

Species	Conditions	Size	CV	Bias	RMSE	Cost ($ 1000)	P	Work days
Australian Wood Duck	Dry	200	0.017	0.400	0.400	179.1	0.01	5.7
Australian Wood Duck	Dry	500	0.010	0.320	0.320	320.9	0.00	10.4
Australian Wood Duck	Dry	1000	0.007	0.216	0.216	517.4	0.28	16.8
Australian Wood Duck	Dry	1500	0.006	0.175	0.175	697.4	0.85	22.8
Australian Wood Duck	Dry	2500	0.004	0.072	0.072	1045.5	1.00	34.3
Australian Wood Duck	Dry	4000	0.003	0.002	0.004	1539.4	1.00	50.7
Australian Wood Duck	Wet	200	0.021	0.506	0.506	183.4	0.00	5.9
Australian Wood Duck	Wet	500	0.013	0.483	0.483	333.3	0.00	10.7
Australian Wood Duck	Wet	1000	0.009	0.433	0.433	544.8	0.00	17.7
Australian Wood Duck	Wet	1500	0.007	0.374	0.374	742.9	0.00	24.2
Australian Wood Duck	Wet	2500	0.006	0.292	0.292	1113.6	0.00	36.4
Australian Wood Duck	Wet	4000	0.004	0.226	0.226	1643.8	0.10	54.0
Grey Teal	Dry	200	0.008	-0.027	0.091	179.2	0.91	5.7
Grey Teal	Dry	500	0.005	-0.035	0.058	321.0	0.99	10.4
Grey Teal	Dry	1000	0.003	-0.042	0.045	517.0	1.00	16.8
Grey Teal	Dry	1500	0.003	-0.050	0.050	697.5	1.00	22.8
Grey Teal	Dry	2500	0.002	-0.028	0.028	1045.5	1.00	34.3
Grey Teal	Dry	4000	0.002	-0.006	0.006	1539.5	1.00	50.7
Grey Teal	Wet	200	0.012	-0.224	0.233	183.5	0.46	5.9
Grey Teal	Wet	500	0.007	-0.208	0.208	333.6	0.48	10.8
Grey Teal	Wet	1000	0.005	-0.169	0.169	544.8	0.68	17.7
Grey Teal	Wet	1500	0.004	-0.146	0.146	742.8	0.83	24.2
Grey Teal	Wet	2500	0.003	-0.141	0.141	1113.4	0.95	36.4
Grey Teal	Wet	4000	0.003	-0.128	0.128	1643.6	0.99	54.0

Table D2. Summary of simulation results for design-based estimates of game duck abundance sampled using a stratified random sampling design.
Size – sample size; CV – coefficient of variation; Bias – relative bias; RMSE – relative root mean square error; Cost – survey cost; P – proportion of RMSE values < 0.2; Work days – number of days to complete survey.

Species	Conditions	Size	CV	Bias	RMSE	Cost ($1000)	P	Work days
Australian Wood Duck	Dry	200	0.108	0.029	0.097	179.0	0.90	5.7
Australian Wood Duck	Dry	500	0.063	0.020	0.056	320.9	1.00	10.4
Australian Wood Duck	Dry	1000	0.037	0.012	0.032	517.4	1.00	16.8
Australian Wood Duck	Dry	1500	0.026	0.010	0.022	697.4	1.00	22.8
Australian Wood Duck	Dry	2500	0.013	0.000	0.010	1045.5	1.00	34.3
Australian Wood Duck	Dry	4000	0.004	-0.004	0.005	1539.0	1.00	50.7
Australian Wood Duck	Wet	200	0.144	0.034	0.118	183.6	0.84	5.9
Australian Wood Duck	Wet	500	0.090	0.040	0.081	333.7	0.96	10.8
Australian Wood Duck	Wet	1000	0.061	0.038	0.060	544.8	1.00	17.7
Australian Wood Duck	Wet	1500	0.047	0.025	0.046	743.0	1.00	24.2
Australian Wood Duck	Wet	2500	0.033	0.016	0.031	1113.5	1.00	36.4
Australian Wood Duck	Wet	4000	0.024	0.014	0.023	1644.2	1.00	54.0
Grey Teal	Dry	200	0.120	–0.013	0.108	178.8	0.87	5.7
Grey Teal	Dry	500	0.069	–0.008	0.057	321.1	0.99	10.4
Grey Teal	Dry	1000	0.038	–0.007	0.030	517.2	1.00	16.8
Grey Teal	Dry	1500	0.026	–0.005	0.024	697.4	1.00	22.8
Grey Teal	Dry	2500	0.012	–0.004	0.010	1045.4	1.00	34.3
Grey Teal	Dry	4000	0.003	–0.001	0.003	1539.1	1.00	50.7
Grey Teal	Wet	200	0.156	–0.046	0.135	183.4	0.77	5.9
Grey Teal	Wet	500	0.099	–0.022	0.086	333.2	0.94	10.7
Grey Teal	Wet	1000	0.066	–0.019	0.057	544.9	0.99	17.7
Grey Teal	Wet	1500	0.050	–0.016	0.046	742.7	1.00	24.2
Grey Teal	Wet	2500	0.035	–0.015	0.030	1113.3	1.00	36.4
Grey Teal	Wet	4000	0.025	–0.009	0.022	1643.9	1.00	54.0

Table D3. Summary of simulation results for model-based estimates of game duck abundance sampled using a multistage random sampling design under 'dry' conditions. Units – number of primary units; Sites – number of secondary units; CV – coefficient of variation; Bias – relative bias; RMSE – relative root mean square error; Cost – survey cost; Work days – number of days to complete survey; P – Proportion of RMSE values < 0.2; n – mean total sampled waterbodies.

Unit size (km)	Units	Sites	CV	Bias	RMSE	Cost	Work days	P	n
10	20	10	0.027	0.622	0.173	78.6	2.5	0.68	91
10	20	25	0.019	0.033	0.156	86.1	2.8	0.71	114
10	20	50	0.019	0.042	0.159	87.2	2.8	0.72	118
10	40	10	0.013	0.007	0.114	125.7	4.0	0.83	180
10	40	25	0.012	0.017	0.110	139.2	4.5	0.86	223
10	40	50	0.012	0.011	0.106	142.8	4.6	0.87	234
10	60	10	0.011	0.007	0.094	167.7	5.4	0.90	270
10	60	25	0.010	0.005	0.087	187.4	6.1	0.94	332
10	60	50	0.010	0.011	0.080	191.9	6.2	0.95	345
10	80	10	0.009	0.002	0.075	206.7	6.7	0.96	359
10	80	25	0.008	0.000	0.072	234.2	7.6	0.97	443
10	80	50	0.008	0.000	0.070	240.2	7.8	0.97	462
25	20	10	0.016	0.026	0.132	96.6	3.1	0.77	130
25	20	25	0.013	0.016	0.110	123.5	4.0	0.85	209
25	20	50	0.012	0.012	0.102	141.1	4.6	0.88	263
25	40	10	0.011	-0.001	0.086	161.4	5.2	0.93	258
25	40	25	0.008	0.005	0.070	215.0	7.0	0.97	418
25	40	50	0.008	0.002	0.067	247.7	8.1	0.98	519
25	60	10	0.008	0.001	0.069	221.4	7.2	0.97	387
25	60	25	0.007	0.001	0.051	299.8	9.8	1.00	623
25	60	50	0.006	-0.002	0.050	352.4	11.5	0.99	782
25	80	10	0.007	-0.003	0.057	279.2	9.1	0.99	517
25	80	25	0.006	-0.001	0.046	385.2	12.6	1.00	833
25	80	50	0.005	-0.002	0.040	454.0	14.9	1.00	1045
50	20	10	0.014	0.013	0.122	122.5	3.9	0.82	170
50	20	25	0.009	0.010	0.076	189.4	6.2	0.96	358
50	20	50	0.008	0.007	0.064	251.4	8.2	0.98	542
50	40	10	0.009	0.004	0.075	212.9	6.9	0.95	342
50	40	25	0.006	0.005	0.049	345.2	11.3	1.00	715
50	40	50	0.005	-0.003	0.039	470.6	15.4	1.00	1087
50	60	10	0.007	0.005	0.061	298.5	9.7	0.98	512
50	60	25	0.005	0.001	0.038	496.7	16.2	1.00	1072
50	60	50	0.004	-0.001	0.029	685.5	22.5	1.00	1632
50	80	10	0.006	0.001	0.050	381.7	12.4	1.00	683
50	80	25	0.004	0.000	0.030	645.5	21.1	1.00	1429
50	80	50	0.004	-0.002	0.022	900.1	29.6	1.00	2183

Table D4. Summary of simulation results for model-based estimates of game duck abundance sampled using a multistage random sampling design under 'wet' conditions. Units – number of primary units; Sites – number of secondary units; CV – coefficient of variation; Bias – relative bias; RMSE – relative root mean square error; Cost – survey cost; Work days – number of days to complete survey; P – Proportion of RMSE values < 0.2; n – mean total sampled waterbodies.

Unit size (km)	Units	Sites	CV	Bias	RMSE	Cost	Work days	P	n
10	20	10	0.017	0.014	0.110	92.1	3.0	0.86	134
10	20	25	0.013	0.010	0.083	119.3	3.9	0.94	218
10	20	50	0.012	0.010	0.080	135.1	4.4	0.95	267
10	40	10	0.011	0.006	0.071	154.1	5.0	0.97	268
10	40	25	0.009	0.003	0.056	207.4	6.8	0.99	432
10	40	50	0.008	-0.003	0.051	237.6	7.8	0.99	525
10	60	10	0.009	0.001	0.057	211.4	6.9	0.99	400
10	60	25	0.007	-0.002	0.046	290.0	9.5	1.00	643
10	60	50	0.007	-0.001	0.042	335.4	11.0	1.00	785
10	80	10	0.008	0.002	0.051	265.5	8.6	0.99	530
10	80	25	0.006	-0.003	0.039	371.3	12.2	1.00	857
10	80	50	0.006	-0.004	0.037	432.8	14.2	1.00	1049
25	20	10	0.015	0.019	0.091	114.1	3.7	0.92	171
25	20	25	0.010	0.008	0.062	181.9	5.9	0.98	370
25	20	50	0.007	–0.001	0.048	260.6	8.5	1.00	608
25	40	10	0.010	0.002	0.064	195.0	6.3	0.98	340
25	40	25	0.007	–0.002	0.042	331.9	10.9	1.00	739
25	40	50	0.005	–0.002	0.031	489.6	16.1	1.00	1217
25	60	10	0.008	–0.001	0.055	273.2	8.9	1.00	511
25	60	25	0.005	–0.002	0.034	476.8	15.6	1.00	1106
25	60	50	0.004	–0.004	0.026	712.3	23.4	1.00	1821
25	80	10	0.007	0.000	0.043	348.9	11.3	1.00	681
25	80	25	0.005	–0.004	0.029	620.7	20.4	1.00	1478
25	80	50	0.004	–0.004	0.022	928.5	30.6	1.00	2410
50	20	10	0.014	0.030	0.088	133.1	4.3	0.93	187
50	20	25	0.009	0.008	0.058	227.2	7.4	0.99	436
50	20	50	0.007	–0.004	0.042	358.3	11.7	1.00	810
50	40	10	0.011	0.011	0.071	232.7	7.5	0.97	372
50	40	25	0.006	0.001	0.042	419.7	13.7	1.00	870
50	40	50	0.004	–0.005	0.028	681.8	22.4	1.00	1618
50	60	10	0.009	0.010	0.057	329.7	10.7	0.98	557
50	60	25	0.005	–0.004	0.032	609.7	19.9	1.00	1306
50	60	50	0.004	–0.004	0.022	1001.0	32.9	1.00	2425
50	80	10	0.008	0.002	0.047	422.9	13.7	1.00	742
50	80	25	0.004	–0.003	0.026	796.0	26.0	1.00	1739
50	80	50	0.003	–0.005	0.019	1318.7	43.3	1.00	3235

Table D5. Summary of simulation results for design-based estimates of game duck abundance sampled using a multistage random sampling design under 'dry' conditions. Units – number of primary units; Sites – number of secondary units; CV – coefficient of variation; Bias – relative bias; RMSE – relative root mean square error; Cost – survey cost; Work days – number of days to complete survey; P – Proportion of RMSE values < 0.2; n – mean total sampled waterbodies.

Unit size (km)	Units	Sites	CV	Bias	RMSE	Cost	Work days	P	n
10	20	10	0.226	-0.060	0.215	82.6	2.7	0.58	104
10	20	25	0.216	-0.015	0.197	93.3	3.0	0.61	136
10	20	50	0.215	0.014	0.190	96.7	3.1	0.65	146
10	40	10	0.158	0.042	0.143	132.8	4.3	0.75	205
10	40	25	0.154	0.015	0.125	153.5	5.0	0.80	269
10	40	50	0.151	-0.011	0.126	160.0	5.2	0.81	288
10	60	10	0.128	-0.038	0.110	178.2	5.8	0.86	306
10	60	25	0.123	-0.005	0.098	209.1	6.8	0.89	401
10	60	50	0.122	-0.008	0.102	219.0	7.1	0.89	432
10	80	10	0.109	-0.024	0.089	222.6	7.2	0.92	410
10	80	25	0.105	-0.003	0.080	264.7	8.6	0.95	539
10	80	50	0.104	-0.004	0.083	276.2	9.0	0.94	574
25	20	10	0.193	0.000	0.221	105.2	3.4	0.57	156
25	20	25	0.175	–0.009	0.164	151.8	4.9	0.70	293
25	20	50	0.167	–0.007	0.156	191.3	6.2	0.71	411
25	40	10	0.135	–0.090	0.148	178.6	5.8	0.72	311
25	40	25	0.120	–0.038	0.110	269.4	8.8	0.85	578
25	40	50	0.116	–0.006	0.103	344.6	11.3	0.88	806
25	60	10	0.105	–0.086	0.125	247.7	8.0	0.80	464
25	60	25	0.094	–0.005	0.081	380.5	12.4	0.94	857
25	60	50	0.090	–0.013	0.078	484.0	15.9	0.96	1172
25	80	10	0.087	–0.085	0.113	313.0	10.2	0.85	614
25	80	25	0.077	–0.031	0.071	481.7	15.8	0.97	1115
25	80	50	0.073	–0.005	0.064	614.4	20.2	0.99	1519
50	20	10	0.168	–0.133	0.262	127.9	4.1	0.42	189
50	20	25	0.139	–0.071	0.149	215.6	7.0	0.72	432
50	20	50	0.131	–0.017	0.135	311.6	10.2	0.77	714
50	40	10	0.111	–0.152	0.211	224.1	7.2	0.52	375
50	40	25	0.092	–0.055	0.104	393.0	12.8	0.87	848
50	40	50	0.082	–0.023	0.083	570.3	18.7	0.96	1371
50	60	10	0.083	–0.154	0.195	314.3	10.2	0.54	555
50	60	25	0.064	–0.013	0.085	553.2	18.1	0.96	1228
50	60	50	0.055	–0.019	0.058	793.8	26.1	1.00	1939
50	80	10	0.066	–0.155	0.190	398.6	12.9	0.55	723
50	80	25	0.046	–0.059	0.071	694.6	22.7	0.99	1558
50	80	50	0.038	–0.020	0.040	983.8	32.3	1.00	2415

Table D6. Summary of simulation results for model-based estimates of game duck abundance sampled using a multistage random sampling design under 'wet' conditions. Units – number of primary units; Sites – number of secondary units; CV – coefficient of variation; Bias – relative bias; RMSE – relative root mean square error; Cost – survey cost; Work days – number of days to complete survey; P – Proportion of RMSE values < 0.2; n – mean total sampled waterbodies.

Unit size (km)	Units	Sites	CV	Bias	RMSE	Cost	Work days	P	n
10	20	10	0.264	–0.061	0.302	96.5	3.1	0.43	146
10	20	25	0.249	–0.007	0.263	131.3	4.3	0.49	252
10	20	50	0.245	–0.004	0.256	150.5	4.9	0.48	313
10	40	10	0.200	–0.066	0.205	161.6	5.2	0.58	289
10	40	25	0.187	0.009	0.178	229.4	7.5	0.64	498
10	40	50	0.184	–0.007	0.164	269.5	8.8	0.67	624
10	60	10	0.168	–0.057	0.165	222.1	7.2	0.68	434
10	60	25	0.155	–0.020	0.138	325.8	10.7	0.76	751
10	60	50	0.154	–0.003	0.137	384.5	12.6	0.78	934
10	80	10	0.148	–0.054	0.145	281.7	9.2	0.75	579
10	80	25	0.137	–0.008	0.117	419.3	13.8	0.82	1002
10	80	50	0.134	–0.007	0.125	494.5	16.3	0.80	1236
25	20	10	0.273	–0.124	0.373	116.9	3.8	0.36	183
25	20	25	0.255	–0.043	0.299	202.0	6.6	0.41	429
25	20	50	0.239	–0.034	0.273	310.4	10.2	0.44	754
25	40	10	0.208	–0.132	0.284	202.5	6.6	0.44	365
25	40	25	0.192	–0.050	0.198	370.6	12.1	0.58	852
25	40	50	0.178	–0.033	0.187	583.0	19.2	0.61	1492
25	60	10	0.174	–0.112	0.223	284.8	9.3	0.52	548
25	60	25	0.158	–0.065	0.165	534.6	17.5	0.69	1274
25	60	50	0.152	–0.026	0.143	853.5	28.1	0.76	2235
25	80	10	0.149	–0.127	0.210	364.1	11.9	0.55	729
25	80	25	0.135	–0.060	0.140	696.5	22.9	0.75	1695
25	80	50	0.129	–0.028	0.121	1116.9	36.8	0.81	2962
50	20	10	0.231	–0.265	0.543	135.9	4.4	0.20	196
50	20	25	0.233	–0.107	0.309	243.7	7.9	0.38	478
50	20	50	0.222	–0.055	0.267	407.6	13.4	0.44	940
50	40	10	0.187	–0.144	0.269	241.0	7.8	0.44	389
50	40	25	0.165	–0.090	0.196	454.7	14.8	0.58	951
50	40	50	0.150	–0.065	0.178	774.5	25.4	0.63	1857
50	60	10	0.135	–0.149	0.220	341.6	11.1	0.50	581
50	60	25	0.120	–0.088	0.150	659.8	21.5	0.71	1422
50	60	50	0.115	–0.045	0.116	1128.7	37.1	0.82	2755
50	80	10	0.097	–0.142	0.185	437.8	14.2	0.58	769
50	80	25	0.082	–0.089	0.115	851.9	27.8	0.84	1868
50	80	50	0.077	–0.047	0.081	1453.2	47.7	0.95	3583

Appendix E

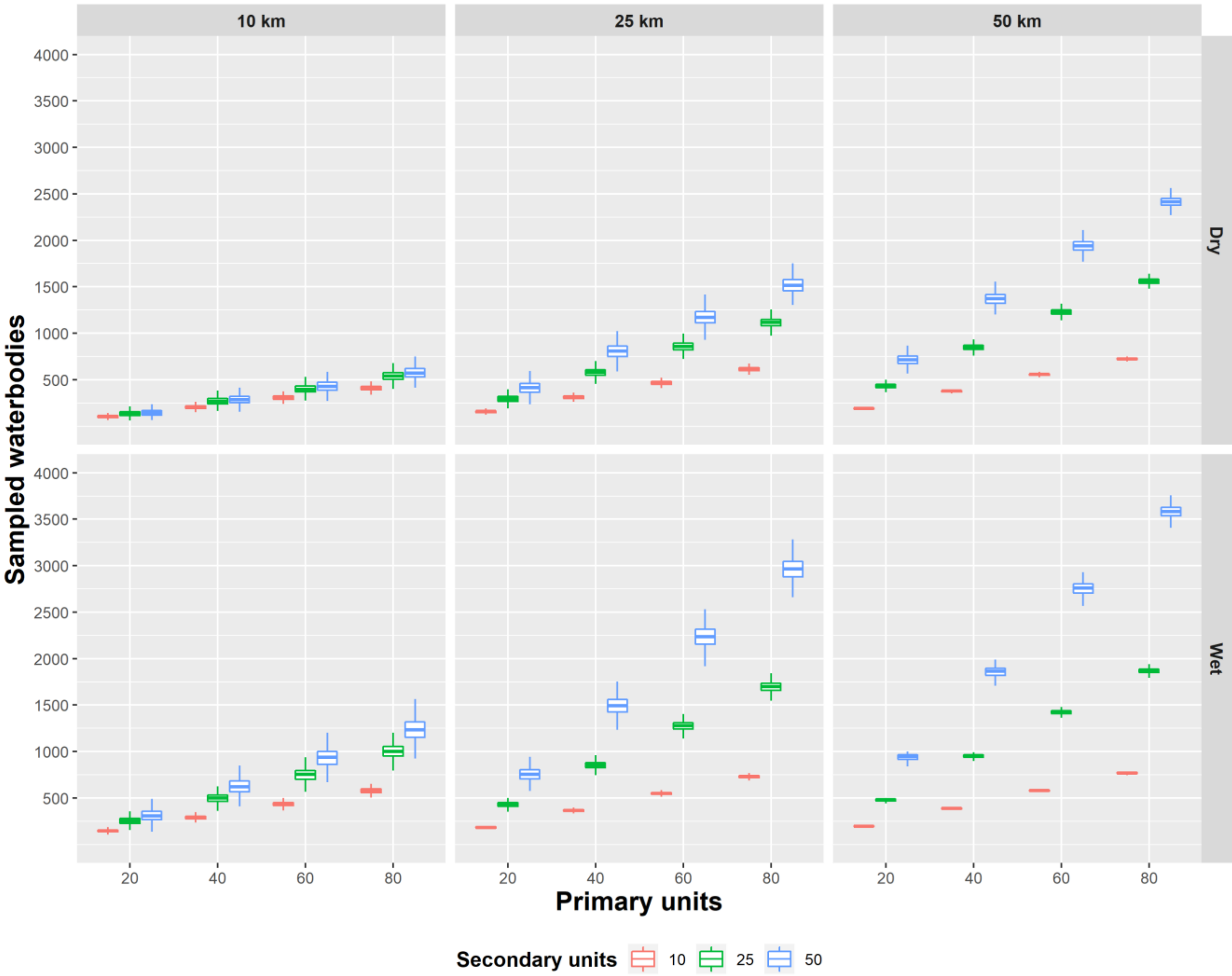


Figure E1. Realised total number of sampled waterbodies under each multistage design for different numbers of primary units, primary unit size (km) and number of secondary units for each condition (‘dry’, ‘wet’).

www.delwp.vic.gov.au

www.ari.vic.gov.au