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Developing a sustainable harvest model for Victorian waterfowl

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Summary

An Expert Scientific Panel ('the panel') was convened by the Adaptive Harvest Management (AHM) subcommittee of the Victorian Hunting Advisory Committee and the Department of Sustainability and Environment (DSE) to recommend a robust scientific approach to sustainable waterfowl harvesting in Victoria that would:

1. consider previous work and evaluate the current harvest approach in Victoria
2. investigate other approaches adopted throughout the world and relevant scientific research into adaptive and other wildlife harvest management models
3. consider the existing literature on the ecology and biology of Australian waterfowl populations (habitat utilisation, population dynamics, movement patterns, etc.) when developing an approach on harvest management
4. identify a scientific credible harvest management model that can be delivered at minimal cost.

The panel comprised 10 members: Dr Graham Mitchell (Chair), Dr David Forsyth (Facilitator), Dr David Ramsey, Dr Michael Conroy, Dr Graham Hall, Professor Richard Kingsford, Dr David Roshier, Dr Clare Veltman, Professor Grahame Webb and Dr Brendan Wintle; and met twice (3–5 December 2008 and 9–10 March 2009).

The panel recommends that an adaptive management approach be taken to the sustainable harvesting of Victorian waterfowl and a prototype model (termed the 'Waterfowl Conservation and Harvesting Model'—WCHM) was developed to illustrate how this approach could operate. The WCHM is a mathematical expression of how the panel believes that waterfowl populations in eastern Australia respond to key environmental drivers (such as wetland availability) and harvest. The WCHM incorporates long-range movements of some waterfowl species in response to local and regional changes in wetland area by linking major patches of waterfowl habitat inside and outside Victoria. The WCHM would use species-specific parameters, with each species' model capturing the key features of that species' dynamics (e.g. potential for long-range movements in response to changes in wetland area). The WCHM explicitly recognises the importance of wetland area for waterfowl populations in eastern Australia and hence the impacts of major changes in that variable on the abundances and distributions of the various species: it is for this reason that 'conservation' features in the name of the model. The WCHM would be used to investigate how different harvest strategies affect the sustainability (defined as projected future abundances) of each waterfowl species. An important feature of the WCHM is its application to the sustainability of non-game waterfowl species and the panel recommends that, if implemented, non-game species (including Freckled Duck) be included.

The WCHM is 'adaptive' because it would be updated annually based on: (i) estimated harvest in the previous hunting season, (ii) estimated wetland area, (iii) estimated waterfowl abundance, and (iv) projected rainfall. Additional monitoring of waterfowl abundances, particularly of Australian Wood Duck, by aerial survey is proposed. The first-year cost of implementing the WCHM was estimated to be $542 000, of which $375 500 would be spent on monitoring waterfowl abundances and harvests. The subsequent ongoing annual cost of the WCHM is likely to be a lesser amount but may change depending upon results of the first year of implementation.

The key benefits of the approach proposed here are:

1. transparency in how the annual harvest regulations (i.e. season length and bag size for each species) are recommended to the Minister, leading to reduced conflict among stakeholders
2. assurance that harvesting in Victoria is unlikely to adversely affect the sustainability of waterfowl populations in eastern Australia

3. increased understanding of the key drivers of waterfowl dynamics in eastern Australia, particularly the relative importance of wetland area and harvesting
4. development and maintenance of waterfowl research, management and monitoring expertise in Victoria.

A key requirement of the proposed approach is that stakeholders (including Ministers) must have confidence in the approach and its recommendations about season lengths and bag sizes; accept that the process is adaptive such that uncertainties should reduce with time; provide sufficient resources to operate the WCHM; and recognise its reliance on the skills of a small number of scientific staff that may not be able to be quickly replaced if they cease their current employment.

1. Introduction

1.1 Background

Decisions about the annual duck hunting season in Victoria have a history of causing conflict between waterfowl hunting organisations, the Department of Sustainability and Environment (DSE, which has the statutory responsibility for the season regulations) and community groups that have a range of often contrary opinions about the aims of waterfowl management.

Conflict between these stakeholder groups is exacerbated by the fact that waterfowl populations in Victoria are influenced by the direct and cumulative effects of climatic conditions upon wetlands within and beyond this state. At a workshop held in September 2002, representatives from major Victorian waterfowl hunting organisations, wetland and waterfowl experts and representatives from DSE, identified that the process for determining the annual waterfowl hunting season arrangements (i.e. whether or not a season will be held and the size of bag limits) is a major point of conflict between stakeholders. Currently, the annual hunting season arrangements are largely based upon (1) data on recent and prevailing weather (including the Southern Oscillation Index), (2) the extent of wetland habitat across eastern Australia, (3) the Eastern Australian Aerial Waterbird Count undertaken by University of New South Wales in collaboration with the eastern States, and (4) summer waterfowl count data provided by DSE staff and Field and Game Australia volunteers for selected Victorian wetlands. The process by which these data are used in decision making for the duck season is the source of disagreement for all stakeholders. As a consequence, it was resolved that an adaptive harvest management approach (AHM) would be the most efficient approach and objective means for establishing duck hunting season conditions.

In 2003, the first AHM subcommittee was convened between DSE and duck hunting organisations. This initial step of analysing existing data produced a report commissioned by DSE (Arthur Rylah Institute for Environmental Research 2003). That report outlined two models that predicted the effects of hunting in Victoria on the eastern Australian game duck populations. The two models represented constant and proportional harvest scenarios largely based on indices of waterfowl abundance, wetland availability and climatic indices. Hunting organisations, although acknowledging the validity of certain aspects of the report, believed that the models presented were too complex and failed to adequately reflect the principles of adaptive harvest management. DSE subsequently developed a decision matrix but this was not agreed upon by all parties. In response to the draft report produced by the Arthur Rylah Institute for Environmental Research (ARI), Field and Game Australia commissioned a report (Webb and Whitehead 2004) that concurred that adaptive management was a sound and logical approach to regulating Victoria's duck hunting seasons, and would partly address some conflicts that existed between stakeholders. However, the authors felt that although the report produced by ARI identified key elements vital for an adaptive management approach, further work was needed to provide a robust framework to implement such a program. Webb and Whitehead (2004) outlined three main issues that they felt should be addressed in the future:

1. a simplified approach to regulating duck hunting
2. a larger commitment to monitor abundance of waterfowl
3. a greater commitment to monitor the impacts of hunting.

Despite these investigations and efforts to develop an approved approach to decision making, a model was not produced and disagreement over harvesting arrangements continued.

In early 2007, DSE met with Field and Game Australia to progress resolution of the issue by reconvening the AHM subcommittee. At its meeting on 19 July 2007, the Victorian Hunting Advisory Committee agreed to reconvene the AHM subcommittee and endorsed DSE's suggestion to establish an independent expert scientific panel to advise on a robust and objective approach to waterfowl harvest management. It was resolved that the expert scientific panel would consist of at least five members, a chair and a facilitator.

1.2 Approved Terms of Reference for the Expert Scientific Panel

The AHM subcommittee stipulated that 'The Expert Scientific Panel will recommend a robust scientific approach to sustainable waterfowl harvesting in Victoria that would:

- consider previous work and evaluate the current harvest approach in Victoria;
- investigate other approaches adopted throughout the world and relevant scientific research into adaptive and other wildlife harvest management models;
- consider the existing literature on the ecology and biology of Australian waterfowl populations (habitat utilisation, population dynamics, movement patterns etc.) when developing an approach on harvest management;
- identify a scientific credible harvest management model that can be delivered at minimal cost; and,
- produce a manuscript to be published in a relevant scientific journal.

In delivering the above, the panel should identify constraints and benefits of the model proposed.'

2 Methods

2.1 Panel selection, membership and meetings

The panel's chair and facilitator were chosen by DSE. The panel chair and facilitator then met with the AHM subcommittee to identify other possible panel members. The key criterion was that the panel members would have expertise in one or more of the following five research areas: waterfowl biology, population ecology, population modelling/statistics, wildlife harvest science and Australian wetland ecology.

An overview of the project, including the terms of reference, was sent to each of the possible panel members together with an invitation to express their interest in being a panel member. The people who expressed an interest in being a panel member were sent further information, including the dates of the first meeting, and a document for them to sign if they agreed to be a panel member.

The panel consisted of Dr Graham Mitchell (Chair), Dr David Forsyth (Facilitator), Dr David Ramsey, Dr Michael Conroy, Dr Graham Hall, Professor Richard Kingsford, Dr David Roshier, Dr Clare Veltman, Professor Grahame Webb and Dr Brendan Wintle. The affiliations of the panel members are listed in Appendix 1. Dr Conroy indicated that although he could not attend any meetings he was keen to participate in the panel's deliberations by email.

The panel met twice. The first meeting was 3–5 December 2008 and was attended by all panel members except Drs Conroy and Wintle. The following six presentations were made to the panel on the 3rd (afternoon) and 4th (morning) of December:

- background on the project and history of waterfowl harvesting in Victoria (Mr Ron Waters)
- Victorian waterfowl hunters' perspective on AHM (Mr Rod Drew and Mr Bob Cooper)
- overview of waterfowl harvesting in Tasmania (Dr Graham Hall)
- satellite tracking of Grey Teal (Dr David Roshier)
- summer waterfowl counts in Victoria: sampling scheme and trends (Mr Richard Loyn)
- aerial survey of waterbirds in eastern Australia (Professor Richard Kingsford).

The remainder of the meeting involved the panel discussing a robust scientific approach to sustainable waterfowl harvesting in Victoria. Based on these discussions, it was agreed that a prototype model would be developed prior to the second meeting.

The second meeting was 9–10 March 2009 and was attended by all panel members except Drs Conroy and Wintle. The panel first discussed the prototype harvest model and then presented it to the AHM subcommittee. Following discussions with the AHM subcommittee, the panel further discussed aspects of the model. The remainder of this report documents the sustainable harvest model that the panel recommends for Victorian waterfowl.

3 Panel findings

3.1 Definitions

For the purposes of conducting its deliberations, the panel agreed that there was utility in defining ten concepts implicit within the brief:

3.1.1 Conservation

The sum total of actions taken to preserve and maintain waterfowl (game and non-game ducks, geese and swans) within Victoria.

3.1.2 Sustainable harvest

A sustainable harvest is achieved within an AHM by optimising the harvest objective (e.g. ‘maximise cumulative harvest’) over a long time horizon. Under that objective, the future harvest would decrease if the short-term harvest causes the population to decline. This definition ensures that harvesting does not increase the likelihood of the waterfowl population becoming extinct.

3.1.3 Model

A mathematical expression of hypotheses about the functioning of nature and the impact of environmental drivers, such as wetland availability and human-interventions such as harvest. Model predictions can be tested objectively by comparison to data with the purpose both of improving prediction accuracy and discriminating between alternative hypotheses.

3.1.4 Adaptive

The repeated cycle through which new knowledge, sometimes generated by testing a model, is incorporated within the model to improve predictive accuracy and to discriminate between alternative hypotheses, particularly those relevant to informing decision making.

3.1.5 Resilience

The resilience of many waterfowl species in Victoria, despite ongoing reductions in wetland area and quality, and various forms of population harvest and control over the last 100+ years, reflects their high mobility, the fundamental importance of immigration and emigration (to and from wetlands outside of Victoria), and the high breeding potential when optimal conditions prevail (inside and/or outside Victoria). From this perspective, most waterfowl species in Victoria are resilient.

3.1.6 Threats

The major long-term threat to waterfowl populations in Victoria, regardless of species resilience, is the ongoing loss and degradation of wetlands used for reproduction, growth and maintenance, inside and outside of Victoria. The impacts of controlled hunting of wild populations, by comparison, (i) cannot be quantified on the basis of available data, (ii) are likely to be species-specific, and (iii) are unlikely to be quantified unless an AHM is implemented.

3.1.7 Monitoring

The systematic collection of data over time that provide estimates of waterfowl population parameters at various levels of resolution.

3.1.8 Absolute abundance

The actual number of individuals in a defined population.

3.1.9 Relative abundance

A measure of abundance that is correlated with absolute abundance to varying degrees of accuracy and precision.

3.1.10 Correction factors

Mathematical relationships used to predict absolute abundance from relative abundance.

3.2 Principles of a sustainable harvest model

The panel considered that the following five principles should guide the development of a sustainable harvest model for Victorian waterfowl.

3.2.1 'Sustainability' requires knowledge about population size over a sufficiently long time horizon

Following the definition of harvest above, evaluating the sustainability of harvesting on an animal population requires knowing about abundance (population size) and in particular changes (trends) in population size over time. The United States of America's Fish and Wildlife Service has used an adaptive approach to the management of harvesting of Mallard Duck (*Anas platyrhynchos*) in North America and the main objective is to maximise long-term harvest and to ensure that harvest does not produce population sizes below the goals expressed in the North American Waterfowl Management Plan (Nichols et al. 2007). In Australia, the sustainability of the commercial harvests of kangaroos is evaluated using the metric of population size (e.g. Pople and Grigg 1998; Department of Environment and Conservation [New South Wales] 2006).

Knowing about population sizes and trends requires monitoring. The population sizes of mallard ducks and kangaroos are both estimated using aerial survey (Pople and Grigg 1998; Department of Environment and Conservation [New South Wales] 2006; U.S. Fish and Wildlife Service 2008). Monitoring of waterfowl populations in eastern Australia, including Victoria, is conducted annually (in September-October) using aerial survey (Kingsford et al. 1999; Kingsford and Porter 2009). Ground counts have been conducted annually (in February/March) at some Victorian wetlands since 1987 (Loyn 1991; R. Loyn, Department of Sustainability and Environment, personal communication). Both the aerial and ground surveys estimate the relative rather than absolute abundance of waterfowl.

3.2.2 Some harvested species move across the Victorian border

It has long been known that some of the waterfowl species that are harvested in Victoria are highly mobile (Norman and Powell 1981; Frith 1982; Braithwaite et al. 1986). For example, some Grey Teal captured in inland South Australia and fitted with satellite transmitters travelled hundreds of kilometres in a few days (Roshier et al. 2008a,b). The high mobility exhibited by some waterfowl species enables them to exploit ephemeral wetlands that occur following rain or inundation. Large numbers of individuals of mobile waterfowl species can quickly appear or disappear from wetlands inside and outside Victoria (Frith 1982; Kingsford and Norman 2002).

None of the waterfowl species harvested in Victoria are endemic to Victoria: all occur in other Australian states and territories. Accordingly, the panel proposes that the sustainability of harvesting be defined in terms of population size both inside and outside Victoria. Hence, the movement of large numbers of some waterfowl species across the Victorian border requires that population sizes and processes outside of Victoria will need to be included in the model. Similarly, species that are incidentally harvested in Victoria (e.g. Freckled Duck, *Stictonetta naevosa*) can also be included in the model. For the purposes of this report, the panel classified the eight species of waterfowl that are harvested in Victoria as either 'mobile' or 'sedentary' (Table 1), recognising that individuals of all species are capable of long-distance movements. Mobile species are those that frequently move large distances in response to changes in wetland availability. Sedentary species are less likely to move large distances.

Table 1. Suggested classification of harvested waterfowl species as either 'mobile' or 'sedentary'.

Mobile	Sedentary
Australasian Shoveler (*Anas rhynchotis*)	Chestnut Teal (*Anas castanea*)
Grey Teal (*Anas gracilis*)	Australian Shelduck (*Tadorna tadornoides*)
Hardhead (*Aythya australis*)	Australian Wood Duck (*Chenonetta jubata*)
Pacific Black Duck (*Anas superciliosa*)	
Pink-eared Duck (*Malacorhynchus membranaceus*)	

3.2.3 Population dynamics vary with species

Although little is known about the population dynamics of some of the legally or incidentally harvested species, the abundances of many species are known to differ greatly in time and space, particularly for the mobile species (Kingsford and Porter 2009). The observed variation in population dynamics probably reflects underlying differences in the responses of vital rates (i.e. age- and sex-specific survival and reproductive rates) to environmental conditions and interventions, such as harvesting. The panel therefore considers that the sustainability of each harvested waterfowl species should be considered separately.

3.2.4 Models must include key drivers of waterfowl population sizes

Models that attempt to explain and/or predict the population sizes of each waterfowl species must include the key drivers of population size. All of the waterfowl species are dependent on the availability of wetlands to a greater or lesser extent, and there is strong evidence that the abundance of the harvested mobile species in eastern Australia fluctuates with wetland area (review in Kingsford and Porter 2009; R.T. Kingsford, University of New South Wales, unpublished data). The one exception is the Australian Wood Duck, which commonly utilises farm dams and associated pasture as well as natural waters: the abundance of this species is largely determined by the abundance of farm dams (Kingsford 1992). Models that attempt to explain and predict the population sizes of all of the harvested waterfowl species except the Australian Wood Duck therefore need to include wetland area: models of the Australian Wood Duck population need to include availability of pasture and farm dams.

3.2.5 Continued declines in wetland area will have major negative effects on population sizes of some waterfowl species

The Eastern Australian Aerial Waterbird Count has shown the important role of wetland area for the abundance of the harvested waterfowl species in eastern Australia (R.T. Kingsford, University of New South Wales, unpublished data): the low abundances of waterfowl in 2002–2008 correspond with very low wetland availability. Declines in wetland availability are due to below-average rainfall, draining of wetlands, regulation of rivers, diversion of water for irrigation and floodplain development (e.g. Kingsford 2000; Kingsford and Norman 2002; Kingsford and Porter 2009). These factors are the major threats to the sustainability of waterfowl populations and continued declines in wetland area, for whatever reason(s), would have further major negative effects on population sizes of waterfowl species.

3.3 Title

Given the underlying importance of conservation to all stakeholders and to all panel members it was decided that the title of the model should be: *Waterfowl Conservation and Harvest Model* (WCHM). The title also reflects the utility of the model for understanding the sustainability of non-game waterfowl species such as Blue-billed Duck (*Oxyura australis*), Musk Duck (*Biziura lobata*), Freckled Duck and Royal Spoonbill (*Platalea regia*).

3.4 Development of a prototype WCHM

Development of the model was guided by the philosophy that the WCHM should be an integral component of AHM. AHM explicitly recognises that the consequences of harvesting regulations cannot now be predicted with certainty because the population dynamics of waterfowl are potentially subject to many potentially interacting variables, of which harvest is one. AHM provides a framework for making objective harvesting decisions that are optimal in the face of that uncertainty (Williams and Johnson 1995). The eventual goal of an AHM strategy is to reduce uncertainty about the effects of harvest through a cycle of monitoring, assessment and decision making and to increase our capacity to learn about the system (Johnson et al. 2002). As it may require many iterations of the AHM process to reduce the uncertainty around the effects of harvest to acceptable levels, effective implementation of AHM requires a long-term commitment to all the facets of the AHM process.

To make harvest decisions adaptively, the model must include uncertainty about the following two processes that are likely to influence the outcome of harvesting decisions:

1. Effects of harvest on waterfowl populations, particularly whether harvesting is additive to natural mortality or if populations can (wholly or partially) compensate for harvesting. There is also likely to be some uncertainty associated with the size of the harvest for a given set of harvest regulations.
2. Effects of environmental fluctuations on waterfowl population dynamics (i.e. survival, recruitment and movement rates), particularly as they relate to the wetting and drying of major wetland complexes. This process recognises that fluctuations in the extent of wetland areas outside Victoria exert considerable influence on population dynamics and dispersal patterns of some species inside Victoria.

To capture these sources of uncertainty in models requires dealing with uncertainty at two levels. *Parameter uncertainty* deals with the magnitude of variation associated with population vital rates such as survival, recruitment and movement rates. *Structural uncertainty* is an additional layer that deals with incomplete or uncertain knowledge about which mechanisms operate on the population. Parameter uncertainty is usually dealt with by using probability distributions for uncertain population parameters while structural uncertainty is dealt with by expressing a range of hypotheses (models) about how different processes may operate on population dynamics (Johnson et al. 1997).

3.4.1 Objectives of AHM

Developing optimal strategies for regulating waterfowl harvest requires an objective (or objectives) describing the goals of management as well as a set of regulatory options that can be imposed by management. The objectives of the WCHM were stated as: (i) maximising the cumulative long-term harvest, and (ii) sustaining the long-term abundances of waterfowl populations. Although achievement of (i) implies achievement of (ii), it is recognised that ‘sustainable’ could be defined in different ways and could involve social, ethical or economic considerations. Additionally, this could also involve some spatial aspect (e.g. harvest prohibited on particular wetlands). The regulatory options compose the suite of alternative harvest regulations that are (adaptively) chosen to achieve the desired management goals in the optimal way (i.e. achieve the optimal harvest management strategy). The levers of management for waterfowl harvest usually consist of varying the length of the hunting season and the bag limit for each species but may also include an option of a closed season or restricting harvesting on designated wetlands (Loyn 1991).

3.4.2 Base structure of WCHM

Given the considerations outlined above, a base model structure was developed using the free statistical language program R (R Development Core Team 2009) to predict the response of a particular waterfowl species to harvesting at a single wetland or wetland complex. The model is a discrete time, population projection matrix with two stages, adults and juveniles. The model also separately accounts for males and females of each stage. The projection interval of the model is one year with the survey considered to occur just prior to the breeding season so that juveniles are completing their first year. The life cycle describing the transition of individuals between stages is given in Figure 1.

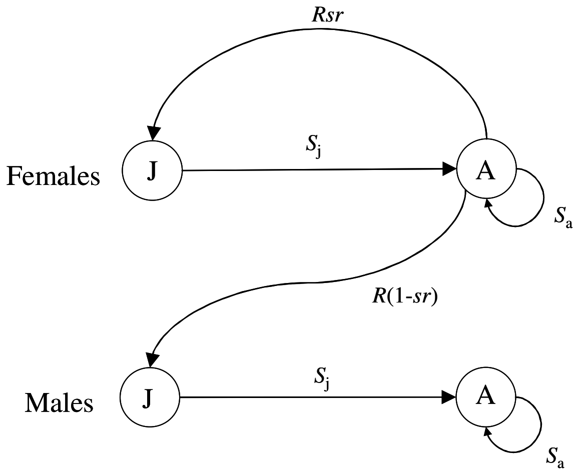

Figure 1. Life cycle diagram describing transition of juveniles (J) to adult (A) stages for a population inhabiting a single wetland or wetland complex. S_j – annual juvenile survival rate; S_a – annual adult survival rate; *R* – recruitment (fertility) rate (juveniles per adult female); *sr* –sex ratio of recruits.

The dynamics of the local population can be described mathematically as

$$\mathbf{n}(t+1)=\mathbf{A}\mathbf{n}(t), \qquad \text{equation 1}$$

where **n**(*t*) is a vector of abundances of individuals in each stage and sex at time *t* and **A** is the projection matrix containing the transition rates between stages (e.g. survival and recruitment) (Caswell 2001). Hence, from equation 1, the matrix population vector **n** and transition matrix **A** representing Figure 1 are

$$\begin{bmatrix} n_{jf} \\ n_{af} \\ n_{jm} \\ n_{am} \end{bmatrix}(t+1)=\begin{bmatrix} 0 & Rsr & 0 & 0 \\ S_j & S_a & 0 & 0 \\ 0 & R(1-sr) & 0 & 0 \\ 0 & 0 & S_j & S_a \end{bmatrix}\begin{bmatrix} n_{jf} \\ n_{af} \\ n_{jm} \\ n_{am} \end{bmatrix}(t),$$

where n_{jf}, n_{af} are the abundance of juvenile and adult females and n_{jm}, n_{am} are the abundance of juvenile and adult males, respectively. *R* is the recruitment (fertility) rate (juveniles at time *t*+1 per female at time *t*), *sr* is the sex ratio of recruits and S_j and S_a are the juvenile and adult annual survival rates.

Each local population inhabiting a wetland or wetland complex (patch) are also considered to be linked by the movement or dispersal of individuals. Hence, equation 1 can be generalised to multiple patches by combining transition matrices for each patch with movement or dispersal probabilities for each stage to produce a spatial metapopulation model (Hunter and Caswell 2005). For example, if there are only 2 patches then the state of the metapopulation can be described by the following vector:

$$\mathbf{N}(t) = \left(\frac{\text{patch 1}}{\text{patch 2}} \right) = \left(\begin{array}{c} n_{11} \\ n_{21} \\ n_{31} \\ n_{41} \\ \hline n_{12} \\ n_{22} \\ n_{32} \\ n_{42} \end{array} \right),$$

where $n_{ij}(t)$ is the abundance of stage i in patch j at time t. The spatial transition matrix **B** is then constructed from the individual local transition matrices **A** and corresponding dispersal matrices **M**,

$$\mathbf{B} = \left(\begin{array}{c|c} \mathbf{A_1} & \mathbf{M_{2\to1}} \\ \hline \mathbf{M_{1\to2}} & \mathbf{A_2} \end{array} \right), \qquad \text{equation 2}$$

where $\mathbf{A}_1$, $\mathbf{A}_2$ are the transition rates (survival, recruitment) in patches 1 and 2, respectively, and $\mathbf{M}_{1\to2}$, $\mathbf{M}_{2\to1}$ are the probabilities of moving from patch 1 to 2 and 2 to 1 for each stage. Equation 2 is easily generalised to any number of patches. By combining the sub-matrices **A** and **M** in some sequential order within the projection interval means we can also model the demography and dispersal processes in sequential order (i.e. demography then dispersal or vice versa). This is achieved by the use of the vec-permutation matrix **P** (Hunter and Caswell 2005). For example, if we wish to model demography within a patch first and then disperse individuals among patches the transition matrix **B** is calculated as

$$\mathbf{B} = \mathbf{P}^{\mathsf{T}}\mathbf{MPA}\,. \qquad \text{equation 3}$$

Alternatively, if we wish to model dispersal among patches first and then demography within a patch, the corresponding transition matrix is given by

$$\mathbf{B} = \mathbf{AP}^{\mathsf{T}}\mathbf{MP}\,, \qquad \text{equation 4}$$

where $\mathbf{P}^{\mathrm{T}}$ is the transpose of the vec-permutation matrix. One advantage of this approach is that it eases calculation of the sensitivity and elasticity of the population growth rate to changes in the stage- and patch-specific demography and dispersal parameters (Hunter and Caswell 2005).

3.4.3 Local population regulation

Plausible models of biological populations should recognise that populations cannot grow without limit (Brook and Whitehead 2005). Competition for resources is likely to increase as the density of individuals increases and this is likely to be reflected, in turn, by changes in the population vital rates. This negative feedback between the density of the population and survival and recruitment rates or *density-dependence* was included in the WCHM to increase biological realism. Density-dependence provides the theoretical foundation for assessing the extent to which mortality from harvest of waterfowl can be compensated for by improved survivorship or recruitment (Hilborn et al. 1995).

In the WCHM, density-dependent changes in either recruitment or survival were linked to changes in the area of the local wetland. This is predicated on the assumption that competition for key resources is likely to intensify as the wetland contracts and conversely, the capacity for increased growth is enhanced when the wetland fills or expands. This is likely to be especially relevant for ephemeral wetlands (Kingsford and Norman 2002). To incorporate density-dependent survival and/or recruitment, equation 1 was modified to

$$\mathbf{n}(t+1) = \mathbf{A}(Q)\mathbf{n}(t), \qquad \text{equation 5}$$

where $\mathbf{A}(Q)$ is a density-dependent transition matrix with matrix entries that depend on population abundance Q. The survival and/or recruitment matrix entries in **A** are assumed to vary with population abundance by

$$V(Q) = \frac{V_0}{1 + a\left(\dfrac{Q}{K(w)}\right)^{\theta}}, \qquad \text{equation 6}$$

where $V(Q)$ is the vital rate (either survival or recruitment) at population abundance Q, V_0 is the vital rate estimate at (near) zero abundance, K is the maximum population abundance that can be supported for wetland area w, and a and θ are constants governing the strength and linearity of density-dependence. Using equation 6, population abundance within a wetland patch with constant wetland area is assumed to follow theta-logistic type population growth (Gilpin and Ayala 1973).

As the strength of the density-dependent relationships in either recruitment or survival are uncertain for all waterfowl species in Australia, the WCHM can incorporate competing models, for example, by expressing either a strong or weak belief in the density-dependent relationships (Figure 2). For the mobile species there is likely to be a limited effect of density-dependent population limitation because their food resources have their own dynamics independent of the number of waterfowl consuming them. Furthermore, resources for mobile species are either super-abundant (i.e. little or no density dependence) or scarce: in the latter case birds will disperse such that density dependence is avoided. However, there is likely to be density-dependent population limitation for mobile species at the continental scale, where resources must eventually limit total population size.

Linking wetland carrying capacity (K) to wetland area (w) implicitly assumes that large wetlands support more waterfowl than small wetlands. The relationship between wetland area and waterfowl abundance is poorly understood but it is recognised that artificial water bodies, such as dams, are likely to be less important for mobile waterfowl species than natural water bodies because dams tend to be deep and are generally unsuitable for feeding and breeding (Kingsford and Norman 2002). However, farm dams are likely to be important for Australian Wood Duck

(Kingsford 1992). For example, a preliminary analysis of the relationship between waterfowl abundance and wetland area undertaken by Arthur Rylah Institute for Environmental Research (2003) indicated a non-linear convex-up relationship (Figure 3). Alternative models are linear and convex-down (Figure 3). Hence, a priority area of investigation would be to determine the nature of the relationship between waterfowl abundance estimates and wetland area to better inform the parameter estimates for this critical component of the model.

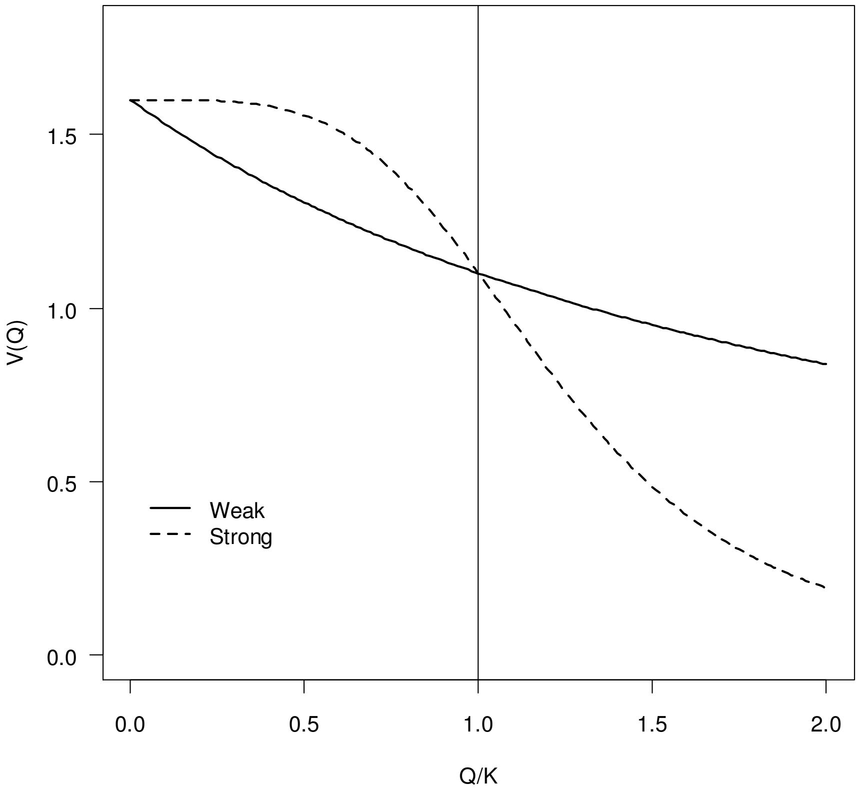

Figure 2. Example of strong or weak density-dependent relationships for recruitment. The relationship is shown as the recruitment rate *V(Q)* versus the population abundance relative to *K* (*Q/K*). Lines represent either weak (solid line) or strong (dashed line) density-dependence. Parameters are V_0=1.6, *a*=0.45, *θ*=1 (weak DD) or *θ*=4 (strong DD).

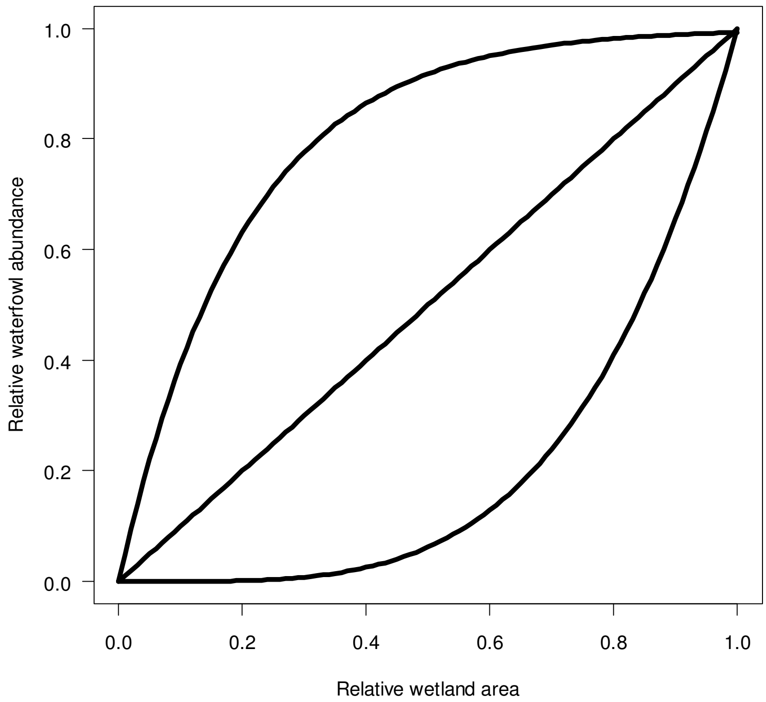

Figure 3. Three possible relationships between wetland carrying capacity (*K*), as indexed by waterfowl abundance, and wetland area (*w*).

3.4.4 Dispersal between wetland patches

Many of the game species of waterfowl such as the Grey Teal and Pink-eared Duck are considered to be highly mobile or even nomadic with individuals reported to move hundreds or thousands of kilometres, often in response to distant flooding or high rainfall events at the destination (Roshier et al. 2008b). On the other hand, species such as Australian Wood Duck are considered to be relatively sedentary (Frith 1982). Movement of Grey Teal appears to be a complex behavioural strategy that allows individuals to not only exploit distant flooding or high rainfall events but also to conduct largely exploratory movements interpreted as maximising knowledge of the spatial distribution of wetland resources at broad landscape scales (Roshier et al. 2008b).

It is assumed here that the main proximate cue for dispersal between wetlands is the occurrence of flooding or high rainfall events in the catchments of those wetlands to which they are dispersing (e.g. Frith 1963, 1982; Briggs and Holmes 1988; Kingsford and Norman 2002; Roshier et al. 2002; Roshier et al. 2008a,b). However, the proximity of the two wetland patches also needs to be considered because waterfowl species differ in their dispersal ability.

Dispersal between wetland patches was included in the WCHM model. Dispersal between wetland patches was dependent on both the distance between patches and the change in wetland area at the destination relative to the change at the origin. If movement occurs, individuals at the destination are then subject to the demographic characteristics within the local patch. However, the model also has the option of simulating local demography first, followed by movement (e.g. equation 3). An alternative model could include density-dependent dispersal between wetlands.

For *m* wetland patches, the probability of dispersal between patch *j* and patch *k* was modelled as a multinomial logistic function of both distance between patches and relative change in wetland area between patches:

$$P(y_j = k) = \frac{\exp(X_j \beta_k)}{1 + \sum_{n=1}^{m} \exp(X_j \beta_n)}, \qquad \text{equation 7}$$

where X_j are the values for the covariates for distance between patches and change in wetland area between patch j and patch k, and β_k are the coefficients governing the strength of the response to covariates. Dispersal transitions were multinomial probabilities as dispersal from patch j to each of the alternative patches (including the probability of not dispersing) must sum to 1. While intuitively plausible and consistent with current understanding about cues for movement in nomadic waterfowl species, a major drawback with including this process in the WCHM model is the lack of information that could be used to estimate the strength of the effect of wetland area changes on dispersal probability (i.e. the β in equation 7). Some information on the effect of distance between patches can be estimated for Grey Teal, Pacific Black Duck and Australian Wood Duck from data given in Table 6 in Frith (1959) who tallied band returns with distance from the banding site for these species between 1957 and 1958. A logistic regression fitted to the cumulative proportion of band returns against the midpoint of each distance class revealed that only 27% of Grey Teal were estimated to remain at the banding site in the year since banding versus 62% of Australian Wood Duck (Figure 4). Of those that did disperse, there was only a 1% chance that Australian Wood Duck would disperse further than approximately 550 km with the equivalent figure for Grey Teal being 950 km (Figure 4). Note that the dispersal probabilities in Figure 4 will to some extent reflect the spatial distribution of hunters relative to the banding site.

There are no similar data that can be used to estimate the effect of relative wetland area changes on dispersal probability, but this could perhaps be addressed in the future by re-analysing banding data. For the present, we deal with this uncertainty by constructing multiple models expressing different beliefs about the strength of relative wetland area change on dispersal probability that are consistent with qualitative models about this effect (e.g. Roshier et al. 2001, 2002). An example of dispersal probability curves for wetland area changes categorised into different strength of the effect (‘weak’ or ‘strong’) for Grey Teal and Australian Wood Duck are given in Figure 5. Additional models are also available for Pacific Black Duck (not shown) which are intermediate between Grey Teal and Australian Wood Duck. It is expected that these dispersal curves would also apply to other waterfowl species with similar life histories.

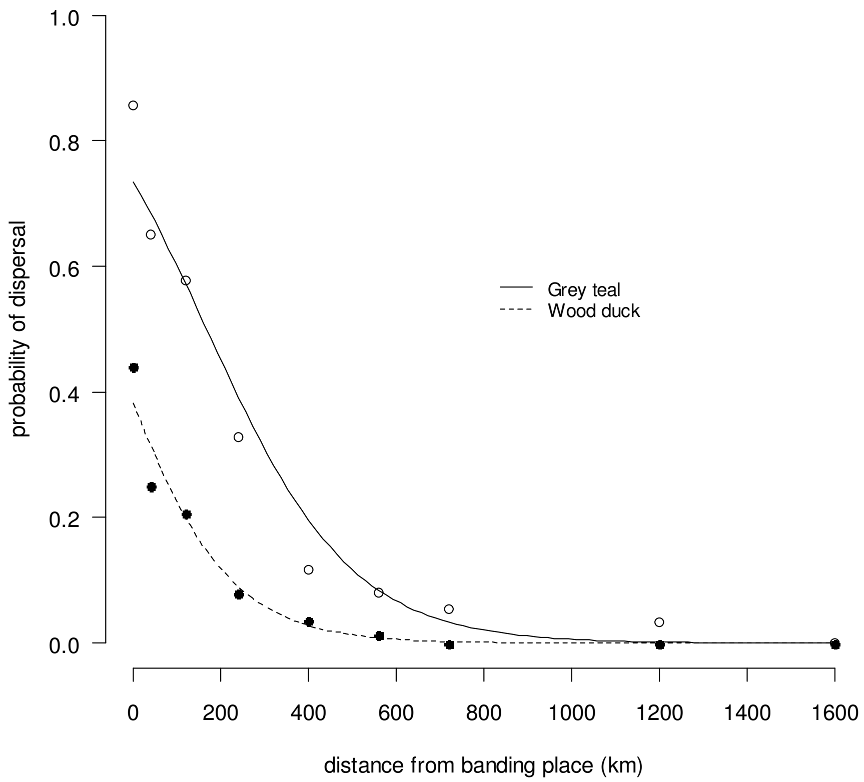

Figure 4. Probability of dispersal versus distance from the site of banding for Grey Teal and Australian Wood Duck from a logistic regression fitted to data on band returns between 1957 and 1958. Lines are the modelled probabilities and open and closed circles are the observed cumulative probabilities for Grey Teal and Australian Wood Duck, respectively, from Table 6 in Frith (1959).

3.4.5 Harvest

Harvest is incorporated into the model separately for each patch and is expressed as a harvest rate (proportional offtake) of each stage and sex class by a modification to equation 5:

$$\mathbf{n}(t+1) = \mathbf{A}(Q)\mathbf{n}(t) - \mathbf{H}\mathbf{n}(t), \qquad \text{equation 8}$$

where **H** is a matrix giving the harvest rate for each stage and sex class in the diagonal of the matrix and 0 elsewhere and is particular to local patch. For wetland patches with no harvesting (i.e. refuges), the elements of **H** are all set to 0.

3.4.6 Harvest regulations

In AHM, managers are required to set harvest regulations for the coming season, usually deciding on a combination of daily bag limit and season length for each species. Optimal harvest strategies are then developed by using models to forecast the effects of implementing a given set of regulations for the current season on the population abundance in the next season. Each year the set of regulations are chosen adaptively so that some objective is achieved over the long term such as maximising cumulative long-term harvest. However, there is uncertainty associated with the realised rate of harvest given a set of harvest regulations as managers can only expect to approximately control the realised harvest rate through the setting of harvest regulations. Such uncertainty is termed 'partial controllability' (e.g. Williams et al. 2002; Nichols et al. 2007).

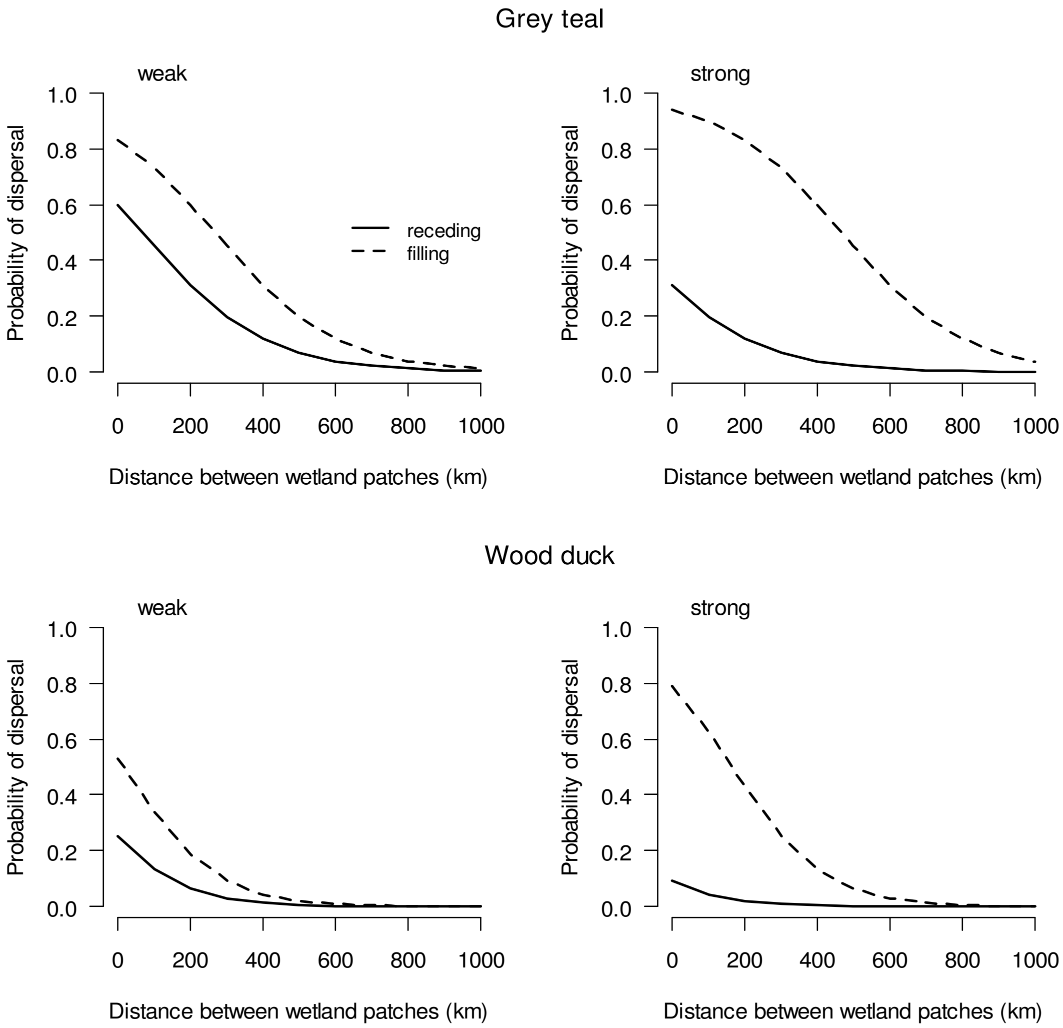

Figure 5. Probability of dispersal between two nominal wetland patches against the distance between those patches for Grey Teal (top row) and Australian Wood Duck (bottom row). Pacific Black Duck (not shown) are intermediate between Grey Teal and Australian Wood Duck. Each graph expresses different hypotheses (models) reflecting different beliefs about the strength of the effect of relative change in wetland area on the dispersal probability (weak/strong). Lines give the corresponding probabilities where the destination wetland is either receding or filling relative to the wetland at the origin.

To develop optimal harvest strategies, AHM models must describe the relationship between harvest regulations and the harvest rate as defined in the model (i.e. equation 8) that recognises the uncertainty or partial controllability of the harvest rate associated with a given set of regulations. North American AHM models have approached this by grouping historical estimates of harvest rates with associated harvest regulations into categories such as ‘liberal’, ‘moderate’ or ‘conservative’ regulatory alternatives (Williams et al. 2002). An alternative approach is to establish a statistical relationship between regulatory alternatives and harvest rates. For example, Conroy et al. (2005) used Bayesian modelling of band returns to estimate the realised harvest rate given values for bag limit and season length using a linear logistic model:

$$\text{logit}(h_t) = \beta_0 + \sum_{j=1}^{n} \beta_j X_{jt} + \varepsilon_t ,$$

where h_t is the harvest rate at time t, X_{jt} are the values for j^{th} covariate (such as bag limit, season length and possibly others) at time t and β_0, β_j are coefficients describing the relationship and ε_t is a random effect controlling the stochastic nature (uncertainty) of the relationship. An example of the modelled realised harvest rate given variations in bag limits and length of season based on the modelling work for American Black Duck (*Anas rubripes*) harvests in the United States of America (Conroy et al. 2005) is given in Figure 6.

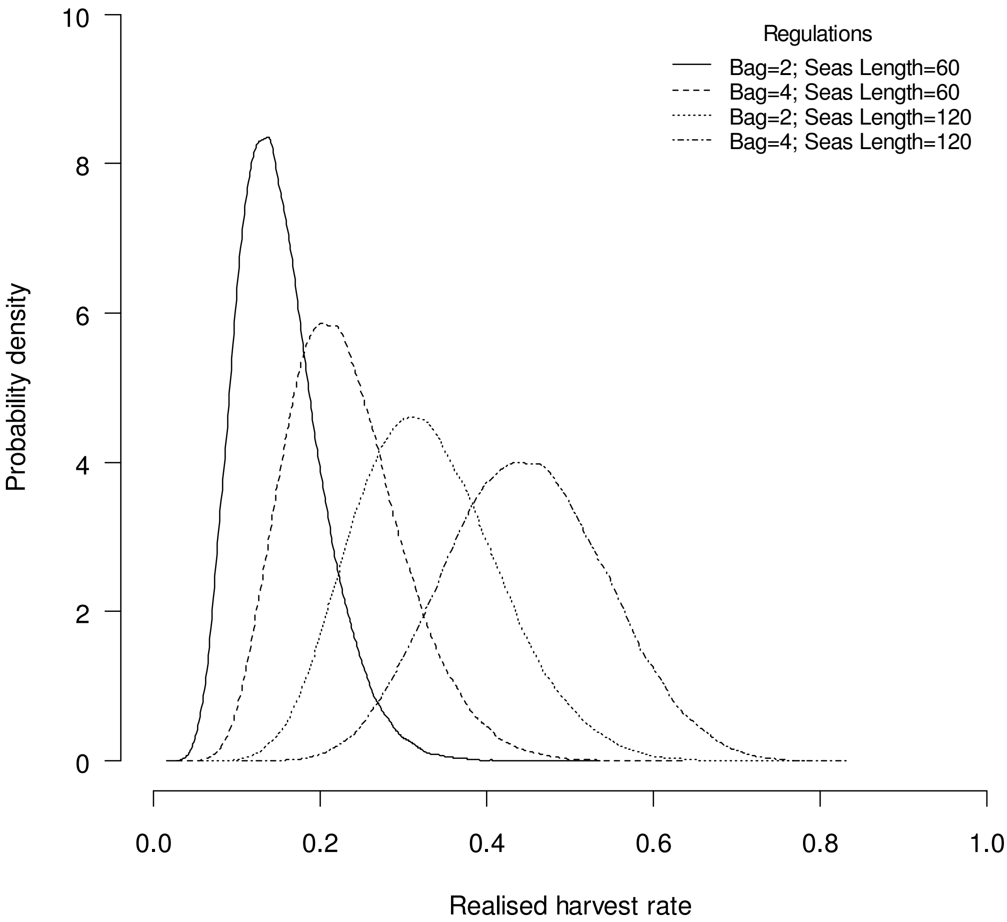

Figure 6. Variation in the rate of harvest for a given set of harvest regulations based on manipulating the bag limit and length of the hunting season length (in days) for American Black Duck. Density distributions are based on the Bayesian analysis for American Black Duck harvests given in Conroy et al. (2005).

3.4.7 Developing AHM models for Victorian waterfowl

The sections above outline the components proposed for the base WCHM model for Victoria. Due to the paucity of data for many of the mechanisms in the model (e.g. density-dependence and dispersal), uncertainty around the contributions of these mechanisms to waterfowl demography needs to be expressed through alternative or competing models (structural uncertainty). As a counterpoint to models containing density-dependent transition rates and/or dispersal probabilities, we also include three other models where these effects are absent viz;

- No density-dependence or dispersal between wetland patches. For this model dispersal is turned off and survival and recruitment are constant.
- No density-dependence. Survival and recruitment are constant but birds are allowed to disperse between wetland patches. These models assume that harvest mortality is additive to natural mortality.
- No dispersal between patches but survival and recruitment are density-dependent. This model was constructed to examine the hypothesis that population regulation within a wetland patch is

through local demography only. Hence, in this model dispersal cannot 'rescue' a local patch from extinction.

If uncertainties in the strength of either density-dependence or dispersal relationships are also included as different models then the complete model set contains nine competing models representing our uncertainty in the processes, and their magnitude, affecting the population dynamics of waterfowl (Table 2). Each of the nine models would need to be applied to each of the harvested species and any incidentally harvested species of interest (e.g. Freckled Duck).

Achieving the goal of finding the optimal sustainable harvest strategy depends on the ability to specify models that can predict population responses over a range of real-world conditions (Johnson et al. 2002). Hence, models must be able to specify the effects of harvest regulations and uncontrolled environmental variation on the size of the harvest and the resulting population size of each game waterfowl species. Uncertainty around each of these effects is accounted for by having a set of alternative models that represent competing hypotheses about what processes affect population dynamics. However, to be suitable for inclusion in the AHM process, candidate models must meet two criteria (after Johnson et al. 2002):

1. Models must imply different harvest strategies or there is no value in learning which model is the best predictor of population response (from a management perspective).
2. Models must describe different responses to harvest that are detectable by a monitoring program or the AHM process will fail to identify the most appropriate model.

It is for these reasons that the specification of alternative models suitable for AHM is one of the most challenging components of the AHM process. Although the set of candidate models in Table 2 captures the key population dynamic processes identified by the panel, there may be other plausible models that could be included. However, any addition to the model set must conform to the two criteria above to be useful for inclusion in the AHM process.

Table 2. List of models representing hypotheses about the dynamics of waterfowl inhabiting a spatial metapopulation. The 'no density-dependence' models assume that survival and recruitment are constant over time and space.

Model	Process uncertainty
1	no density-dependence – no dispersal
2	no density-dependence – weak dispersal
3	no density-dependence – strong dispersal
4	weak density-dependence – no dispersal
5	strong density-dependence – no dispersal
6	strong density-dependence – strong dispersal
7	strong density-dependence – weak dispersal
8	weak density-dependence – strong dispersal
9	weak density-dependence – weak dispersal

3.4.8 Simulated harvest of waterfowl given changes in water availability at other wetlands

To explore whether the nine candidate models specified above will be suitable for inclusion in the AHM process, we simulated waterfowl dynamics for Grey Teal and Australian Wood Duck under each model, under harvest and no harvest conditions, to determine the degree of discrepancy between the predictions for each of the models. This is a limited test of criterion 1 above because if alternative models predict different dynamics for a given harvest strategy, this would imply different harvest strategies under each model to achieve the objective of maximising cumulative harvest. The results of the tests conducted here should be interpreted with caution because the model parameterisation is incomplete.

Simulations were carried out on four wetland patches, three nominally located in the vicinity of Nagambie, Sale and Werribee in Victoria (Figure 7) and one outside of Victoria nominally located in the vicinity of Lake Eyre in central Australia (Figure 7). Only the Sale wetland was subject to harvesting. To illustrate the effects of the different demographic processes on waterfowl dynamics, we simulated wetland areas over a 50 year period (Figure 8).

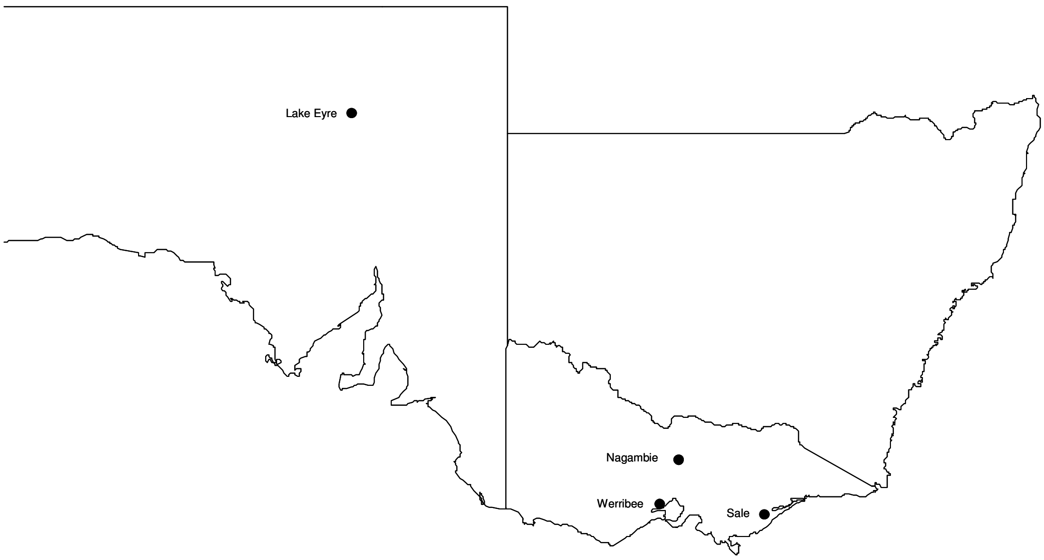

Figure 7. Locations of the four wetland patches used in model simulations.

The Werribee wetland, which is part of the Western Treatment Plant that treats about 485 million litres of sewage a day, was assumed to have constant area over the 50-year timeframe. The Nagambie wetland was simulated to show a steady decline in area up to year 25 followed by a steady increase while the Sale wetland was simulated to show a steady increase over the 50 year period. The Lake Eyre wetland was simulated to have the lowest average area over the 50 year period interrupted by high rainfall/flooding events every 15 years which resulted in an eight-fold increase in the wetland area for one year. Following this flood event, the Lake Eyre wetland returned to its average area (Figure 8). Although hypothetical, these differing patterns of environmental conditions for each wetland serve to illustrate their contrasting effects on waterfowl dynamics. For the purposes of these simulations, the carrying capacity of each wetland was assumed to be linearly related to wetland area (e.g. Figure 3) with the carrying capacity equal to 1.5 times the wetland area.

Models containing weak density-dependent effects were assumed to apply on recruitment only using Equation 6 with the shape parameter θ set to 1.0. This is equivalent to linear density-dependence from logistic growth (i.e. the solid line in Figure 2). Models containing strong density-dependent effects were assumed to apply to both survival and recruitment again with θ set to 1.0. Models with $\theta > 1.0$ (i.e. forward-peaked or 'over-compensatory') could be considered as alternative models for density-dependence.

Models containing the effects of 'strong' or 'weak' effects of wetland area on dispersal probabilities used the multinomial logistic formulation in equation 7. The effects of distance between wetland patches on dispersal were assumed to be species-specific (Figures 4 and 5).

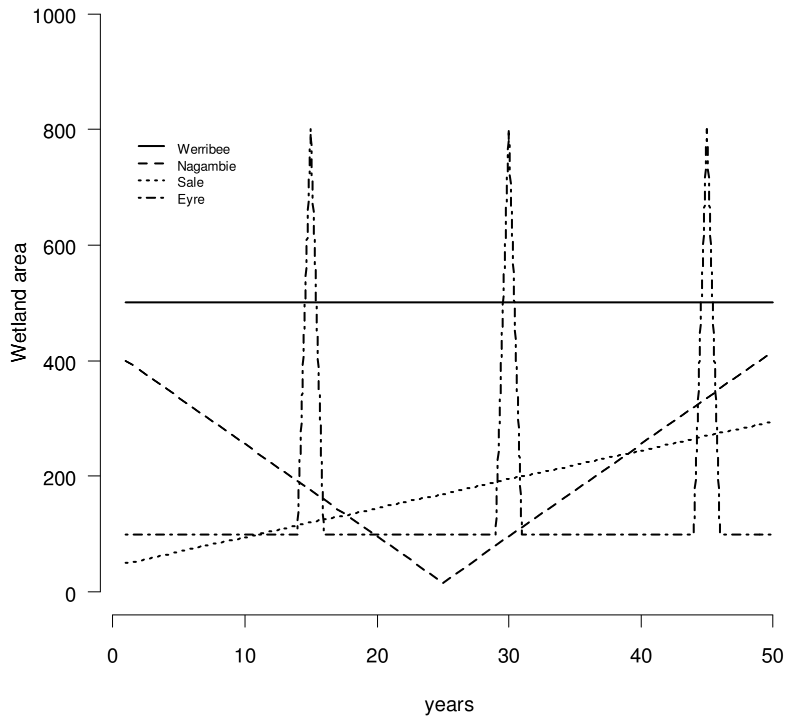

Figure 8. Simulated patterns of wetland area over 50 years for four wetlands used in model simulations.

3.4.9 Waterfowl vital rates

Estimates of survival and recruitment rates for Australian waterfowl are based primarily on data collected from banding programs during the 1950's-1970's (Frith 1963; Norman 1970). However, composite dynamic life table estimates of mortality rates derived from these data are considered to be biased (Burnham and Anderson 1979). Halse et al. (1993) estimated survival and harvest rates for Grey Teal and Pacific Black Duck using the band recovery models of Brownie et al. (1985). Annual survival rates of Pacific Black Duck were 63% and 56% for adult and juvenile birds while adult Grey Teal had an annual survival rate of 55%. Average hunting mortality rates were estimated to be 23% and 17% for Pacific Black Duck and Grey Teal, respectively.

For modelling the dynamics of waterfowl using the WCHM, we require estimates of survival and recruitment rates at carrying capacity (i.e. rate of increase $\lambda_k = 1.0$) and at (near) zero population abundance, where it is assumed that populations are increasing at their maximal rate (λ_{max}). To represent Grey Teal and Australian Wood Duck populations, the following projection matrices were used that produced the desired rates of increase:

$$\mathbf{A}_k = \begin{bmatrix} 0 & 0.94 & 0 & 0 \\ 0.48 & 0.55 & 0 & 0 \\ 0 & 0.94 & 0 & 0 \\ 0 & 0 & 0.48 & 0.55 \end{bmatrix} \quad \text{and} \quad \mathbf{A}_{\max} = \begin{bmatrix} 0 & 1.31 & 0 & 0 \\ 0.67 & 0.77 & 0 & 0 \\ 0 & 1.31 & 0 & 0 \\ 0 & 0 & 0.67 & 0.77 \end{bmatrix},$$

where $\lambda_k \mathbf{n} = \mathbf{A}_k \mathbf{n}$ and $\lambda_{\max} \mathbf{n} = \mathbf{A}_{\max} \mathbf{n}$ at equilibrium and $\lambda_k = 1.0$ and $\lambda_{max} = 1.4$. The values for $\mathbf{A}_k$ were found by assuming an adult survival rate of 55% and a ratio of juvenile to adult survival of 0.88 (i.e. Grey Teal adult survival estimate and ratio of juvenile to adult Pacific Black Duck survival from Halse et al. [1993]). These values were assumed to represent estimates of juvenile and adult survival at carrying capacity (*K*). The recruitment rate *R* was then found numerically that gave the desired rate of increase λ_k. The values for $\mathbf{A}_{max}$ were found by scaling the values of $\mathbf{A}_k$ so that the rate of increase equalled λ_{max}. The value for λ_{max} used here (1.4) is within the plausible range for the maximal rate of increase for waterfowl (λ_{max}; North American Mallard = 1.7, American Wood Duck = 1.35, Australian Magpie Goose=1.3; Jensen 2002; Brook and Whitehead 2005; Garrettson 2007). For the purposes of the simulations outlined below, we assume that the dynamics of Grey Teal and Australian Wood Duck differ only in their dispersal probabilities (e.g. Figure 5).

3.4.10 Grey Teal

Without harvesting, the population dynamics of Grey Teal appear to differ greatly under each of the nine models with dispersal playing a dominant role in driving inter- and intra-wetland variability (Figure 9). Large fluctuations in abundance at each wetland driven by the flooding events at the Lake Eyre wetland can be clearly seen in models containing strong dispersal effects (models 3, 6 and 8). This is in contrast to the model without dispersal and density-dependence, which had no change in abundance.

Including a 20% annual harvest at the Sale wetland had profound effects on some model predictions (Figure 9). Local extinction of teal at the Sale wetland are predicted from models without dispersal and either weak or no density-dependence. In addition, teal are also predicted to decline markedly at the other Victorian wetlands under models that include dispersal and weak or no density-dependence (models 2, 3, 8 and 9; Figure 9).

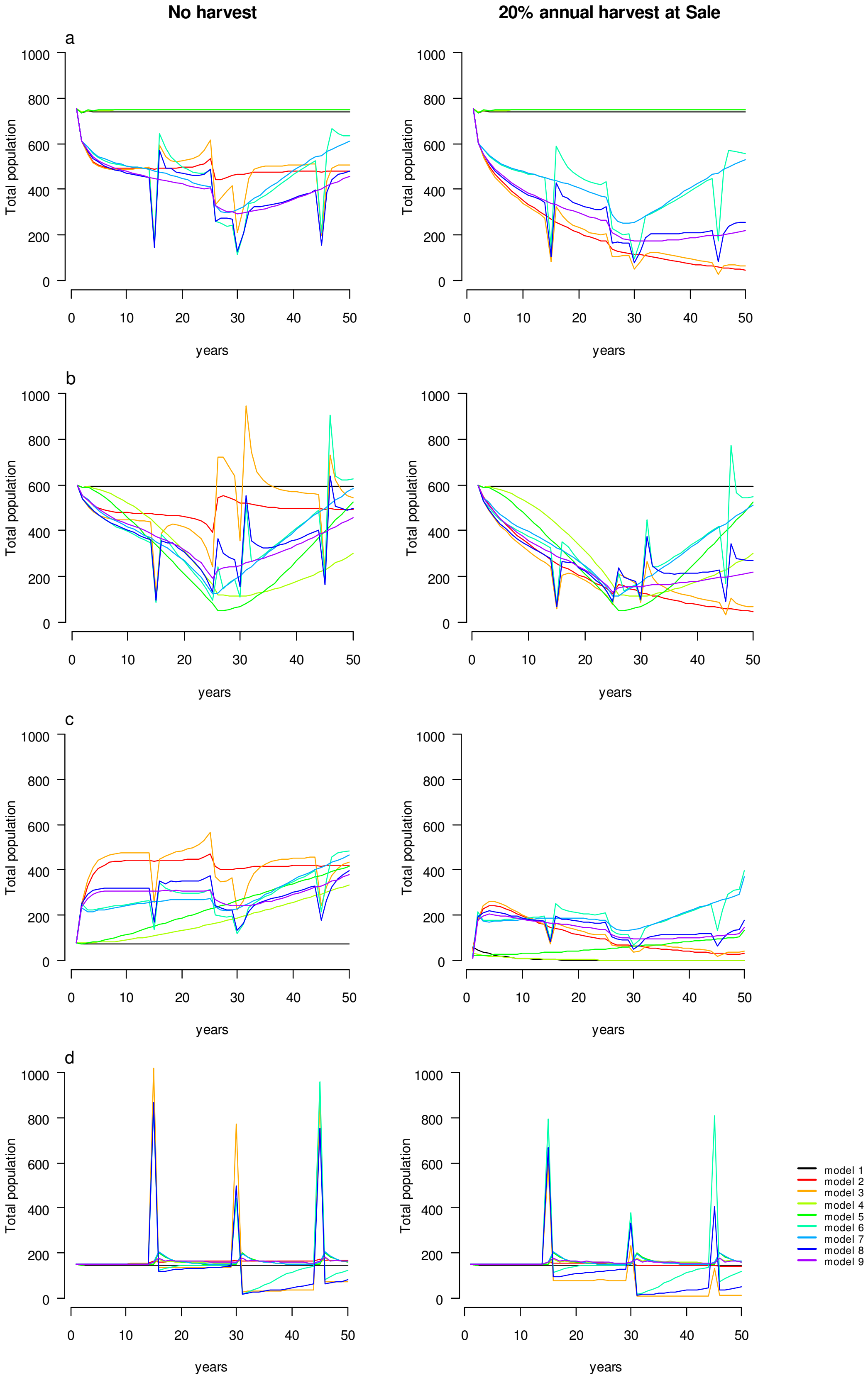

Figure 9. Predicted 50-yr dynamics of Grey Teal at (a) Werribee, (b) Nagambie, (c) Sale, and (d) Lake Eyre without harvesting (left column) and with a 20% annual harvest at Sale (right) for each of the nine models in Table 2 and using the time series of wetland areas given in Figure 8.

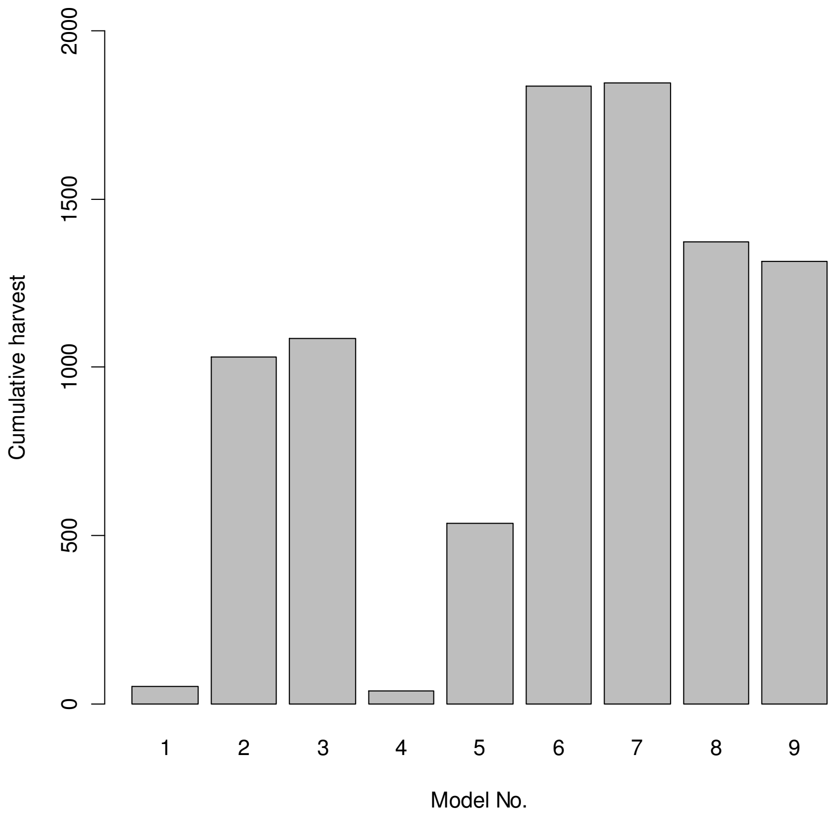

Figure 10. Cumulative harvest of Grey Teal at the Sale wetland for each of the nine alternative models of waterfowl dynamics in Table 2.

The cumulative harvest over the 50 year time period differed markedly between models. Cumulative harvest was highest for models containing just dispersal compared with models containing just density-dependence (models 1–5; Figure 10). However, there was little difference in the cumulative harvest for models with either strong or weak dispersal effects, when density-dependence was present (models 6-9; Figure 10).

3.4.11 Australian Wood Duck

In the absence of harvesting, the population dynamics of Australian Wood Duck are far less influenced by the flooding events at the Lake Eyre wetland than are Grey Teal (Figure 11). However, dispersal is still a dominant feature of the dynamics within the Victorian wetlands. As for Grey Teal, the filling of wetlands first at Sale and then Nagambie results in an influx of ducks from the other Victorian wetlands. Highest abundances in filling wetlands relative to stable or drying wetlands are predicted by models 2 and 3 containing strong and weak dispersal but no density-dependence. The dynamics in Figure 11 indicate that predictions from some models are similar (e.g. models 6 and 7 and models 8 and 9), suggesting only minor effects of strong and weak dispersal, particularly in the presence of density-dependence. Hence, some rationalisation of the model space could be undertaken for this species.

Imposing a 20% annual harvest at the Sale wetland further highlighted the similarity among the predictions from the alternative models (Figure 11). The resulting predictions under harvest suggest that the model space could reasonably be reduced to four or five alternatives by removing models containing alternative strengths of dispersal. The cumulative harvest of Australian Wood Duck was lower than that for Grey Teal for models containing dispersal (Figure 12). As for Grey Teal, there was little difference in the cumulative harvest for models containing strong or weak dispersal effects in the presence of density-dependence (Figure 12).

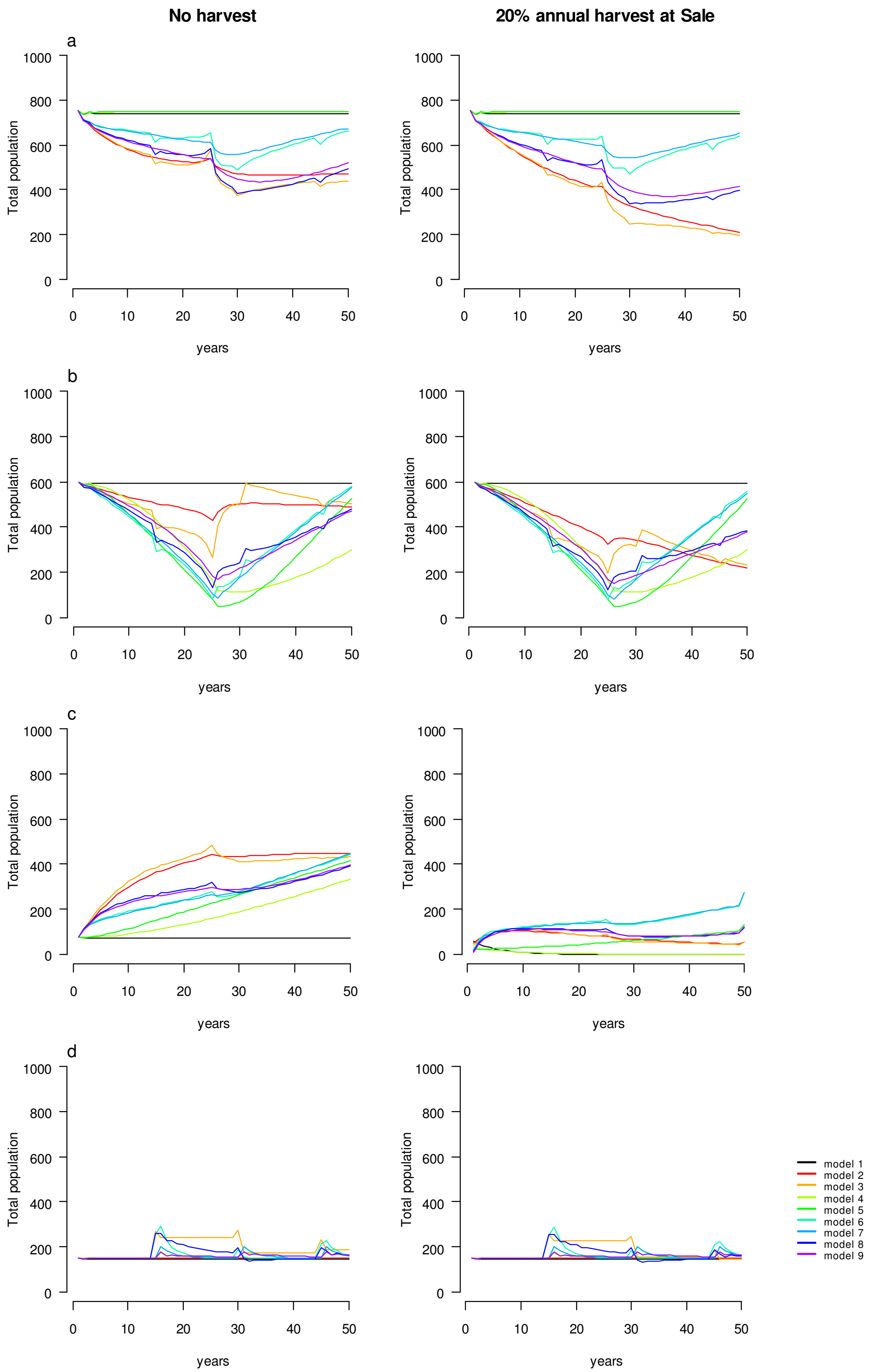

Figure 11. Predicted 50-yr dynamics of Australian Wood Duck at (a) Werribee, (b) Nagambie, (c) Sale, and (d) Lake Eyre without harvesting (left column) and with a 20% annual harvest at Sale (right column) for each of the nine models in Table 2 and using the simulated time series of wetland areas given in Figure 8.

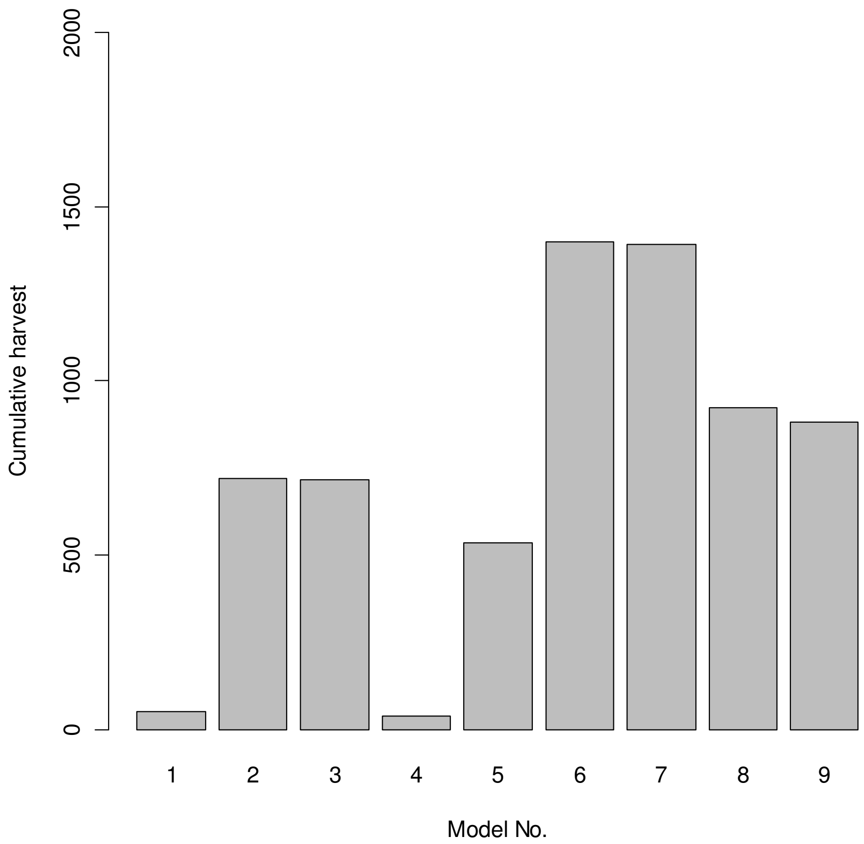

Figure 12. Cumulative harvest of Australian Wood Duck at the Sale wetland for each of the nine alternative models of waterfowl dynamics in Table 2.

3.4.12 Determining optimal harvest strategies

Having derived a suite of alternative models (hypotheses) of the effects of harvest and uncontrolled environmental variables on waterfowl populations, the next stage in the AHM process involves an iterative sequence of decision making and model validation. The decision-making step involves the prediction of the optimal harvest regulations for a given year, conditional on the uncertainty in waterfowl dynamics expressed by each of the alternative models of the system. Deriving the optimal harvest decision also requires an objective function in which each decision can be evaluated. The objective function is a mathematical representation of the management goals or objectives outlined previously; that is, maximising the long-term cumulative harvest subject to some 'sustainability' constraints (e.g. economic, social or political). An example of such an objective function is:

$$\sum_{t=0}^{T} u(Q_t) H_t$$

where , equation 9

$$u(Q) = \begin{cases} 1, & Q > Q_{\min} \\ 0, & \text{otherwise} \end{cases}$$

where Q_t is the waterfowl population at time t and H_t is the harvest rate at time t (derived from management regulations). Harvest is valued by a utility function $u(Q)$ that devalues the harvest to zero when the population size Q falls below some threshold Q_{min}. This is just one example of a constraint related to 'sustainability' and others are possible. The optimal harvest strategy is then the sequence of harvest regulatory decisions that maximises the objective function in equation 9, subject to the constraints (e.g. Hauser et al. 2007).

This type of sequential decision making under uncertainty can be analysed within the framework for stochastic control problems from decision theory (Williams et al. 2002). A popular algorithm for solving these kinds of decision problems is discrete stochastic dynamic programming (SDP; Clark and Mangel 2000). SDP involves working backwards from some future time step and calculating the short- and long-term rewards (as defined by the objective function) associated with each possible management regulation and system state. Uncertainty is incorporated by calculating the expected rewards associated with uncertain outcomes (e.g. alternative models) based on their specified probabilities of occurring (e.g. model weights) (Johnson et al. 1997).

3.4.13 Model validation and updating

Following the prediction of the optimal harvest regulations for a given year, predictions of the population size under these harvest regulations are determined for each of the alternative models. Model validation then involves comparing model predictions to newly acquired monitoring data to ascertain the degree of support between model predictions and data. The result of this process is that the model(s) with the highest predictive power receive more support (and hence are more influential in setting harvest regulations) in subsequent iterations. Thus, sequential iteration of this process results in the reduction of uncertainty about system behaviour and the effects of management over time. The level of support for each model is expressed as a model probability or weight that compares the ability of a model to predict the change in population size, relative to other models. The process of updating these model weights with monitoring data proceeds using Bayes' theorem:

$$\Pr(M_{i,t} \mid X_t) \propto \Pr(X_t \mid M_i)\Pr(M_{i,t-1}), \qquad \text{equation 10}$$

where $\Pr(M_{i,t} \mid X_t)$ is the probability of model i at time t given monitoring data X_t at time t, $\Pr(X_t \mid M_i)$ is the probability of the data X_t given model M_i (the likelihood) and $\Pr(M_{i,t-1})$ is the probability of model M_i at the previous time period (the prior probability). Thus, the updated model probability for model i in the current year ($M_{i,t}$) is a function of how well it predicted the observed monitoring data (X_t) multiplied by the model probability in the previous year ($M_{i,t-1}$), relative to how all the other models predicted the observed monitoring data.

3.4.14 Dealing with structural and parameter uncertainty

While it is proposed that uncertainty over the importance of biological processes for waterfowl dynamics be handled using alternative structural models, further investigation of the model space is required. Although simulations similar to those conducted here will contribute to defining the appropriate array of alternative models, many of the gaps *might* be resolved by an analysis of existing data. For example, data exist to quantify the relationship(s) between wetland area and equilibrium densities of waterfowl (i.e. carrying capacity). Likewise, an analysis of band recoveries over an appropriate spatial scale could be used to inform stage-specific survival and harvest rates and the nature of the relationship between wetland area and dispersal probabilities. Finally, an analysis of bag return surveys (Norman and Powell 1981; Loyn 1991) and concomitant harvesting regulations is required to quantify the uncertainty around the relationship between the harvest rate and harvest regulations. These analyses could reduce some of the structural uncertainty around waterfowl models as well as define the appropriate amount of parameter uncertainty to incorporate into these models to facilitate the development of fully stochastic models required by the AHM process.

3.5 Implementation of the WCHM and AHM

The WCHM aims to place the decision-making process used to manage duck harvesting in Victoria on an objective scientific basis. It uses a model, described in detail above, that incorporates the main factors believed to influence the distributions and abundances of duck species and the ways in which populations are expected to respond to harvesting. Each year, results obtained from applying the model will be used to further refine and adapt it, which is expected to lead to increasing predictive accuracy and greater understanding about the effects of harvest on duck populations. This is the essence of AHM.

3.5.1 Wetland patches proposed for the WCHM

It is proposed that the WCHM encompass predictions for at least 11 major wetland complexes (‘patches’) inside Victoria (Table 3). It is also proposed that the WCHM includes five wetland complexes outside Victoria (all of which are currently sampled in the Eastern Australian Aerial Waterfowl Count) that may have major impacts on the demography and dispersal of waterfowl utilising Victorian wetlands. The panel’s rationale for selecting these particular wetland complexes was that: (i) having a total of less than 20 wetland complexes was practical from a modelling perspective (i.e. there was a finite number of complexes that we could include), (ii) the 11 wetland complexes inside Victoria were thought to be the most important habitats and/or hunting areas for the mobile waterfowl species in this state, and (iii) historical data were available for most of these wetland complexes (e.g. from the Eastern Australian Aerial Waterfowl Count and the Summer Waterfowl Count; see below) and these data would aid in the initial implementation of the WCHM. Although not an exhaustive list, the panel believed that these wetland complexes comprise the most important wetlands for waterfowl (particularly the mobile species) in Victoria and some outside the state.

Table 3. The 16 major wetland complexes that would be included in the Waterfowl Conservation and Harvesting Model.

Inside Victoria	Outside Victoria
Horsham Lakes	Coorong/Lower Murray lakes (SA)
Bolac region	Lake Eyre Basin (SA, Qld)
Kerang Lakes	Riverina (NSW)
Corangamite Lakes	Paroo River catchment (NSW)
Werribee (Western Treatment Plant)	Lake Galilee (Qld)
Cooper/Wallenjoe	
Corner Inlet	
Barmah/Millewa	
Lake Buloke	
Hattah Lakes	
Gippsland Lakes	

However, it is likely that the recommended aerial monitoring of waterfowl (see below) will identify other areas that are important for waterfowl species inside Victoria (particularly the sedentary species Australian Wood Duck and Australian Shelduck). The wetland complexes listed in Table 3 should therefore be seen as a starting point and potentially subject to change when additional information (particularly monitoring data) becomes available.

3.5.2 Monitoring requirements for the WCHM

The WCHM model requires information about waterfowl abundances inside and outside Victoria, the size of the harvest and the age–sex structure of the harvest to be collected annually so that the model can be updated to identify the optimal harvest regulations for each hunting season. As the WCHM is further developed and refined (with historical and new data) the monitoring requirements should be evaluated in terms of relative contribution to the predictive ability of the model. Such evaluations would likely lead to a more simplified and cost-effective mix of monitoring that optimally updates the WCHM. The details of the monitoring requirements are as follows.

3.5.2.1 Estimates of waterfowl abundances inside and outside Victoria

Eastern Australian Aerial Waterfowl Count (EAAWC)

The Eastern Australian Aerial Waterfowl Count (EAAWC) is currently flown annually in October and includes three east–west transects within Victoria (Kingsford and Porter 2009). The EAAWC provides estimates of relative abundance along these transects using a methodology that has been standardised to control some of the biases. Continuing this survey program will be important for providing annual species-specific estimates of relative waterfowl abundance for some of the 11 wetland complexes identified as being important within Victoria. The EAAWC also includes the five wetland complexes outside Victoria that are believed to contain waterfowl that move in and out of Victoria. The annual EAAWC estimates of waterfowl abundance in these five wetland complexes would also be included in the WCHM model. There are additional wetlands of significance within Victoria that are not currently sampled in the EAAWC and the most cost-effective way to estimate abundance in these patches will be to add additional transects to the EAAWC program to include these wetlands. The case for using the EAAWC to provide one tier of annual abundance estimates is compelling, but the panel recognises the need to develop correction factors so that absolute rather than relative abundance is estimated. It is therefore recommended that correction factors be estimated in the first year of implementation.

Sedentary Waterfowl Survey (SWS)

Estimating the abundances of the sedentary waterfowl species requires a different survey methodology because these species are likely to be more abundant on and around farm dams and watercourses rather than in the wetland complexes sampled by the EAAWC (Table 3). However, there is no current standardised survey program providing relative or absolute estimates of abundance for these species. It is therefore recommended that the abundances of the sedentary species (particularly Australian Wood Duck and Australian Shelduck) in Victoria be estimated annually in October with a new monitoring program that we term the Sedentary Waterfowl Survey (SWS). To develop the SWS we recommend that:

1. Expert opinion is sought from those familiar with these species in order to subdivide Victoria into areas (strata) on the basis of expected waterfowl densities (e.g. high, medium and low density areas).
2. A stratified systematic sampling program be designed and implemented using, but not necessarily restricted to, helicopter-based surveys of sub-samples of habitat.
3. The stratum with the highest expected densities of waterfowl should have the most transects per unit area and the stratum with the lowest expected densities the least transects per unit area (Thompson et al. 1998).
4. Resources are directed at determining detection probabilities and correction factors so that the SWS can estimate absolute rather than relative abundance (Conroy et al. 1988; Thompson et al. 1998; Koneff et al. 2008).

Some modification of the SWS should be expected based on the first year's results to optimise its cost-effectiveness. The proposed methodology is similar to that used to estimate the abundance of waterfowl species annually in North America (Conroy et al. 1988; Koneff et al. 2008) and is used in at least one region of New Zealand by New Zealand Fish and Game (R.J. Barker, University of Otago, personal communication). The SWS survey would also generate abundance estimates for the mobile waterfowl species, which could supplement the data from the EAAWC surveys. The SWS may also identify new wetland patches that are important for sedentary and/or mobile waterfowl species.

Summer Waterfowl Count (SWC)

A ground-based waterfowl count, termed the Summer Waterfowl Count (SWC), has been conducted in Victoria annually during February/March since 1987 (Loyn 1989, 1991; Purdey and Loyn 2009). In 2009, counts were made at 161 wetlands (64% of which were considered 'dry' and zero waterfowl were counted there) and 64 886 waterfowl of species that could legally be hunted in 2009 were counted (Purdey and Loyn 2009). However, it is unclear how numbers of waterfowl counted in the SWC are related to the total number of waterfowl residing in Victoria. For example, in 2009 the lower 95% confidence interval for the estimated number of waterfowl harvested in Victoria (193 361) was almost three times greater than the number counted in the SWC (Gormley and Turnbull 2009). The SWC provides species-specific estimates of relative abundance immediately prior to the hunting season (which traditionally opens on the third Saturday in March). Although not critical to the WCHM, it is recommended that the SWC continues and that its estimates of relative abundance be included as far as possible in the WCHM.

3.5.2.2 Harvest estimates

Harvest Telephone Survey (HTS)

The number of waterfowl harvested during the Victorian hunting season is currently estimated with a Harvest Telephone Survey (HTS). The HTS is a telephone survey of a random sample of Victorian Game Licence holders. Samples of hunters are called immediately after opening weekend and then at two-week intervals for the remainder of the season (Barker 2006; Gormley and Turnbull 2009). Respondents are asked how many ducks of each species they harvested during the period of interest, enabling the total statewide harvest to be estimated. The questions asked during the HTS would need to be modified to ensure that species-specific harvest estimates are available for each of the 11 Victorian wetland complexes (Table 3): these data are critical for the WCHM model.

Opening Weekend Surveys (OWS)

Opening Weekend Surveys (OWS) of the species composition (and age for some species) of hunters' bags have been conducted at some of the major public wetlands in Victoria for many years (Norman and Powell 1981). The OWS involves DSE and Parks Victoria staff conducting enforcement duties also recording the number of each species harvested by hunters that they encounter at a wetland. Although the OWS does not sample hunters hunting on private property, it can nevertheless provide estimates of the age- and sex-composition of the harvest within most of the 11 wetland patches that are important for the WCHM. It is critical that ages (i.e. juvenile and adult) be estimated for a sample of each of the game waterfowl species in the 11 wetland patches inside Victoria: minor modification of the OWS and additional training (for age- and sex-determination) of staff would be required to achieve this.

New South Wales Game Bird Management Program

The Game Bird Management Program (GBMP) allows rice growers in the Riverina and Murray areas of New South Wales to protect their crops from the impacts of waterfowl using hunters licensed by Game Council NSW and the NSW National Parks & Wildlife Service. The GBMP is managed by the NSW National Parks & Wildlife Service and annual species-specific harvests are collated by that organisation. These annual harvests may be large for some species and given the proximity of these areas to Victoria they are potentially important for the dynamics of waterfowl in Victoria. It is therefore recommended that the New South Wales waterfowl harvests be included in the WCHM model.

3.5.2.3 Habitat surveys

The WCHM requires annual estimates of wetland extent for each of the wetland patches. Roshier et al. (2008b) used Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to quantify the area of wetlands available to Grey Teal in Australia. MODIS technology can be used to provide monthly estimates of wetland extent and we recommend that these estimates be used in the WCHM model. Another option is the development of a hydrological model of wetland catchments that can predict wetland extent from precipitation measurements. Calibration of the hydrological model could be done using MODIS estimates of wetland area.

3.5.3 Timing and cost of implementing the WCHM and AHM

The key data and analytical requirements of the WCHM are summarised in Table 4. The main costs of the WCHM are: (i) labour costs associated with the development and annual updating of the models, (ii) aerial monitoring surveys conducted annually during October, (iii) processing satellite imagery to determine wetland extent in each of the wetland complexes or regions, and (iv) estimating hunter harvest. Initial development of the WCHM would require substantial analyses of existing data whereas annual updating would be less labour intensive.

A time-schedule for implementing the WCHM is provided in Table 5. It is recommended that the first two years of implementation be conducted by ARI scientists overseen by a steering committee. The steering committee would be responsible for ensuring that the WCHM provides the required information for decision making (i.e. credible harvest recommendations) and its terms of reference should include guidance, advocacy and budget endorsement. It is recommended that the steering committee include at least one international expert in the adaptive harvest management of waterfowl.

The first year of implementation involves two key tasks that would not be needed in subsequent years (analyses of historical data and completion of the species-specific models; Table 5) and it is difficult to estimate how long it will take to complete these tasks. Funding for the implementation of the model should therefore be confirmed as soon as possible (and by 1 May 2010 at the latest) to maximise the time available to complete those tasks.

After two years of implementation, it should be possible for DSE policy staff to run the WCHM with relatively minor input from ARI scientists. The feasibility of DSE policy staff running the WCHM could be considered by the steering committee during the Year 2 review.

We used ARI’s project-costing model to estimate the cost of implementing the WCHM. The estimated cost therefore assumes that the key monitoring and modelling components of the WCHM would be conducted by ARI in Years 1 and 2. The first-year cost of providing a fully operational WCHM and recommended harvest regulations was estimated to be $542 000, of which $375 500 would be spent on monitoring and the remainder would be spent on analysing historical data and setting parameters for the model. There is uncertainty about the cost of annual monitoring and this component could change based on the first year’s results. The cost of using the WCHM to recommend harvest regulations in Year 2 and beyond was estimated to be c. $475 000, but this could be subject to change depending on experiences during the first year.

Table 4. Key data requirements/analyses for implementing the WCHM.

Key requirement
A. Initial analyses of historical data
1. Estimate relationships between harvest regulations (season length and daily bag limit) and estimated harvest size.
2. Estimate relationships between estimated wetland area (from satellite imagery or other sources) and estimated waterfowl abundances (from EAAWC and any other sources) in the key wetland complexes.
3. Estimate relationships between dispersal probability and environmental variables such as distance between wetland complexes and relative changes in wetland area for as many game species as data is available.
4. Estimate population vital rates for as many game species as historical data are available for.
B. Ongoing annual data collection/analyses
1. Estimate waterfowl abundances in each of the key wetland complexes inside and outside Victoria with existing and additional transects in the EAAWC fixed-wing survey.
2. Estimate the abundances of sedentary waterfowl in Victoria with a new helicopter survey (SWS).
3. Estimate the age–sex composition of waterfowl harvested by hunters in opening weekend bag surveys.
4. Estimate the annual harvest of each species by telephone survey.
5. Update relationships between estimated wetland area (from satellite imagery) and estimated waterfowl abundances.
6. Update the model with new data/analyses and use the model to estimate the next harvest regulations.

Table 5. Time-schedule for implementing the WCHM.

Key task	Time (start–finish)
Year 1	
Budget approved	1 May 2010
Steering committee established	1 June 2010
Analyses of historical data	1 June–30 November 2010
Complete construction of species-specific models	1 June–30 November 2010
Conduct aerial surveys (EAAWC and SWS)	1 October–31 October 2010
Test run of model for predicting species-specific harvest regulations for the 2011 season	1 December–31 December 2010
Recommended harvest regulations for 2011 provided to Minister	1 January 2011
Bag survey to estimate age and sex of harvested waterfowl	Opening weekend 2011 season
Telephone surveys to estimate total hunter harvest	Biweekly during 2011 season
Review of Year 1 and recommended budget for Year 2 endorsed by steering committee	31 March 2011
Year 2 and beyond	
Budget approved	1 June 2011
Conduct aerial surveys (EAAWC and SWS)	1 October–31 October 2011
Incorporate monitoring data into the species-specific models and predict harvest regulations for the 2012 season	1 November–30 November 2011
Recommended harvest regulations for 2012 provided to Minister	1 December 2011
Bag survey to estimate age and sex of harvested waterfowl	Opening weekend 2012 season
Telephone surveys to estimate total hunter harvest	Biweekly during 2012 season
Review of Year 2 and recommended budget for Year 3 endorsed by steering committee	31 March 2012

3.6 Application of the model to non-game waterfowl species

The WCHM provides an important opportunity to evaluate the sustainability of game and non-game waterfowl species. Non-game waterfowl species such as Freckled Duck, Blue-billed Duck, Musk Duck, Royal Spoonbill, Dusky Moorhen (*Gallinula tenebrosa*), Purple Swamphen (*Porhyrio porhyrio*) and Eurasian Coot (*Fulica atra*) would be counted in the EAAWC and SWS surveys (section 3.5.2.1) and it should be straightforward to include these species in the WCHM. Given the potential for Victorian populations of non-game waterfowl species to decline in response to continued reductions in wetland availability, the panel strongly recommends that the opportunity be taken to include at least some non-game waterfowl species in the WCHM. The question of which non-game waterfowl species to include in the WCHM would best be answered after analysis of the first year of monitoring data, but given the interest in hunting-related mortality on Freckled Duck (Loyn 1989) it would be wise to at least include this species. The panel emphasises the potential of the WCHM as a tool for conserving game and non-game waterfowl species.

3.7 Concluding remarks

The panel considers that its discussions, in conjunction with the presentations from state and interstate experts, met the Approved Terms of Reference for the Expert Scientific Panel (section 1.2). We believe that the sustainable harvest model proposed here is a robust approach that adapts key elements from the long-running North American adaptive harvest management program (U.S. Fish and Wildlife Service 2008) to the eastern Australian context (Roshier et al. 2002; Roshier et al. 2008a,b; Kingsford and Porter 2009). Relative to other possible sustainable harvest models the approach proposed here can be delivered at minimal annual cost. The panel believes that the key benefits of the WCHM proposed here are:

1. Transparency in how the annual harvest regulations (i.e. season length and bag size for each species) are recommended to the Minister, leading to reduced conflict among stakeholders.
2. Assurance that harvesting in Victoria is unlikely to adversely affect the sustainability of waterfowl populations in eastern Australia.
3. Increasing knowledge of the drivers of waterfowl dynamics in eastern Australia, particularly the relative importance of wetland area and harvesting.
4. Provision of long-term standardised monitoring information about the abundances of waterfowl populations (both hunted and non-hunted species) in Victoria.
5. Development and maintenance of waterfowl research, management and monitoring expertise within Victoria.

There are some key requirements of the proposed WCHM and AHM that need to be recognised. Stakeholders (including Ministers) must:

1. Have confidence in the approach and its recommendations about season lengths and bag sizes.
2. Accept that the process is adaptive such that uncertainties should reduce with time.
3. Provide sufficient resources to enable the implementation and ongoing operation of the WCHM.
4. Recognise that the WCHM relies on the skills of a small number of scientific staff that may not be able to be quickly replaced if they cease their current employment.

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