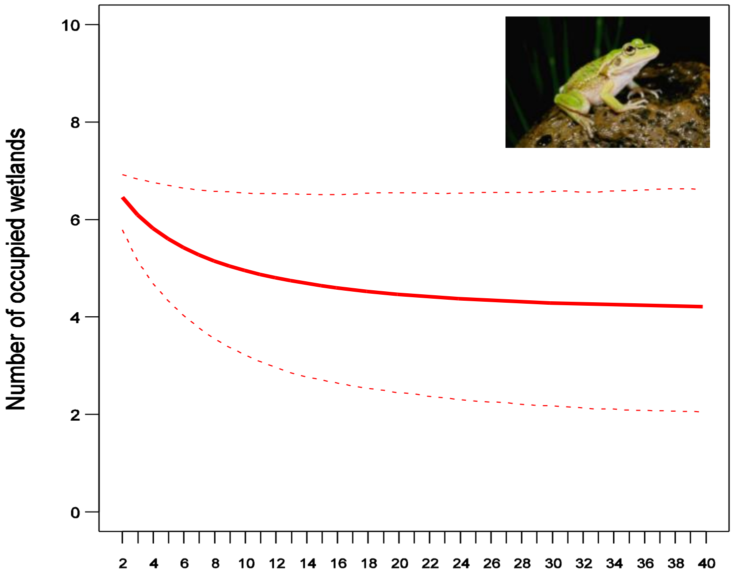
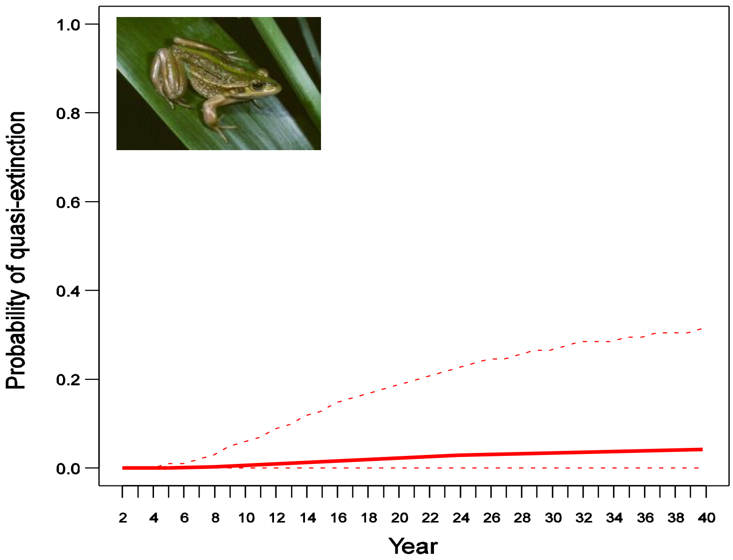
Metapopulation viability of the Growling Grass Frog in Melbourne's urban growth areas





Prepared for

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Executive Summary

The Growling Grass Frog (*Litoria raniformis*) is a large, semi-aquatic hylid frog that occurs across the temperate regions of southern Australia. It is an endangered species, being listed as such on the IUCN Red List 2010, and listed as vulnerable to extinction under the Commonwealth *Environmental Protection and Biodiversity Conservation Act* 1999 (EPBC Act).

In Victoria, a pressing issue for the conservation of *L. raniformis* is the fate of remnant populations of the frog that occur on the urban-fringe of Melbourne. *Litoria raniformis* remains widespread across the plains to the south-east, north, west and south-west of the city, yet these populations are under increasing pressure from urban expansion. The persistence of *L. raniformis* is dependent on the maintenance of networks of large permanent or semi-permanent wetlands, because the species typically exists in a balance of recurrent population extinction and colonisation. Urban expansion may disrupt or eliminate these dynamics, through the destruction of wetlands, through changes to wetland size and quality, and by interrupting dispersal opportunities between wetlands.

This study was undertaken to inform the Victorian Government's Sub-regional Species Strategy for the Growling Grass Frog (Organ *et al.* 2011; DSE 2012). The strategy represents a key requirement of the Strategic Impact Assessment (DSE 2009) for Melbourne's urban growth under the EPBC Act. Our project sought to assess the viability of metapopulations of *L. raniformis* within one urban growth area (Whittlesea-Hume on Melbourne's northern fringe), both under current conditions and under several possible urbanisation scenarios. It also sought to analyse the effectiveness and inform the use of habitat creation schemes ('offsetting') to mitigate the impacts of urbanisation on metapopulation viability, as proposed within the sub-regional strategy

Specific objectives were therefore:

1) To assess metapopulation viability for *L. raniformis* in one of Melbourne's urban growth areas under current conditions (no urban expansion);
2) To quantify changes in metapopulation viability for *L. ranformis* in one of Melbourne's urban growth areas given urban expansion and the retention of different sized habitat corridors, and;
3) To assess the extent to which habitat creation schemes ('offsetting') can mitigate any increased risk of metapopulation extinction resulting from urban expansion in one of Melbourne's urban growth areas.

The key findings and recommendations arising from this study are listed below.

Key findings

Metapopulation viability under current conditions (no urban expansion)

- The viability of the three focal metapopulations appears high given maintenance of current conditions, with low mean estimates of the probability of quasi-extinction. However, there was considerable uncertainty about this for two metapopulations, with probabilities of quasi-extinction after 30 years possibly being as high as 0.59.

Metapopulation viability given urban expansion and no habitat offsetting

- Riparian habitat corridors of 1000–800 m in width (500–400 m either side of streams) entailed relatively minor increases in the probability of quasi-extinction for each of the focal metapopulations (mean estimate of the probability of quasi-extinction of 0.09, mean upper 95% CI for this probability of 0.53).
- Riparian habitat corridors of 200 m or less (100 m or less either side of streams) entailed relatively high increases in the probability of quasi-extinction for each of the focal metapopulations (mean estimate of the probability of quasi-extinction of 0.67, mean upper 95% CI for this probability of 0.9)
- Riparian habitat corridors of 600–400 m (300–200 m either of streams) represent a middle ground in terms of increases in the probability of quasi-extinction (mean estimate of the probability of quasi-extinction of 0.21), but uncertainty around the predictions suggested that large increases in extinction risk were possible under these scenarios (mean upper 95% CI of the probability of quasi-extinction of 0.74).

Metapopulation viability given urban expansion and offsetting with wetland creation

- Strategic creation of semi-permanent wetlands reduced the probability of quasi-extinction for each of the focal metapopulations.
- For two of the three metapopulations examined, six or more wetlands were required to fully offset the increase in the probability of quasi-extinction resulting from urban expansion (when corridors of 200 m or 100 m either side of the streams were maintained). However, the addition of four new wetlands significantly limited the effects of urban expansion in all cases.
- Decreases in the probability of quasi-extinction following wetland creation were similar for the 400 m and 200 m habitat corridors (200 m or 100 m either side of the streams). However, we caution that this may be an unrepresentative and/or unrealistic result.

Recommendations

Metapopulation viability under current conditions (no urban expansion)

- Even without urban development, some metapopulations of *L. raniformis* around Melbourne may face significant risk of extinction over coming decades, and may require targeted wetland creation or enhancement schemes to minimise this risk. Studies such as the one reported here could be undertaken to identify 'at risk' metapopulations.

Metapopulation viability given urban expansion and no habitat offsetting

- Riparian habitat corridors of ≤ 200 m in width (≤ 100 m either side of streams) entail significant increases in the risks of quasi-extinction for metapopulations of *L. raniformis*. It would be prudent to avoid such small corridors. Habitat corridors of ≥ 800 m (≥ 400 m either side of streams) represent the most risk adverse scenario for the metapopulations studied here, with corridors of 600–400 m (300–200 m either side of streams) being a middle ground. Under the latter scenarios, the metapopulations studied here displayed small increases in the mean estimates of quasi-extinction risk, but there was considerable uncertainty around these estimates.

Metapopulation viability given urban expansion and offsetting with wetland creation

- Habitat offsetting through wetland creation appears a viable approach to mitigating the impacts of urbanisation on *L. raniformis*, but considerable investment may be required for some metapopulations (six or more dedicated wetlands).
- When created wetlands are placed close to large, permanent pools along streams, managers should strive to create semi-permanent wetlands rather than permanent ones if the development of permanent wetlands requires connection to the storm-water system, and the construction of semi-permanent ones do not.
- Wetland enhancement should be considered as a complimentary approach to wetland creation for mitigating the impacts of urbanisation on metapopulations of *L. raniformis*. Modelling similar to that presented here could be used to quantify the value of alternate wetland enhancement and creation schemes.
- Decision analyses represent a potentially powerful tool for conservation planning for *L. raniformis* on a metapopulation-by-metapopulation basis, and should be pursued for decision-making at this scale.
- Implementing an adaptive approach to the management of *L. raniformis* in Melbourne's urban growth areas should be explored, with focus on refining the existing metapopulation model for this species.

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1.1 The Growling Grass Frog

1.1.1 General ecology in southern Victoria

The Growling Grass Frog (*Litoria raniformis*) is a member of the 'bell frog' species complex (Anura: Hylidae), a group of morphologically and ecologically similar frogs found across the temperate regions of southern Australia (Pyke 2002). The species inhabits lowland environments in the south-east of the continent, including (or formerly including) parts of the Australian Capital Territory, New South Wales, Victoria, South Australia and Tasmania (Pyke 2002).

Populations of *L. raniformis* in southern Victoria have now been the focus of considerable research, owing to the species endangered status, and its persistence in landscapes subject to urban, industrial and agricultural development (see further below). *Litoria raniformis* occupies a wide-variety of wetlands across this region, including slow-flowing sections of rivers and streams, lakes, swamps and billabongs (Hamer and Organ 2008; Heard *et al.* 2010; Heard *et al.* 2012a). It is also known to inhabit a variety of artificial wetlands, including flooded quarries, farm dams and water treatment ponds (Hamer and Organ 2008; Heard *et al.* 2010; Heard *et al.* 2012a). The species is highly aquatic, being most often observed in or close to the water during both diurnal and nocturnal activity (Heard *et al.* 2008).

Like other member of the 'bell frog' complex, *L. raniformis* is highly fecund. Germano and White (2008) report a maximum clutch size of 4563. Heard *et al.* (2012b) assessed growth rates, age at maturity and adult survival rates amongst remnant populations of *L. raniformis* around Melbourne. Their data confirm that this species displays a 'fast' life-history strategy, characterised by rapid growth and maturation (attainment of adult size within 100 days of metamorphosis), and low adult survival rates.

1.1.2 Metapopulation dynamics

A metapopulation is a set of discrete populations of a species that are connected by migration (Hanski 1998, 1999). Broadly speaking, one can expect most species to form metapopulations at some spatial scale, because most species display some spatial discontinuity in their population structure (Royle and Dorazio 2008). Nevertheless, metapopulation theory is usually applied to species which display very clear spatial population structuring, given either natural patchiness of their habitat, or patchiness resulting from anthropogenic habitat fragmentation (Hanski 1998, 1999).

Metapopulations display various structures, but are most often categorised as 'mainland-island' or 'classical' metapopulations (Harrison and Taylor 1997; Hanski 1999). The former represents situations in which individual populations vary substantially in size, with large, stable populations regularly exporting individuals to smaller surrounding populations. Mainland-island metapopulations are relatively stable systems, because the large 'mainland' populations are resistant to extinction (Harrison and Taylor 1997;

Hanski 1999). Classical metapopulations, on the other hand, are highly dynamic. In these systems, all populations are sensitive to stochastic perturbations (demographic, environmental or genetic), leading to frequent population extinction. These extinctions are offset by colonisation of vacant habitat patches, because extinctions are generally spatially heterogeneous, producing a consistent supply of migrants from remaining extant populations within the system (Harrison and Taylor 1997; Hanski 1999).

Heard *et al.* (2012a) argued that the classical metapopulation concept represents a useful model of the population dynamics of *L. raniformis* in the vicinity of Melbourne. They presented several pieces of evidence to support this conclusion. Firstly, the wetlands inhabited by *L. raniformis* in this region are inherently patchy, consisting of chains of pools along streams, as well as adjacent off-stream wetlands such as farm dams, swamps and flooded quarries. This, in combination with the highly aquatic nature of the species, its low rate of dispersal between wetlands, and the very steep decline in rate of dispersal with distance, suggests that assemblages of frogs occupying individual wetlands may be considered spatially discrete populations. Secondly, Heard *et al.* (2012a) presented evidence that the regional persistence of *L. raniformis* entails a balance between population extinction and (re)colonisation. Indirect evidence came from the 'fast' life-history traits of *L. raniformis* (high fecundity, rapid growth and low adult survival), because these traits are considered adaptive to frequent population turnover (Hanski 1999). Direct evidence came from observations of frequent changes in wetland occupancy through time, consistent with recurrent population extinction and colonisation. The identification of a strong relationship between the probability of wetland colonisation by *L. raniformis* and the density of neighbouring extant populations (a proxy for immigration rate, typically called 'connectivity'; Hanski 1999) was also in-line with the processes operating in classical metapopulations (Heard *et al.* 2012a).

1.1.3. Urbanisation as a key threatening process

Litoria raniformis is an endangered species. It is listed as such on the IUCN Red List 2010, and listed as vulnerable to extinction under the Commonwealth *Environmental Protection and Biodiversity Conservation Act* 1999 (hereafter EPBC Act). The species is listed as endangered is Victoria (DSE 2003).

The decline and disappearances of numerous populations of *L. raniformis* last century probably had various causes (Mahony 1999). Nevertheless, habitat loss, degradation and fragmentation, coupled with severe stochastic perturbations, were probably universally important (Heard *et al.* 2012b). Being largely restricted to plains and foothill country, populations of *L. raniformis* have a long history of exposure to urbanisation, and both agricultural and industrial expansion. Habitat loss, degradation and fragmentation are important outcomes of these land-uses for amphibians (Hazell 2003; Cushman 2006; Hamer and McDonnell 2008). Heard *et al.* (2012b) argue that this habitat alternation may have been the ultimate driver of metapopulation collapse for *L. raniformis* during the periods of sharpest decline (~1975–1985), with the proximate driver being the coincidence of severe drought and the introduction of the exotic pathogen *Batrachochytrium dendrobatidis* (chytrid fungus). The basic idea is that habitat loss, degradation and fragmentation would have caused inflated rates of extinction amongst remnant populations of *L. raniformis* during periods of drought and chytrid epidemics, as well as reduced rates of (re)colonisation.

Habitat loss, degradation and fragmentation continue to be key threatening processes for *L. raniformis* across its range. However, there is particular concern about the effect of these processes on the persistence of remnant populations of the frog on the urban fringe of Melbourne. Despite being once widespread around Melbourne, contemporary records suggest a marked contraction in the regional distribution of *L. raniformis*. Extant populations are now largely restricted to the plains to the west, north and south-east of Melbourne, either on the extremities of the urban boundary, or beyond it (Heard *et al.* 2010). This retraction is of concern in its own right, but it is also problematic when considering current plans for the expansion of Melbourne's metropolitan zone over the next two decades. Recent planning proposals by the Victorian government have identified five areas in which this development will be focussed, all of which occur on the plains to the west, north and south-east of the city (DPCD 2009). Current proposals for Melbourne's urban growth therefore entail the development of a significant proportion of land which supports remnant populations of *L. raniformis* around the city (Figure 1).

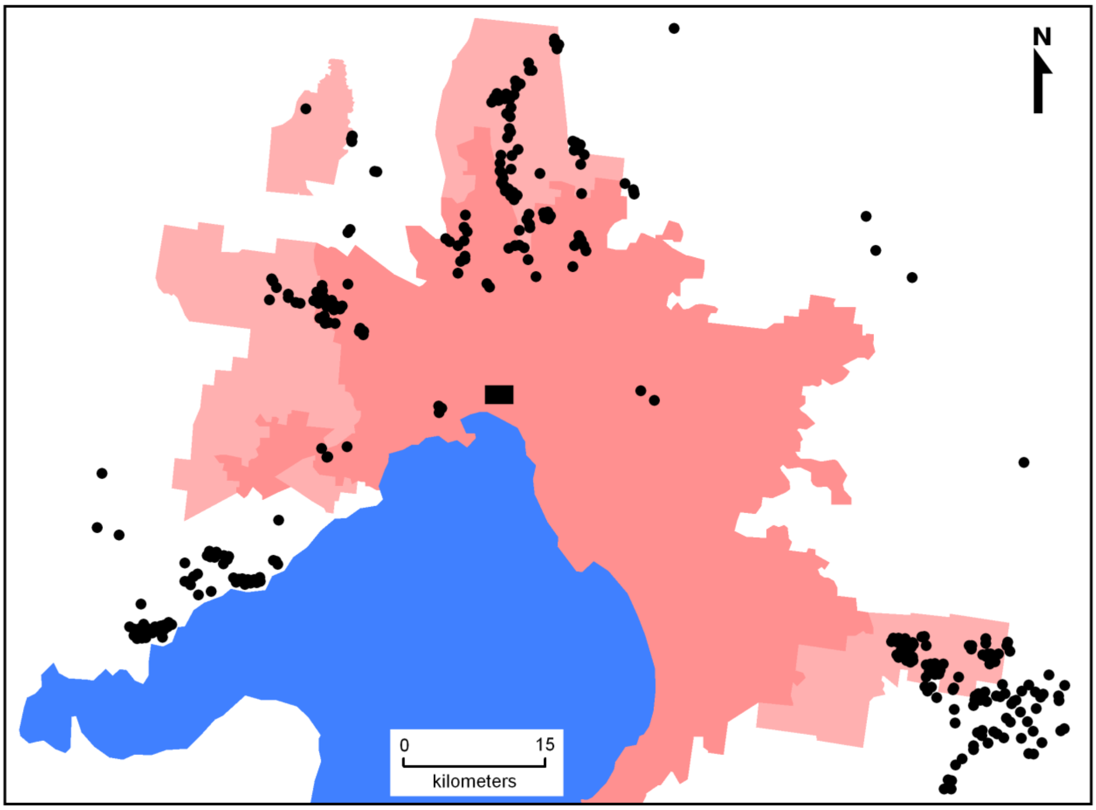

Figure 1. The distribution of remnant populations of *Litoria raniformis* in the vicinity of Melbourne, Victoria, relative to proposed urban growth areas. Records of the species available in the Atlas of Victorian Wildlife from the year 2000 onwards (●) are overlain on the current urban zone (red shading) and the proposed extensions to this zone (pink shading). The blue shaded area is Port Phillip Bay and the black rectangle the central business district of the city.

1.2 Metapopulation viability analyses

In conservation biology, 'viability' refers to the concept of population viability; the ability of populations to survive and adapt in the long-term (Soulé 1987). Population viability, strictly defined, is the ongoing existence of a population of the same species, and the ability for evolutionary processes to continue amongst them (Soulé 1987). More practically, population viability refers to the probability that a population will survive (or go extinct) over a given time period. Population viability analysis (PVA) describes a suite of quantitative techniques that have emerged to estimate these probabilities (Beissinger 2002).

Contemporary PVAs rarely deal with single populations, because most species to which they are applied display some population sub-division (Morris and Doak 2002). Moreover, habitat fragmentation is almost ubiquitous as a threatening process for these species (Lindenmayer and Fischer 2006). Hence, contemporary PVAs are more aptly termed metapopulation viability analyses, or MPVAs.

Several forms of MPVAs are currently available (Morris and Doak 2002; McCarthy 2009). The most complex are those which model the internal demographic processes of the constituent populations, as well as immigration and emigration between them. These models typically require detailed knowledge of the life-history and demography of the focal species, including such things as age-specific fecundity and survival, population sizes and carry capacities, mechanisms of density dependence, effects of stochasticity on vital rates, dispersal rates and distances. The data-intensive nature of these approaches represents an important constraint for their use, but it also provides considerable flexibility to model processes such as spatially-variable demographic parameters, habitat dynamics, and spatially-correlated disturbance regimes (Morris and Doak 2002; McCarthy 2009). On the other end of the spectrum are approaches known as stochastic patch occupancy models, or SPOMs. These models are designed specifically for 'classical' metapopulation dynamics, in which population extinction and recolonisation occurs with some frequency (Sjögren-Gulve and Hanski 2000; Hanski 2002). Rather than attempting to model the demographic processes of the constituent populations, SPOMs model stochastic changes in the existence of populations, due to recurrent extinction and colonisation. There are two main approaches, but we will only consider one given its particular relevance to this report.

Sjögren-Gulve and Ray (1996) introduced a logistic regression-based SPOM that may be developed using observations of population extinction and colonisation. The basic idea is to gather multiple observations of these events through time, and then use regression approaches to parameterise logistic equations describing the effects of particular patch- and landscape-scale variables on the probabilities of extinction and colonisation. The underlying theory is that: (i) the probability of extinction should be related to population size, which is in turn determined by patch area and quality, and; (ii) the probability of colonisation should be related to immigration rate, which is in turn determined by the density of neighbouring extant populations (or 'connectivity', as above) (Sjögren-Gulve and Hanski 2000; Hanski

2002). The resulting logistic equations can then be used to predict changes in the occupancy status of each patch in a metapopulation through time. We explain the machinery of this technique in detail below (see section 2.3), but the key point is that one can simulate changes in occupancy status of each habitat patch through time (given their per time-step probability of extinction and colonisation, as described by the logistic equations), and monitor the change in the number of extant populations through time. By doing these simulations many times, one can derive estimates of the probability of metapopulation extinction or quasi-extinction through time, by calculating the proportion of simulations at each time step in which the number of extant populations has fallen to zero, or below some predefined threshold (Sjögren-Gulve and Hanski 2000; Hanski 2002).

1.3 Project scope and objectives

1.3.1 Scope

As outlined above, the proposed expansion of Melbourne's urban growth boundary, through dedicated growth areas to the west, north and south-east of the city, will impact upon many remnant populations of *L. raniformis*. As this species is considered endangered in Victoria, and, specifically, because it is listed as nationally vulnerable to extinction under the EPBC Act, the Victorian Government has developed the Sub-regional Species Strategy for the Growling Grass Frog (DSE 2012). This strategy represents a key requirement of the Strategic Impact Assessment (DSE 2009) for Melbourne's urban growth under the EPBC Act.

This study was undertaken to inform the Sub-regional Species Strategy for the Growling Grass Frog. The project sought to assess the viability of metapopulations of *L. raniformis* within one urban growth area, both under current conditions and under several possible future urbanisation scenarios. It also sought to analyse the effectiveness and inform the use of habitat creation schemes ('offsetting') to mitigate the impacts of urbanisation on metapopulation viability, as proposed within the sub-regional strategy.

1.3.2 Objectives

This project had three specific objectives:

1) To assess metapopulation viability for *L. raniformis* in one of Melbourne's urban growth areas under current conditions (no urban expansion);
2) To quantify changes in metapopulation viability for *L. ranformis* in one of Melbourne's urban growth areas given urban expansion and the retention of different sized habitat corridors, and;
3) To assess the extent to which habitat creation schemes ('offsetting') can mitigate any increased risk of metapopulation extinction resulting from urban expansion in one of Melbourne's urban growth areas.

2. Methods

2.1 Metapopulation model

The study of Heard *et al.* (2012a) provides a basis for developing a logistic regression-based stochastic patch occupancy model (SPOM) for *L. raniformis*. As above, these models are developed using observed changes in patch occupancy through time (generally annual changes), which are interpreted as recurrent population extinction and colonisation. Heard *et al.* (2012a) monitored the occurrence of *L. raniformis* at 167 wetlands across Melbourne's northern fringe over a period of six years (2001/2002 to 2006/2007; total surveys =1380). They observed extinction at 26 wetlands and (re)colonisation of 19.

As we outline below, we have used the data of Heard *et al.* (2012a) to parameterise logistic equations describing the effect of several patch- and landscape-scale variables on the probabilities of extinction and colonisation for *L. raniformis*. We employed a Bayesian approach, which allows uncertainty in the effects of each variable on the probabilities of extinction and colonisation to be fully described, and incorporated into subsequent simulations of metapopulation viability. For the purposes of this report, we focus on a simplified model in which the probability of extinction is a function of effective wetland area (*EA*) and connectivity (*S*), while the probability of colonisation is a function of connectivity. The relationship between the probability of extinction and connectivity represents a 'rescue effect', in which immigrants from neighbouring populations can rescue populations from extinction (Hanski 1999).

Effective area of the wetland was defined as:

$$EA_i = \frac{A_i \times H_i}{H_{max}} , \quad \text{Eq. 1}$$

where A_i is the surface area of wetland i and the surrounding 100 m terrestrial zone (in $\log_e$ square metres), H_i is the hydroperiod of wetland i measured on an ordinal scale between 1 (only remains inundated for months at a time during periods of high rainfall) and 4 (permanently inundated), and H_{max} is the maximum hydroperiod score (4). There are several points to be made concerning this measure. The first is that the extent of the terrestrial zone is based upon the observed use of that zone by *L. raniformis* in northern Melbourne for foraging and other activities (Heard *et al.* 2008). The second is that the terrestrial zone excludes urbanised areas (roads or buildings) to account for the fact that these areas are uninhabitable for *L. raniformis*. The third point is that adjusting wetland area for hydroperiod is important, because the carrying capacity of a wetland should be closely tied to the fluctuation in water-levels it is likely to display.

Connectivity in each year of the study was defined as:

$$S_{it} = \sum w_{ij} \times y_{jt} , \quad \text{(Eq. 2)}$$

where w_{ij} is the inverse of the Euclidean distance (km) between the centre of wetland i and each of its j neighbouring wetlands within a 1 km radius, and y_{jt} is the occupancy status of each neighbour j (one if the wetland is occupied, zero if not) in each year t. The size of the radial neighbourhood region was set at 1 km given the superiority of this neighbourhood in earlier analyses (Heard *et al.* 2012a). This measure includes both the density of neighbouring populations as well as their distance from the focal wetland, because it down-weights the contribution of neighbours that are further away (at the rate of $1/\text{distance}_{ij}$).

Logistic equations describing simple additive, linear effects of these variables on the probabilities of extinction and colonisation for *L. raniformis* were derived using the technique of Royle and Kéry (2007) – a Bayesian formulation of the approach to modelling occupancy turnover introduced by Mackenzie *et al.* (2003, 2006). This approach has the benefit of accounting for false-absences in the survey data-set, arising from detection probabilities < 1. We implemented this technique using Markov Chain Monte Carlo sampling (MCMC) in *OpenBUGS* v. 3.1.2 (Thomas *et al.* 2006). Estimates of the parameters of the logistic equations for the effects of wetland area and connectivity on the annual probabilities of extinction and colonisation were derived from 5000 MCMC iterations, after discarding the first 25000 iterations as a 'burn-in'. The resulting equations were:

$$\log\left(\frac{e_{it}}{1-e_{it}}\right) = 7.29 - 0.96 \times EA_i - 0.09 \times S_{it}\,, \qquad \text{(Eq. 3)}$$

and

$$\log\left(\frac{c_{it}}{1-c_{it}}\right) = -3.82 + 0.12 \times S_{it}\,, \qquad \text{(Eq. 4)}$$

where e_{it} is the probability of extinction at wetland i between time t and $t+1$, c_i is the probability of colonisation of wetland i between t and $t+1$, EA_i is the effective area of wetland i and S_{it} is the connectivity of wetland i at time t. Note that only the mean estimates of the parameters of the equations are shown. However, as alluded to above, the Bayesian MCMC approach adopted here represents the full uncertainty in these parameters by producing a distribution of estimates (an estimate for each iteration of the MCMC chain), rather than a simple point estimate (McCarthy 2007). See Figure 2 for a depiction of the relationships described by equations 3 and 4, and the uncertainty around these relationships.

Combining these equations to develop the SPOM for *L. raniformis* was achieved by inserting them into the standard equation for changes in patch occupancy through time (Mackenzie *et al.* 2003, 2006):

$$O_{i\,t+1} = o_{it}\,(1-e_{it}) + (1-o_{it})c_{it}\,, \qquad \text{(Eq. 5)}$$

where $O_{i\,t+1}$ is the probability of occupancy of wetland i at time $t+1$, o_{it} is the occupancy status of wetland i at time t, and e_{it} and c_{it} are the probabilities of extinction and colonisation at wetland i between time t and time $t+1$, as defined by equations 3 and 4.

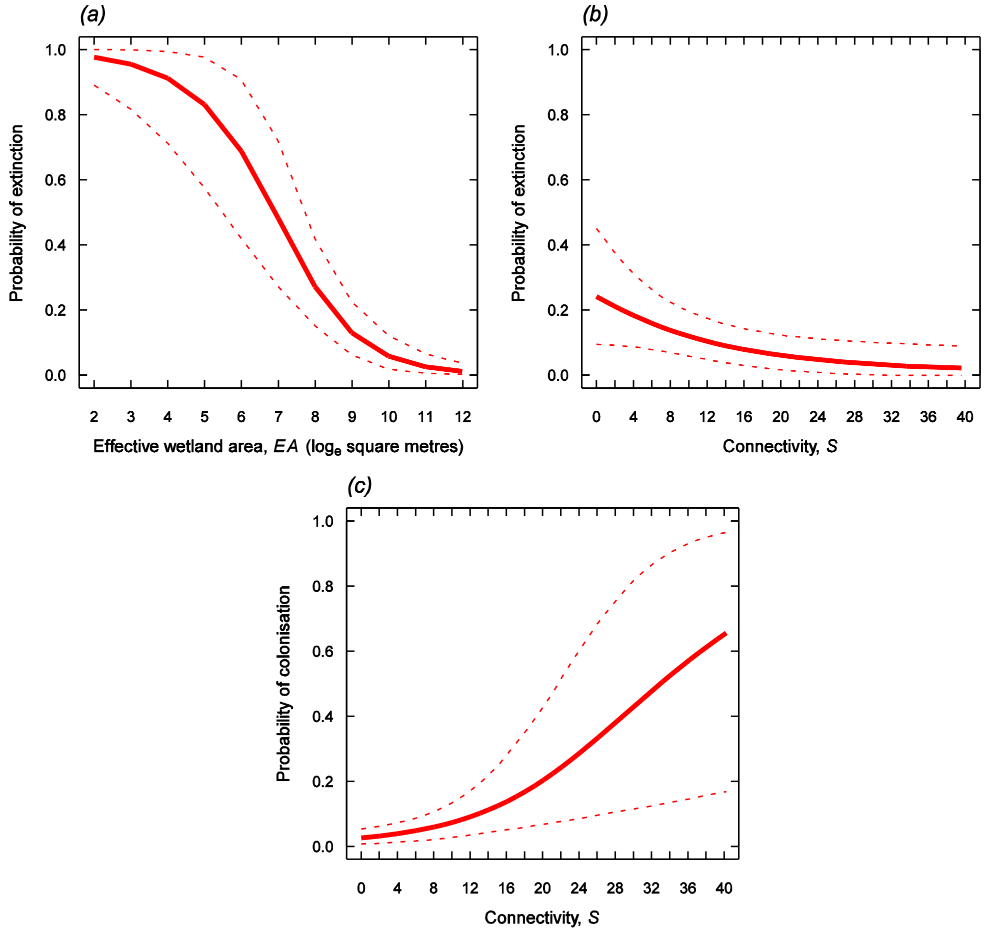

Figure 2. Relationships between annual probability of extinction and effective wetland area and connectivity for *Litoria raniformis* (*a–b*), and between the annual probability of wetland colonisation and connectivity (*c*). The solid lines represent the estimated mean relationships, and the dashed lines the 95% credible intervals of the estimates. Relationships are shown with all other variables held at their mean values.

2.2 Study area and focal metapopulations

This study sought to assess metapopulation viability for *L. raniformis* within one of Melbourne's growth areas. The Whittlesea-Hume growth area on Melbourne's north was selected for this purpose (Figure 3). This is the region where the study of Heard *et al.* (2012a) was conducted, which had two advantages for this project. Firstly, it meant that the SPOM outlined above was directly relevant to the study area. Secondly, the survey work conducted by Heard *et al.* (2012a) provided a basis for identifying specific metapopulations on which to work, and delineating their spatial extent and composition.

Three metapopulations were selected within the upper catchment of the Merri Creek (Figure 3–6). Each represents a reasonably discrete cluster of wetlands distributed over an area of 1.7–8.2 sq. km. We considered these metapopulations to be representative of those to be affected by urban growth in the Whittlesea-Hume area, as well as those to be more broadly affected by urban growth around Melbourne. All three metapopulations are located within the Whittlesea-Hume growth area (as defined in DPCD 2009; see Figure 3), and are characterized by a mosaic of farmland and riparian corridors, and

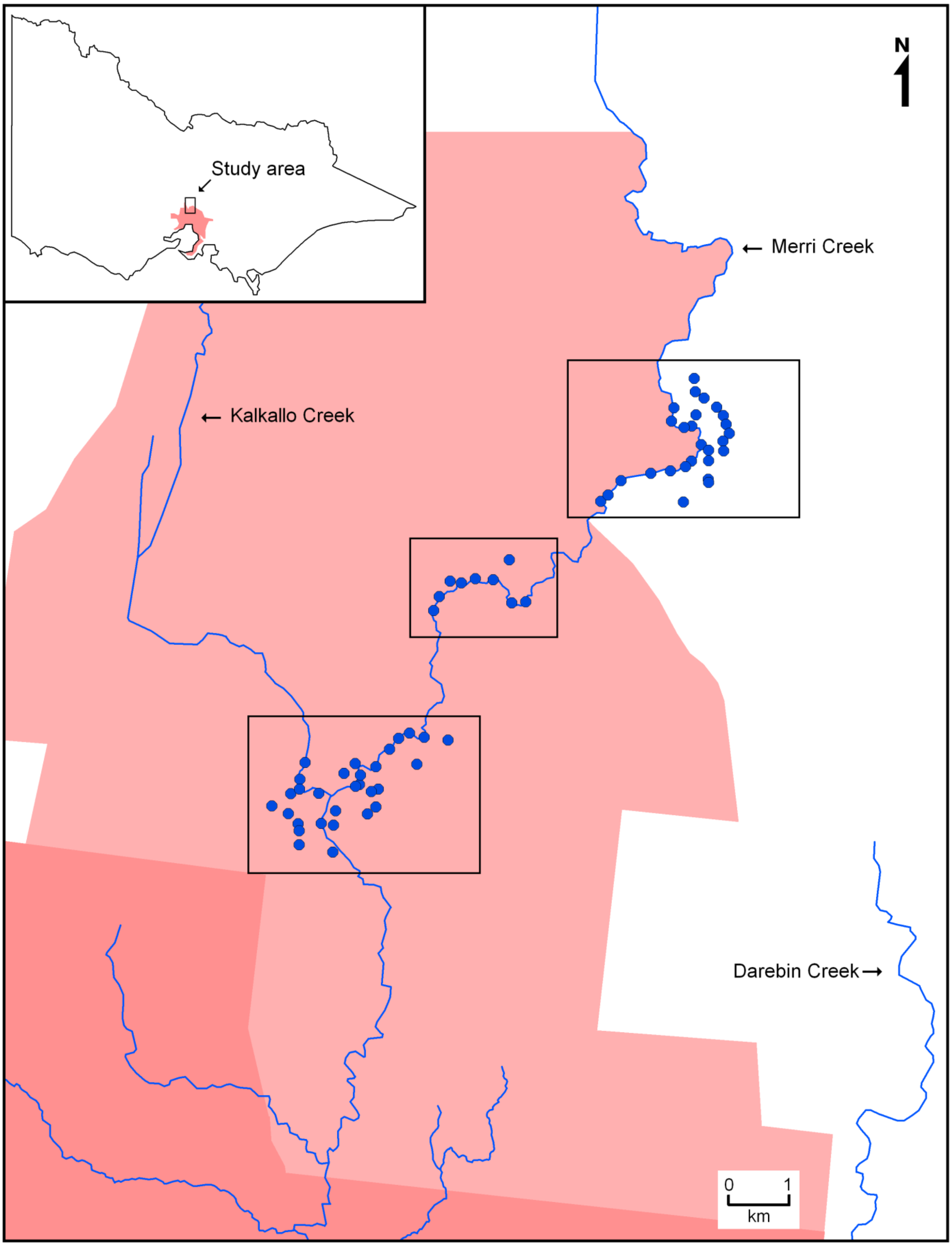

Figure 3. Location of the study area, encompassing the upper catchment of the Merri Creek catchment in the Whittlesea-Hume growth area, Melbourne. The three rectangles delineate the focal metapopulations, with the blue dots representing the constituent wetlands for each metapopulation (pools along streams plus off-stream wetlands). From north to south the three metapopulations are Merriang, Bald Hill and Donnybrook. The red shading shows the approximate extent of current urban growth zone, and the pink shading the proposed expansion to that zone (DPCD 2009). Note that this map does not show proposed land uses within the urban growth zones. See DPCD (2009) for detailed maps of proposed land uses.

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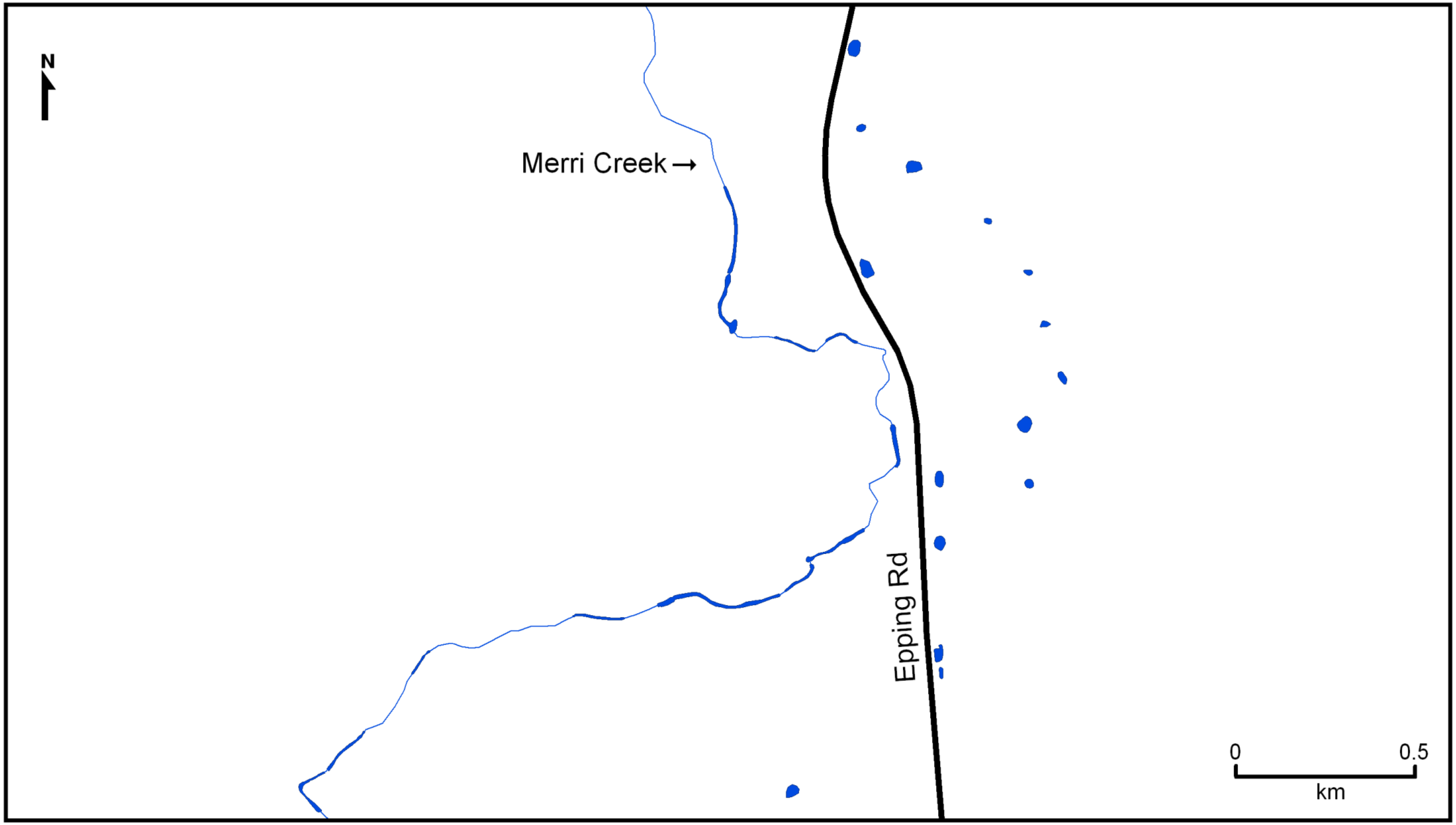

Figure 4. The Merriang metapopulation, showing the distribution of both in-stream wetland habitat (pools along the Merri Creek) and off-stream wetland habitat (farm dams). Only off-stream wetlands within 500 m of Merri Creek where included when delineating the focal metapopulations (see text).

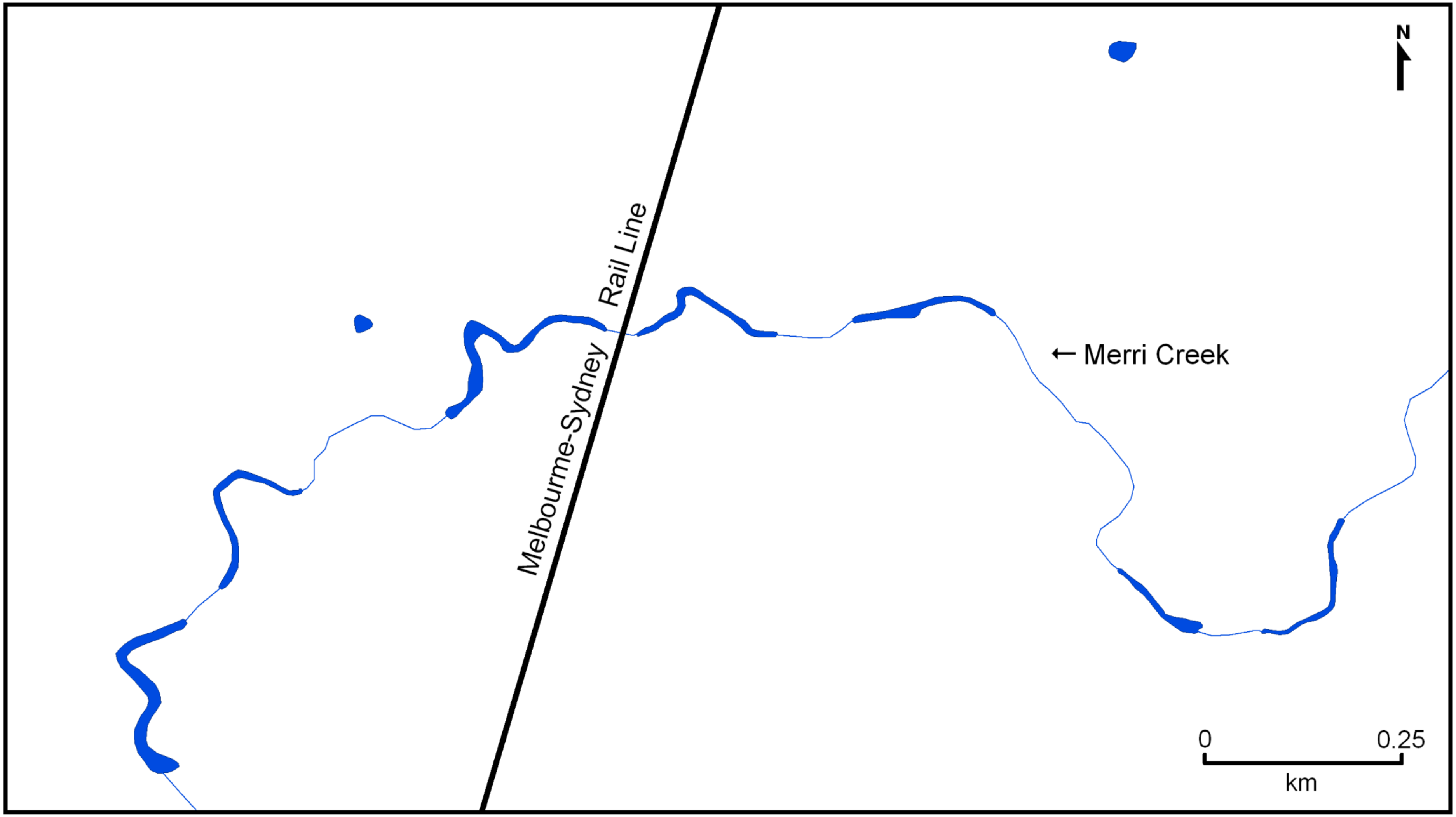

Figure 5. The Bald Hill metapopulation, showing the distribution of both in-stream wetland habitat (pools along the Merri Creek) and off-stream wetland habitat (a quarry and farm dam). Only off-stream wetlands within 500 m of Merri Creek where included when delineating the focal metapopulations (see text).

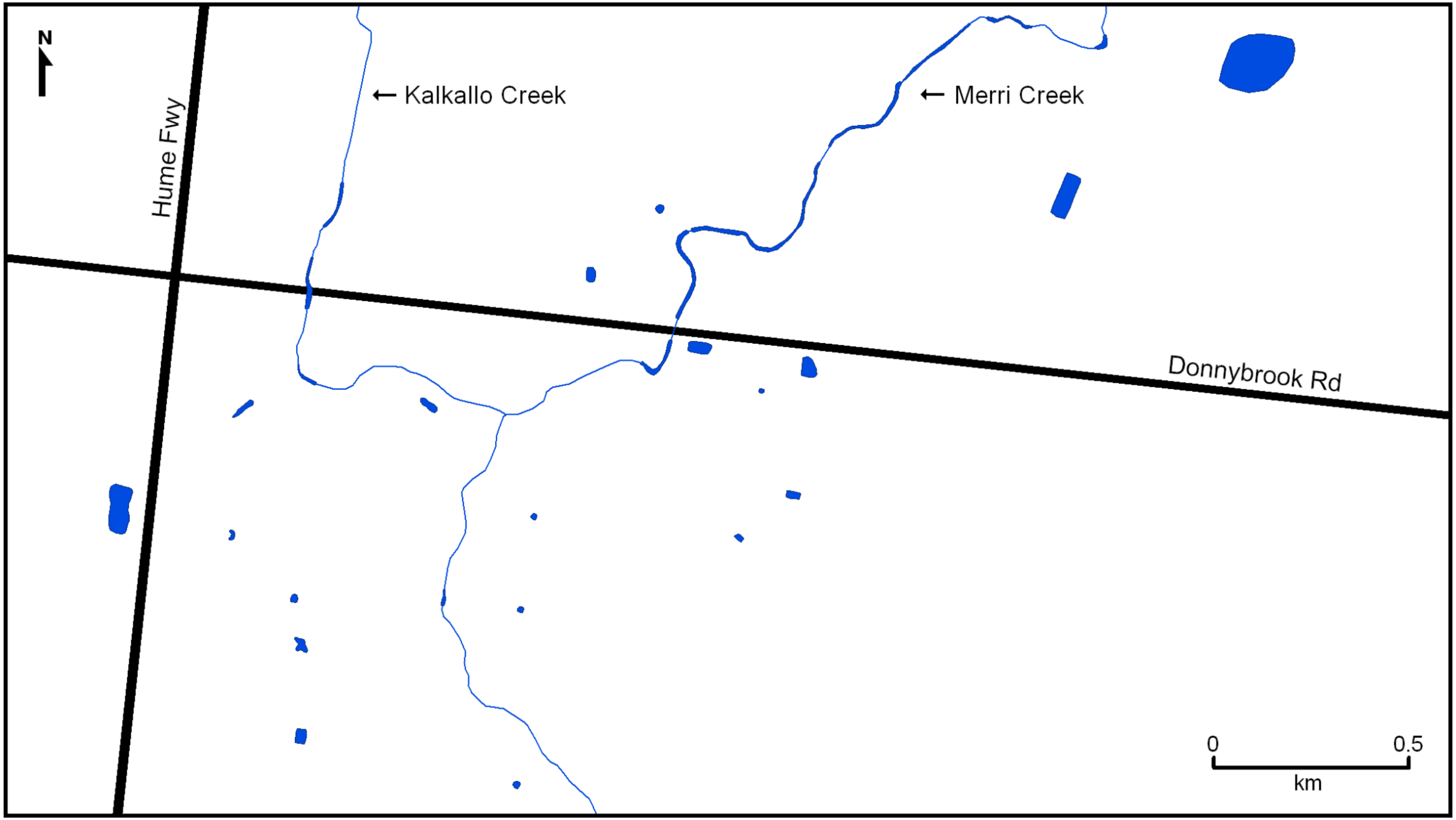

Figure 6. The Donnybrook metapopulation, showing the distribution of both in-stream wetland habitat (pools along the Merri Creek) and off-stream wetland habitat (farms dams). Only off-stream wetlands within 500 m of Merri Creek where included when delineating the focal metapopulations (see text).

currently minimal urban infrastructure. These features are typical of the majority of locations around Melbourne in which remnant populations of *L. raniformis* persist.

Delineating each metapopulation involved several steps. Existing knowledge of the distribution of *L. raniformis* in each area between 2001 and 2007 (Heard *et al.* 2012a) was first used to roughly delineate the extent and approximate boundaries of each metapopulation. We subsequently included any pools along each stream that were within 500 m of previously occupied wetlands, as well as any pools that were adjacent to these pools. We stopped adding adjacent pools when there were breaks in their distribution, resulting from long sections of riffles, or shallow sections dominated by dense riparian vegetation. Finally, we included any off-stream wetlands that were within 500 m of an included pool. The choice of a 500 m threshold for the inclusion or exclusion of wetlands when delineating these metapopulations was based on the fact that only limited dispersal occurs beyond this range, and hence, populations separated by 500 m of more can be expected to have limited influence on each other's dynamics (Heard *et al.* 2012a). We discuss the limitations and ramifications of our approach to delineating metapopulations below (see section 2.4). Appendix 1 provides the locations and characteristics of wetlands included in each metapopulation.

2.3 Metapopulation viability analysis

2.3.1 General approach

The basic machinery of conducting metapopulation viability analysis using a SPOM is the simulation of stochastic changes in the occupancy of each patch through time, according to their per time-step probabilities of population extinction and colonisation. For one time-step to the next, the process is as follows: (i) estimate the probability of occupancy for each patch at the second time-step (O_{it+1}), according to the occupancy statuses of each patch at the first time step (o_{it}) and the probabilities of population extinction (e_{it}) and colonisation (c_{it}); (ii) compare $O_{i,t+1}$ for each patch to a random number between 0 and 1 to determine whether extinction or colonisation actually occurs between the first and second time-steps (extinction occurs at occupied patches when $O_{i,t+1}$ is less than the random number, and colonisation occurs at unoccupied patches when $O_{i,t+1}$ is less than the random number), and; (iii) collate the patch occupancy statuses at the second time-step. One simply repeats this process for as many time-steps as the simulation is intended to run, and keeps track of the number of occupied patches (extant populations) through time. As above, by doing these simulations many times one can derive estimates of the probability of metapopulation extinction or quasi-extinction through time, by calculating the proportion of simulations at each time step in which the number of extant populations has fallen to zero, or below some predefined threshold (Sjögren-Gulve and Ray 1996; Hanski 1999, 2002).

We conducted simulations following this general procedure for each of the focal metapopulations using *OpenBUGS* v. 3.1.2 (Thomas *et al.* 2006). In all cases, 50 simulations were conducted over a period of 30 years. This represents a relatively small number of simulations, but preliminary checks revealed that the benefits of increasing the number of simulations were small (i.e., little change in the precision of the viability estimates), while the computational costs were large. The choice of the time period was guided by the desire to allow enough time for the metapopulation to react to the simulated management, without reaching too far into the future (as is generally advised for population viability analyses; Morris and Doak 2002).

The Bayesian MCMC approach used to estimate the parameters of equations 3 and 4 does not produce point estimates of these parameters, but rather a series of estimates which reflects the posterior probability density of each parameter. We propagated this uncertainty through to the simulations of metapopulation viability. Simulations were therefore run for each of the 5000 estimates of the parameters of equations 3 and 4 we derived. The result was a distribution of estimates of metapopulation viability which reflects uncertainty in the parameters of the underlying equations. We summarise this distribution by its mean and 95% credible interval (95% CI). A 95% CI is the bounds within which there is a 95% chance that a parameter lies. For example, if the 95% CI for a particular parameter (x) was 0.2–0.8, we would say that there is a 95% chance that parameter x is between 0.2 and 0.8.

Following the recommendations of Morris and Doak (2002), we focus on the probability of metapopulation quasi-extinction in this report. All models of population dynamics will be inaccurate to some degree, because they cannot include all processes influencing those dynamics (Morris and Doak 2002, see further below). Focussing on metapopulation quasi-extinction rather than outright extinction represents a means of implicitly incorporating such inaccuracies, because it essentially places a conservative buffer on the predictions. An important possible inaccuracy of our model is that it excludes spatially-correlated catastrophes, which can have important ramifications for the viability of metapopulations (Hanski 1991, 1999). The model is built on stochastic extinction at each time-step, but it does not include widespread and correlated extinctions arising from such things as drought, floods, disease epidemics or fire. These processes are technically relatively easy to incorporat, but they are biologically challenging, as we currently have a poor understanding of their effect on the metapopulation dynamics of *L. raniformis*.

For each of the analyses described below, we used a single threshold of < 3 occupied wetlands to define quasi-extinction. This choice is somewhat arbitrary, but is intended to reflect a middle ground between a liberal risk tolerance threshold that requires less management (1–2 occupied wetlands), and a more conservative threshold that could prove to be a logistically and financially onerous (4–5 occupied wetlands.

2.3.2 Under current conditions (no urban expansion)

As above, simulation of the dynamics of each metapopulation must start from an initial point in which the occupancy of each wetland is predefined. Preferably this would be known occupancy at the initial time point, arising from surveys of all patches in the system. However, it is of little consequence if some of the wetlands are inaccurately assigned to an occupancy state at the first time point, because they will, in most circumstances, quickly attain a probability of occupancy through time that is reflective of their size and connectivity. For each of the focal metapopulations, we began simulations assuming that the occupancy of each wetland was the same as that in the final field season (2006/2007) of the study of Heard *et al.* (2012a). Wetlands not surveyed by Heard *et al.* (2012a) were set to be occupied at the initial time-step.

The effective area of each wetland (as per equation 1) was also set to be equal to that in the 2006/2007 season, with the exception of two wetlands in Donnybrook that have been impacted by the construction of the Donnybrook Rd Interchange. The buffer size of these wetlands was reduced to reflect the expanded road network in this location. All other wetlands appear to remain the same size and to display the same hydroperiod as that in 2006/2007. The characteristics of each wetland for the simulations of metapopulation viability under current conditions were the same as those provided in Appendix 1.

Simulations of metapopulation viability under current conditions assumed that these conditions do not change into the future. Thus, they represent a base-line against which changes to the system (urban expansion, with or without habitat offsetting) can be compared.

2.3.3 With urban expansion but no habitat offsetting

We assessed viability of each metapopulation under six different urbanisation scenarios, defined by the size of the habitat corridor to be maintained along each stream line. The six corridor widths were 1000 m, 800 m, 600 m, 400 m, 200m and 100 m. These corridors are centred on the stream channel, and hence entail buffers of 500 m, 400 m, 300 m, 200 m, 100 m and 50 m either side of the stream. They encompassed the range of riparian habitat corridors considered during development of the Sub-regional Strategy for the Growling Grass Frog (DSE 2012).

The first four habitat corridors entail two possible changes to the metapopulation: (1) loss of off-stream wetlands to urbanisation, and; (ii) reductions in the effective area of off-stream wetlands that remain, given urban encroachment on their buffer zones (defined as 100 m from the wetland edge, as above). The final corridor (100 m) involves these two changes, as well as constriction of the buffer of the in-stream habitat, given urban encroachment. Appendices 2–4 detail the changes to each metapopulation under the six habitat corridors.

Simulations of metapopulation viability under each habitat corridor were conducted by simply altering the network to reflect the changes in wetland number and size prior to the first time step. Thus, the assessments reflect viability once urbanisation has taken place; we have not attempted to model any progressive change in wetland number and size as urbanisation proceeds.

2.3.4 With urban expansion and habitat offsetting

Offsetting habitat loss and degradation through the creation of new wetlands represents an important component of the Sub-regional Strategy for the Growling Grass Frog (Organ *et al.* 2011; DSE 2012). We sought to assess the extent to which these initiatives can mitigate the increased risk of metapopulation extinction resulting from urban expansion, by simulating the inclusion of a standard set of new wetlands within the 400 m and 200 m habitat corridors described above. We did this for each metapopulation.

The creation of between two and eight wetlands was trialled for each metapopulation. Wetlands were set to have a surface area of 1250 sq. m in all cases (total area including circular 100 m buffer = 43250 sq. m), and were set to be semi-permanent. Wetland size and hydroperiod was selected after consultation with Melbourne Water. Wetland size was determined largely by financial and logistical considerations; the choice of a semi-permanent hydroperiod was motivated by the fact that connection to the storm-water system would be required in most cases to ensure that dedicated wetlands were permanent. As discussed below, storm-water is an undesirable water source for these wetlands, given the pollutants it carries.

In all cases, wetlands were paired and placed adjacent to pools along the Merri Creek that had relatively high effective areas. They were placed within 50 m of the stream edge, and were separated by 50 m from shoreline-to-shoreline. The idea being that if the objective of these new wetlands is to minimise the chance of quasi-extinction of the metapopulation, they should be placed close to existing 'high quality' wetlands, creating a core set of sites that display minimal likelihoods of extinction at each time-step. An important further point with regard to the simulated wetland creation schemes, is that the effective area of the new wetlands was defined and measured in exactly the same way as that used for existing wetlands: the water-surface area plus a 100 m terrestrial buffer. As such, the effective area of these new wetlands changes under the different habitat corridors considered (400 m and 200 m), because the smaller retention option constrains the buffer of the new wetlands. The locations of the new wetlands for each metapopulation, and their effective areas, are detailed in Appendices 5–7.

Assessing the change in metapopulation viability resulting from the addition of these wetlands was simply a matter of re-running the analysis for each metapopulation and habitat corridor, but with the new wetlands added at the appropriate locations.

2.4 Limitations

The model on which this project is based represents the culmination of a decade of research on the metapopulation dynamics of *L. raniformis* in Melbourne's urbanising landscapes (Heard *et al.* 2012a). Moreover, this project represents one of very few population viability analyses which have been performed for an Australian amphibian, and the first, that we are aware of, to use a stochastic patch occupancy model for this purpose. It represents an advance on past attempts at conservation planning for *L. raniformis*, which have largely relied on subjective judgement and assumed responses to habitat change.

Nevertheless, this work does have important limitations. The first is that the model excludes several factors that are almost certainly important for the dynamics and viability of metapopulations of *L. raniformis*. The first, as discussed above, is the exclusion of spatially autocorrelated catastrophes that may cause sudden increases in extinction rates over short periods, and possibly even result in metapopulation collapse (Heard *et al.* 2012a,b). Outbreaks of diseases such as chytrid fungus, which is widespread in the study area (Heard *et al.* 2012c), are an obvious example of such catastrophes. Likewise, the model excludes known or potentially important components of habitat quality for *L. raniformis*, such as aquatic vegetation cover, water quality and densities of exotic predatory fish. Heard (2010) found aquatic vegetation cover to be an important determinant of the probability of extinction for *L. raniformis* (see also Heard *et al.* 2010). We excluded this effect from the current model, because the addition of the terrestrial buffer to the measure of effective wetland area caused a strong reduction in its strength. Water quality is not included in the model because the data-set on which the model is built does not include the required water quality information. The same is true for predatory fish densities: Heard *et al.* (2012a) obtained information on the presence or absence of fish in each of the 167 wetlands they monitored, but did not obtain information on the densities of fish, which is likely a more important determinant of the effect of these predators on the extinction probabilities of *L. raniformis*. The exclusion of all of these factors could lead to underestimates of the probability of quasi-extinction.

A related issue is that our modelling approach does not consider changes to wetland condition and/or extinction probabilities of *L. raniformis* in urban landscapes. We have effectively assumed that the relationship between the effective area of wetlands and the probability of extinction of *L. raniformis* will not vary with differing intensities of urbanisation. This assumption may be problematic for several reasons. First, urban wetlands, particularly those subject to storm-water input, may become wholly unsuitable for *L. raniformis*, even if they are large and permanent, given changes to the habitat features described above. Similarly, populations inhabiting wetlands in urban landscapes may be subject to greater levels of environmental stochasticity. Pollution events in storm-water fed wetlands represent one example, as does the increased frequency and severity of high flow events within urban streams (e.g., Walsh 2005). Again, these issues could lead to underestimates of the probability of quasi-extinction.

Conversely, the fact that we have treated the focal metapopulations as independent units could lead to overestimates of the probability of quasi-extinction. While we are confident that the primary off-stream habitat has been included for each of the focal metapopulations, clear discontinuities in the distribution of in-stream habitat were difficult to identity in some cases. Excluded in-stream habitat would not have been large, but its presence could nonetheless lead to overestimates of the extinction probabilities at pools on the extremities of each metapopulation, as well as underestimates of their probabilities of colonisation. Such inaccuracies could ripple though the metapopulation, leading to overall reductions in the probability of occupancy, and heightened probabilities of quasi-extinction.

An additional limitation of our approach is the choice of a single quasi-extinction threshold. Ideally, multiple thresholds would be set, and the sensitivity of the results to these thresholds examined explicitly.

We have not done so here given time and computing constraints. Examining sensitivity to differing quasi-extinction thresholds represents an obvious direction for future work.

Limitations such as these are common to all forms of population viability analysis. Predictions derived from them should subsequently be treated as relative measures of population viability under alternate management strategies, rather than absolute ones (Morris and Doak 2002). As such, we encourage readers of this report to focus on the relative increases or decreases in extinction risk under the different scenarios considered, rather than the outright probabilities.

3. Results

3.1 Metapopulation viability under current conditions (no urban expansion)

The predicted cumulative probabilities of quasi-extinction for the three focal metapopulations, assuming no change from current conditions, are shown in Figure 7. Mean estimates of the probability of quasi-extinction after 30 years were low, being 0.013, 0.153 and 0.031 for the Merriang, Bald Hill and Donnybrook metapopulations, respectively. Nevertheless, there was considerable uncertainty in the estimates of the probability of quasi-extinction for both the Bald Hill and Donnybrook metapopulations. The former displayed an upper 95% CI for the probability of quasi-extinction after 30 years of 0.59, translating to a 59% chance of quasi-extinction at that time-step. The Donnybrook metapopulation displayed an upper 95% CI for the probability of quasi-extinction after 30 years of 0.38, translating to a 38% chance of quasi-extinction at that time-step. The relatively high uncertainty about the probability of quasi-extinction for the Bald Hill metapopulation probably reflects its small size (9 wetlands in total), and the fact that it contains only a few large permanent wetlands along the Merri Creek (see Appendix 1). Thus, even if these wetlands display a high rate of occupancy through time, the metapopulation could frequently slip below the threshold of three occupied wetlands under the more extreme estimates of the relationship between effective area and the probability of extinction. This point appears relevant to the Donnybrook metapopulation as well: only two wetlands at Donnybrook were classified as permanent, meaning that whilst numerous wetlands were physically quite large, their effective areas were low or moderate. The relatively high rate of extinction at these wetlands predicted by the model means that the occupancy trend of the metapopulation is more heavily influenced by the probability of colonisation, which is subject to considerable uncertainty (see Figure 2).

3.2 Metapopulation viability with urban expansion but no habitat offsetting

Changes in the probability of quasi-extinction for each metapopulation under the six urbanisation scenarios are depicted in Figure 8. Recall that these scenarios represent alternate widths of the habitat corridor to be maintained along streams. Thus, '1000 m' represents maintenance of a corridor of 500 m

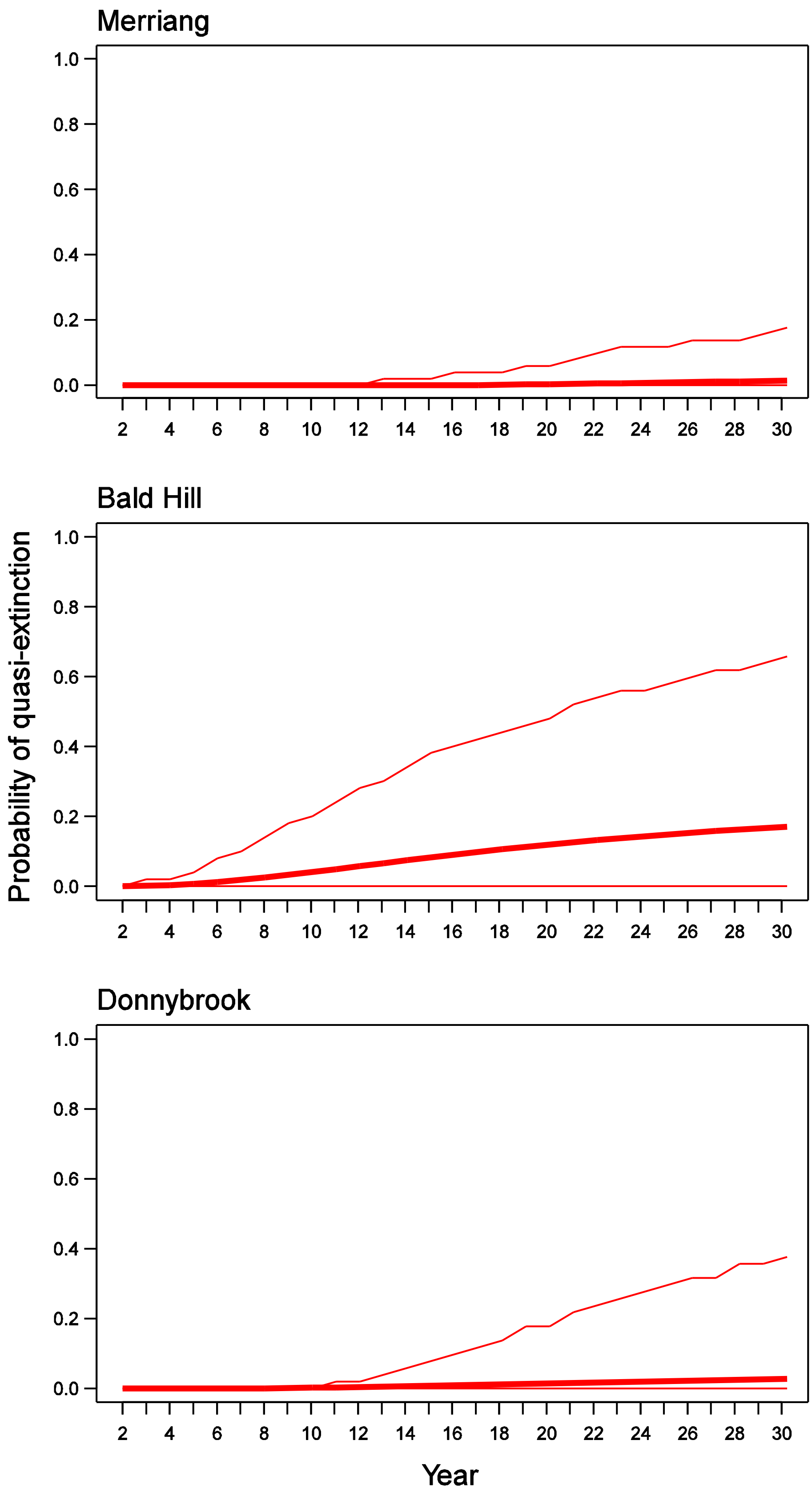

Figure 7. Viability of the Merriang, Bald Hill and Donnybrook metapopulations of *L. raniformis* assuming maintenance of current conditions (no urban expansion). The plots show the predicted probability of quasi-extinction (< 3 occupied wetlands) over 30 years. The thick red line shows the mean estimate of this probability, and the thin lines the 95% credible interval.

either side of the stream, '800 m' represents maintenance of a corridor of 400 m either side of the stream, and so on. The probability of quasi-extinction is measured at the final time-step (30 years).

Estimates of the probability of quasi-extinction after 30 years displayed considerable uncertainty for most scenarios, with a trend towards increasing uncertainty with decreasing width of the habitat corridor. For Merriang (Figure 8a), mean estimates of the probability of quasi-extinction were low–moderate for the 1000 m, 800 m and 600 m corridors (≤ 0.1), but displayed steadily increasing upper 95% CIs (reaching 0.62 for the 600 m corridor). The mean probability of quasi-extinction under the 400 m and 200 m corridors more than doubled from that under the 600 m corridor (due to the loss of several large farms dams). A roughly doubling of the mean probability of quasi-extinction also occurred between the 200 m and 100 m corridors (0.28 to 0.54), due to the combination of the loss of offstream wetlands, and the decrease in the buffer zone of the instream habitat. Upper 95% CIs for the probability of quasi-extinction were > 0.8 for each of the 400 m, 200 m and 100 m habitat corridors.

The pattern of increase in the probability of quasi-extinction for the Bald Hill metapopulation under the alternate habitat corridors was similar to that predicted for Merriang, although the 'jumps' in the extinction risk were not as clear (Figure 8b). Limited increases in the probability of quasi-extinction were predicted for the 1000 m and 800 m corridors (change in the mean estimates, ≤ 0.1), reflecting the limited amount of habitat loss that would occur at this location under these corridor widths. Mean estimates of the probability of quasi-extinction increased to ~0.3 for the 600–200 m corridors (from < 0.18 under the three preceding corridors), with upper 95% CIs for this probability of between 0.72 and 0.78. Preserving just the immediate 50 m either side of the stream at Bald Hill (100 m habitat corridor) raised the mean probability of quasi-extinction by 0.25, to 0.56 (with an upper 95% CI of 0.93).

In Donnybrook, the probability of quasi-extinction is predicted to increase in a roughly linear fashion for the 1000–200 m habitat corridors. As with Merriang and Bald Hill, the mean predicted increase in the probability of quasi-extinction is small for the 1000 m and 800 m corridors, being <0.05. There was considerable uncertainty in the predictions for the next three corridors (600 m, 400 m and 200 m), with upper 95% CIs ranging between zero and ~0.9. However, the mean estimates suggest that important increases in the probability of quasi-extinction occur between the 600 m and 200 m corridors, with the estimate for the latter being over double that of the former (600 m corridor: mean estimate of the probability of quasi-extinction = 0.14; 200 m corridor: mean estimate of the probability of quasi-extinction = 0.32). Strikingly, the mean estimate of the probability of quasi-extinction for the 100 m habitat corridor at Donnybrook was almost triple that of the 200 m corridor (0.32 versus 0.93). This change is far greater than that predicted for the equivalent scenario at both Merriang and Bald Hill. It stems from the fact that the pools along the Merri Creek at Donnybrook are mostly semi-permanent (hydroperiod score of 3), meaning that their effective areas are more sensitive to reductions in their buffer than the permanent pools along the Merri Creek at both Merriang and Bald Hill.

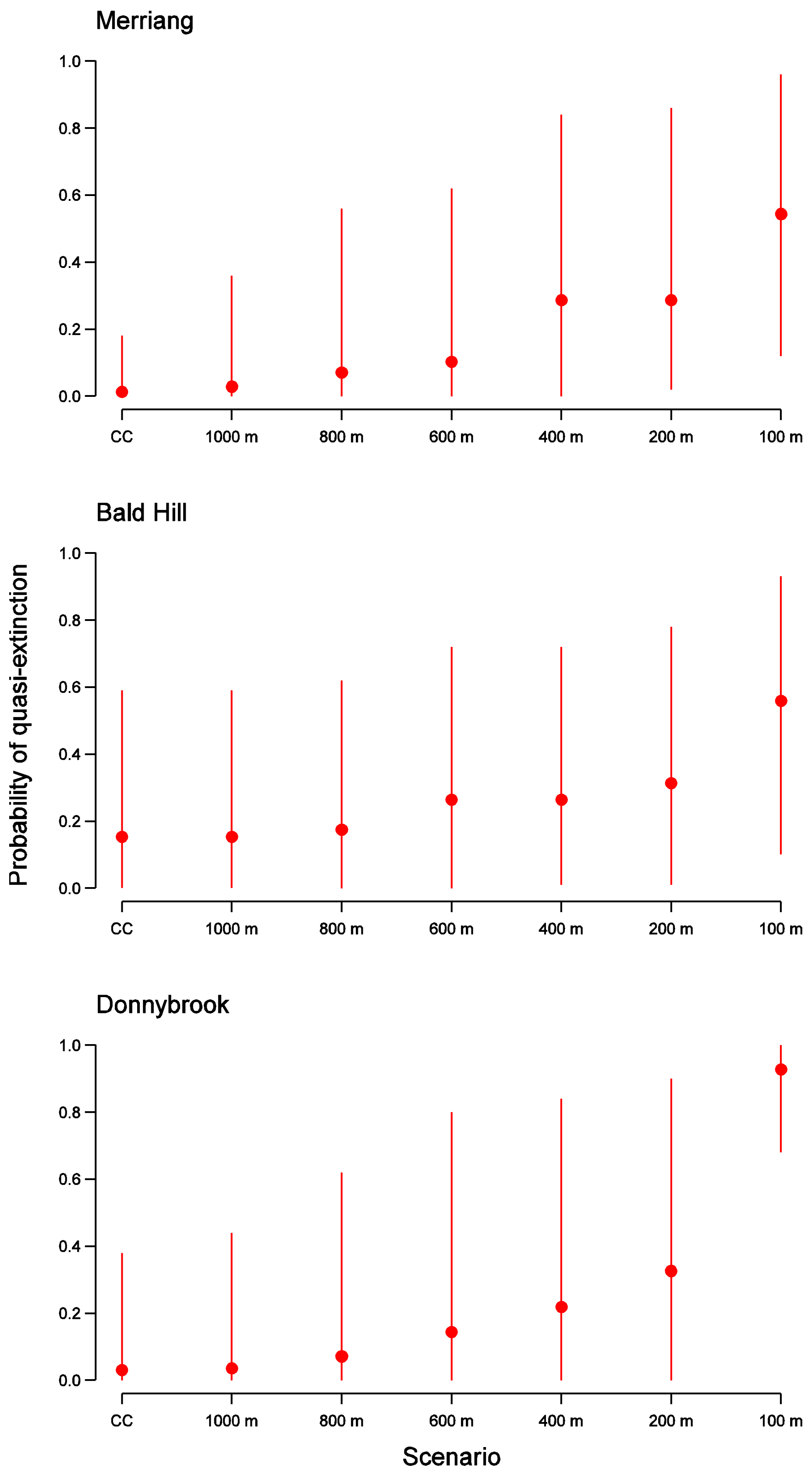

Figure 8. Change in the viability of the Merriang, Bald Hill and Donnybrook metapopulations of *L. raniformis* given urban expansion and six habitat corridor scenarios**.** The plots show the predicted probability of quasi-extinction (< 3 occupied wetlands) after 30 years relative to that given maintenance of current conditions (no urban expansion; 'CC'). The red dots are the mean estimates, and the vertical lines the 95% credible intervals.

3.3 Metapopulation viability with urban expansion and habitat offsetting

Predicted changes in the probability of quasi-extinction for each of the focal metapopulations given urban expansion and habitat offsetting (wetland creation) are depicted in Figures 9–11. Only two of the six habitat corridors considered above were included in this component of the study: 400 m and 200 m corridors along each stream. For each corridor, creation of between two and eight semi-permanent wetlands was trialled. Wetlands were placed in pairs next to the largest pools along the Merri Creek, roughly 50 m from the stream, and roughly 50 m from each other. For comparative purpose, Figures 9–11 also depict the probability of quasi-extinction given the maintenance of current conditions (no urban expansion), and urbanisation without habitat offsetting.

Simulations suggested that habitat corridors of only 400 m or 200 m in width could lead to substantial increases in the probability of quasi-extinction for *L. raniformis* at Merriang without offsetting (Figure 9). The mean estimate of the probability of quasi-extinction under current conditions was just 0.01, with an upper 95% CI of 0.18. The respective figures for the 400 m corridor without habitat offsetting were 0.28 and 0.84. For the 200 m corridor, they were 0.28 and 0.86. Our simulations suggest that substantial investment in replacement wetlands would be required to offset these increases in the probability of quasi-extinction: eight new wetlands were required under the 400 m corridor to reduce the mean estimate of the probability of quasi-extinction to a level comparable with that predicted under current conditions. However, none of the wetland creation schemes reduced the upper 95% CI for the probability of quasi-extinction to that estimated for current conditions (current conditions = 0.18; 400 m corridor plus eight new wetlands = 0.24; 200 m corridor plus eight new wetlands = 0.32). This result stems from the large number of farm dams that would be lost in Merriang under the 400 m and 200 m corridor widths.

At Bald Hill, the number of new wetlands required to offset the impacts of urbanisation was substantially lower (Figure 10). The insertion of two dedicated wetlands reduced the mean probability of quasi-extinction to either less that than predicted given the maintenance of current conditions, or to an equivalent figure (current conditions = 0.15; 400 m corridor plus two new wetlands = 0.11; 200 m corridor plus two new wetlands = 0.15). The same was true for the upper 95% CIs for the probability of quasi-extinction (current conditions = 0.59; 400 m corridor plus two new wetlands = 0.54; 200 m corridor plus two new wetlands = 0.6). With six dedicated wetlands under the either the 400 m or 200 m corridors, the mean probability of quasi-extinction was reduced to ≤ 0.03, with an upper 95% CI of ≤ 0.3. Equivalent figures for given eight new wetlands were ≤ 0.02 and ≤ 0.22.

Probabilities of quasi-extinction equivalent to or lower than those under current conditions were achieved at Donnybrook with the addition of six or more new wetlands (Figure 11). The mean probability of quasi-extinction under current conditions was 0.03, with an upper 95% CI of 0.38. Given a habitat corridor of 400 m and six or more new wetlands, the mean probability of quasi-extinction was ≤ 0.02, with an upper

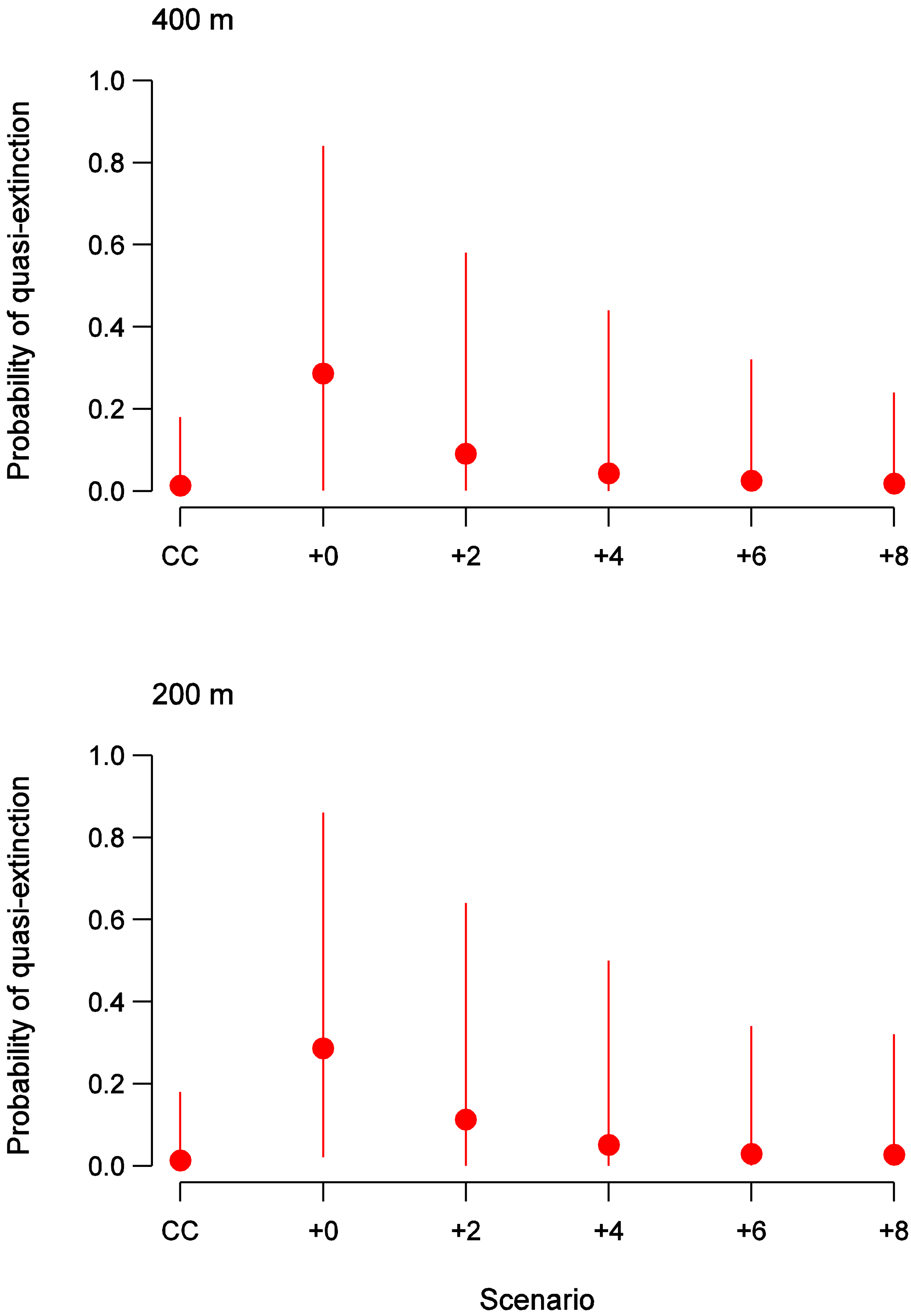

Figure 9. Change in the viability of the Merriang metapopulation of *L. raniformis* given urban expansion and habitat offsetting (creation of new wetlands). The plots show the predicted probability of quasi-extinction (< 3 occupied wetlands) after 30 years under current conditions (no urban expansion; 'CC'), or with either 400 m or 200 m habitat corridors and between zero (+0) and eight (+8) new wetlands. The zero wetlands scenario is equivalent to the 400 m or 200 m corridor scenario shown in Figure 8. The red dots represent the mean estimates, and the vertical lines the 95% credible intervals.

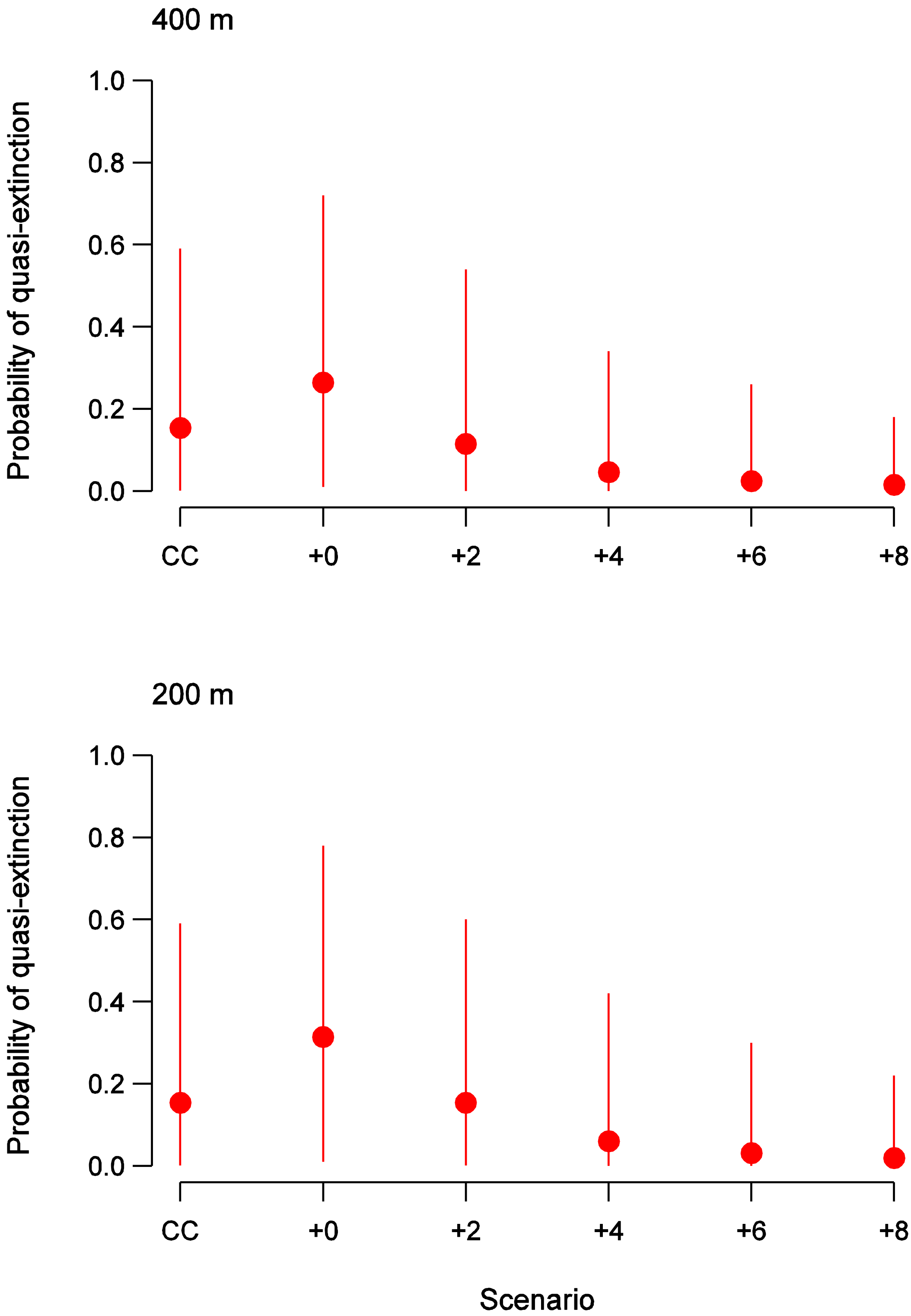

Figure 10. Change in the viability of the Bald Hill metapopulation of *L. raniformis* given urban expansion and habitat offsetting (creation of new wetlands). The plots show the predicted probability of quasi-extinction (< 3 occupied wetlands) after 30 years under current conditions (no urban expansion; 'CC'), or with either 400 m or 200 m habitat corridors and between zero ('+0) and eight ('+8) new wetlands. The zero wetlands scenario is equivalent to the 400 m or 200 m corridor scenario shown in Figure 8. The red dots represent the mean estimates, and the vertical lines the 95% credible intervals.

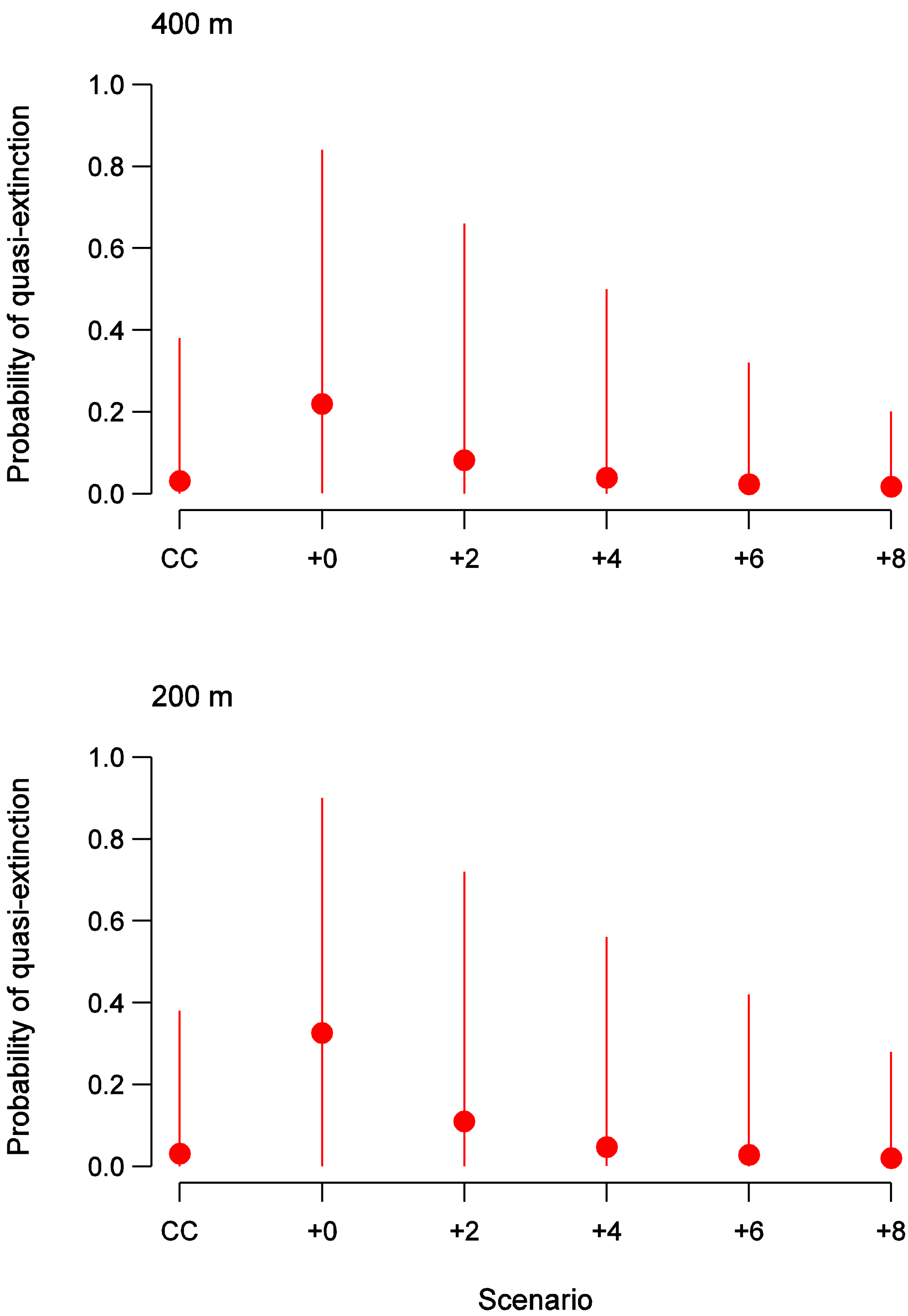

Figure 11. Change in the viability of the Donnybrook metapopulation of *L. raniformis* given urban expansion and habitat offsetting (creation of new wetlands). The plots show the predicted probability of quasi-extinction (< 3 occupied wetlands) after 30 years under current conditions (no urban expansion; 'CC'), or with either 400 m or 200 m habitat corridors and between zero (+0) and eight (+8) new wetlands. The zero wetlands scenario is equivalent to the 400 m or 200 m corridor scenario shown in Figure 8. The red dots represent the mean estimates, and the vertical lines the 95% credible intervals.

95% CI of ≤ 0.32. Given a habitat corridor of 200 m and six or more new wetlands, the mean probability of quasi-extinction was ≤ 0.02, with an upper 95% CI of 0.42

Across the three focal metapopulations, the simulations demonstrate that six or more wetlands are likely to be required to offset the impacts of urbanisation when habitat corridors of only 400 m or 200 m are reserved. Six or more wetlands were required at Merriang and Donnybrook to achieve probabilities of quasi-extinction that were equivalent to those displayed given the maintenance of current conditions. Only two new wetlands were required at Bald Hill to achieve equivalence with current conditions, but this small metapopulation displays a generally high risk of quasi-extinction (upper 95% CI for the probability of quasi-extinction without urbanisation = 0.59). As such, the current extinction risk represents a dubious conservation target for this metapopulation.

Another important general trend across the three metapopulations was the similarity in the quasi-extinction risk between the 400 m and 200 m corridors when habitat offsetting was included. This results from the fact that the extent of wetland loss is similar under these corridor widths, and the fact that the wetland creation schemes we trialled were identical, except for small reductions in the buffer size of new wetlands given a 200 m habitat corridor. As we discuss below, these facts must be taken into account when interpreting the similarity in quasi-extinction risk between the 400 m and 200 m habitat corridors.

4. Discussion

The Growling Grass Frog (*Litoria raniformis*) has long been considered threatened by urban expansion around Melbourne. Despite remaining fairly widespread around the city (see Figure 1), retractions in the distribution of the frog with the advancing urban development have been noted (Heard *et al.* 2010). More recent concern stems from the fact that many remnant populations of *L. raniformis* occur in areas slated as urban growth areas (Heard *et al.* 2010; Figure 1). Ensuring the persistence of the species within these urban growth areas represents an important commitment of the Victorian Government. This study was undertaken to inform the Victorian Government's Sub-regional Strategy for the Growling Grass Frog (Organ *et al.* 2011; DSE 2012). The project sought to assess the viability of metapopulations of *L. raniformis* within one urban growth area, both under current conditions (no urban expansion) and given several possible future urbanisation scenarios. It also sought to assess the likelihoods that habitat creation schemes ('offsetting') proposed within the strategy can mitigate any increased risk of metapopulation extinction resulting from urban expansion.

4.1 Metapopulation viability

For each of the three focal metapopulations of *L. raniformis* – distributed in the vicinity of Merriang, Bald Hill and Donnybrook in the Whittlesea-Hume growth area – the mean estimate of the probability of quasi-extinction (defined as < 3 occupied wetlands) was low over the next 30 years assuming maintenance of current conditions (0.013, 0.153 and 0.031, respectively; Figure 7). This is encouraging. However, there are two reasons why these estimates should be treated with some caution. The first is that the model does not include spatially autocorrelated catastrophes that may cause sudden increases in extinction rates over short periods. Periods of severe drought or disease outbreaks are examples of catastrophes that maybe of considerable importance for *L. raniformis* around Melbourne and elsewhere (Heard *et al.* 2012a,b; see section 2.4). The second reason is the high uncertainty of the predictions for the Bald Hill and Donnybrook metapopulations. For these two metapopulations, the 95% CIs for the probabilities of quasi-extinction after 30 years were 0.38 and 0.59, respectively. Thus, under the more pessimistic estimates of the relationships between the probability extinction and effective wetland area and the probability of colonisation and connectivity encompassed by our model, the Donnybrook metapopulation has close to a 40% chance of quasi-extinction after 30 years, and the Bald Hill metapopulation approximately a 60% chance of quasi-extinction.

Practitioners of population viability analyses are encouraged to use predictions derived from these analyses in a relative sense, because the relativity of the predictions of viability under different management regimes should be reasonably robust, even when the predictions themselves prove inaccurate (Hanski 2002; Morris and Doak 2002). For this reason, we encourage readers to focus on the relative change in the probability of quasi-extinction under differing urbanisation scenarios, rather than the raw predictions. For all three metapopulations, urbanisation scenarios that retained riparian habitat corridors of between 1000–800 m in width (500 m and 400 m either side of the stream) entailed generally small increases in the probability of quasi-extinction, relative to both the maintenance of current conditions, and to the other urbanisation scenarios considered (Figure 8). This result could be an artefact, resulting from our exclusion of wetlands beyond 500 m of each stream when originally defining each metapopulation (see section 2.1). Such wetlands could not, therefore, contribute to the viability of the metapopulations under our definition of 'current conditions'. However, the more likely explanation is that for our focal metapopulations, the 1000 m and 800 m corridors only excluded the loss of only small, shallow farm dams, which contribute little to metapopulation persistence.

At the opposite extreme, urbanisation scenarios involving the retention of habitat corridors of only 200–100 m in width entailed relatively large increases in the probability of quasi-extinction. This was particularly apparent for the 100 m corridor at Donnybrook, where an increase in the probability of quasi-extinction to 1 (= 100% chance of quasi-extinction) was within the 95% CI. Averaging across metapopulations, the relative increase in the mean probability of quasi-extinction given a 200 or 100 m habitat corridor (and no wetland creation) was 0.44 higher than that predicted assuming maintenance of current conditions. However, it should be noted that our model of the metapopulation dynamics of *L. raniformis* will always predict relatively high impacts for corridors that retain less than 100 m either side of the stream. The reason being that our definition of the effective area of wetlands was based on a terrestrial buffer of 100 m, meaning that corridors retaining less than 100 m either side of the stream not only entailed destruction of off-stream wetlands, but also constriction of the size of the in-stream habitat. This effect is biologically realistic, because the first 100 m of land away from the shoreline appears to be particularly important for *L. raniformis* (Heard *et al.* 2008; see also Wassens *et al.* 2008). Nevertheless, readers should be conscious of its implications when interpreting the results of this study.

Unsurprisingly, the 600 m and 400 m corridors represent a middle ground between the above scenarios in terms of increases in the probability of quasi-extinction. The estimates suggest that substantial increases in the probability of quasi-extinction are possible under both corridors for the Merriang and Donnybrook metapopulations, with upper 95% CIs for this probability extending up to 0.84. In Merriang, urban expansion with retention of habitat corridors of 600 m or 400 m would result in the loss of 12 and 15 wetlands, respectively. The equivalent figures for Donnybrook are 10 and 12 wetlands. The predicted increase in the probability of quasi-extinction was lower at Bald Hill, because both the 600 m and 400 m corridors entail the loss of only one small farm dam. Thus, whilst the 600 m and 400 m corridors may entail moderate increases in the probability of quasi-extinction, the actual extent of this increase will be context dependant.

4.2 Habitat offsetting through wetland creation

Creating replacement wetlands is a key component of the Victorian Government's Sub-regional Species Strategy for the Growling Grass Frog (Organ *et al.* 2011; DSE 2012). It is also frequently applied as a conservation tool for *L. raniformis* around the city (see Heard *et al.* 2010). This study provides the first assessment of the ability of wetland creation schemes to offset changes in the viability of metapopulations of *L. raniformis* subject to urbanisation.

We applied a standard scheme for each of the focal metapopulations, entailing the construction of between two and eight semi-permanent wetlands, placed adjacent to pools along the Merri Creek that displayed the highest effective areas. The rationale being that if the objective of these new wetlands is to minimise the chance of quasi-extinction of the metapopulation, the wetlands should be placed close to existing 'high quality' wetlands, creating a core set of sites that display minimal likelihoods of extinction at each time-step. The effective area of these wetlands was based on a surface area of 1250 sq. m, giving a total area of 45230 sq m.

Our modelling suggests that considerable investment in wetland creation will be required to offset increases in quasi-extinction risk under the narrower habitat corridors considered here. Six or more wetlands were required to reduce the probability of quasi-extinction at Merriang and Donnybrook to that displayed without urbanisation. At Bald Hill, the creation of two wetlands was adequate to reduce the probability of quasi-extinction to an equivalent level as that displayed without urbanisation. Nevertheless, the quasi-extinction risk under current conditions is a dubious conservation target for this metapopulation, because it may be as high as 60%.

A further point with regard to the efficacy of wetland creation schemes, is that our analyses suggest that there are only minor differences between the 400 m and 200 m corridors in terms of the predicted quasi-extinction risk. As alluded to above, this result could be interpreted as justification for applying a 200 m habitat corridor rather than a 400 m corridor. However, we caution that this result requires careful interpretation. Firstly, for the metapopulations studied here, the 400 m and 200 m corridors were quite similar in terms of the number of wetlands that would be lost. This limited the decrease in the probability of quasi-extinction for our focal metapopulations, but this may not be representative of the case more generally. Secondly, we did not consider any constraints on the placement of wetlands in this study (topographic, hydrological, geological, etc). Wider riparian corridors will confer greater flexibility with regard to wetland placement, and this flexibility may prove vital for attaining the required density and characteristics of the created wetlands.

The provision of guidelines for the creation of wetlands for *L. raniformis* is beyond the scope of this report (Heard *et al.* 2010 and Organ *et al.* 2011 provide detailed guidelines), but we briefly discuss two interrelated components that are of particular relevance to the analyses conducted here: wetland hydroperiod and water source. We simulated the creation of only semi-permanent wetlands, because the construction of permanent wetlands will, in many cases, require connection to the storm-water network (L. Mitchell, Melbourne Water, pers. comm.). This is problematic for *L. raniformis*, as wetlands fed by storm-water may become wholly unsuitable for the frog overtime, resulting from the accumulation of gross pollutants and sediments, and changes in both the biotic and abiotic environment (Heard *et al.* 2010). We subsequently recommend that when created wetlands are placed close to large, permanent pools along streams (as per our analysis), managers should strive to create semi-permanent wetlands rather than permanent ones if the development of the latter requires connection to the storm-water system, and the creation of semi-permanent wetlands does not.

Lastly, we highlight the fact that we have not considered wetlands enhancement as a supplement to wetland creation for offsetting the effects of wetland loss on *L. raniformis* in urbanising landscapes. Wetland enhancement would be entail increasing the size of existing wetlands, increasing their hydroperiods, and managing other attributes known to influence habitat quality for *L. raniformis* (particularly aquatic vegetation cover, water quality and predatory fish). Such enhancement may prove either logistically or financially superior to wetland creation in some contexts, and may also have a greater influence on metapopulation trajectories for *L. raniformis* (see Heard *et al.* 2010 for further details). We encourage consideration of wetland enhancement as a tool to offset the effects of wetland loss on *L. raniformis* around Melbourne. Assessing the value of wetland enhancement schemes could easily be done using the modelling approach presented here.

4.3 Decision analyses and adaptive management

Our modelling suggests that individual metapopulations of *L. raniformis* may respond quite differently to alternate management scenarios. It also highlights the high degree of uncertainty that management decisions for *L. raniformis* entail, due to uncertainty in current models of the species' metapopulation dynamics. For these reasons, we consider decision analyses and adaptive management to be important components of future management activities for *L. raniformis* around Melbourne.

Decision analyses are formal approaches to identifying the optimal solution amongst a set of potential management actions, given a predefined objective (Maguire 1986). Examples include multi-criteria decision analyses (MCDA) and stochastic dynamic programming (SDM). These techniques may be readily coupled with metapopulation models (such as ours) to identify which of a set of management options will optimise metapopulation viability over a predefined time period (Possingham *et al.* 2002; Drechsler *et al.* 2003; Westphal *et al.* 2003). As an example of how this might be applied to the management of *L. raniformis* in urbanising landscapes, consider the three metapopulations of the frog that we have focussed on in this report. As urbanisation plans are developed for these regions, it will be possible to identify specific impacts to the wetland network, as well as identify, through consultation with developers and other land management agencies, a set of feasible and affordable habitat management options that could be applied to offset those impacts. The metapopulation model we present here, when coupled with either an MCDA or SDM, could be used to formally identify which of those management approaches will minimise the probability of quasi-extinction. As such, it will be possible to identify the optimal management approach on a metapopulation-by-metapopulation basis. We see this as the most useful application of our model for the management of *L. raniformis* around Melbourne, and are currently working on the technical aspects of coupling the model with formal decision analyses (Heard and McCarthy, unpubl.).

Adaptive management is an approach that acknowledges management actions must proceed in the face of uncertainty, and uses monitoring to iteratively update the state of knowledge and the subsequent direction of management (Walters 1986). The management actions discussed above for *L. raniformis* (wetland creation and enhancement) may not contribute significantly to our knowledge of the species' metapopulation dynamics, which would prove very useful for future management of the frog around Melbourne and elsewhere. The process of adaptive management broadly entails a cycle of: (1) developing a model of the dynamics of the relevant system; (2) using that model to identify appropriate management; (3) carrying out management and monitoring of the system response, and; (4) using the resulting data to improve the model and review the management approach (Rumpff *et al.* 2011). In developing a model of the metapopulation dynamics of *L. raniformis*, we have completed the first of these steps, but there remains considerable uncertainty in this model about the relationship between the probability of colonisation and connectivity (in particular). Carefully designed monitoring of wetland creation and enhancement schemes for *L. raniformis* will enable clarification of this relationship. Furthermore, these data could be used to review the structure of the model, including the importance of factors such as aquatic vegetation cover, water quality and predatory fish for the probability of extinction, and the importance of barriers to dispersal (such as roads) for the probability of colonisation. Each of these factors is considered potentially important for the metapopulation dynamics of *L. raniformis*, but current data are largely inadequate to assess this (see section 2.4).

4.4 Conclusions

This study represents the first attempt to model the viability of *L. raniformis* in Melbourne's urbanising landscapes. It has provided important insights into the regional conservation of this species. We conclude by summarising the key findings of this project, and providing a series of recommendations for management and future research.

4.4.1 Key findings

Metapopulation viability under current conditions (no urban expansion)

- The viability of the three focal metapopulations appears high given maintenance of current conditions, with low mean estimates of the probability of quasi-extinction. However, there was considerable uncertainty about this for two metapopulations, with probabilities of quasi-extinction after 30 years possibly being as high as 0.59.

Metapopulation viability given urban expansion and no habitat offsetting

- Riparian habitat corridors of 1000–800 m in width (500–400 m either side of streams) entailed relatively minor increases in the probability of quasi-extinction for each of the focal metapopulations (mean estimate of the probability of quasi-extinction of 0.09, mean upper 95% CI for this probability of 0.53).
- Riparian habitat corridors of 200 m or less (100 m or less either side of streams) entailed relatively high increases in the probability of quasi-extinction for each of the focal metapopulations (mean estimate of the probability of quasi-extinction of 0.67, mean upper 95% CI for this probability of 0.9)
- Riparian habitat corridors of 600–400 m (300–200 m either of streams) represent a middle ground in terms of increases in the probability of quasi-extinction (mean estimate of the probability of quasi-extinction of 0.21), but uncertainty around the predictions suggested that large increases in extinction risk were possible under these scenarios (mean upper 95% CI of the probability of quasi-extinction of 0.74).

Metapopulation viability given urban expansion and offsetting with wetland creation

- Strategic creation of semi-permanent wetlands reduced the probability of quasi-extinction for each of the focal metapopulations.

- For two of the three metapopulations examined, six or more wetlands were required to fully offset the increase in the probability of quasi-extinction resulting from urban expansion (when corridors of 200 m or 100 m either side of the streams were maintained). However, the addition of four new wetlands significantly limited the effects of urban expansion in all cases.
- Decreases in the probability of quasi-extinction following wetland creation were similar for the 400 m and 200 m habitat corridors (200 m or 100 m either side of the streams). However, we caution that this may be an unrepresentative and/or unrealistic result.

4.4.2 Recommendations

Metapopulation viability under current conditions (no urban expansion)

- Even without urban development, some metapopulations of *L. raniformis* around Melbourne may face significant risk of extinction over coming decades, and may require targeted wetland creation or enhancement schemes to minimise this risk. Studies such as the one reported here could be undertaken to identify 'at risk' metapopulations.

Metapopulation viability given urban expansion and no habitat offsetting

- Riparian habitat corridors of ≤ 200 m in width (≤ 100 m either side of streams) entail significant increases in the risks of quasi-extinction for metapopulations of *L. raniformis*. It would be prudent to avoid such small corridors. Habitat corridors of ≥ 800 m (≥ 400 m either side of streams) represent the most risk adverse scenario for the metapopulations studied here, with corridors of 600–400 m (300–200 m either side of streams) being a middle ground. Under the latter scenarios, the metapopulations studied here displayed small increases in the mean estimates of quasi-extinction risk, but there was considerable uncertainty around these estimates.

Metapopulation viability given urban expansion and offsetting with wetland creation

- Habitat offsetting through wetland creation appears a viable approach to mitigating the impacts of urbanisation on *L. raniformis*, but considerable investment may be required for some metapopulations (six or more dedicated wetlands).
- When created wetlands are placed close to large, permanent pools along streams, managers should strive to create semi-permanent wetlands rather than permanent ones if the development of permanent wetlands requires connection to the storm-water system, and the construction of semi-permanent ones do not.
- Wetland enhancement should be considered as a complimentary approach to wetland creation for mitigating the impacts of urbanisation on metapopulations of *L. raniformis*. Modelling similar to that presented here could be used to quantify the value of alternate wetland enhancement and creation schemes.

- Decision analyses represent a potentially powerful tool for conservation planning for *L. raniformis* on a metapopulation-by-metapopulation basis, and should be pursued for decision-making at this scale.
- Implementing an adaptive approach to the management of *L. raniformis* in Melbourne's urban growth areas should be explored, with focus on refining the existing metapopulation model for this species.

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Appendix 1. Attributes of the focal metapopulations under current conditions (no urban expansion). The co-ordinates of each wetland are provided, along with their type (pool along a stream [stream] or off-stream wetland [SWB]) and effective areas.

Merriang

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79363963	2	5.396819813
2	Stream	325253	5848348	71360	11.17549277	3	8.381619575
3	Stream	324971	5849224	84020	11.33881014	4	11.33881014
4	Stream	325414	5848623	55603	10.92599244	3	8.194494327
5	Stream	324927	5849007	71520	11.17773241	4	11.17773241
6	SWB	325300	5849710	41625	10.63645623	3	7.97734217
7	SWB	325319	5849491	37981	10.54484131	3	7.908630985
8	SWB	325463	5849387	44430	10.7016702	4	10.7016702
9	SWB	325669	5849236	37920	10.54323396	2	5.271616978
10	SWB	325781	5849097	38210	10.55085254	2	5.27542627
11	SWB	325333	5849108	42345	10.65360563	4	10.65360563
12	SWB	325826	5848956	32511	10.38933377	3	7.792000329
13	SWB	325876	5848807	40380	10.60608989	3	7.954567419
14	SWB	325771	5848680	40167	10.60080104	3	7.950600781
15	SWB	325783	5848517	36903	10.51604813	3	7.887036096
16	SWB	325535	5848531	41731	10.63899954	3	7.979249653
17	SWB	325536	5848355	41312	10.62890829	2	5.314454147
18	SWB	325534	5848051	38746	10.5647828	3	7.923587103
19	SWB	325540	5848001	34676	10.45380308	2	5.226901542
20	SWB	325126	5847676	43770	10.68670393	3	8.015027948
21	Stream	323768	5847690	64760	11.07844341	3	8.308832556
22	Stream	323889	5847790	62900	11.04930144	2	5.524650721
23	Stream	324587	5848151	61900	11.03327546	2	5.516637729
24	Stream	324909	5848192	107400	11.58431546	4	11.58431546
25	Stream	325159	5848257	55670	10.92719668	3	8.195397511
26	Stream	325261	5848928	50603	10.83176614	2	5.415883071
27	Stream	325134	5848900	52958	10.87725443	2	5.438627213

Bald Hill

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	SWB	322264	5846727	42170	10.64946	4	10.64946
4	Stream	322535	5846042	76070	11.23941	4	11.23941
5	Stream	321025	5845897	89008	11.39648	4	11.39648
6	Stream	321116	5846127	81290	11.30578	3	8.479334
7	SWB	321292	5846378	39070	10.57311	2	5.286555
8	Stream	321478	5846350	91716	11.42645	4	11.42645
9	Stream	322000	5846400	72450	11.19065	3	8.392989

Donnybrook

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	320748	5843374	55040	10.91582	3	8.186862
2	SWB	319807	5843041	41624	10.63643	4	10.63643
3	Stream	319745	5843011	46070	10.73792	3	8.053438
4	Stream	319825	5843192	76677	11.24736	3	8.435518
5	Stream	320076	5843333	120600	11.70023	3	8.775176
6	SWB	318368	5842686	54360	10.90338	3	8.177538
7	SWB	320117	5842962	46161	10.73989	3	8.054918
8	Stream	318829	5843122	53422	10.88598	3	8.164483
9	SWB	320002	5842925	35268	10.47073	2	5.235366
10	SWB	319739	5843382	38740	10.56463	2	5.282314
11	SWB	319555	5843220	42730	10.66266	1	2.665664
12	SWB	319139	5842892	44460	10.70235	3	8.026759
13	SWB	318679	5842887	46630	10.75	3	8.0625
14	Stream	318914	5843400	55278	10.92013	3	8.190098
15	Stream	320298	5843617	88970	11.39605	3	8.547041
16	Stream	320449	5843799	79000	11.2772	3	8.457902
17	SWB	320073	5842668	39597	10.58651	3	7.939881
18	SWB	319937	5842555	37994	10.54518	2	5.272592
19	SWB	319412	5842609	36890	10.5157	2	5.257848
20	SWB	319379	5842372	37220	10.5246	2	5.262301
21	Stream	318824	5842962	45476	10.72494	2	5.36247
22	SWB	318798	5842397	36385	10.50191	3	7.876434
23	SWB	318640	5842560	38740	10.56463	2	5.282314
24	SWB	318815	5842281	40398	10.60654	4	10.60654
25	SWB	318815	5842048	40459	10.60804	3	7.956033
26	SWB	319367	5841926	37090	10.5211	3	7.890827
27	Stream	319181	5842400	41510	10.63369	2	5.316845
28	Stream	320629	5843883	58190	10.97147	3	8.228602
29	Stream	320871	5843812	41142	10.62478	3	7.968589
30	SWB	321259	5843767	108200	11.59174	3	8.693802

Appendix 2. Attributes of the Merriang metapopulation under differing urbanisation scenarios. The scenarios represent the preservation of stream corridors that are 1000 m, 800 m, 600 m, 400 m, 200 m and 100 m in width. The co-ordinates of each remaining wetland are provided, along with their type (pool along a stream [stream] or off-stream wetland [SWB]) and effective areas.

1000 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	SWB	325319	5849491	35300	10.47164	3	7.853729
7	SWB	325669	5849236	27220	10.21171	2	5.105854
8	SWB	325781	5849097	27690	10.22883	2	5.114413
9	SWB	325333	5849108	42345	10.65361	4	10.65361
10	SWB	325826	5848956	24330	10.09947	3	7.574599
11	SWB	325876	5848807	24670	10.11334	3	7.585007
12	SWB	325771	5848680	40167	10.6008	3	7.950601
13	SWB	325783	5848517	36903	10.51605	3	7.887036
14	SWB	325535	5848531	41731	10.639	3	7.97925
15	SWB	325536	5848355	41312	10.62891	2	5.314454
16	SWB	325534	5848051	36244	10.49803	3	7.873522
17	SWB	325540	5848001	26500	10.1849	2	5.09245
18	Stream	323768	5847690	64760	11.07844	3	8.308833
19	Stream	323889	5847790	62900	11.0493	2	5.524651
20	Stream	324587	5848151	61900	11.03328	2	5.516638
21	Stream	324909	5848192	107400	11.58432	4	11.58432
22	Stream	325159	5848257	55670	10.9272	3	8.195398
23	Stream	325261	5848928	50603	10.83177	2	5.415883
24	Stream	325134	5848900	52958	10.87725	2	5.438627

800 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	SWB	325333	5849108	42345	10.65361	4	10.65361
7	SWB	325771	5848680	25790	10.15774	3	7.618307
8	SWB	325783	5848517	24170	10.09287	3	7.569651
9	SWB	325535	5848531	41731	10.639	3	7.97925
10	SWB	325536	5848355	41312	10.62891	2	5.314454
11	Stream	323768	5847690	64760	11.07844	3	8.308833
12	Stream	323889	5847790	62900	11.0493	2	5.524651
13	Stream	324587	5848151	61900	11.03328	2	5.516638
14	Stream	324909	5848192	107400	11.58432	4	11.58432
15	Stream	325159	5848257	55670	10.9272	3	8.195398
16	Stream	325261	5848928	50603	10.83177	2	5.415883
17	Stream	325134	5848900	52958	10.87725	2	5.438627

600 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	SWB	325333	5849108	42345	10.65361	4	10.65361
7	SWB	325535	5848531	41731	10.639	3	7.97925
8	SWB	325536	5848355	41312	10.62891	2	5.314454
9	Stream	323768	5847690	64760	11.07844	3	8.308833
10	Stream	323889	5847790	62900	11.0493	2	5.524651
11	Stream	324587	5848151	61900	11.03328	2	5.516638
12	Stream	324909	5848192	107400	11.58432	4	11.58432
13	Stream	325159	5848257	55670	10.9272	3	8.195398
14	Stream	325261	5848928	50603	10.83177	2	5.415883
15	Stream	325134	5848900	52958	10.87725	2	5.438627

400 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log$_e$ total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	SWB	325535	5848531	34586	10.4512	3	7.838403
7	Stream	323768	5847690	64760	11.07844	3	8.308833
8	Stream	323889	5847790	62900	11.0493	2	5.524651
9	Stream	324587	5848151	61900	11.03328	2	5.516638
10	Stream	324909	5848192	107400	11.58432	4	11.58432
11	Stream	325159	5848257	55670	10.9272	3	8.195398
12	Stream	325261	5848928	50603	10.83177	2	5.415883
13	Stream	325134	5848900	52958	10.87725	2	5.438627

200 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log$_e$ total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	Stream	323768	5847690	64760	11.07844	3	8.308833
7	Stream	323889	5847790	62900	11.0493	2	5.524651
8	Stream	324587	5848151	61900	11.03328	2	5.516638
9	Stream	324909	5848192	107400	11.58432	4	11.58432
10	Stream	325159	5848257	55670	10.9272	3	8.195398
11	Stream	325261	5848928	50603	10.83177	2	5.415883
12	Stream	325134	5848900	52958	10.87725	2	5.438627

100 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log$_e$ total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	16730	9.724959	2	4.862479
2	Stream	325253	5848348	28650	10.26291	3	7.697182
3	Stream	324971	5849224	35190	10.46852	4	10.46852
4	Stream	325414	5848623	21860	9.992414	3	7.49431
5	Stream	324927	5849007	29570	10.29452	4	10.29452
6	Stream	323768	5847690	26030	10.167	3	7.625254
7	Stream	323889	5847790	24100	10.08997	2	5.044984
8	Stream	324587	5848151	23570	10.06773	2	5.033865
9	Stream	324909	5848192	47660	10.77185	4	10.77185
10	Stream	325159	5848257	20510	9.928668	3	7.446501
11	Stream	325261	5848928	18970	9.850614	2	4.925307
12	Stream	325134	5848900	21080	9.95608	2	4.97804

Appendix 3. Attributes of the Bald Hill metapopulation under differing urbanisation scenarios. The scenarios represent the preservation of stream corridors that are 1000 m, 800 m, 600 m, 400 m, 200 m and 100 m in width. The co-ordinates of each remaining wetland are provided, along with their type (pool along a stream [stream] or off-stream wetland [SWB]) and effective areas.

1000 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	SWB	322264	5846727	42170	10.64946	4	10.64946
4	Stream	322535	5846042	76070	11.23941	4	11.23941
5	Stream	321025	5845897	89008	11.39648	4	11.39648
6	Stream	321116	5846127	81290	11.30578	3	8.479334
7	SWB	321292	5846378	39070	10.57311	2	5.286555
8	Stream	321478	5846350	91716	11.42645	4	11.42645
9	Stream	322000	5846400	72450	11.19065	3	8.392989

800 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	SWB	322264	5846727	26280	10.17656	4	10.17656
4	Stream	322535	5846042	76070	11.23941	4	11.23941
5	Stream	321025	5845897	89008	11.39648	4	11.39648
6	Stream	321116	5846127	81290	11.30578	3	8.479334
7	SWB	321292	5846378	39070	10.57311	2	5.286555
8	Stream	321478	5846350	91716	11.42645	4	11.42645
9	Stream	322000	5846400	72450	11.19065	3	8.392989

600 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	Stream	322535	5846042	76070	11.23941	4	11.23941
4	Stream	321025	5845897	89008	11.39648	4	11.39648
5	Stream	321116	5846127	81290	11.30578	3	8.479334
6	SWB	321292	5846378	39070	10.57311	2	5.286555
7	Stream	321478	5846350	91716	11.42645	4	11.42645
8	Stream	322000	5846400	72450	11.19065	3	8.392989

400 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	Stream	322535	5846042	76070	11.23941	4	11.23941
4	Stream	321025	5845897	89008	11.39648	4	11.39648
5	Stream	321116	5846127	81290	11.30578	3	8.479334
6	SWB	321292	5846378	37436	10.53039	2	5.265194
7	Stream	321478	5846350	91716	11.42645	4	11.42645
8	Stream	322000	5846400	72450	11.19065	3	8.392989

200 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	Stream	322535	5846042	76070	11.23941	4	11.23941
4	Stream	321025	5845897	89008	11.39648	4	11.39648
5	Stream	321116	5846127	81290	11.30578	3	8.479334
6	Stream	321478	5846350	91716	11.42645	4	11.42645
7	Stream	322000	5846400	72450	11.19065	3	8.392989

100 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	23330	10.0575	3	7.543122
2	Stream	321706	5846418	29817	10.30283	4	10.30283
3	Stream	322535	5846042	31220	10.34881	4	10.34881
4	Stream	321025	5845897	40124	10.59973	4	10.59973
5	Stream	321116	5846127	35410	10.47475	3	7.856062
6	Stream	321478	5846350	41099	10.62374	4	10.62374
7	Stream	322000	5846400	29340	10.28671	3	7.71503

Appendix 4. Attributes of the Donnybrook metapopulation under differing urbanisation scenarios. The scenarios represent the preservation of stream corridors that are 1000 m, 800 m, 600 m, 400 m, 200 m and 100 m in width. The co-ordinates of each remaining wetland are provided, along with their type (pool along a stream [stream] or off-stream wetland [SWB]) and effective areas.

1000 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	320748	5843374	51860	10.8563	3	8.142227
2	SWB	319807	5843041	41624	10.63643	4	10.63643
3	Stream	319745	5843011	46070	10.73792	3	8.053438
4	Stream	319825	5843192	76677	11.24736	3	8.435518
5	Stream	320076	5843333	120600	11.70023	3	8.775176
6	SWB	320117	5842962	46161	10.73989	3	8.054918
7	Stream	318829	5843122	53422	10.88598	3	8.164483
8	SWB	320002	5842925	35268	10.47073	2	5.235366
9	SWB	319739	5843382	38740	10.56463	2	5.282314
10	SWB	319555	5843220	42730	10.66266	1	2.665664
11	SWB	319139	5842892	44460	10.70235	3	8.026759
12	SWB	318679	5842887	46630	10.75	3	8.0625
13	Stream	318914	5843400	55278	10.92013	3	8.190098
14	Stream	320298	5843617	88970	11.39605	3	8.547041
15	Stream	320449	5843799	79000	11.2772	3	8.457902
16	SWB	320073	5842668	26600	10.18867	3	7.6415
17	SWB	319937	5842555	23730	10.0745	2	5.037248
18	SWB	319412	5842609	36890	10.5157	2	5.257848
19	SWB	319379	5842372	37220	10.5246	2	5.262301
20	Stream	318824	5842962	45476	10.72494	2	5.36247
21	SWB	318798	5842397	36385	10.50191	3	7.876434
22	SWB	318640	5842560	31213	10.34859	2	5.174295
23	SWB	318815	5842281	40398	10.60654	4	10.60654
24	SWB	318815	5842048	29840	10.30361	3	7.727704
25	SWB	319367	5841926	37090	10.5211	3	7.890827
26	Stream	319181	5842400	41510	10.63369	2	5.316845
27	Stream	320629	5843883	58190	10.97147	3	8.228602
28	Stream	320871	5843812	41142	10.62478	3	7.968589
29	SWB	321259	5843767	88110	11.38634	3	8.539756

800 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	319807	5843041	41624	10.63643	4	10.63643
2	Stream	319745	5843011	46070	10.73792	3	8.053438
3	Stream	319825	5843192	76677	11.24736	3	8.435518
4	Stream	320076	5843333	120600	11.70023	3	8.775176
5	SWB	320117	5842962	41767	10.63986	3	7.979896
6	Stream	318829	5843122	53422	10.88598	3	8.164483
7	SWB	320002	5842925	35268	10.47073	2	5.235366
8	SWB	319739	5843382	38740	10.56463	2	5.282314
9	SWB	319555	5843220	42730	10.66266	1	2.665664
10	SWB	319139	5842892	44460	10.70235	3	8.026759
11	SWB	318679	5842887	46630	10.75	3	8.0625
12	Stream	318914	5843400	55278	10.92013	3	8.190098
13	Stream	320298	5843617	88970	11.39605	3	8.547041
14	Stream	320449	5843799	79000	11.2772	3	8.457902
15	SWB	319412	5842609	36890	10.5157	2	5.257848
16	SWB	319379	5842372	37220	10.5246	2	5.262301
17	Stream	318824	5842962	45476	10.72494	2	5.36247
18	SWB	318798	5842397	21050	9.954656	3	7.465992
19	SWB	318815	5842281	24880	10.12182	4	10.12182
20	SWB	319367	5841926	37090	10.5211	3	7.890827
21	Stream	319181	5842400	41510	10.63369	2	5.316845
22	Stream	320629	5843883	58190	10.97147	3	8.228602
23	Stream	320871	5843812	41142	10.62478	3	7.968589

600 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	319807	5843041	41624	10.63643	4	10.63643
2	Stream	319745	5843011	46070	10.73792	3	8.053438
3	Stream	319825	5843192	76677	11.24736	3	8.435518
4	Stream	320076	5843333	120600	11.70023	3	8.775176
5	Stream	318829	5843122	53422	10.88598	3	8.164483
6	SWB	320002	5842925	24940	10.12423	2	5.062114
7	SWB	319739	5843382	38740	10.56463	2	5.282314
8	SWB	319555	5843220	41562	10.63494	1	2.658735
9	SWB	319139	5842892	44460	10.70235	3	8.026759
10	SWB	318679	5842887	46630	10.75	3	8.0625
11	Stream	318914	5843400	55278	10.92013	3	8.190098
12	Stream	320298	5843617	88970	11.39605	3	8.547041
13	Stream	320449	5843799	79000	11.2772	3	8.457902
14	SWB	319412	5842609	36890	10.5157	2	5.257848
15	SWB	319379	5842372	37220	10.5246	2	5.262301
16	Stream	318824	5842962	45476	10.72494	2	5.36247
17	SWB	319367	5841926	37090	10.5211	3	7.890827
18	Stream	319181	5842400	41510	10.63369	2	5.316845
19	Stream	320629	5843883	58190	10.97147	3	8.228602
20	Stream	320871	5843812	41142	10.62478	3	7.968589

400 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	319807	5843041	41624	10.63643	4	10.63643
2	Stream	319745	5843011	46070	10.73792	3	8.053438
3	Stream	319825	5843192	76677	11.24736	3	8.435518
4	Stream	320076	5843333	120600	11.70023	3	8.775176
5	Stream	318829	5843122	53422	10.88598	3	8.164483
6	SWB	319739	5843382	38740	10.56463	2	5.282314
7	SWB	319139	5842892	44460	10.70235	3	8.026759
8	SWB	318679	5842887	27440	10.21976	3	7.664818
9	Stream	318914	5843400	55278	10.92013	3	8.190098
10	Stream	320298	5843617	88970	11.39605	3	8.547041
11	Stream	320449	5843799	79000	11.2772	3	8.457902
12	SWB	319412	5842609	27246	10.21266	2	5.106331
13	SWB	319379	5842372	26000	10.16585	2	5.082926
14	Stream	318824	5842962	45476	10.72494	2	5.36247
15	SWB	319367	5841926	36510	10.50534	3	7.879006
16	Stream	319181	5842400	41510	10.63369	2	5.316845
17	Stream	320629	5843883	58190	10.97147	3	8.228602
18	Stream	320871	5843812	41142	10.62478	3	7.968589

200 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	319807	5843041	27400	10.2183	4	10.2183
2	Stream	319745	5843011	46070	10.73792	3	8.053438
3	Stream	319825	5843192	76677	11.24736	3	8.435518
4	Stream	320076	5843333	120600	11.70023	3	8.775176
5	Stream	318829	5843122	53422	10.88598	3	8.164483
6	SWB	319739	5843382	18460	9.823362	2	4.911681
7	SWB	319139	5842892	34270	10.44203	3	7.831519
8	Stream	318914	5843400	55278	10.92013	3	8.190098
9	Stream	320298	5843617	88970	11.39605	3	8.547041
10	Stream	320449	5843799	79000	11.2772	3	8.457902
11	Stream	318824	5842962	45476	10.72494	2	5.36247
12	Stream	319181	5842400	41510	10.63369	2	5.316845
13	Stream	320629	5843883	58190	10.97147	3	8.228602
14	Stream	320871	5843812	41142	10.62478	3	7.968589

100 m

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	319745	5843011	22358	10.01494	3	7.511205
2	Stream	319825	5843192	34052	10.43564	3	7.826733
3	Stream	320076	5843333	54780	10.91108	3	8.18331
4	Stream	318829	5843122	21945	9.996295	3	7.497221
5	Stream	318914	5843400	22090	10.00288	3	7.50216
6	Stream	320298	5843617	37610	10.53503	3	7.901269
7	Stream	320449	5843799	32190	10.37941	3	7.784558
8	Stream	318824	5842962	15267	9.633449	2	4.816724
9	Stream	319181	5842400	13080	9.47884	2	4.73942
10	Stream	320629	5843883	21880	9.993328	3	7.494996
11	Stream	320871	5843812	13788	9.531554	3	7.148665

Appendix 5. Attributes of the Merriang metapopulation given urbanisation with a stream corridor of either 400 m or 200 m in width, and habitat offsetting (addition of new wetlands). The co-ordinates of each wetland are provided, along with their type (pool along a stream [Stream] or off-stream wetland [SWB]) and effective areas. The wetlands highlighted in red are the simulated created wetlands.

400 m with semi-permanent wetlands added

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log$_e$ total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	SWB	325535	5848531	34586	10.4512	3	7.838403
7	Stream	323768	5847690	64760	11.07844	3	8.308833
8	Stream	323889	5847790	62900	11.0493	2	5.524651
9	Stream	324587	5848151	61900	11.03328	2	5.516638
10	Stream	324909	5848192	107400	11.58432	4	11.58432
11	Stream	325159	5848257	55670	10.9272	3	8.195398
12	Stream	325261	5848928	50603	10.83177	2	5.415883
13	Stream	325134	5848900	52958	10.87725	2	5.438627
14	SWB	325034	5848252	45230	10.71951	3	8.03963
15	SWB	325089	5848280	45230	10.71951	3	8.03963
16	SWB	324978	5848234	45230	10.71951	3	8.03963
17	SWB	324920	5848242	45230	10.71951	3	8.03963
18	SWB	325123	5848318	45230	10.71951	3	8.03963
19	SWB	324862	5848259	45230	10.71951	3	8.03963
20	SWB	325161	5848361	45230	10.71951	3	8.03963
21	SWB	324804	5848255	45230	10.71951	3	8.03963

200 m with semi-permanent wetlands added

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	324098	5848030	48710	10.79364	2	5.39682
2	Stream	325253	5848348	71360	11.17549	3	8.38162
3	Stream	324971	5849224	84020	11.33881	4	11.33881
4	Stream	325414	5848623	55603	10.92599	3	8.194494
5	Stream	324927	5849007	71520	11.17773	4	11.17773
6	Stream	323768	5847690	64760	11.07844	3	8.308833
7	Stream	323889	5847790	62900	11.0493	2	5.524651
8	Stream	324587	5848151	61900	11.03328	2	5.516638
9	Stream	324909	5848192	107400	11.58432	4	11.58432
10	Stream	325159	5848257	55670	10.9272	3	8.195398
11	Stream	325261	5848928	50603	10.83177	2	5.415883
12	Stream	325134	5848900	52958	10.87725	2	5.438627
13	SWB	325034	5848252	36717	10.51100	3	7.88325
14	SWB	325089	5848280	37640	10.53582	3	7.90187
15	SWB	324978	5848234	37931	10.54352	3	7.90764
16	SWB	324920	5848242	36617	10.50827	3	7.88120
17	SWB	325123	5848318	35780	10.48514	3	7.86386
18	SWB	324862	5848259	32440	10.38715	3	7.79036
19	SWB	325161	5848361	32010	10.37380	3	7.78035
20	SWB	324804	5848255	32560	10.39084	3	7.79313

Appendix 6. Attributes of the Bald Hill metapopulation given urbanisation with a stream corridor of either 400 m or 200 m in width, and habitat offsetting (addition of new wetlands). The co-ordinates of each wetland are provided, along with their type (pool along a stream [Stream] or off-stream wetland [SWB]) and effective areas. The wetlands highlighted in red are the simulated created wetlands.

400 m with semi-permanent wetlands added

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	Stream	322535	5846042	76070	11.23941	4	11.23941
4	Stream	321025	5845897	89008	11.39648	4	11.39648
5	Stream	321116	5846127	81290	11.30578	3	8.479334
6	SWB	321292	5846378	37436	10.53039	2	5.265194
7	Stream	321478	5846350	91716	11.42645	4	11.42645
8	Stream	322000	5846400	72450	11.19065	3	8.392989
9	SWB	321430	5846431	45230	10.71951	3	8.03963
10	SWB	321380	5846397	45230	10.71951	3	8.03963
11	SWB	321486	5846411	45230	10.71951	3	8.03963
12	SWB	321379	5846339	45230	10.71951	3	8.03963
13	SWB	321540	5846431	45230	10.71951	3	8.03963
14	SWB	321365	5846285	45230	10.71951	3	8.03963
15	SWB	321304	5846301	45230	10.71951	3	8.03963
16	SWB	321247	5846285	45230	10.71951	3	8.03963

200 m with semi-permanent wetlands added

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	Stream	322305	5846022	61030	11.01912	3	8.264341
2	Stream	321706	5846418	72228	11.18758	4	11.18758
3	Stream	322535	5846042	76070	11.23941	4	11.23941
4	Stream	321025	5845897	89008	11.39648	4	11.39648
5	Stream	321116	5846127	81290	11.30578	3	8.479334
6	Stream	321478	5846350	91716	11.42645	4	11.42645
7	Stream	322000	5846400	72450	11.19065	3	8.392989
8	SWB	321430	5846431	28560	10.25976	3	7.69482
9	SWB	321380	5846397	29500	10.29215	3	7.71911
10	SWB	321486	5846411	36984	10.51824	3	7.88868
11	SWB	321379	5846339	39170	10.57567	3	7.93175
12	SWB	321540	5846431	33920	10.43176	3	7.82382
13	SWB	321365	5846285	43419	10.67865	3	8.00899
14	SWB	321304	5846301	36636	10.50879	3	7.88159
15	SWB	321247	5846285	33450	10.41781	3	7.81336

Appendix 7. Attributes of the Donnybrook metapopulation given urbanisation with a stream corridor of either 400 m or 200 m in width, and habitat offsetting (addition of new wetlands). The co-ordinates of each wetland are provided, along with their type (pool along a stream [Stream] or off-stream wetland [SWB]) and effective areas. The wetlands highlighted in red are the simulated created wetlands.

400 m with semi-permanent wetlands added

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	319807	5843041	41624	10.63643	4	10.63643
2	Stream	319745	5843011	46070	10.73792	3	8.053438
3	Stream	319825	5843192	76677	11.24736	3	8.435518
4	Stream	320076	5843333	120600	11.70023	3	8.775176
5	Stream	318829	5843122	53422	10.88598	3	8.164483
6	SWB	319739	5843382	38740	10.56463	2	5.282314
7	SWB	319139	5842892	44460	10.70235	3	8.026759
8	SWB	318679	5842887	27440	10.21976	3	7.664818
9	Stream	318914	5843400	55278	10.92013	3	8.190098
10	Stream	320298	5843617	88970	11.39605	3	8.547041
11	Stream	320449	5843799	79000	11.2772	3	8.457902
12	SWB	319412	5842609	27246	10.21266	2	5.106331
13	SWB	319379	5842372	26000	10.16585	2	5.082926
14	Stream	318824	5842962	45476	10.72494	2	5.36247
15	SWB	319367	5841926	36510	10.50534	3	7.879006
16	Stream	319181	5842400	41510	10.63369	2	5.316845
17	Stream	320629	5843883	58190	10.97147	3	8.228602
18	Stream	320871	5843812	41142	10.62478	3	7.968589
19	SWB	319857	5843295	45230	10.71951	3	8.03963
20	SWB	319914	5843287	45230	10.71951	3	8.03963
21	SWB	319961	5843252	45230	10.71951	3	8.03963
22	SWB	319865	5843239	45230	10.71951	3	8.03963
23	SWB	320019	5843238	45230	10.71951	3	8.03963
24	SWB	319869	5843183	45230	10.71951	3	8.03963
25	SWB	320072	5843259	45230	10.71951	3	8.03963
26	SWB	320109	5843300	45230	10.71951	3	8.03963

200 m with semi-permanent wetlands added

Site	Type	Easting (GDA94)	Northing (GDA94)	Total area (sq. m)	Log_e total area (sq. m)	Hydroperiod	Effective area (EA)
1	SWB	319807	5843041	27400	10.2183	4	10.2183
2	Stream	319745	5843011	46070	10.73792	3	8.053438
3	Stream	319825	5843192	76677	11.24736	3	8.435518
4	Stream	320076	5843333	120600	11.70023	3	8.775176
5	Stream	318829	5843122	53422	10.88598	3	8.164483
6	SWB	319739	5843382	18460	9.823362	2	4.911681
7	SWB	319139	5842892	34270	10.44203	3	7.831519
8	Stream	318914	5843400	55278	10.92013	3	8.190098
9	Stream	320298	5843617	88970	11.39605	3	8.547041
10	Stream	320449	5843799	79000	11.2772	3	8.457902
11	Stream	318824	5842962	45476	10.72494	2	5.36247
12	Stream	319181	5842400	41510	10.63369	2	5.316845
13	Stream	320629	5843883	58190	10.97147	3	8.228602
14	Stream	320871	5843812	41142	10.62478	3	7.968589
15	SWB	319857	5843295	44969	10.71373	3	8.03530
16	SWB	319914	5843287	43296	10.67582	3	8.00686
17	SWB	319961	5843252	37599	10.53473	3	7.90105
18	SWB	319865	5843239	42020	10.64590	3	7.98443
19	SWB	320019	5843238	30960	10.34045	3	7.75534
20	SWB	319869	5843183	35779	10.48512	3	7.86384
21	SWB	320072	5843259	31100	10.34496	3	7.75872
22	SWB	320109	5843300	33150	10.40880	3	7.80660