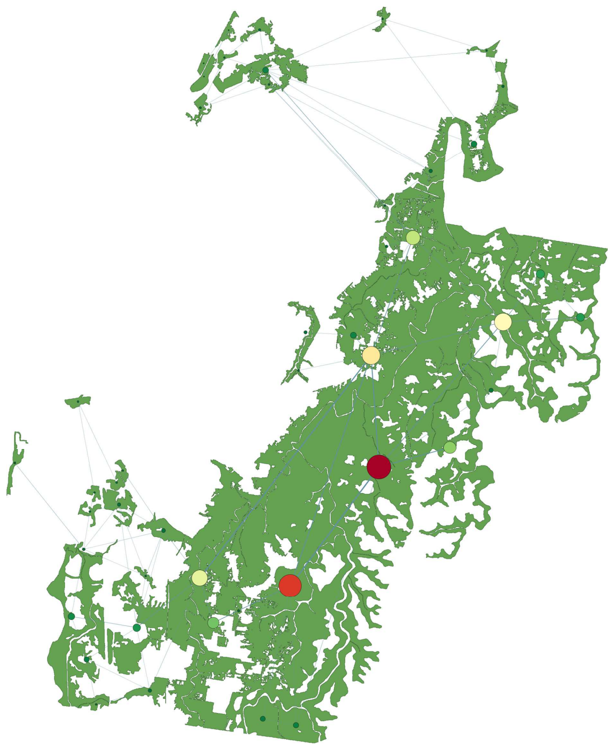
Identifying Least-Cost Dispersal Pathways for Koalas within the Campbelltown City Council Local Government Area



Final Report to Campbelltown City Council

September 2018

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Abbreviation	Description
CCC	Campbelltown City Council
BEC	Biolink Ecological Consultants
CKPoM	Comprehensive Koala Plan of Management
DIIC	Delta Integral Index of Connectivity
GAP CLoSR	General Approach to Planning Connectivity from Local Scales to Regional
LGA	Local Government Area
PCT	Plant Community Type
PKFT	Preferred Koala Food Tree
PKH	Preferred Koala Habitat
PRV	Percentage Resistance Value
RMS	Roads and Maritime Services
SC	Statewide Class

CoLS

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How to cite this report:

Biolink. 2018. *Identifying Least Cost Dispersal Pathways for Koalas within the Campbelltown City Council Local Government Area*. Biolink Ecological Consultants, Uki, NSW.

Summary

Koalas inhabiting the Campbelltown City Council (CCC) Local Government Area (LGA) have long been the focus of scientific and community interest. While available data indicates that the population has experienced a measure of recovery over the last 20 years, current population size estimates for the CCC LGA imply a koala population estimate of less than 200 individuals, the majority of which occur in the area between Minto Heights and Wedderburn. This relatively low number warns of little ground for complacency given the vulnerability of the greater part of the recovering population to a fire event, the impacts of which could impede the recovery process.

This report is part of an ongoing series intended to inform longer-term management of the Campbelltown koala population, and more specifically aims to identify locations for connecting areas of Preferred Koala Habitat (PKH) at a fine scale across the CCC LGA. To achieve this, previously classified Primary and Secondary (2B) PKH patches > 10 ha as well as all other vegetated areas and/or land uses within the CCC LGA were mapped according to the resistance they presented to koala movement. In this way the entire surface of the LGA was coded for costs to koala dispersal. Areas of highest cost to koala movement include fenced train lines, highways, aqueducts and heavy industrial and commercial development. Examples of lower-cost land uses are non-PKH vegetation and areas of low density development. Examination of the PKH habitat matrix and the associated connectivity issues were thereafter conducted in accordance with the analytical and spatial framework offered by the *General Approach to Planning Connectivity from Local Scales to Regional* (GAP CLoSR) package, in concert with the supporting *Graphab* software package.

Output identified that the greater proportion of the CCC LGA (31,052 ha) currently functions as a single, interconnected landscape component comprised of 44 habitat patches linked by 82 least-cost pathways. A second, much smaller (171 ha) landscape component in the far north-west of the LGA comprises three habitat patches linked *via* three least-cost pathways disconnected from the rest of the LGA by the Lachlan Way aqueduct. Considering the larger of the two landscape components, no least-cost pathways occur in the central, heavily urbanised portion of the LGA; rather, they are concentrated in the north near Macquarie Fields and Denham Court and in the south-west in the vicinity of Gilead respectively. Connectivity in this latter area is additionally reliant upon crossing Appin Road and the Lachlan Way aqueduct in order to link the Nepean and Georges Rivers catchments and their associated koala populations *via* areas of PKH on the Wedderburn Plateau in the east, to smaller areas of higher carrying capacity PKH in the west.

Long-term conservation planning for the Campbelltown koala population requires a strategic and considered approach to managing the issue of koala population recovery and associated range expansion as koalas continue to move across the landscape and occupy areas of formerly unoccupied habitat. Independently of knowledge about the current conservation / population status of koalas in the CCC LGA, *Graphab* output identified the habitat matrix between Kentlyn and Wedderburn as supporting the most important patch attributes in terms of size and capacity to offer

linkage support to associated patches. Given this background, the future upgrading of Appin Road and increasing development pressure in the south-western area of Campbelltown mandate the need for informed connectivity analyses as a pre-requisite to finalising road design and other development outcomes.

Recommendations arising from the outcomes of the GAP CLoSR analyses include the need to consider how best to consolidate effective integration of connectivity needs at three locations along the Lachlan Way aqueduct as a part of landscape-themed connectivity outcomes in the southwest of the CCC LGA. With a view to maintaining newly established connectivity between koala populations of the Georges and Nepean Rivers, design concepts / solutions for consideration are also recommended for three locations associated with the Appin Road upgrade at Rosemeadow South, Beulah and Mallaty's Creek which have additionally been identified by the GAP CLoSR process as offering the most suitable dispersal pathway opportunities.

1. Introduction

The Campbelltown City Council (CCC) Local Government Area (LGA) is located in the Macarthur region to the south-west of Sydney, New South Wales and encompasses an area of 31,200 ha. Koalas inhabiting the CCC LGA have been the focus of scientific and community interest since the 1980's (Cork *et al*. 1988; Sheppard, 1990; Phillips and Callaghan 2000; Ward 2002; Lunney *et al*., 2010). Currently estimated to have a widely dispersed[1] population of less than 200 animals (Biolink Ecological Consultants (BEC) 2016), data derived from analyses of historical koala records and ongoing field assessments indicates that the CCC LGA koala population – contrary to many others in eastern New South Wales and Queensland - has experienced a measure of recovery over the last 20 years (BEC 2017; 2018).

This report is part of an ongoing series of management related studies intended to assist CCC in enabling the potential for a long-term sustainable management framework for the Campbelltown koalas to be achieved. At the time of drafting this report, the ongoing recovery trend referred to in the preceding paragraph is manifesting itself and amongst other things in greater numbers of koalas being struck by motor vehicles along Appin Road between Campbelltown & Appin. There is also evidence of occupancy in habitat areas to the west of Appin Road in areas where koalas have not previously been reported, amongst the implications of which is that koala populations in the Nepean and Georges Rivers catchments, previously regarded as separate populations for management purposes, are now in direct contact (BEC 2017).

The key to long-term sustainable management of free-ranging koala populations is knowledge. Building on available knowledge indicating and ongoing recovery trend, there is merit in knowing how best to build resilience into the population so that the potential for longer-term population viability can be maximised such that the population is better placed to withstand the impacts of stochastic impacts from catastrophic fire events which have likely played a significant historical role in terms of influencing population distribution and conservation status, the threat now elevated given the future uncertainties associated with climate change. The best way to achieve such resilience will be to have viable population cells widely distributed and occupying habitat outliers that are effectively insulated from large-scale fire events, so enabling recolonization to occur. In order to do this, linkages need to be secured across the landscape.

As its name implies, the *Generalised Approach to Planning Connectivity at Local and Regional Scales* (GAP CLoSR) developed by Lechner and Lefroy (2014) offers a GIS-based approach with a supporting

[1] This a reflection of the large home range areas required to sustain individual koalas

analytical and spatial framework that enables objective examination of issues associated with processes of historical habitat fragmentation and landscape-scale connectivity. Amongst other things GAP CLoSR does this by considering the ecological needs and movement characteristics of a given target species and the extent to which the planning landscape functions to impede and/or facilitate movement, including considerations such as patch size and the location of areas of preferred habitat, the greatest distance of open ground that can be crossed and the distances that can be moved in a connected landscape. Output from the GAP CLoSR process thus enables identification of key landscape 'components' and associated habitat 'patches' linked *via* a system of 'least-cost pathways', these being the shortest pathway between two habitat patches within a given area as a function of land cover resistance (*i.e*. barriers to movement) as well as knowledge about ranging patterns and dispersal behaviour.

It is the exploration of connectivity across the landscape and specifically the identification of least-cost dispersal pathways for koalas that is the primary focus of this report. A series of conceptualised linkages were identified for the purpose of the draft Comprehensive Koala Plan of Management (CKPoM) endorsed by Council (CCC 2017). While these linkages were intuitively informed, the Greater Sydney area and the CCC LGA in particular is also about to undergo a period of further expansion and development in the south-west. Analyses such as that offered by the GAP CLoSR process thus have the capacity to inform future planning decisions by offering objective analyses of connectivity across the planning landscape at a key point in ecological time. Knowledge of the locations of least-cost pathways also has the potential to inform future planning decisions by way of identifying key locations for linkage consolidation and/or future rehabilitation / restoration.

The purpose of this project was to take a more informed and scientifically-driven approach to the issue of connectivity considerations for koalas across the CCC LGA and in so doing enable a comparative examination of connectivity options by way of:

- Identifying key landscape components and habitat patches of PKH associated with koala conservation across the CCC LGA,
- Prioritising the habitat patch network in terms of size and intra-component connectivity,
- Identifying and prioritising least-cost pathways between the patches within each component for long-term koala conservation benefit,
- Examining issues of conservation relevance to the continued functionality of these least-cost pathways in light of potential future development.

2. Methodology

i) Study area and koala records

The CCC LGA is located along on the eastern edge of the Cumberland Plain to the southwest of Sydney, NSW and covers an area of 31, 200 ha. (Figure 1). Koala records from the most recent koala generation (2011 - 2017) were obtained from Bionet.

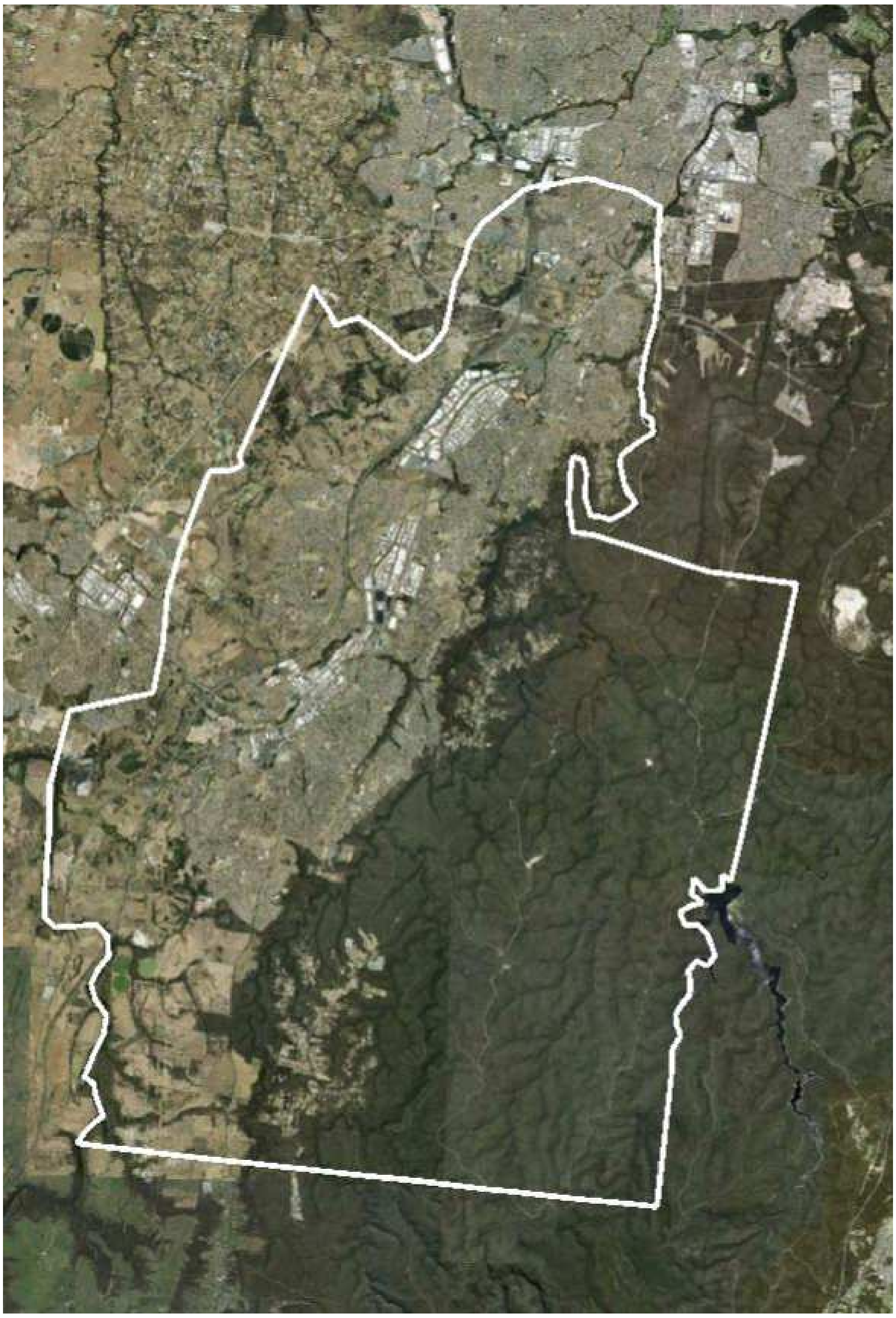

Figure 1: Location of the CCC LGA (white polygon) along the eastern periphery of the Cumberland Plain to the south-west of Sydney, NSW.

ii) Allocating resistance to land-use for koala movement

For low-density koala populations such as that which naturally occur in the CCC LGA, the costs of moving across the vegetated landscape are higher than for those occupying higher carrying capacity landscapes elsewhere; this is because the distances between individual Preferred Koala Food Trees (PKFTs) are invariably greater.

The percentage resistance value (PRV) refers to the effort or cost that it takes a koala to cross a particular land-use class. A PRV of 100% is the baseline cost indicating that it takes a koala 50 m of effort to cross a distance 50 m, 200% equates to an effort equivalent to 100 m to cross 50 m and so on. These PRVs are based on Lechner and Lefroy's (2014) initial recommendations for each land-use category, refined herein according to species-specific knowledge.

iii) Determination of a gap-crossing threshold

In order to determine the maximum distance that a koala was likely to travel from a vegetated area (the gap-crossing threshold), we calculated the Euclidian distance of all CCC LGA koala records that were located in non-vegetated areas from that of the nearest patch of mapped vegetation (including both PKH and other non-PKH mapped vegetation).

Of the 240 koala records for the study area, 89 were located outside mapped vegetation polygons. The largest distance a koala record was located from mapped vegetation was ~ 220 m and the average distance was ~ 44 m. Only 2.2% of koala records were located > 200m from vegetation and 14.6% were located between 100 - 200 m from mapped vegetation. The remaining 83.2% of records were within 100 m of mapped vegetation (indeed, 40.4% were within 10 m of mapped vegetation). On the basis of this knowledge we applied a buffer of 220 m around all mapped vegetation in order to best delineate the gap-crossing threshold. For areas beyond this buffer zone we applied a complete barrier to movement (*i.e.* ∞ dispersal cost) (Appendix 1, Section E refers).

iv) Creation of a dispersal cost surface

The various land-use layers that make up the CCC LGA landscape were used to create a *dispersal cost surface*; this is a rasterised[2] surface where each pixel's value represents a dispersal cost for koalas that is derived from the land cover type, reflecting the potential ecological costs of traversing this area. This approach requires evaluation of individual land cover resistance levels, based on a practical consideration of both the likelihood of koala movement and the hazards that are likely to be encountered, herein defined as the extent of localised resistance.

The dispersal cost surface incorporates considerations of localised resistance related to the following land-use attributes:

[2] A matrix of cells or pixels organized into rows and columns.

1. Transport infrastructure *(i.e*. roads and railway lines),
2. Hydrology (drainage lines, canals, artificial waterbodies, aqueduct),
3. Vegetation cover (including, but not limited to Preferred Koala Habitat),
4. Mining and quarrying,
5. Agricultural activities (grazing & horticulture) and
6. Urban, Commercial and Industrial Areas.

Each of the preceding land-use layers (*e.g*. cadastre, roads, Strahler stream orders, vegetation mapping) were available as a consequence of ongoing work with CCC. Where appropriate, digital data relating to linear landscape elements such as watercourses and infrastructure such as railway lines and roads were underlain with available satellite imagery in order to identify potential connectivity opportunities for koalas, whereupon dispersal costs were lowered accordingly (see below - Appendix 1 refers).

v) Coding of Statewide Class (SC) / Plant Community Types (PCTs)

For the purpose of this project all SC/PCTs recognised by the vegetation mapping layer were categorised in accord with criteria of BEC (2016) used to identify areas of PKH based on considerations of presence / absence / dominance relating to the following PKFT species: Grey Box *Eucalytpus. moluccana*, Grey Gum *E. punctata*, Manna Gum *E. viminalis* and Forest Red Gum *E. tereticornis*. Based on this knowledge, SCs/PCTs could be classified hierarchically in terms of their inherent koala carrying capacity as follows:

- **Primary Koala Habitat** – SC/PCT wherein 'primary' PKFTs comprise the dominant or co-dominant overstorey species.
- **Secondary Koala Habitat (Class A)** – SC/PCT wherein 'primary' PKFTs are a sub-dominant component of the overstorey species (typically alluvial deposits).
- **Secondary Koala Habitat (Class B)** – Primary PKFTs absent, SC/PCT dominated by one or more 'secondary' PKFTs.
- **Secondary Koala Habitat (Class C)** - Primary PKFTs absent, one or more 'secondary' PKFTs present within SC/PCT as a sub-dominant component of overstorey species.

Collectively, SC/PCTs coded in accord with the preceding classification system qualify as PKH for koala conservation and management purposes. SC/PCTs that did not contain PKFTs were classified as '**Other**' vegetation for analysis purposes.

As already alluded to in ii) above, the allocation of cost must be determined in a different way for PKH compared to all other categories. In areas of PKH categorised as 'Primary', the smaller home range sizes needed to sustain an individual koala require less daily movement, notwithstanding that such movement in itself carries costs associated with exposure and misadventure. In the subsequent series of Secondary habitat types (*i.e*. A, B and C), home ranges are by necessity larger, due to the increasingly sparser distribution of PKFTs. This requires larger daily movements to be undertaken, with associated higher costs. Because the physical movement through Secondary habitats is costlier for koalas, this requires a higher cost metric to be applied. All PKH (Primary and Secondary Classes) are considered 'no cost' when incorporated into a habitat patch in the GAP CLoSR framework. In order to qualify as a habitat patch *per se*, a minimum size threshold, defined by the user, must be exceeded. In cases where the amount of available habitat does not meet this threshold, Secondary PKH classes carry progressively higher costs to traverse than Primary PKH, which is the only land use that is 'no cost' in all contexts. At the other end of this spectrum, SC/PCTs that did not contain PKFTs were classified as '**Other**' vegetation for analysis purposes and incurred a higher cost again, as did areas of cleared land or cleared land with scattered trees.

For the purpose of GAP CLoSR analyses we have continued to develop and refine a standardised set of resistance parameters for koalas which are supported by ecological correlates that can be applied throughout the species range. Notwithstanding the need to acknowledge localised departures from a standardised set as particular circumstances arise (*e.g*. the Lachlan Way aqueduct and other channelled watercourses such as occur in the CCC LGA), the use of a standardised approach enables a consistent approach to be applied across the koala's range. The current detail of this standardisation process in terms of the relationship between a given cost parameter and their associated ecological correlate is provided in Appendix 1.

vi) Layering for rasterization purposes

Because multiple data / land-use layers are used to form the dispersal cost surface it is frequent that polygons from one layer (*e.g*. roads) will intersect another data layer (*e.g.* vegetation). In such instances it is important to define which data layer has values that take precedence. Data layers were defined as having the following order of precedence, in terms of their cost value:

1. Gap-crossing threshold layer,
2. Connectivity structures spanning roads, train lines and aqueducts,
3. Train lines and aqueduct,
4. Roads,
5. Hydrology,
6. Vegetation, including PKH, and
7. Urban / Commercial / Industrial / Agricultural land uses.

Preliminary investigations of surface complexity resulted in a determination to utilise a pixel size of 6 m x 6 m for rasterization purposes.

vii) Identifying landscape components, habitat patches and least-cost dispersal pathways

Graphic approaches can be used to represent ecological landscapes in terms of 'nodes' and 'edges', where the former exist as key 'patches' of interconnected habitat within a larger (regional) network of ‘landscape components’, while the edges of landscape components, in theory at least, represent the interface between separate / disconnected matrices of habitat. In this framework, ‘edges’ may also refer to the least-cost pathways between interconnected habitat patches. To this end we determined to use a minimum patch size of 10 ha and the supporting *Graphab* software functions developed by Foltête *et al*. (2012) to identify key landscape components and associated patch networks therein. We also used the *Graphab* functions to identify least-cost dispersal pathways across the study area using a threshold method. To this end and rather than relying on Euclidian distance, cost considerations were used to incorporate information from the landuse layer whereby a cumulative cost threshold of 300,000% was deemed to be that beyond which a pathway could not be formed. The calculation of this value is informed by ancillary koala ecology considerations / metrics (Appendix 1 Section E refers).

viii) Graphab settings and metrics

Analyses were run using minimum patch sizes of 10 ha, 20 ha and 50 ha respectively. Patch connexity was set to 4, meaning that a habitat ‘patch’ consists of the central pixel with its four neighbors if they were of the same value. Patches were simplified for planar graphing purposes to streamline the creation of polygonal boundaries, thereby accelerating analysis. Topology was also complete, meaning that all links that did not otherwise cross habitat patches were considered. The cumulative cost was determined from the landscape map using the maximum cumulative cost threshold as defined in the preceding section.

The primary graph metric utilized for analysis was the Delta Integral Index of Connectivity (DIIC) which is expressed as the product of patch capacities (which in this case was determined by habitat patch size) divided by the number of links between them, with the sum divided by the square of the study area using the calculations of Pascual-Hortal and Saura (2006). The DIIC, as opposed to either the global- or component-IIC, describes the relative importance of each graphic element by computing the rate of variation in the global metric induced by the removal of either patches or paths. The result of a Delta metric is presented at a local level (that of habitat patch or pathway) but also by reference to the global level (*i.e*. the entire study area).

3. Results

i) Land use layer and associated dispersal cost surface

Rasterisation of the input landuse layers resulted in a large series of pixels which were checked and coded manually for resistance in accord with values detailed in Appendix 1. Figure 2 illustrates the fine scale complexities of the dispersal cost surface, including the gap crossing layer, for a section of the CCC LGA in comparison to available satellite imagery and Figure 3 demonstrates this cost dispersal surface more broadly for the entire LGA.

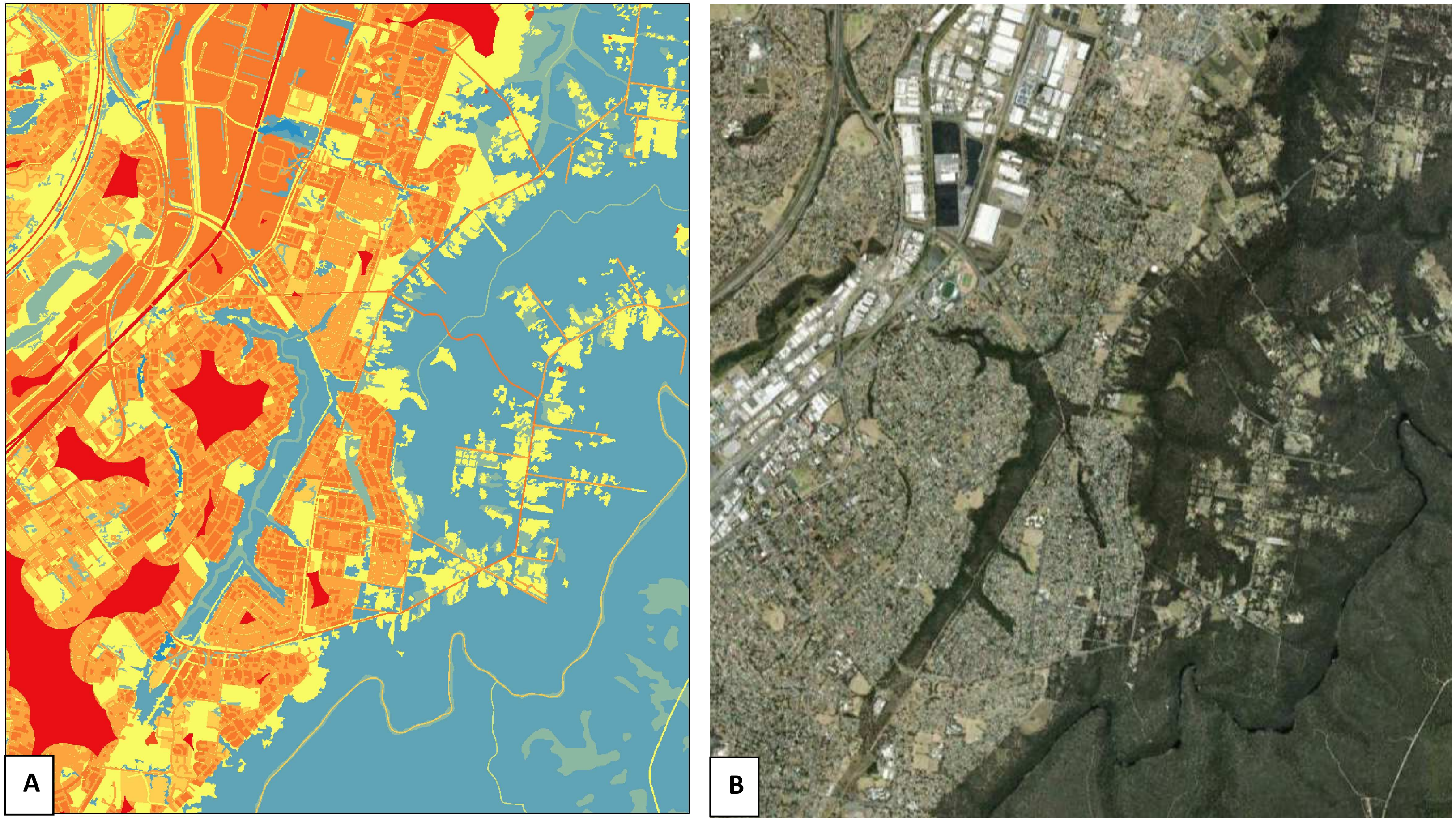

Figure 2: An example of the dispersal cost surface for a section of the CCC LGA in the vicinity of Leumeah, Ruse and Minto Heights (A), compared to satellite imagery (B) for the same area. High cost (red) represents a land type that is either difficult for koalas to traverse, lower costs (blue) are easy to traverse. Note that the area is costed for a range of land uses including vegetation type, agriculture, urban and commercial development, industry, transportation infrastructure and hydrology. The large patches of red represent the gap-crossing threshold, meaning that these areas are > 220m from any mapped vegetation and therefore not likely to be crossable by koalas.

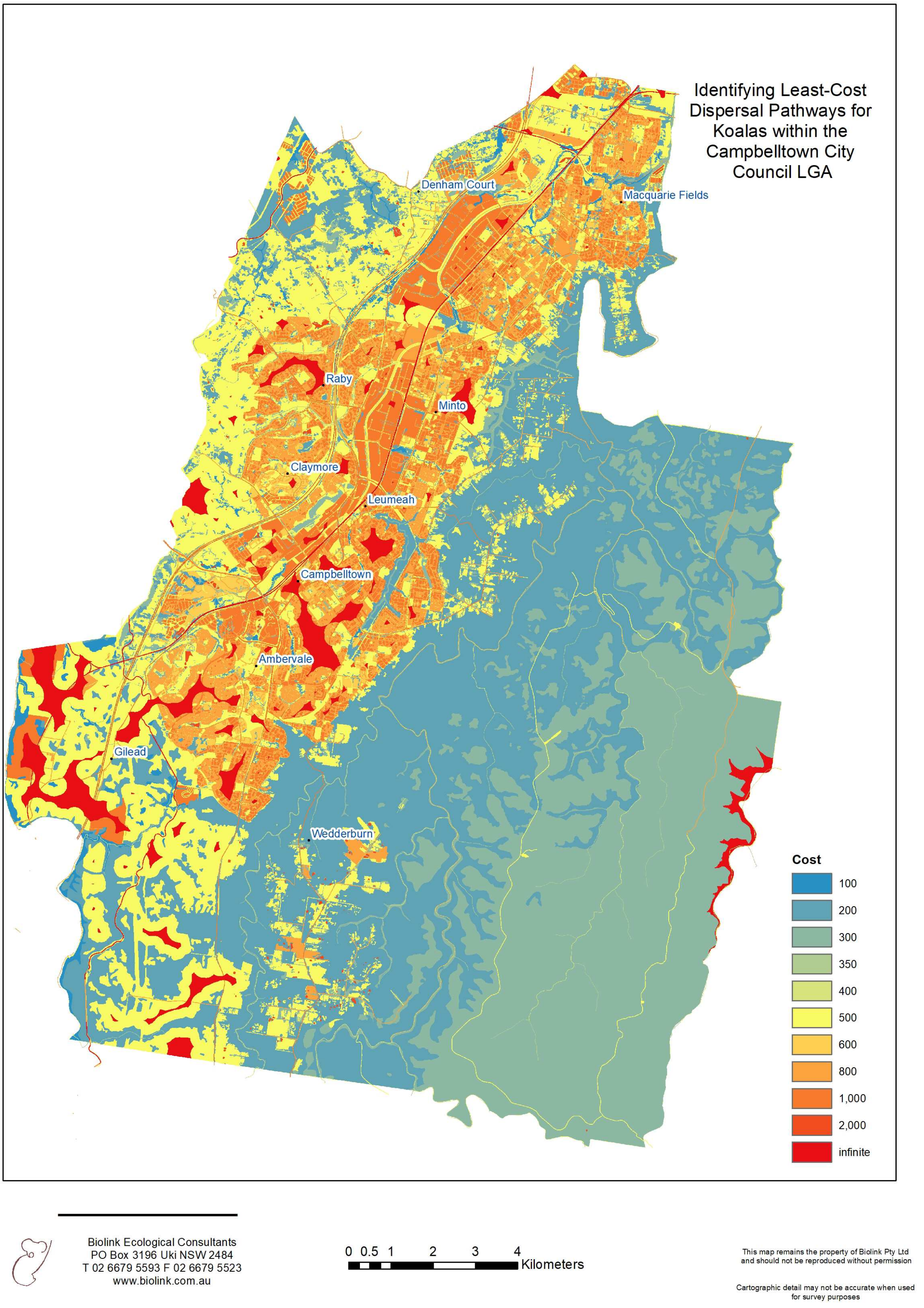

Figure 3: Dispersal cost surface for the CCC LGA.

ii) Graphab / GAP CLoSR output

Table 1 summarises the baseline GAP CLoSR output metrics for the study area in terms of increases in the minimum PKH patch size from 10 ha, to 20 ha and 50 ha. The highest numbers of potential least-cost dispersal pathways are identified by considering all areas of PKH to a minimum size of 10 ha and given that our objective is to characterise linkage areas across gaps in the habitat, there is greater ecological benefit to consider the highest number of practicable pathways; further analysis and figures are thus based on this minimum patch size. If a 20 ha or 50 ha minimum patch size is used, the loss of smaller, unidentified patches and pathways could lead to a failure to consider important linkage areas in planning or management.

Table 1. Baseline connectivity elements identified on the basis of required access to 10 ha, 20 ha and 50 ha minimum PKH patch sizes.

Landscape Element / Patch size	10 ha	20 ha	50 ha
Landscape components	2	2	1
Habitat patches	47	30	22
Least-cost pathways	85	49	39

Graphab output for the study area is illustrated in terms of landscape components and associated habitat patch networks connected by least-cost pathways (Figure 4). At the 10 ha habitat patch scale, this output implies that the CCC LGA consists of two landscape components, the smaller of the two comprising just three habitat patches connected by three least-cost pathways located at the very north-western edge of the CCC LGA where it adjoins the Camden and Liverpool LGAs. Thereafter, the remainder of the LGA (31,052 ha) is determined to function as a separate landscape component comprised of 44 habitat patches connected by 82 least-cost pathways. Areas of potential connectivity between the east and west of the study area occur in the north of the CCC LGA, around Macquarie Fields and Denham Court, and to the south of Gilead around Wedderburn and Menangle. Figures 5 and 6 display this output at a higher resolution for both the north-western edge of the LGA and the south-west of Campbelltown respectively.

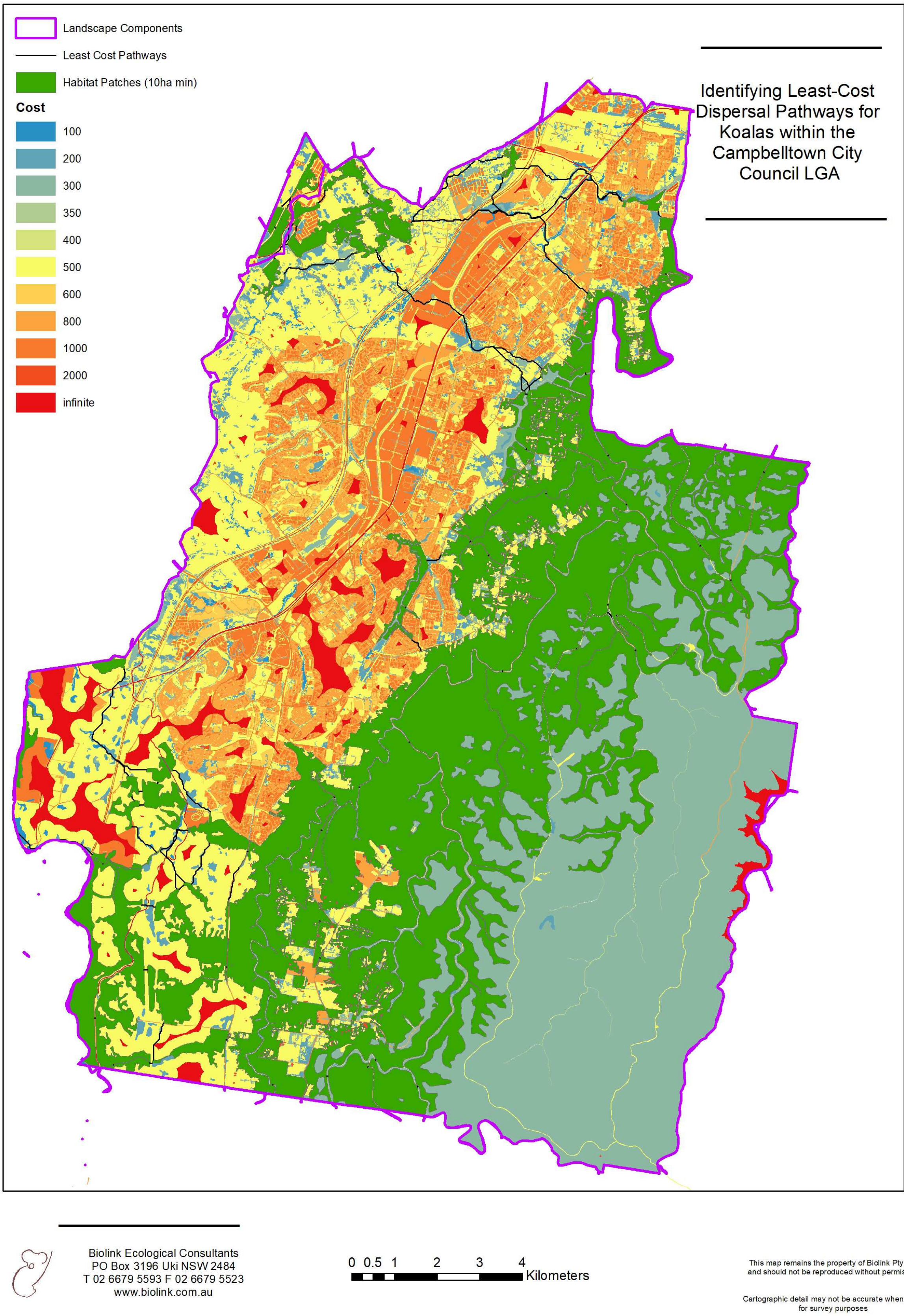

Figure 4: Dispersal cost surface for the CCC LGA which comprises two landscape components (purple outlines) consisting of 47 habitat patches (10 ha minimum size) connected by 85 least-cost pathways, the locations of which are illustrated by black lines.

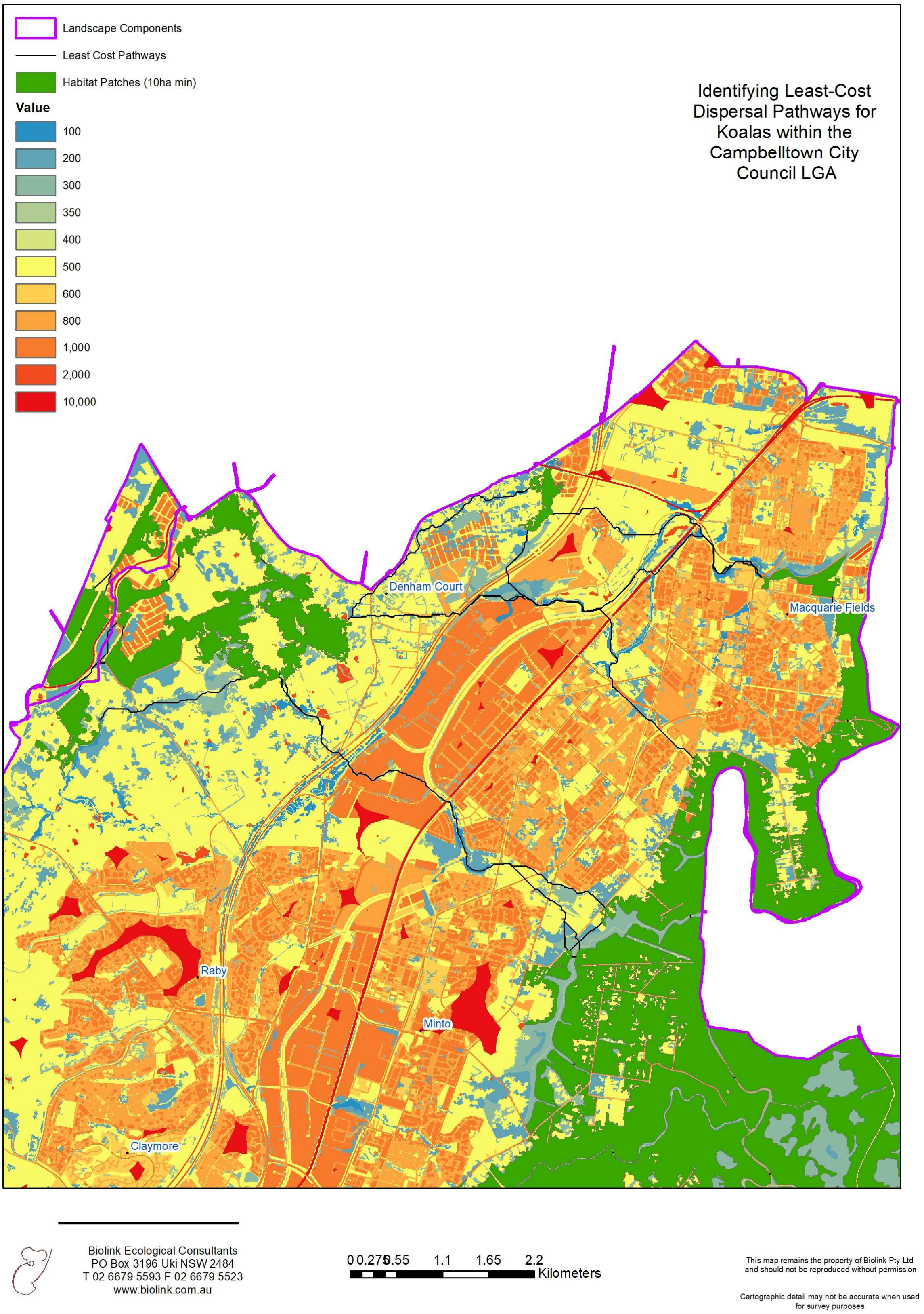

Figure 5: Higher resolution of potential least-cost pathways (black lines) in the northern part of the CCC LGA. Potential for connectivity is dependent upon ribbons of PKH, generally following watercourses, winding through otherwise urban areas; four railways crossings are also incorporated.

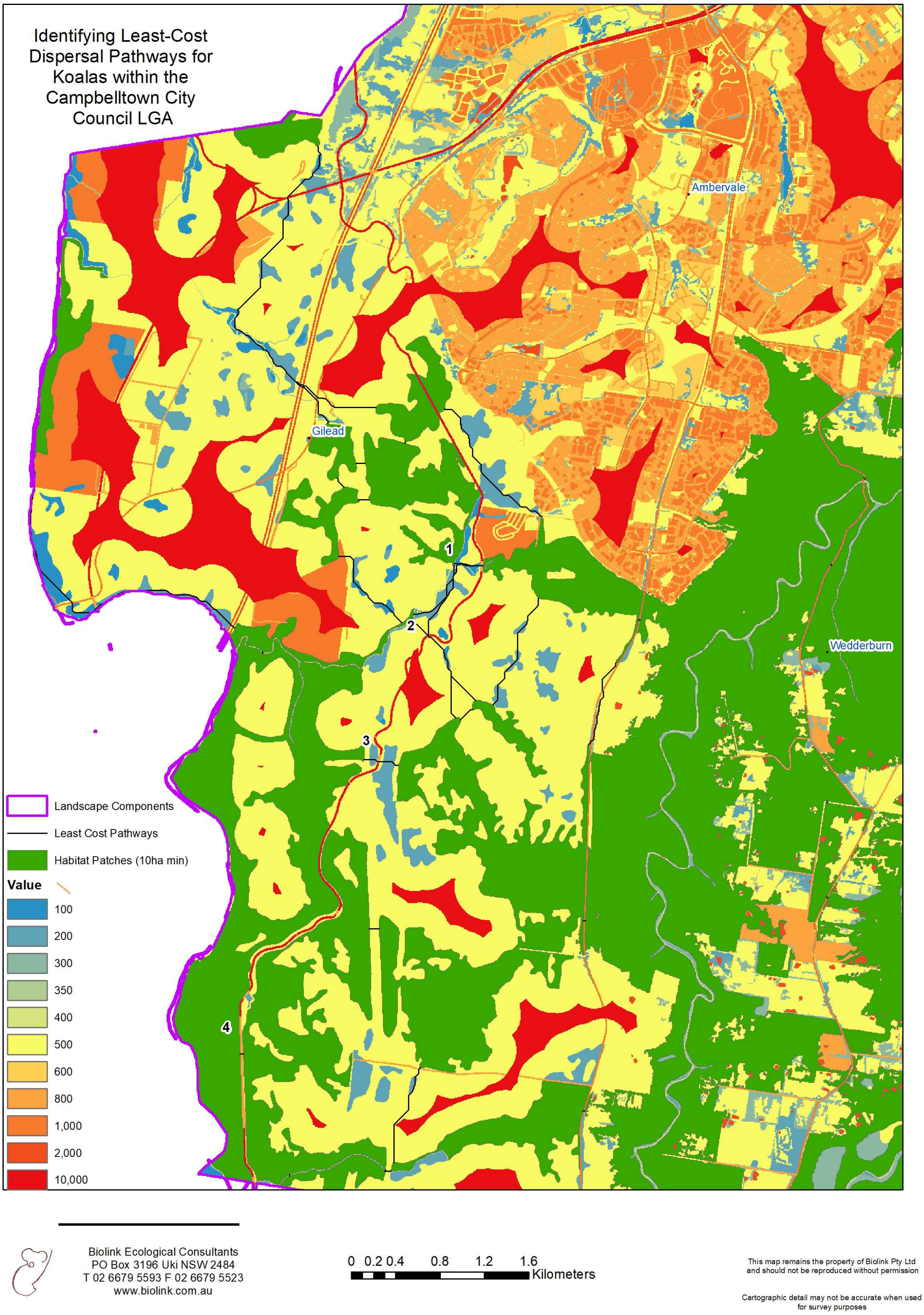

Figure 6: Higher resolution of least-cost pathways (black lines) in the south-western portion of the CCC LGA. East-west movement out of the large habitat patches of the Wedderburn Plateau is dependent upon crossing both Appin Road and the Lachlan Way aqueduct. Areas where aqueduct crossings are theoretically possible are numbered 1 – 4.

East-west connectivity in the north of the LGA from Macquarie Fields towards Denham Court is not discussed in further detail in this report, given the lack of evidence for current koala occupancy in the habitat patches to the north-west (Figure 7). Occupancy in the south is documented for both the east and west of the LGA, with recent movement of koalas from habitat on the Wedderburn Plateau, across Appin Road, through the Beulah biobanking site and as far as the Nepean River near Menangle (Figure 7).

The relative importance of PKH patches across the CCC LGA, as defined by the graph-metrics generated by Graphab, identifies the habitat area along the Georges River between Kentlyn and Wedderburn as the largest and most consolidated for long-term management purposes (Figure 8). Outside of this area, the habitat patch network between the Georges and Nepean Rivers in the vicinity of the Beulah biobanking site is also identified as important. Linkages connecting elements within the large Kentlyn-to-Wedderburn habitat matrix are identified as being the most important to the overall connectivity of study area, while linkages following the Beulah biobanking site and Noorumba Reserve are also identified as substantially contributing to overall connectivity (Figure 8).

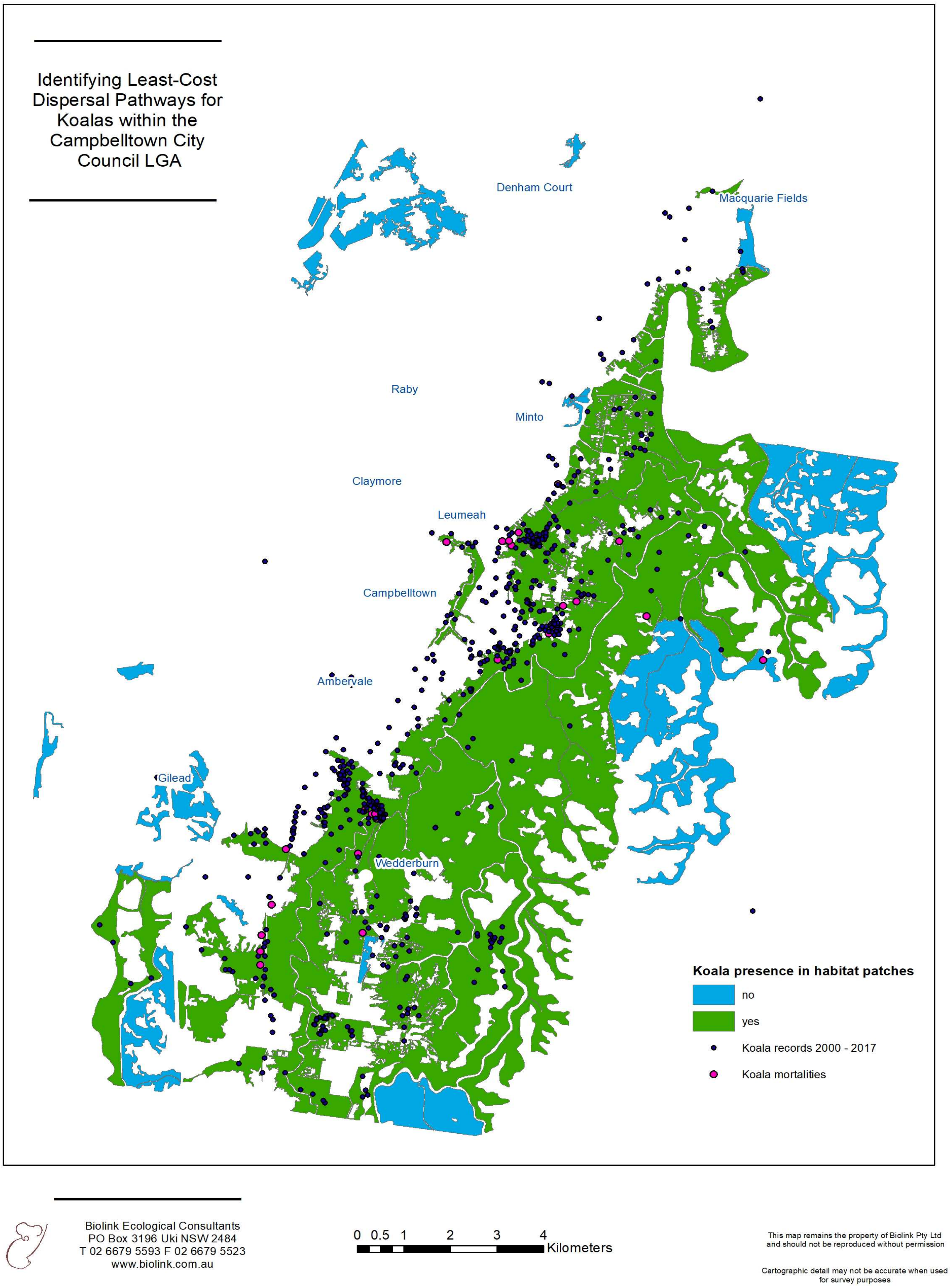

Figure 7: Habitat patches identified by Graphab, here intersected with koala records (shown as black circles) from the most recent koala generation (2011-2017), are coloured green. Habitat patches with no/unknown koala occupancy are coloured blue. The locations of known koala mortalities are shown as pink circles.

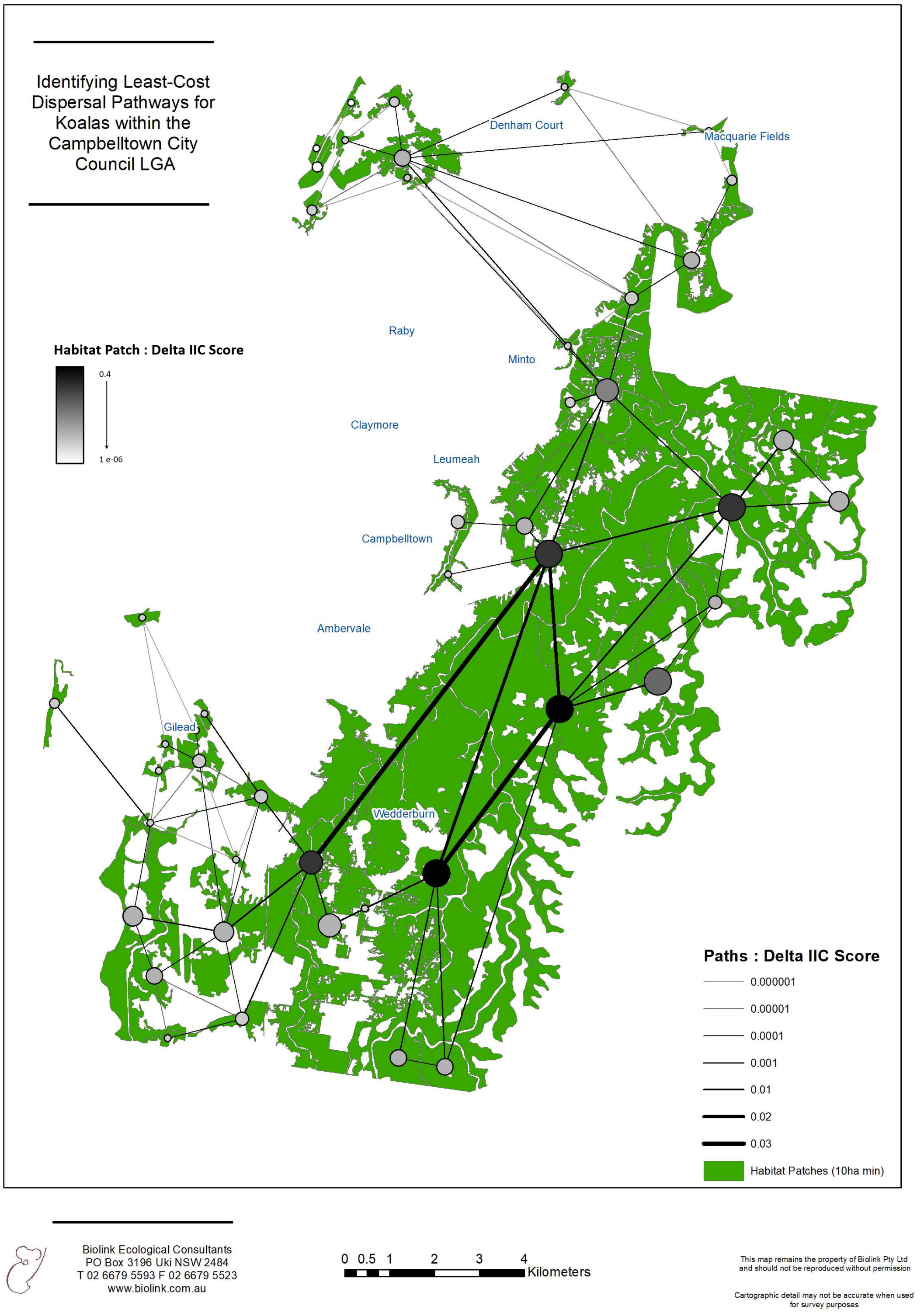

Figure 8: Delta Integral Interconnectivity (DIIC) scores for habitat patches and associated linkages. This metric characterises the importance of patches and linkages to the network and is computed by measuring the effects of patch / linkage removal to overall connectivity. Habitat patches are represented by circles - colour represents their importance (DIIC score) with the most important patches, in terms of their contribution to overall connectivity, shown in the darkest colour (higher DIIC score). Circle size represents patch capacity (calculated from total area). The importance of each linkage to overall connectivity is represented by the thickness of the line, thicker lines being the most important (higher DIIC score). Note that linkages do not represent the ‘real paths’ as shown in previous figures, but are the Euclidian distance between two patches.

4. Discussion

This project is the first to undertake an informed and objective examination of existing connectivity pathways and linkage opportunities for koalas across the CCC LGA.

Of the 47 habitat patches > 10 ha utilised identified by GAP CLoSR framework, sixteen contain koala records from the most recent three koala generations (2000 - 2017). There are 28 least-cost pathways connecting these currently occupied habitat patches, all of which are located in the east and south-west of the LGA. It is noteworthy that connections between the east and west of the study area are reliant entirely upon successful crossings by koalas of both the Lachlan Way aqueduct and Appin Road between Rosemeadow South and Appin Village. Potential linkages in north of the CCC LGA have also been identified. These are questionable in terms of indicative conservation investments in restoration / rehabilitation because of a lack of evidence for koala occupancy in the very north-west of the LGA (Figure 7) and an absence of connectivity and/or habitat patches to the north in the adjoining Camden Council and Liverpool City Council LGAs.

For the greater part of its route the Lachlan Way aqueduct offers little opportunity for successful crossings by koalas and other non-volant mammals. Fine-scale inspection of satellite imagery however, revealed four areas that offered potential crossing opportunities (locations numbered 1 – 4 respectively in Figure 6 of this report). Of these, crossing 4 is the most substantive (a navigable interface ~ 800 m in width) and thus offers the greatest opportunity through a known area of PKH. From the south, this area connects to a linear strip of riparian habitat associated with Mallaty's Creek which is independently identified as a key east-west linkage across Appin Road between the Georges and Nepean River catchments. Connectivity opportunities to the north are more complex to unravel and/or consolidate but are clearly anchored to the Beulah biobanking site which has also been identified by the GAP CLoSR analysis as fundamental to maintaining east-west linkage. The Beulah site is also associated with access to crossing 3 along The Lachlan Way; this is a 72 m section where the aqueduct is suspended above a gully with PKH on both sides. Elsewhere, crossing 1 is a 100 m section of the aqueduct which is enclosed within piping, with some potential for koala movement under the concrete footings of the pipe. Preferred Koala Habitat abuts this crossing on either side, offering a medium level of potential utility. Crossing 2 is a 4 m wide vehicle bridge with surrounding agricultural land including scattered trees. The nearest PKH is 230 m away on the east and 138 m away to the west, these distances implying a low potential utility in the absence of strategic replanting to consolidate the linkage.

The importance of establishing and maintaining strategic linkages at Rosemeadow, Beulah and Mallaty's Creek as initially identified by the Campbelltown CKPoM is strongly reinforced by the GAP CLoSR analyses, least-cost dispersal pathways across Appin Road being independently identified in all three locations previously identified by BEC (2017). The general area between South Campbelltown and Appin village is also identified as an important patch matrix by the *Graphab* output.

One of the underlying assumptions of the GAP CLoSR approach is the notion of 100% occupancy. Aside from considerations of patch size in the graph-metric output (the DIIC score), this means that all habitat patches are weighted equally in terms of their connectivity potential and the least-cost dispersal pathways that are subsequently identified, as opposed to an outcome that may be more biased by a reliance of a contemporaneous residency distribution pattern. In this regard it is important to recognise that the least-cost dispersal pathways are linear representations of linkages that are not spatially explicit. This means that while the location has been identified, precise dimensions and more specifically width has not been specified. This is also advantageous given that precise dimensions of linkages / corridors can then be adapted in response to local knowledge and the needs of a given target species and/or suite of species as required. For koalas, BEC (2017) promoted an optimal corridor width of ~ 425 m based upon considerations of female home range size. While this is a useful and scalable metric that reflects the low koala carrying capacity of the landscape, it is also evident from available studies in CCC LGA that koalas will use areas with a narrower width than this. Invariably, final corridor width in most instances will likely reflect other considerations; it goes without saying that wider is better in order to reduce the potential negative impacts associated with edge effects, more so in areas where related themes such as water quality must also be considered.

In terms of the south-western LGA, graph metrics independently identified the overall importance of the linkage matrix that currently exists between the Nepean and Georges River catchments in in the area between South Campbelltown and Appin village. Three main pathways are identified by the analyses, the more important of which stems from large habitat area to the east of Appin Road across the Beulah biobanking site and thereafter across the Gilead area to the Nepean River. It follows that this area should notionally become the focus of connectivity planning, the intent to optimise functionality of the existing connectivity network in this area. Other important dispersal pathways in the area between South Campbelltown and Appin village are located at Mallaty's Creek and the Noorumbah Reserve at Rosemeadow respectively. Overriding considerations in this regard are opportunities to traverse the barrier otherwise represented by the Lachlan Way aqueduct. As we have alluded to in terms of the current landscape, crossing areas 1, 3 & 4 in Figure 6 of this report thus become focal points for connectivity planning, the intent of which should be to ensure that potential east-west connectivity outcomes at these locations are not compromised by poor planning decisions/design.

It is clear that future upgrading of Appin Road will need to consider the matter of maintaining connectivity in the broader context of encouraging a final design by government to also reduce the potential for vehicle-strike along the road alignment in this location (mapped in Figure 7). While not a specific requirement of this project brief, design solutions to assist in minimising the impacts of the road upgrade while still accommodating connectivity needs are available, ranging from a extended lead-in (to the upgrade) at Rosemeadow so as to enable a design solution (slower vehicle speed enforced by roundabout and koala-grids), an overpass in the general vicinity of the Beluah biobanking site and an engineering solution at Mallaty Creek so as to create either an elevated road section or excavated area beneath any upgraded road alignment through which koala movement can occur.

Recommendations

1. Council engage with NSW Roads & Maritime Services regarding the need for connectivity measures to be provided in the vicinity of Noorumbah Reserve, the Beulah biobanking site and Mallaty's Creek as part of an integrated connectivity outcome for the southwestern corner of the CCC LGA, and
2. Pursuant to 1 above and with a view to effectively connecting the Nepean and Georges River populations, Council strive to consolidate and deliver an east-west corridor design for koalas focussed on least-cost dispersal pathway locations at the Noorumbah Reserve, the Beulah biobanking site and Mallaty's Creek, all of which are to be collectively linked to the Lachlan Way Crossing Points 1, 3 and 4.

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