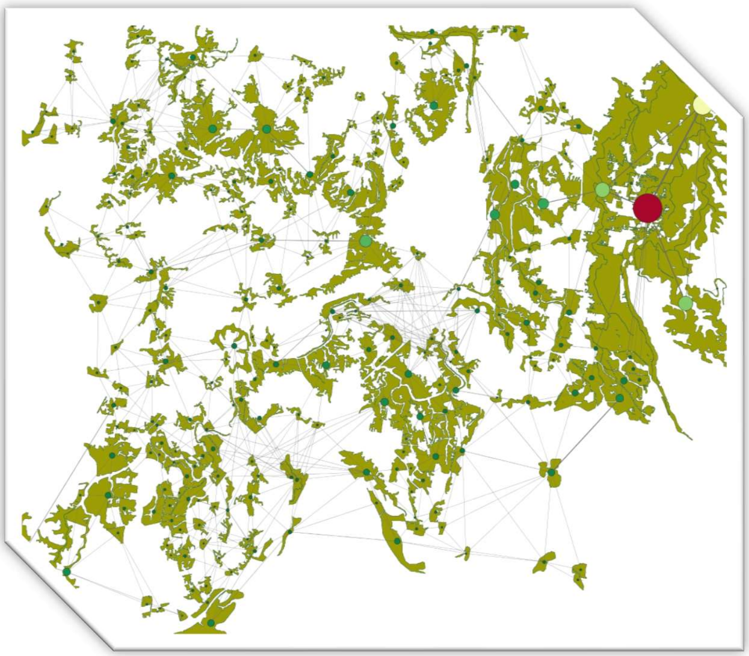
Koala Corridor Project

Campbelltown City Council & Wollondilly Local Government Areas: Greater Macarthur Growth Area.



Report to NSW Office of Environment & Heritage

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Abbreviation	Description
BEC	Biolink Ecological Consultants
CCC	Campbelltown City Council
CKPoM	Comprehensive Koala Plan of Management
dIIC	delta-Integral Index of Connectivity
DoPE	Department of Planning and Environment
FPSP	Full Proposed Structure Plan
GAP CLoSR	General Approach to Planning Connectivity from Local Scales to Regional
GMGA	Greater Macarthur Growth Area
LGA	Local Government Area
PKFT	Preferred Koala Food Tree
PKH	Preferred Koala Habitat
PRV	Percentage Resistance Value
OEH	Office of Environment and Heritage
RMS	Roads and Maritime Services
SC	Statewide Class
VCT	Vegetation Community Types
WS	Wollondilly Shire

CoLS

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1. Summary

The Campbelltown City Council (CCC) and Wollondilly Shire (WS) Local Government Areas (LGAs) are located in the Macarthur region of south-western Sydney. While koalas inhabiting the CCC LGA have been the focus of scientific and community interest since the early 1980's, those in the adjoining WS LGA to the south have only recently become the focus of investigation. Available information based on consideration of historical koala records analyses and the aforementioned research imply that the two populations are in fact one and the same, with recent sightings along the eastern edge of the more southerly WS LGA commensurate with a known recovery trend in the north. Koalas in both areas share similar ecological traits such as preferred food tree species.

There is a need build resilience into these recovering koala populations so that they are capable of better withstanding the impacts of future development and stochastic impacts such as fire. One way to achieve such resilience will be to have population cells widely distributed and occupying habitat outliers that are arguably protected to varying degrees from catastrophic fire events. In order to do this, viable linkages and associated habitat patches need to be secured across the landscape. Parts of the Campbelltown and Wollondilly LGAs additionally form the Greater Macarthur Growth Area (GMGA) and are about to undergo a period of further expansion and development. Elements of such expansion in addition to an increased development footprint dedicated to urbanisation, include the upgrading of arterial roads, some of which have seen an increased rate of koala road-kill in recent years.

The *Generalised Approach to Planning Connectivity at Local and Regional Scales* (GAP CLoSR) offers a GIS-based spatial and analytical framework that enables examination of issues associated with landscape-scale habitat fragmentation and connectivity. Analyses such as that offered by the GAP CLoSR process have the capacity to inform future planning decisions by offering objective assessment of the landscape at a key point in ecological time. This report describes the application of GAP CLoSR to examine issues relating to the future impacts of land use change on koala movements in the GMGA and surrounding areas. Working from a baseline connectivity and patch-matrix assessment covering an area of 90,000 ha, analyses considered the fragmentation and connectivity issues arising from full implementation of an envisaged structure plan for the southern part of the GMGA between South Campbelltown and Appin in concert with two options relating to the future upgrading of Appin Road.

A baseline (*status quo*) GAP CLoSR analysis of the current vegetated landscape using a minimum Preferred Koala Habitat (PKH) patch size of 10 ha implied that the study area currently functioned as seven separate landscape components comprised of 218 PKH patches that were notionally

interconnected by 476 least-cost dispersal pathways. The associated delta-Integral Index of Connectivity (d-IIC) graph-metrics confirmed the importance of the consolidated linear linkages of PKH that skirts the eastern parts of the study area along the Georges River from Long Point through Kentlyn and Wedderburn and Appin down to the east of Wilton and Bargo in the south. In the area from Long Point in the CCC LGA to the east of Appin, analysis independently identified the habitat patch matrix that currently connects the Nepean and Georges Rivers catchments in the vicinity of the Beulah biobanking site as amongst the most important, with other east-west linkages also identified at Appin, Rosemeadow South / Noorumba Reserve and Ousedale-Mallaty.

Implementation of the full structure plan within the GMGA results in significant fragmentation of the associated landscape with implications for adjoining areas beyond the GMGA boundary. While the area within the development footprint remained as a single landscape component with no net loss of habitat patches (subject to provisions), at a locally-focussed 10 ha habitat patch level of resolution, implementation of the full structure plan resulted in a 36% reduction in the number of least-cost dispersal pathways. In terms of modelled scenarios, it was additionally determined that the upgrading of Appin Road with a fence along the eastern edge only would result in reduced connectivity options that will achieve little in terms of reducing vehicle-strike potential. Depending on final design, fencing of Appin Road so as to provide an impermeable barrier to koalas would result in the loss of either three or four locally significant least-cost pathways that were independently identified by the analysis as regionally important and currently facilitating the east-west movement of koalas through this area. Consequently, a reliance on pathways that remained to service connectivity at either end of the fence were also deemed likely to result in increased mortality levels due to dispersing koalas having to navigate urban landscapes in south Campbelltown and Appin village.

Resolution of the preceding considerations should involve a fencing program along both sides of the Appin Road as a requirement of any upgrading, in addition to the integrated maintenance of connectivity in key locations. There are at least three opportunities to achieve this latter outcome, involving landscape / traffic managing solution at the northern end where Appin Road enters Rosemeadow South, one or more dedicated fauna overpasses in the vicinity of the Beulah bio-banking site and an engineering solution sufficient to enable installation of an elevated road surface, bebo arch or similar structure towards the southern end near the head of Mallaty's Creek. Graph-metric output further implies that consideration should also be given to a re-evaluation of the scale of the final FPSP footprint so as to give some effect to the outcomes in terms of recognising the importance of the habitat linkage network through areas to the west of Appin Road between South Campbelltown and Appin village. Consolidation of the key linkages and effectively integrating associated dispersal pathways into the development footprint will be required to achieve this outcome.

2. Introduction

The Campbelltown City Council (CCC) and Wollondilly Shire (WS) Local Government Areas (LGA) are located in the Macarthur region of south-western Sydney. While koalas inhabiting the CCC LGA have been the focus of scientific and community interest since the early 1980's (Cork *et al*. 1988; Sheppard, 1990; Phillips and Callaghan 2000; Ward 2002; Lunney *et al*., 2010), it is only recently that those in the adjoining WS LGA have become the focus of research effort (NSW Office of Environment & Heritage (OEH), unpublished report). Available information based on consideration of historical koala records analyses in the CCC LGA, (Biolink Ecological Consultants (BEC) 2016) now indirectly supported by the aforementioned research effort and associated field assessments in the adjoining WS LGA to the south imply that the two populations are in fact one and the same, with recent increased sightings along the eastern edge of the more southerly WS LGA commensurate with the known recovery trend in the north.

At the time of preparing this report, the ongoing trend of koala population recovery referred to in the preceding paragraph is manifesting itself in increasingly greater numbers of koalas (including breeding females) being struck and killed by motor vehicles along the arterial road network between Campbelltown, Appin and Wilton. Correlated with this trend in the CCC LGA at least is an extension of areas of generational persistence (*i.e.* presence of resident koala populations) from the Wedderburn area to habitat areas to the west of Appin Road where koalas have not previously been reported. The implications of this knowledge, now supported by field assessments, imply that koala populations in the Nepean and Georges Rivers catchments that up until recently were considered to be separate populations for management purposes are now in direct contact (BEC 2017, 2018); not surprisingly, the two populations sharing similar, if not identical ecological traits such as preferred food tree species.

The key to long-term sustainable management of free-ranging koala populations is knowledge. Based on understandings of koala density, occupancy rate and the amount of habitat containing preferred koala food tree species, BEC (2016) estimated the entire CCC LGA koala population population to comprise approximately 200 koalas. Given this circumstance and amongst other things, there is now an arguable need to know how best to build resilience into the recovering population so that it is capable of better withstanding the impacts of future stochastic impacts such as fire, which have likely played a significant role in the past in influencing population distribution in the past. The best way to achieve such resilience will be to have population cells more widely distributed and occupying habitat outliers that are better protected from catastrophic fire events, so enabling recolonization to occur. In order to assist this process, viable linkages need to be secured across the landscape.

As it's name implies, the *Generalised Approach to Planning Connectivity at Local and Regional Scales* (GAP CLoSR) developed by Lechner and Lefroy (2014) is a GIS-based planning tool and supporting spatial / analytical framework that enables the examination and modelling of issues associated with connectivity. Amongst other things, GAP CLoSR does this by taking into account the ecological needs and movement characteristics of a given target species, and the extent to which the existing landscape impedes and/or influences movement. Importantly, the process is inclusive of key ecological considerations such as (i) the locations of areas of preferred habitat, (ii) the greatest distance of open ground that can be crossed, and (iii) the distances that can be moved across the landscape. Output from the GAP CLoSR process thus enables identification and compartmentalisation of habitat patches linked *via* a system of notional least-cost pathways, these being the shortest pathway between two vegetated patches within a given habitat compartment/component as a function of land cover resistance (*i.e*. barriers to movement). It is important to recognise that while the locations of least cost pathways are spatially explicit, the associated spatial dimensions such as width are not specified.

It is the exploration of connectivity across the current and envisaged future landscape that is the primary focus of this report. Parts of the CCC and WS LGAs form the Greater Macarthur Growth Area (GMGA) and are about to undergo a period of further expansion and development. Commensurate with an increased development footprint dedicated to urbanisation is the upgrading of arterial roads such as Appin Road, which has seen an increasing rate of koala road-kill in recent years. Analyses such as that offered by the GAP CLoSR process have the capacity to inform future planning decisions by offering informed analyses of the landscape at a key point in ecological time.

The purpose of this project was to take a strategic but analytical approach to connectivity issues by examining and better understanding the potential impacts arising from progressive development of the GMGA. This was firstly done by undertaking a landscape-scale baseline (*status quo*) analysis of habitat patches and connectivity, prior to investigating the potential impacts of two future planning scenarios[1] as follows:

1. a development (Structure Plan) footprint with Appin Road as a multi-lane dual carriage way, fenced on eastern side, and
2. a development (Structure Plan) footprint with Appin Road as a multi-lane dual carriage way, fenced on eastern side with a crossing at Ousedale-Mallaty corridor.

[1] Scenarios were explicitly specified by NSW OEH.

This report follows on from an earlier draft submitted in July 2018 which utilised a different vegetation mapping layer and considered other specified development scenarios. Pursuant to this report and a presentation of the results to a meeting in Sydney on the 3rd August 2018, a request was received for previously considered scenarios and some reporting requirements to be changed. To this end we have endeavoured to incorporate changes to reporting requirements where possible, but were unable to accommodate others such as corridor / linkage widths which we considered to be peripheral and so distract from the specific objective of the initial project brief.

3. Methodology

3.1. Study area

The primary focal area for this project was the southern portion of the GMGA as identified by the NSW Department of Planning & Environment (DoPE). The GMGA traverses the southwestern portion of the CCC LGA extending into the north-eastern corner of the adjoining WS LGA. The southern part of the GMGA includes all activities related to the Full Proposed Structure Plan (FPSP) including changes to transportation infrastructure and urban development. To effectively capture this area and to place it into an appropriate landscape context, we identified a study area of approximately 90,000 ha, the eastern half of which captured the area which the majority of historical and more recent koala research work has been undertaken, where the associated areas of koala habitat are located and within which the GMGA occurs (**Figure 1**).

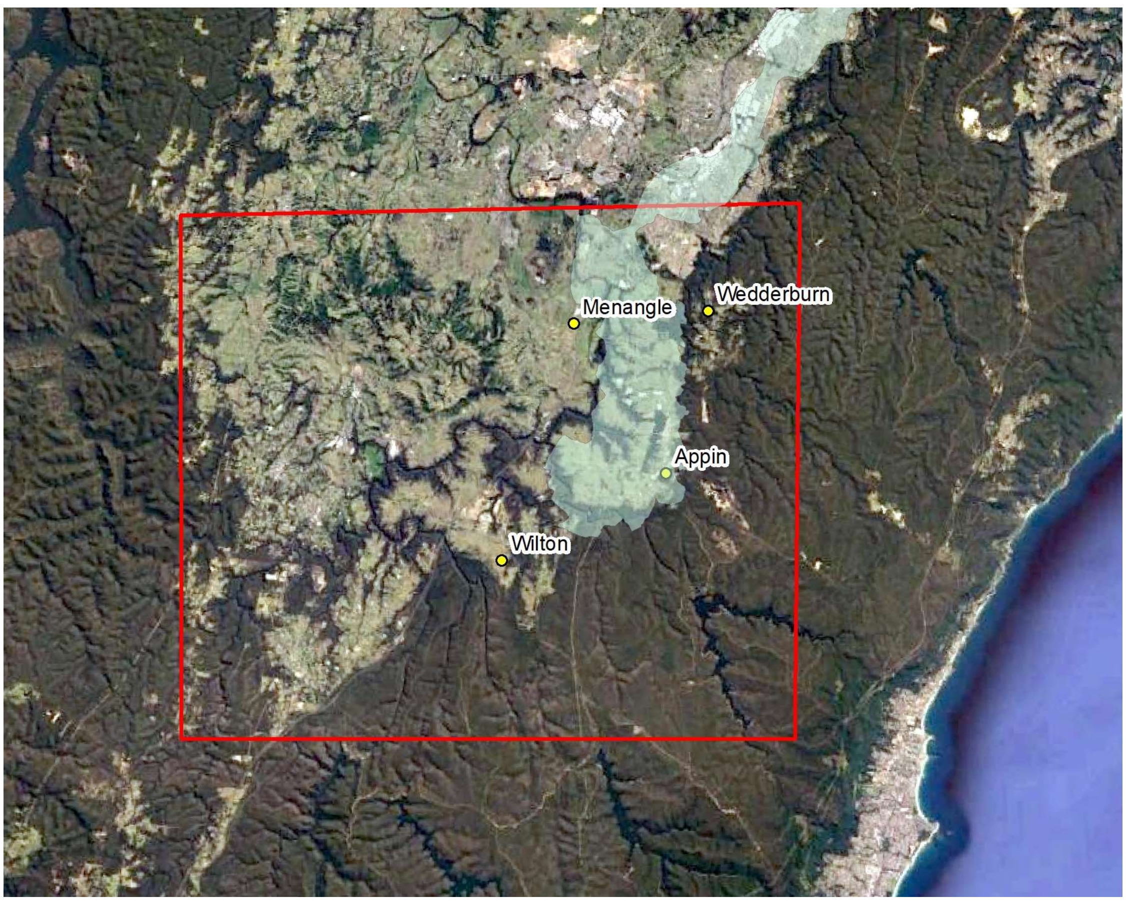

Figure 1: The study area boundaries, as defined by the red square, incorporate the southern portion of the Greater Macarthur Growth Area (GMGA), shown in pale green in the upper right-hand corner. This boundary includes all activities pertaining to infrastructure and urban development changes as outlined in the FPSP.

3.2. Allocating resistance to land use for koala movement

The Percentage Resistance Value (PRV) refers to the effort or cost that it takes a koala to cross a particular land-use type or class and is based on the notion that 100% resistance value takes 100 m of effort to cross a distance 100 m, 200% = takes an effort equivalent to 200 m to cross 100 m and so on. These resistance values are based on Lechner and Lefroy's (2014) initial recommendations for each land use category but have been refined herein according to species-specific expertise.

The Land use layer

Spatial data layers relating to both natural and human-influenced land uses 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 ecological costs for an individual to traverse the area. This requires evaluation of individual resistance levels, based on a practical assessment of both the likelihood of koala movement and the hazards that are likely to be encountered, herein defined as the extent of localised resistance.

For this project the *Dispersal Cost Surface* incorporated considerations of resistance related to the following landscape attributes:

i. Transport infrastructure *(i.e*. roads and railway lines),
ii. Hydrology (drainage lines, canals, aqueduct),
iii. Vegetation cover (including Preferred Koala Habitat [PKH]),
iv. Mining and quarrying,
v. Agricultural activities (grazing & horticulture) and
vi. Urban, Commercial and Industrial Areas.

Spatial data layers relating to the preceding attributes were obtained from a variety of sources, including that already available to us as a consequence of our ongoing work with CCC (*e.g*. cadastre, roads, Strahler stream orders, vegetation mapping) and through licence / confidentiality agreements with NSW OEH data broker (Satellite imagery, GMGA and FPSP). Where appropriate, digital data layers detailing linear elements such as watercourses and infrastructure such as railway lines, roads *etc.* were underlain with satellite imagery in order to identify potential connectivity opportunities for koalas (e.g. underpasses and/or bridges), whereupon dispersal costs for that particular land use type were lowered accordingly. Other publicly available spatial data was accessed through the NSW Government Portal.

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

Gap-crossing layer

In order to determine the maximum distance that a koala was likely to travel from vegetation, BEC (2018b) calculated the Euclidian distance of all koala records to the nearest patch of mapped vegetation (including both PKH and other non-PKH mapped vegetation) in the CCC LGA. This analysis determined a maximum distance of 220 m that a koala had been recorded from a patch of vegetation. On the basis of this knowledge we applied a buffer of 220 m around all mapped vegetation. For areas outside this buffer zone we applied a complete barrier to movement (*i.e*. infinite dispersal cost).

3.3. Vegetation Cover

Vegetation mapping was provided by OEH ("SWSydneyVegStitched"). For portions of the far north and south-east of the study area that were not covered by this mapping layer we used publicly available spatial data, accessed through the NSW Government Portal as follows:

OEH. 2013. *The Native Vegetation of the Sydney Metropolitan Area* Volume 2. Vegetation Community Profiles Version 3. NSW Office of Environment & Heritage, Sydney.

Wollongong VIS map 2356.

In order to only capture those areas which are currently vegetated we deleted polygons classified as "cleared" in the "Broad Veg" column and polygons classified as "high disturbance" in the "Dist_Class" column. Some areas classified as "scattered trees" in the Dist_Class" column were also deleted. Further inspection of satellite imagery allowed the determination of polygons which did not accurately characterise vegetated areas, and these were also removed.

Classification of Statewide Class (SC) / Vegetation Community Types (VCTs)

For naturally occurring low-density koala populations such as those inhabiting the CCC and WS LGAs, the costs of moving across the vegetated landscape are higher than for those occupying higher carrying capacity landscapes; this is because the distances between individual Preferred Koala Food Trees (PKFTs) and/or for purposes of social contact between individuals are invariably greater.

For the purpose of this project all SC/VCTs recognised by the preceding mapping layers and represented within the study area were coded using the same hierarchical classification system previously used by BEC (2016) to identify areas of Preferred Koala Habitat (PKH) in the CCC LGA, expanded as necessary to include considerations of presence / absence / dominance relating to the following local PKFTs: grey box *Eucalyptus moluccana*, woolybutt *E. longifolia*, grey gum *E. punctata*, manna gum *E. viminalis* and forest red gum *E. tereticornis*. Based on this knowledge, SCs/VCTs were classified in terms of their inherent koala carrying capacity as follows:

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

Collectively, SC/VCTs coded in accord with the preceding classification system qualify as PKH for koala conservation and management purposes. SC/VCTs that did not contain PKFTs were classified as '**Other**' vegetation for analysis purposes. There is broad congruity of the preceding classification system with that of the High, Medium and Low quality habitat rankings designated by the OEH Wollondilly koala study (**Appendix 1**).

The allocation of cost metric is determined in a different way for PKH compared to all other categories. By example, in areas of SCs/VCTs categorised as Primary Koala Habitat, small home range sizes require less daily movement – that movement itself carrying costs associated with exposure and predation. In the subsequent series of Secondary habitat type (*i.e*. A, B and C), home ranges are by necessity larger, due to the commensurately sparser distribution of PKFTs. This requires greater daily movements to be undertaken, with associated higher costs. Because the physical movement through Secondary habitats is more costly to the koala, this leads us to recognise the need for a higher cost. 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.

For the purpose of this project but also informed by other GAP CLoSR projects we have undertaken (BEC 2017, 2018b) we have continued to develop and refine a standardised set of resistance parameters for koalas that were ecologically defined and hence broadly applicable 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. Our current approach to this standardisation process is detailed in **Appendix 2**. In order to enable a fine-scale understanding and to optimise flexibility for planning purposes, we approached the majority of our analyses using a 10 ha minimum habitat patch size.

3.4. Layering for Rasterization Purposes

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

i. Connectivity structures spanning roads, train lines and aqueducts.
ii. Train lines and aqueduct
iii. Roads
iv. Hydrology
v. Vegetation cover (including PKH and non-PKH vegetation)
vi. 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.

3.5. Identifying Landscape Components, Linkage Networks and Least-cost Dispersal pathways

Graphic approaches can be used to represent ecological landscapes in terms of nodes and edges, whereby the former exist as interconnected habitat patches within a larger (regional) network of landscape components, while the edges, in theory at least, represent connectivity between such components. To this end, we used the supporting *GraphHab* software function developed by Foltête *et al*. (2012) to identify key components and associated patch networks/linkages. We also used the *GraphHab* function to identify least-cost dispersal pathways using a threshold method. To this end and as opposed to a reliance on Euclidian distance, cumulative costs paths were used to incorporate information from the PRVs of the dispersal cost surface, with a maximum cumulative cost threshold of 300,000 beyond which a pathway would not be formed.

3.6. *Graphab* Settings and Metrics

Principal settings stipulated in the *GraphHab* software package included patch connexity, which 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 using the maximum cumulative cost threshold as defined in the preceding section.

The primary graph metric output required from analyses 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 can be presented both at a local level (that of habitat patch or pathway) but also by reference to the global level (*i.e*. the entire study area). The dIIC thus offers a useful overall measure of connectivity that takes into account the area of habitat and connectedness between patches. The dIIC index is also calculated between pairs of nodes (patches) and is a measure of the level of connectivity between patches.

3.7. Scenario modelling

The revised instructions required us to consider the following scenarios:

a) A development (FPSP) footprint including Appin Road as a multilane dual carriage way, fenced on eastern side.

A spatial data layer of detail regarding envisaged FDSP outcomes for the GMGA was provided by NSW OEH for incorporation into the dispersal cost surface. For GAP CLoSR purposes we subjugated affected polygons from the vegetation cover mapping layer to reflect the developed landscape that was envisaged and then parameterised the area with land-use metrics and dispersal costs associated with related **Appendix 3** components that related to the GMGA FPSP infrastructure detail that was provided. This approach required changes from background dispersal cost metrics of 150% – 500% that were otherwise applicable to former habitat areas and cleared areas with trees respectively, to that of 2000% imposed by highest-density Urban Areas. Lands identified (but not confirmed) for Environmental Protection, were replaced with a blanket value of 250%, reflective of the fact that these areas either have the capacity to be regenerated to or otherwise predominantly comprise Secondary (Class B) koala habitat. Areas identified as urban footprint capable land that has been changed to conservation were replaced with a value of 200%, reflective of their value, or potential value as Secondary (Class A) koala habitat. The proposed Sydney Orbital was coded with a cost metric applicable to an unfenced motorway (5000%). Additional arterial roads (1000%) and a train line (infinite cost) were also costed according to the cost of similar existing infrastructure as detailed in **Appendix 3**).

The required fence along the eastern side of Appin Road was incorporated as a single line of 6 m x 6 m pixels each of which carried an infinite costing to reinforce the impermeability notion.

b) A development (FPSP) footprint with Appin Road as a multi-lane dual carriage way, fenced on eastern side with a crossing at Ousedale-Mallaty corridor.

In terms of the envisaged FPSP, this scenario was costed as described above. No specifications were provided as to what form a crossing at the Ousedale – Mallaty's corridor might look like. Subject to this qualification we determined to decrease over a distance of 100 m the cost metric otherwise applicable to the single line of pixels as we have described above, to that of non-PKH vegetation.

4. Results

Rasterisation of the input land use layer resulted in a large series of pixels that were checked and coded manually for resistance in accord with values detailed in **Appendix 1**. An example illustrating the fine-scale complexities of the resistance coded land use layer is provided in **Figure 2**.

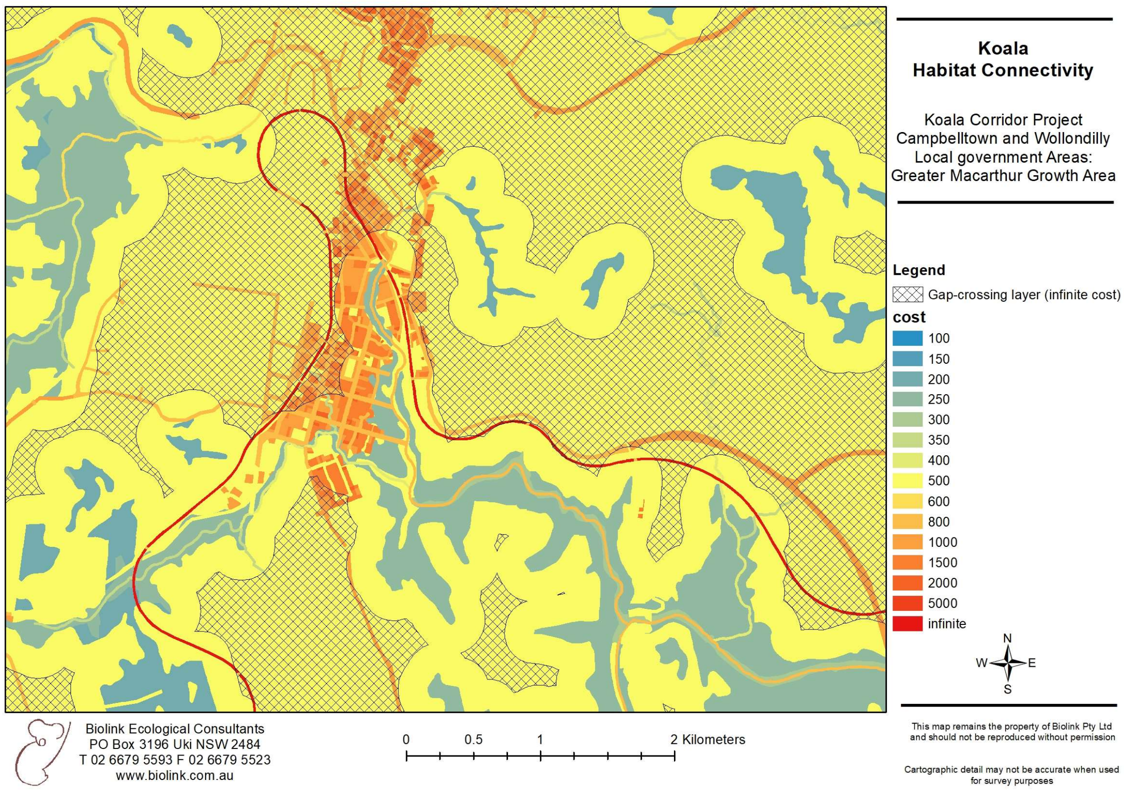

Figure 2: The area south of Picton coded to reflect a variety of cost metrics relating to koala movement/dispersal. The cross-hatched and orange/red areas represent infra-structure and/or land surfaces that are difficult for koalas to traverse whereas low cost (blue) offer relatively easier traverses. Note that the area is costed for a range of land uses including vegetation type, agriculture, urban development, industry, transportation infrastructure and hydrology, among others. The thin red line represents a fenced train line with various areas where crossings may occur in orange. The gap crossing layer (in cross hatch) represents all those areas which are greater than 220 m from any mapped vegetation.

4.1. Baseline (*Status quo*)

The baseline (*status quo*) cost-dispersal surface for the study area is presented in **Figure 3**, with *GraphHab* output for the same area illustrated in terms of landscape components, associated habitat patch networks and least-cost pathways in **Figure 4**. At the 10 ha habitat patch scale of analyses, output determined that the study area functioned as seven discrete landscape components collectively comprised of 218 identifiable habitat patches notionally connected by 476 least-cost pathways. The largest landscape component comprises the entire south and the north-east of the study area, incorporating the GMGA and the development footprint of the FPSP, with the exception of the very north-west of the FPSP, near Camden south, and western portions of the Great Sydney Orbital and the train line. Within those parts of the study area intersecting with the GMGA, there are 36 habitat patches and 69 least-cost dispersal pathways. **Figure 5** displays this output at a higher resolution for the area surrounding Appin Road, which is crossed by four least-cost pathways as follows: (1) immediately south of Rosemeadow South in the vicinity of the Noorumbah Reserve, (2) at the Beluah Biobanking site, (3) at Ousedale – Mallaty and (4) directly north of Appin township. For comparison purposes, **Table 1** summarises the baseline (*status quo*) output GAP CLoSR metrics for the study area based on three different minimum PKH patch sizes. The highest number of potential movement pathways, and thus greatest flexibility for planning purposes, are identified by considering all areas of PKH to a minimum patch size of 10 ha.

Table 1. Baseline (*status quo*) GAP CLoSR connectivity attributes and associated elements (components, patches and pathways) identified on the basis of 10-ha, 20-ha and 50-ha minimum patch sizes and required access to correspondingly sized patches of Preferred Koala Habitat throughout the study area.

Connectivity Attribute / PKH Patch size	(10 ha)	(20 ha)	(50 ha)
Landscape Components	7	6	4
Habitat patches	218	134	68
Least-cost dispersal pathways	476	273	129

The relative importance of PKH patches across the study area, as defined by the graph-metrics generated by *GraphHab* (d-IIC scores), identifies the PKH area between Kentlyn, Wedderburn and Appin as the largest and most consolidated in terms of the long-term management of the GMGA (**Figure 6**). The associated d-IIC scores express the value of each habitat patch as serving a linkage function with higher d-IIC scores expressing the incrementally greater importance of a habitat patch to overall connectivity. Within this habitat patch network, the Beulah biobanking site and adjoining habitat to the east along Appin Road is identified as the most important in a local context (patches along the east of Appin Road, d-IIC = 0.0934, d-IIC = 0.0658; patch at Beluah d-IIC = 0.0088). East-west connectivity also occurs through the Noorumba Reserve (d-IIC = 0.0037) and Mallaty's Creek (d-IIC = 0.0026). Two habitat patches further to the west in the vicinity of Menangle, which the Beluah, Noorumba and Mallaty patches all connect with, also receive high scores (d-IIC = 0.0122, d-IIC = 0.0078). Further to the south, habitat to the west of Appin township provides additional east-west connectivity (d-IIC = 0.0166). All the aforementioned d-IIC scores illustrate the value of each habitat patch to overall connectivity. In addition to this, the linkages themselves are also scored, according to how their presence or absence impacts upon local and regional connectivity. The d-IIC scores for east-west linkages from the large habitat patches in the east, through Noorumba, Beluah, Mallaty and Appin are d-IIC = 0.0009; 0.0018; 0.0006; 0.0058 respectively. These linkage pathways are illustrated in **Figure 6**. Graph-metrics for the entire study area are illustrated in **Appendix 4**, where at a more regional scale beyond the GMGA and FPSP, large habitat networks to the south and south-west are identified as having both high patch capacity (based on habitat patch size, represented by circle size) and importance to the overall linkage of the region (represented by colour; **Appendix 4).**

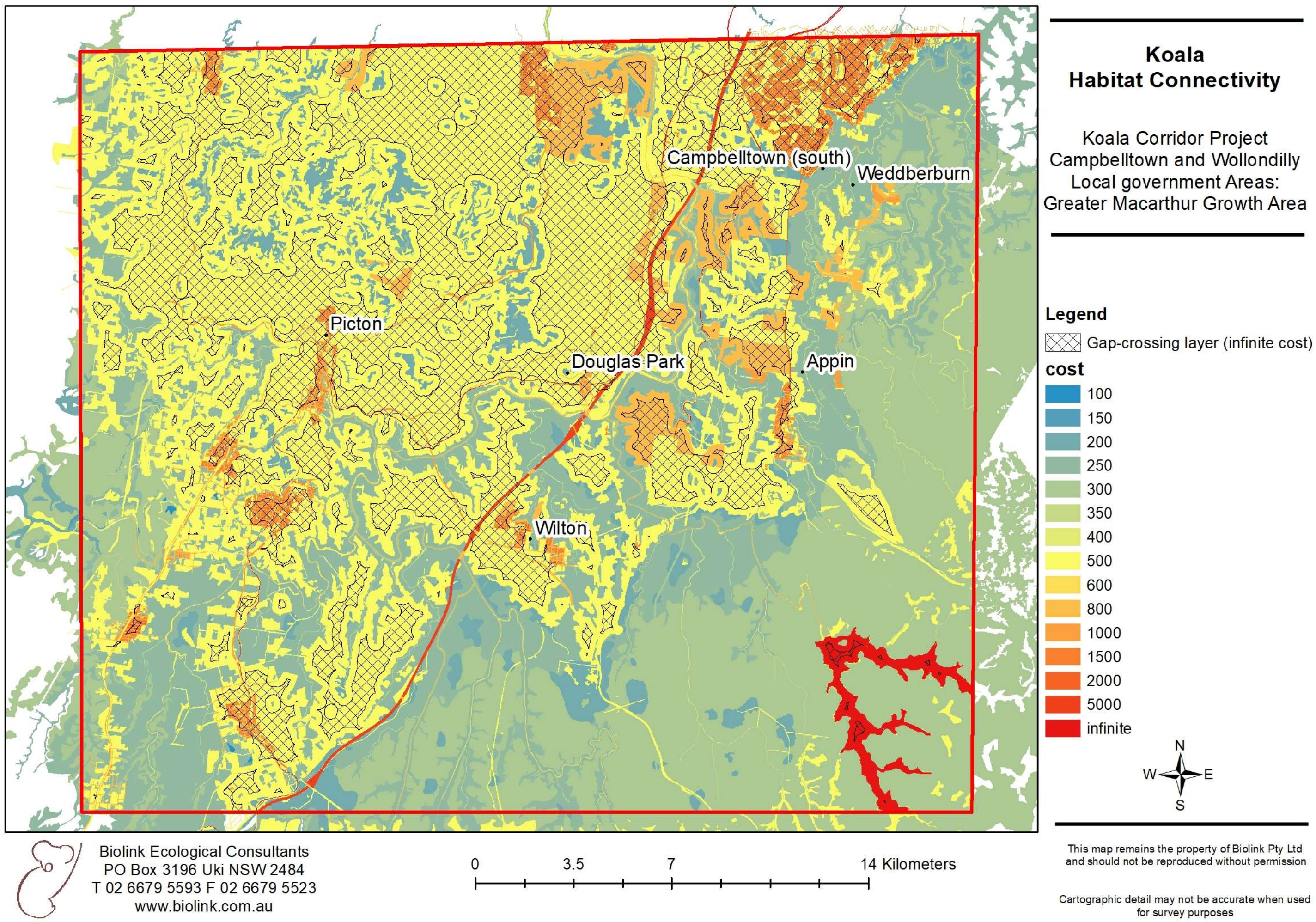

Figure 3: Cost dispersal surface for the Campbelltown – Wollondilly study area

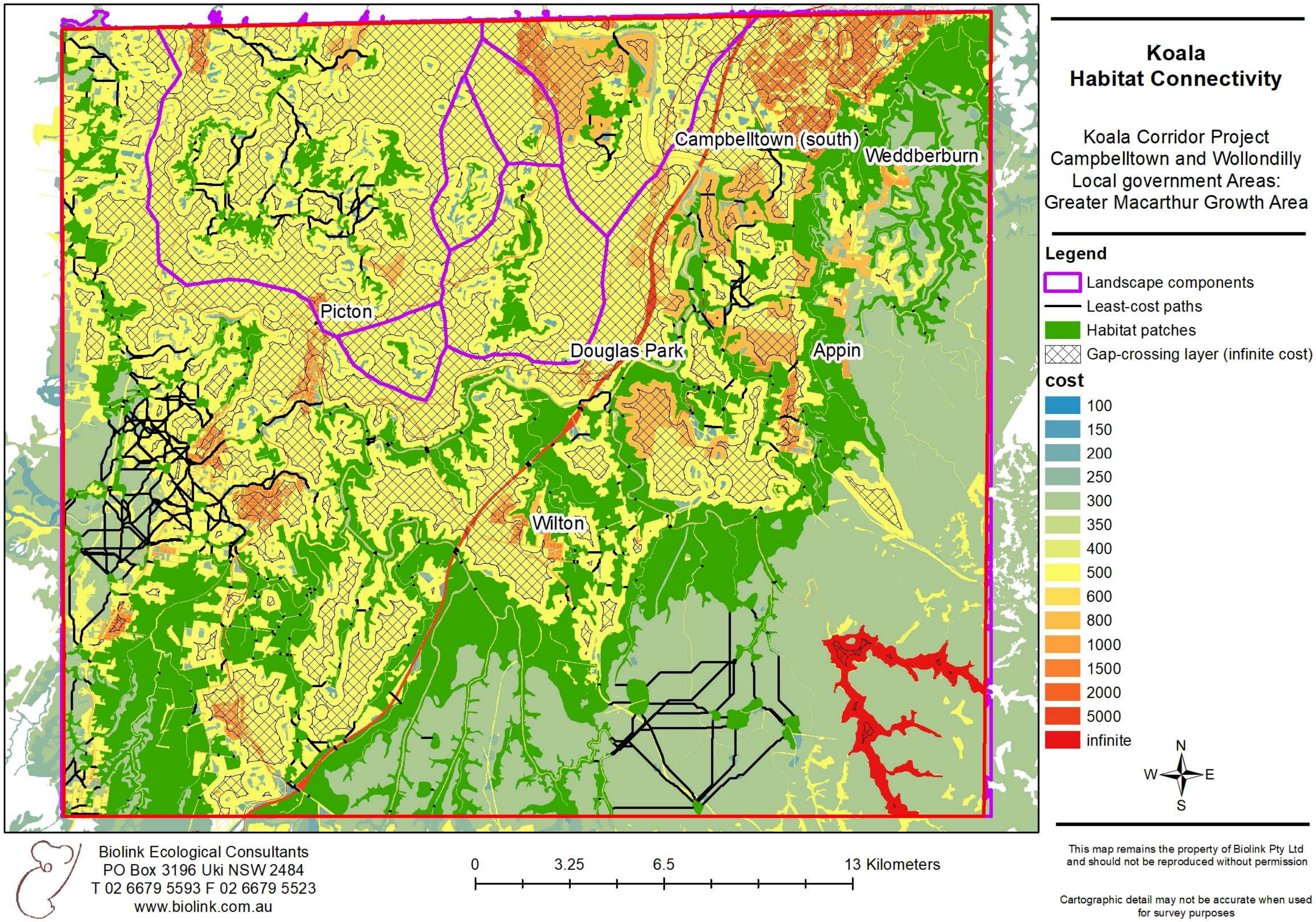

Figure 4: The study area comprises seven landscape components consisting of 218 habitat patches (10 ha minimum size) connected by 476 least-cost pathways.

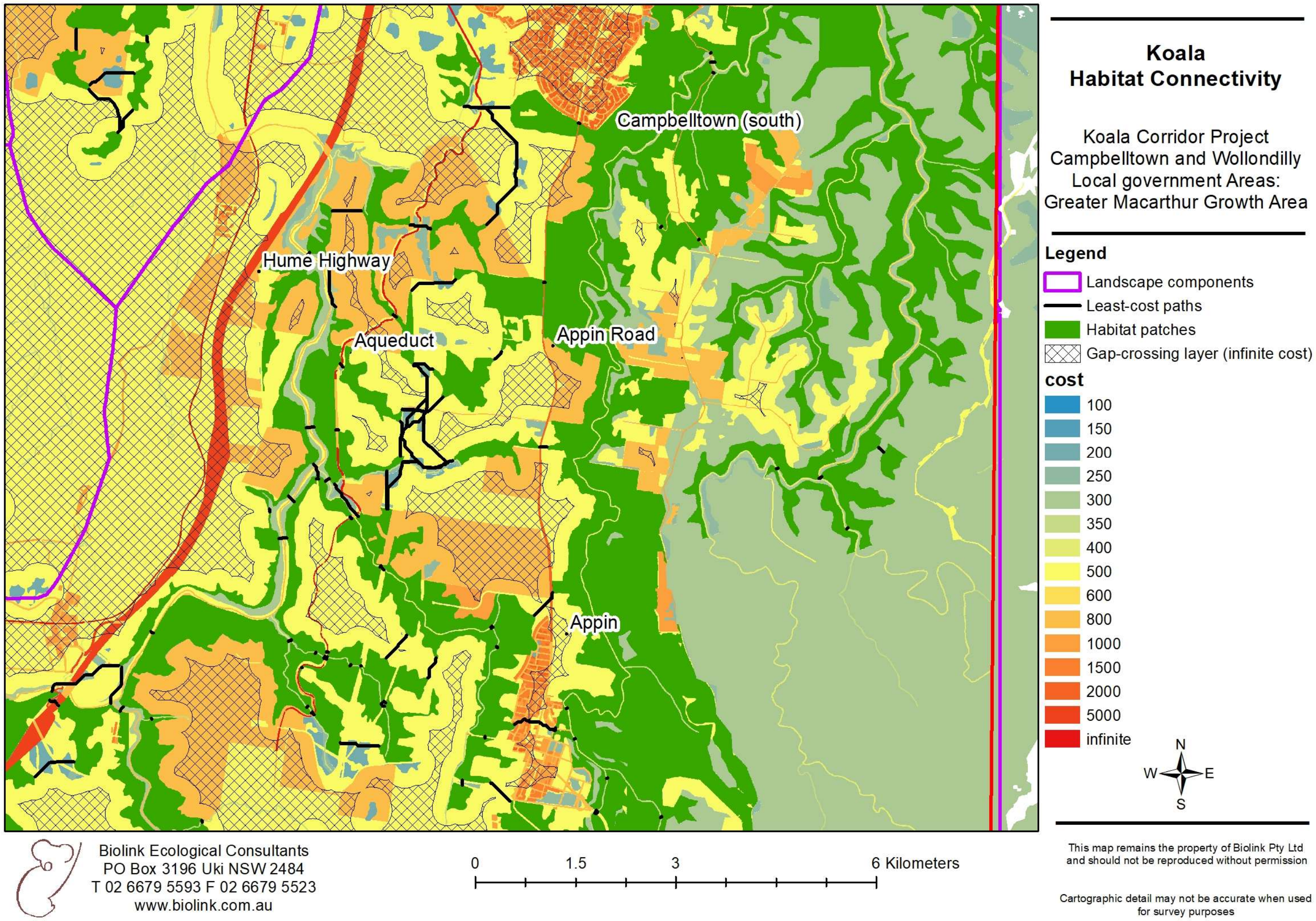

Figure 5: Higher resolution of habitat connectivity in the area surrounding Appin Road - seen as a dark orange line (2000 cost), running from South Campbelltown to Appin. It is crossed by four least-cost pathways; (1) directly south of Rosemeadow South, (2) the Beluah biobanking site, (3) Ousedale-Mallaty's Creek and (4) just north of Appin township.

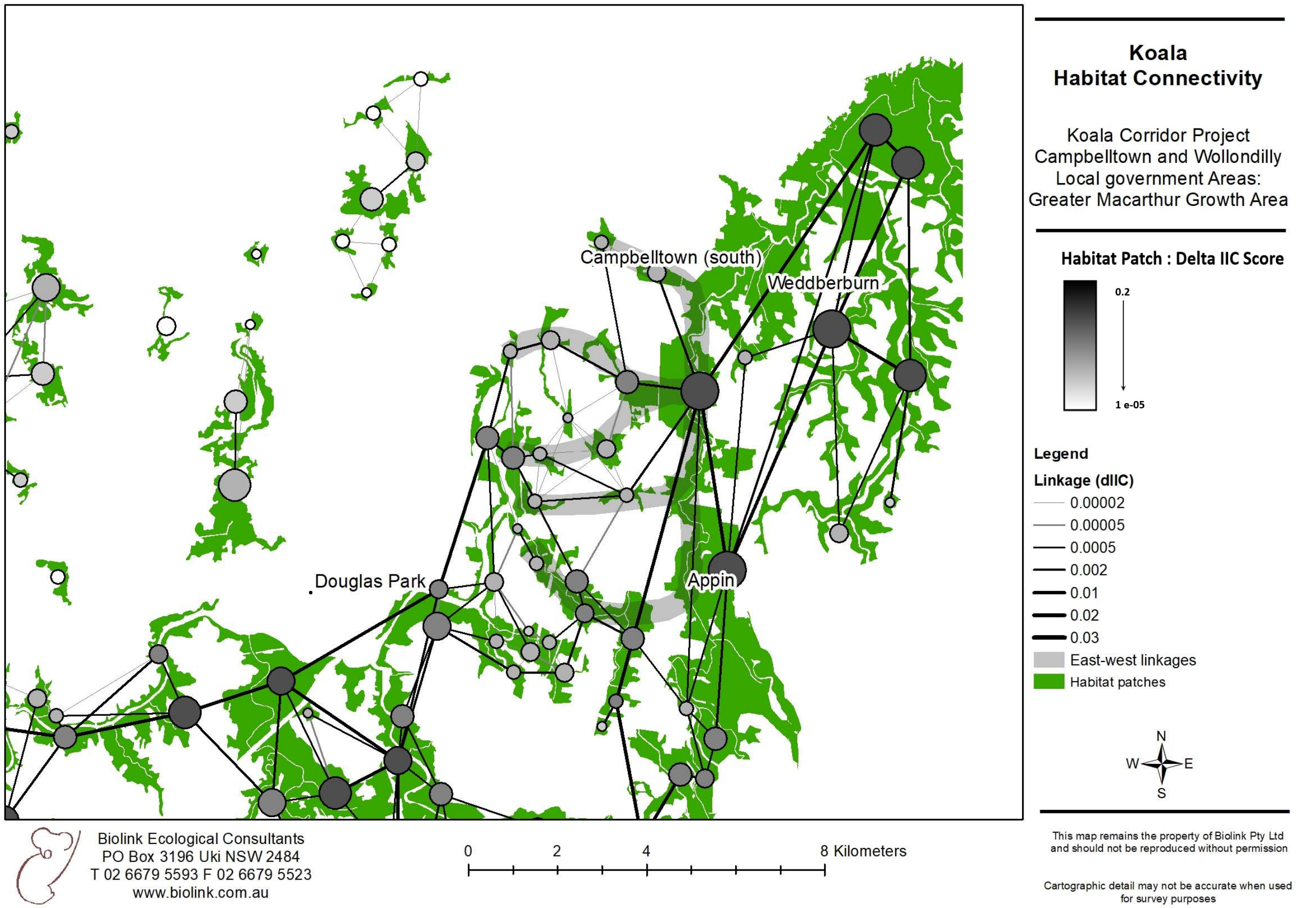

Figure 6: Baseline delta-Integral Interconnectivity (dIIC) graph-metrics and associated scores and weightings for habitat patches and linkages for the area to be impacted by the FPSP and associated upgrading of Appin Road. This metric characterises the importance of patches and linkages to the network and is computed by measuring the effects of patch / linkage removal to overall connectivity. Habitat patches are represented by circles with the most important patches, in terms of their contribution to overall connectivity, shown in the darkest shade (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. Areas over-shaded in grey show indicative linkages of relevance to GMGA.

Scenario 1 – *The FPSP footprint including Appin Road as a multi-lane dual carriage way, fenced on the eastern side.*

The cost-dispersal surface for the study area inclusive of the FPSP and an Appin Road upgrade fenced only on the eastern side is presented in **Figure 7**, while *GraphHab* output for the same area is illustrated in terms of landscape components and associated habitat patch networks and notional least-cost pathways in **Figure 8**. At the 10 ha habitat patch scale of analyses, output determined that the study area continues to function as seven discrete landscape components collectively comprised of 208 identifiable habitat patches connected by 405 least-cost pathways. Compared to the baseline scenario, at the regional scale this scenario results in a 5% loss of patches and a 15% loss of pathways. The largest landscape component is similar to the baseline scenario, incorporating the development footprint of the FPSP and now extending slightly further to the north-west. Within the GMGA however, there are 38 habitat patches and 44 least-cost paths, with implementation of the FPSP and the Appin Road upgrade fenced only on the eastern side resulting in a 5.55% increase in the number of habitat patches but a 36.23% loss of pathways. The increased number of habitat patches directly pertains to the most north-westerly portion of the FPSP footprint, where areas mapped as "Environmental Conservation to be Confirmed" comprise lands that were not included in the baseline considerations. Pathways are lost throughout the development footprint, with the highest concentration lost from the area between Mallaty's Creek and Beluah. **Figure 9** displays this output at a higher resolution for the area surrounding Appin Road, which has seen the loss of the three least-cost pathways at the Beluah Biobanking site, at Ousedale – Mallaty, and directly north of Appin township. Depending on exactly where the Appin Road upgraded commences in the north, a further crossing that currently enables access by koalas to the Noorumba Reserve may also be lost. **Table 2** summarises the Scenario 1 output GAP CLoSR metrics for the study area.

Table 2. Full implementation of structure plan that includes Appin Road as a multilane dual carriageway fenced on the eastern side. Results are for 10 ha minimum patch sizes. Figures in brackets are initial baseline (status quo) values derived from Table 1.

Connectivity Attribute	No. Elements
Landscape Components	7 (7)
Habitat patches	208 (218)
Least-cost pathways	405 (476)

Scenario 2 - *The FPSP footprint with Appin Road as a multilane dual carriage way, fenced on eastern side with a crossing at Ousedale-Mallaty corridor.*

This scenario results in little change to that predicted above, the primary difference being the restoration of a single pre-FPSP least-cost pathway at Ousedale – Mallaty. **Figure 10** displays the *GraphHab* output at high resolution for the GMGA inclusive of the FPSP and an Appin Road upgrade fenced only on the eastern side but with a crossing at Ouesdale – Mallaty. **Table 3** summarises the Scenario 2 output GAP CLoSR metrics.

Table 3. Full implementation of structure plan that includes Appin Road as a multilane dual carriageway fenced on the eastern side, with a crossing at Ousedale-Mallaty. Results are for 10-ha minimum patch sizes. Figures in brackets are initial baseline (*status quo*) values derived from Table 1.

Connectivity Attributes	No. Elements
Landscape components	7 (7)
Habitat patches	208 (218)
Least-cost pathways	406 (476)

Figure 11 illustrates changes to the d-IIC graph-metric output arising from implementation of the FPSP with a crossing at Ousedale Mallaty, while Table 4 summarises associated changes in terms of d-IIC metric values. The most evident change following implementation of the FPSP is the isolation of the Beulah biobanking site and a redundancy of its current connectivity role which in turn, renders problematical the functioning of remaining linkages which will otherwise be required to be fed from the west, while the removal of crossing opportunity at the Beulah location additionally creates one or more pathway bottlenecks. This situation will become exacerbated if the crossing at Noorumba Reserve is also compromised.

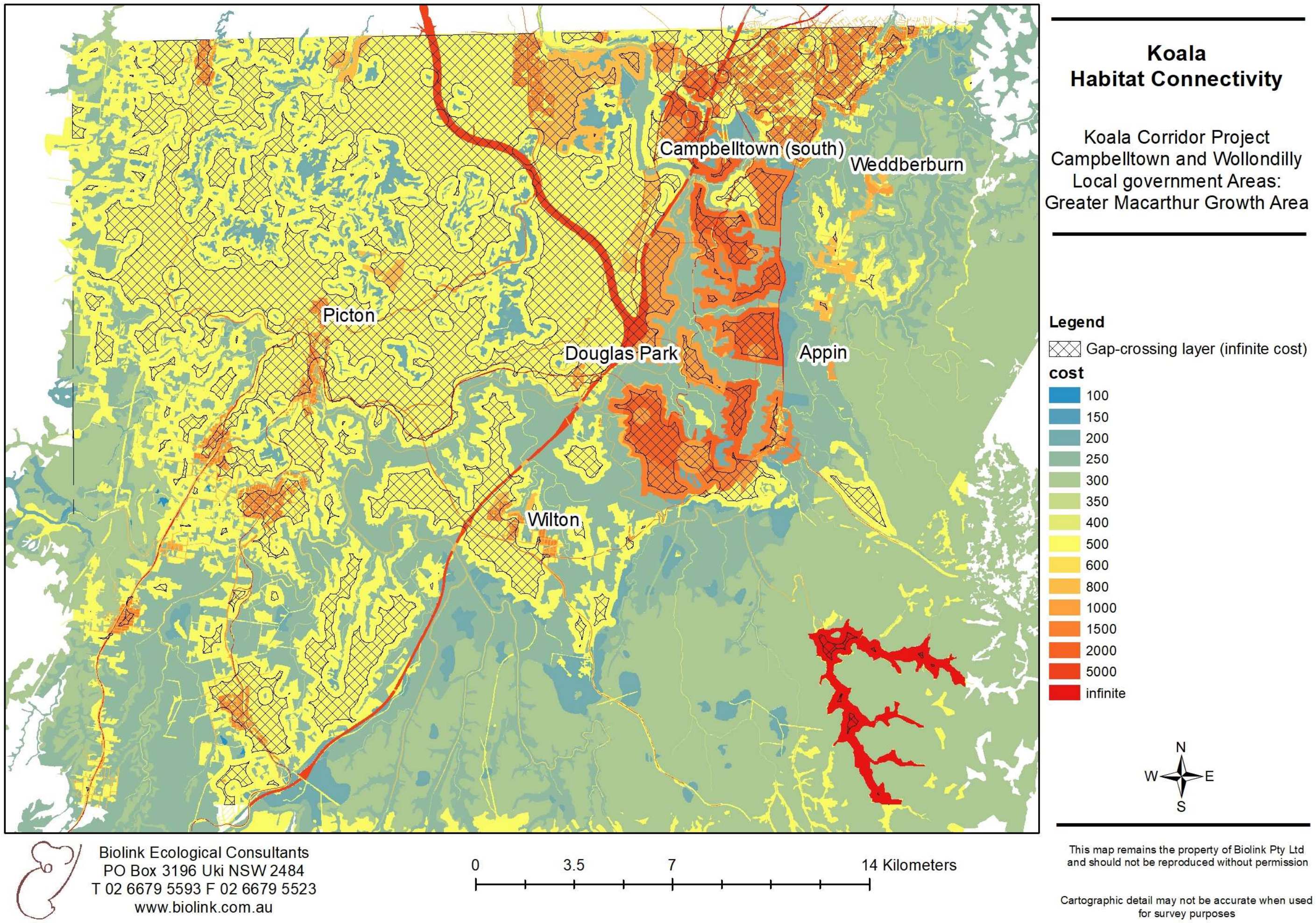

Figure 7: Cost dispersal surface for the Campbelltown – Wollondilly study area under Scenario 1 (FPSP plus Appin Road exclusion fenced).

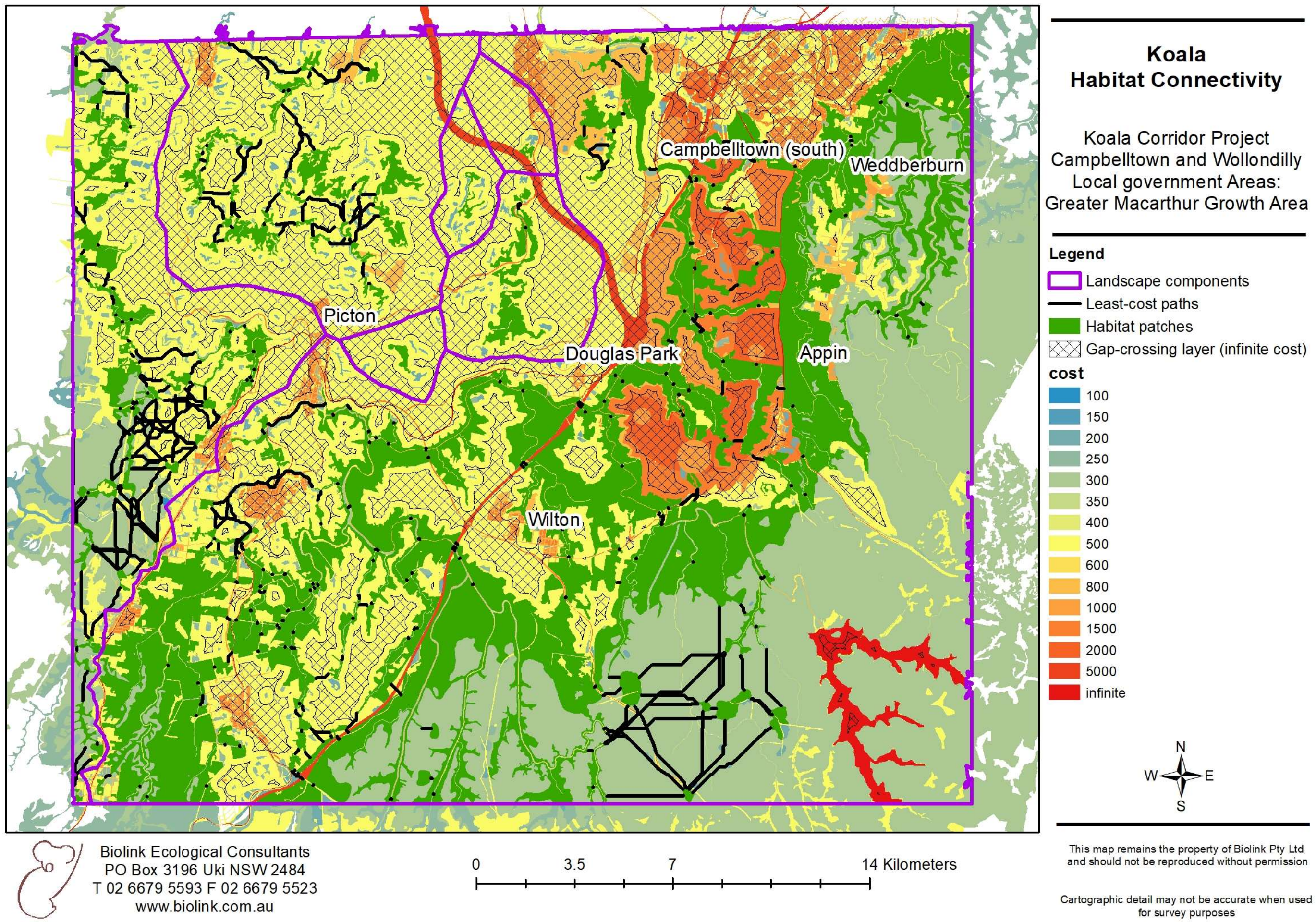

Figure 8: Under Scenario 1, the study area comprises seven landscape components consisting of 208 habitat patches (10 ha minimum size) connected by 405 least-cost pathways. Habitat connectivity in the Appin Road alignment-and development footprint is impacted at the local and regional scale through the loss of 10 habitat patches > 10 ha and 71 least-cost pathways.

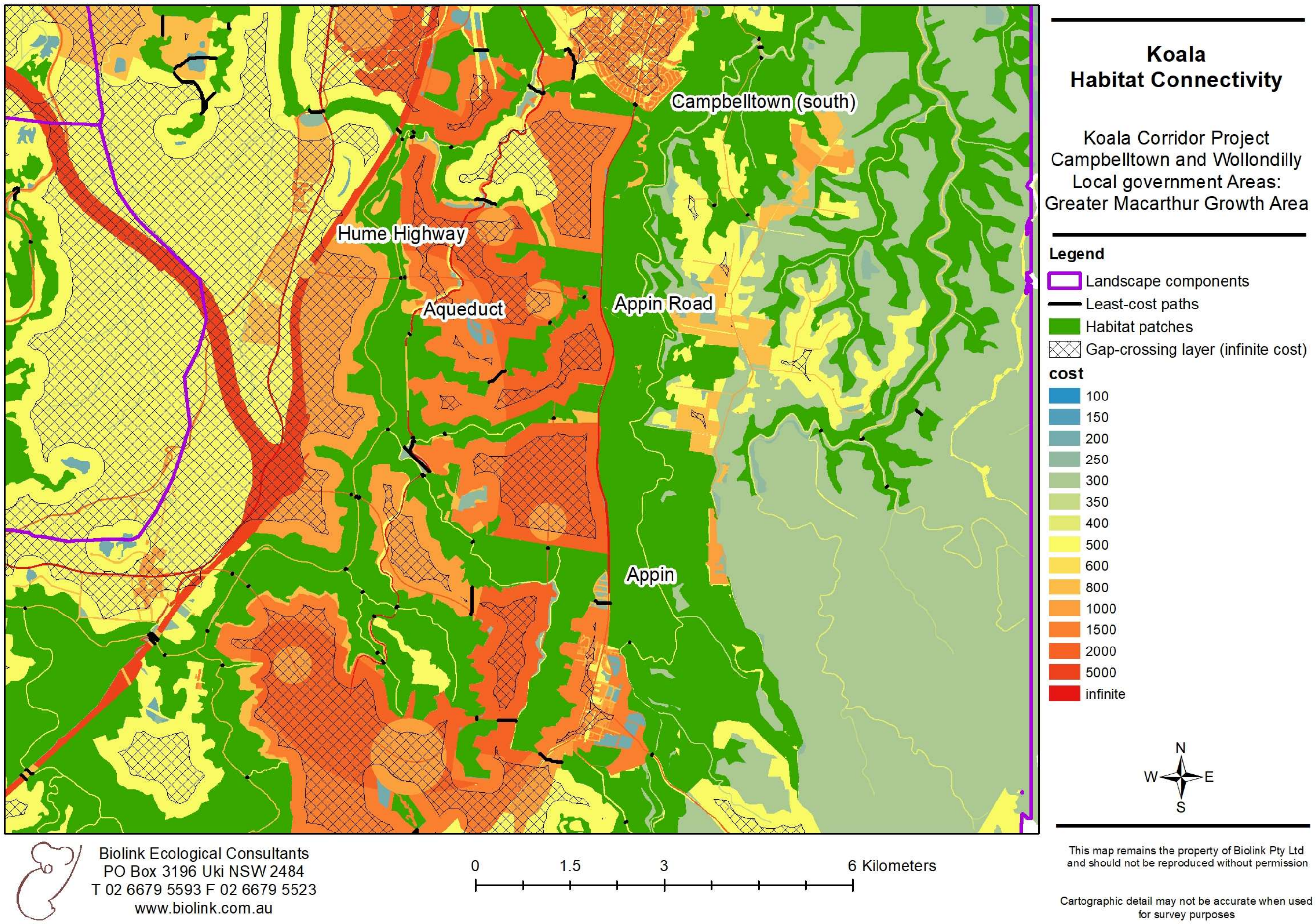

Figure 9: Higher resolution of habitat connectivity under Scenario 1 in the area surrounding Appin Road - seen as a red line (infinite cost), running from South Campbelltown to Appin. Habitat connectivity is impacted at the local scale through the loss of two key east-west linkages (Beleuah biobanking site and Ousedale-Mallaty's Creek) and the movement of one linkage further to the south, from north of Appin to moving through the township itself. Connectivity is maintained at regional scale.

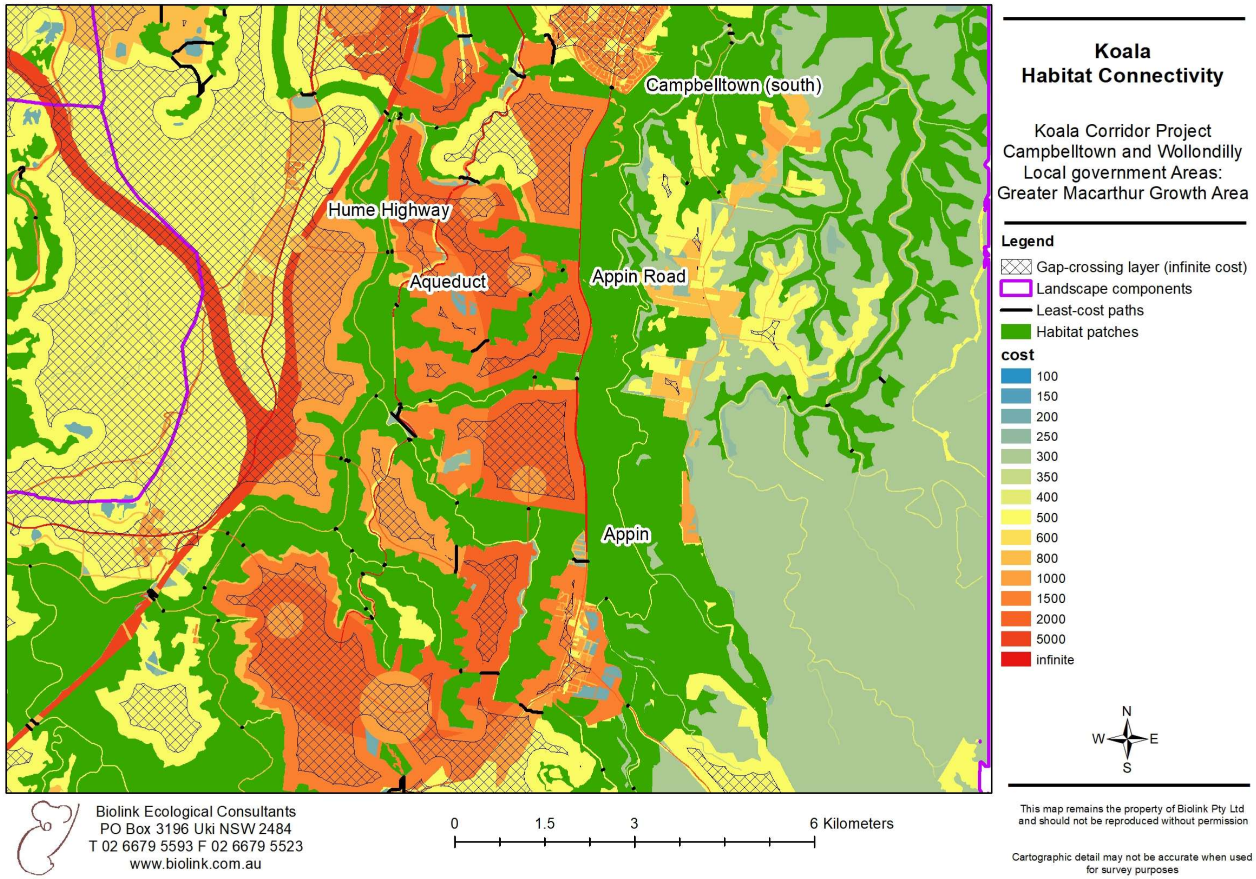

Figure 10: High resolution of habitat connectivity under Scenario 2 in the area surrounding Appin Road - seen as a red line (infinite cost), running from South Campbelltown to Appin, with a 100 m wide, vegetated crossing at Ousedale-Mallaty's Creek. A pathway is formed at this crossing, seen roughly half way between Campbelltown (south) and Appin, increasing the total number of pathways by one, to 406. All other factors remain unchanged from Scenario 1.

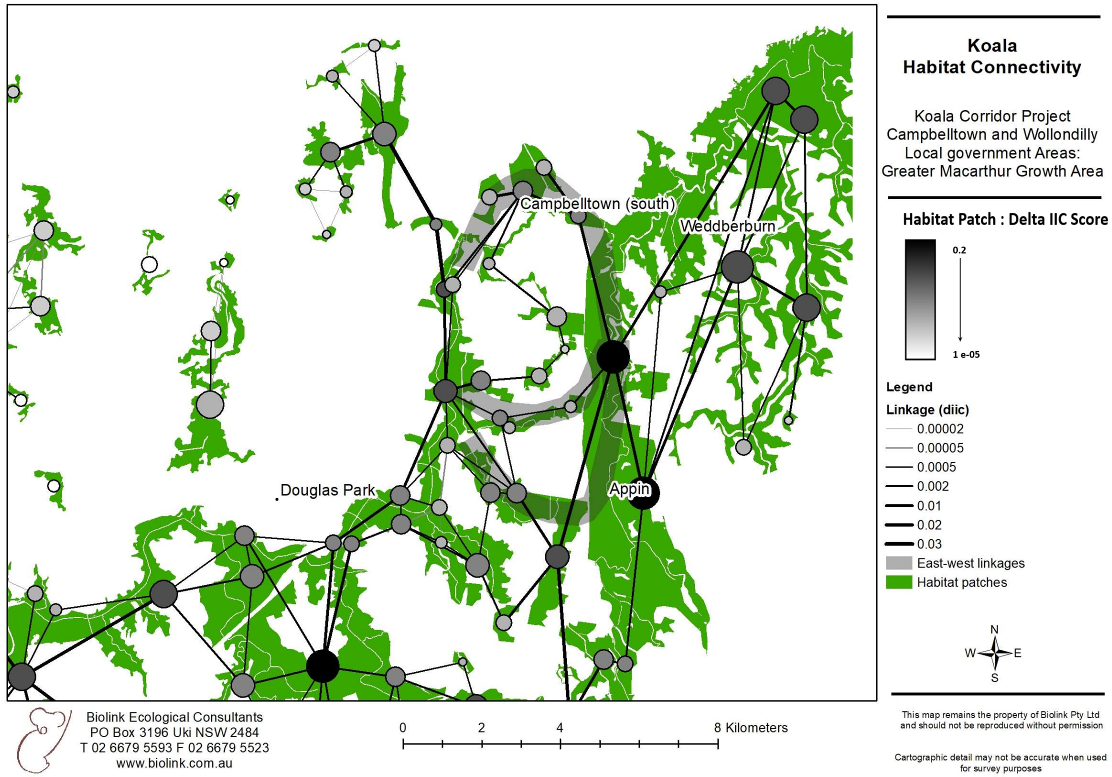

Figure 11: delta-Integral Interconnectivity (dIIC) outcomes for habitat patches and associated linkages for the area to be impacted by the FPSP and associated upgrading of Appin Road according to Scenario 2. This metric characterises the importance of patches and linkages to the network and is computed by measuring the effects of patch / linkage removal to overall connectivity. Habitat patches are represented by circles with the most important patches, in terms of their contribution to overall connectivity, shown in the darkest shade (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 straight-line, shortest Euclidian distance between two patches. Areas over-shaded grey show indicative linkages of relevance to GMGA.

Table 4. Changes in d-IIC metrics resulting from implementation of FPSP and the associated upgrading of Appin Road, with a crossing at Ousedale-Mallaty (Scenario 2). Higher scores represent a larger contribution to connectivity.

	d-IIC scores	Baseline (status quo)	Scenario 2
Habitat patches	Noorumba	0.0037	0.0106
	Beluah	0.0088	0.0048
	Mallaty	0.0026	0.0028
	Appin	0.0166	0.0386
East-west linkages	Noorumba	0.0009	0.0057
	Beluah	0.0018	n/a
	Mallaty	0.0006	0.0009
	Appin	0.0058	0.0179

5. Discussion

This project utilised a specialised spatial analysis and analytical framework GAP CLoSR to examine aspects of landscape connectivity related to the longer-term conservation and management of free-ranging koala populations in key parts of the CCC and WS LGAs that will become the subject of increased development pressure arising from progressive urbanisation and associated road works within the southern portion of the GMGA. We foresee that the value of such an approach is that it provides an initial means of identifying habitat patches with high value for maintaining overall connectivity and associated non-habitat linkage areas in an otherwise fragmented habitat matrix. Through the process of identifying the locations of least-cost dispersal pathways, output identifies locations that represent best practice ecological and planning investment by characterizing the most appropriate areas for consolidation and/ or rehabilitation.

One of the underlying assumptions of the GAP CLoSR approach is the notion of 100% occupancy by the focal species, in this case the koala. 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 koala 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, Biolink (2017) promoted an optimal buffer / 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 the 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.

Following submission of our initial draft report it was suggested that we should not discount vegetation communities on sandstone as koala habitat. In considering this request we determined that vegetation communities on sandstone had not been discounted, but for the most part neither were they preferred koala habitat (PKH) for the following reasons:

a) In order for a vegetation community to qualify as PKH it must contain Preferred Koala Food Tree species (PKFTs). Based on our review of community descriptions and floristic attribute tables associated with each of the contributing mapping reports, the majority of communities on sandstone do not contain PKFTs and hence the correct classification for koala management purposes is as 'Other' vegetation (or Low Quality Habitat as the case may be). The presence of 'Other' vegetation is however considered for the purpose of creating a cost-dispersal surface, the associated cost metric marginally higher than that of Secondary (C) Class habitat as defined in this report, and

b) Given the extent of Other / Low Quality Habitat and its lack of association with data relating to occupancy and/or habitat use by koalas within the study area, to include 'Other' vegetation as PKH would be to both disregard available data / knowledge and unduly force graph-metrics such as that associated with the d-IIC determinations into arguably erroneous output.

Based on a minimum patch size of 10 ha, baseline GAP CLoSR analyses indicated that the study area currently functioned as seven discrete landscape components comprised of 218 habitat patches that were connected via a notional network of 426 pathways, within which the GMGA was identified as functioning as a single landscape component. Graph-metrics identified a key linkage along both sides of the Georges River between Appin and Campbelltown South / Wedderburn, from which connectivity between the Georges River corridor and the Nepean River is centrally affected primarily through the Beulah biobanking site and Mallaty's Creek linkages. Predictably perhaps, implementation of the FPSP was determined by analyses to have a negative effect on connectivity outcomes at the local scale, most notably in the Beluah locality. Baseline (*status quo*) graph-metrics for the GMGA unambiguously identify this locality as important in terms of accommodating east-west connectivity at the local and regional landscape level of resolution. We again reiterate our earlier advice that this knowledge mandates the need for a revised FPSP and associated planning approach that seeks to minimise the loss of connectivity within that area of the GMGA between Rosemeadow South and Appin village to the maximum extent possible. The final design solution for the Appin Road upgrade is thus of fundamental importance to future koala conservation outcomes.

In its current state Appin Road clearly bisects an area that is the focus of increasing numbers of east/west koala movements, the numbers of animals known to have already been killed along this road likely representing less than half of the real number. The fencing of Appin Road along the eastern side only so as to create a barrier to east-west koala movement reflects neither best practice nor makes ecological sense given that it will have no material effect in terms of reducing koala road-kill numbers. *GraphHab* output indicates the loss of three locally significant dispersal pathways under Scenario 1 and two pathways under Scenario 2. At the local scale this cost should be considered as ecologically significant given that fencing will create a barrier approximately 6 km in length immediately abutting a large patch of high-quality habitat, against which dispersing koalas from both directions will be required to navigate. In addition to an increased potential for vehicle-strike, the fence will result in high levels of agonistic interactions along the length of the fence as dispersing koalas encounter resident animals. There is also the chance of creating higher levels of domestic dog attack, disease and other misadventure issues at either end where dispersing koalas will be required to traverse urbanized areas in order for connectivity and genetic exchange to be maintained, or otherwise enter the road reserve where they will in all likelihood be killed by vehicle-strike.

The d-IIC scores associated with enforced pathways that remain at either end of the fence indicate that the loss of linkages through Beluah (and potentially Ousedale-Mallaty) creates a greater dependence on pathways to the north and south of the road upgrade. Consideration of a fence along the eastern side only warrants further discussion in terms of cost effectiveness and likely efficacy. Amongst other things, it assumes that all koala movement is unidirectional (*i.e*. from east to west) when, given the presence of populations in the west this is not the case. Again, it had been suggested to us that we might consider including in our discussion that such an outcome (*i.e*. a fence on the eastern side of the road only) might be better for koalas than no fence on the road. We do not support this assertion for the following reasons:

a) Studies have demonstrated that fences function to impede the movement of koalas but typically work best when installed in conjunction with crossing structures such as underpasses or overpasses, reinforced by the installation of koala-grids at fence ends and intersections to reinforce the exclusion principle,
b) Studies have demonstrated that Koalas encountering fences will travel along them until an opening is located, whereupon a crossing attempt will be attempted. This means that in the absence of measures to enforce the exclusion principle, vehicle-strike clusters will occur at the ends of the fencing,
c) Koalas also occur to the west of Appin road. If moving from west to east, they will become trapped in the road corridor where they will be susceptible to vehicle-strike.
d) A fence along one side of the road only will give no effect to a crossing at Ouesdale – Mallaty beyond providing another access point onto the road for koalas dispersing from the east.

Assuming that the FPSP incorporates lands identified (but not confirmed) for Environmental Protection and areas identified as urban footprint capable land that has been changed to conservation, there will be no net loss of habitat patches within the GMGA. Within the same boundary however, GAP CLoSR identifies a 36.23 % loss of pathways. These lost pathways occur through-out the GMGA but are most concentrated between the Beluah biobanking site and at Mallaty's Creek. Under both Scenarios 1 and 2, the direct east-west passage of koalas to Beluah is cut-off by the Appin Road upgrade and continued connectivity relies on pathways to the north via Noorumba (as discussed above) and to the south via Mallaty's Creek, where pathway loss is the most pronounced. This places the continued value of the Beluah biobanking site under some provision.

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 bio-banking 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. Fencing along both sides of Appin Road along with other measures that reinforce the exclusion objective will be required to effectively manage connectivity and deal with the issue of vehicle-strike.

The results of this project imply that some consideration could be given to a re-evaluation of the scale of the final FPSP footprint so as to give some effect to the outcomes in terms of consolidating key linkage areas to the west of Appin Road. The preservation of key linkages and effectively integrating associated dispersal pathways into the development footprint is required to achieve this outcome.

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