A scientific approach to developing habitat rehabilitation strategies in aquatic environments: A case study on the endangered Macquarie perch (*Macquaria australasica*) in the Lachlan catchment

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NON-TECHNICAL SUMMARY

A scientific approach to developing habitat rehabilitation strategies in aquatic environments: A case study on the endangered Macquarie perch (*Macquaria australasica*) in the Lachlan catchment

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NON TECHNICAL SUMMARY:

Macquarie perch (*Macquaria australasica*) is a medium sized upland fish native to the southern catchments of the Murray-Darling Basin. Populations have declined substantially in range and abundance since the mid 1900s and the species is classified as endangered. Habitat degradation has been identified as one of the causes of population decline. Habitat protection at sites occupied by remnant populations, and the rehabilitation of degraded habitats in river reaches that isolate population fragments should be a central component of recovery plans for Macquarie perch. Although some data are available on the habitat occupied by Macquarie perch, there are two reasons why further information is required. Firstly, there is insufficient detail in the generally qualitative habitat description to guide habitat rehabilitation activities. Secondly, the data that are available only represent a very small proportion of the total distribution of Macquarie perch. Therefore, further analyses that quantify the habitat needs of Macquarie perch, and mapping activities that describe the distribution and abundance of those habitat features should be an integral first step in targeted habitat rehabilitation projects. The upper Lachlan catchment provides the most suitable location to study the habitat associations of Macquarie perch as it contains potentially the most abundant, widespread and regularly recruiting remnant population within the New South Wales portion of the Murray-Darling Basin. Further, it has a continuous length of ~500 km of waterways with uninterrupted fish passage representing a broad range of values for most aquatic habitat variables and a broad range of levels of habitat disturbance, from minimally disturbed to heavily degraded.

We sampled fish communities at 42 sites dispersed throughout the Abercrombie and Lachlan Rivers within the Lachlan catchment upstream of Wyangala Dam. Additionally, 37 habitat variables were mapped along a continuous 125 km reach of the Abercrombie River, a continuous 156 km reach of the Lachlan River, a continuous 91 kms of the Crookwell River, a continuous 33 kms of Blakney Creek and at six discontinuous 1 km reaches within Lake Wyangala, a large impoundment flooding the confluence of the Abercrombie and Lachlan rivers. Habitat variables were quantified at the 1 km reach scale. Macquarie perch – habitat associations were successfully modelled using an Artificial Neural Network (ANN) approach using half of the fish sampling sites to train the ANN model and the other half of the dataset to validate the model outputs. The ANN approach produced consistent models estimating the pseudo-probability that Macquarie perch is

present at a 1 km reach scale and was able to accurately predict whether the species was collected or not at 85% of the reaches set aside to test the model.

Although Macquarie perch were not abundant, they were the most common large freshwater fish collected and the equal 2nd most widespread of ten native species collected from the Lachlan and Abercrombie Rivers. Just under half of the individuals collected were new recruits (young-of-year fish). Macquarie perch were more abundant and widespread in the mid reaches of the Abercrombie River than in the Lachlan River.

Only three of the 37 habitat variables were primarily important correlates of whether Macquarie perch is likely to occupy a reach or not. These are the area of run mesohabitat, number of small complex rock piles and area of riffle mesohabitat. Our analyses suggest that either a minimum area of run or riffle mesohabitat, or a minimum number of small complex rock piles are required to satisfy the habitat needs of Macquarie perch. Two other habitat variables were found to have equivalent relative contributions to that of riffle mesohabitat; the length of undercut bank and the number of large simple snags per kilometre. However, neither variable was found to be a primary driving variable. The length of undercut bank only influenced the probability of occupancy of Macquarie perch when the availability of run, riffle or small complex rock pile habitats are limiting, in which case an increasing length of undercut bank reduced the probability of occupancy. Although it had an equivalent relative contribution, we were not able to decipher the relationship between Macquarie perch occupancy and the number of large simple snags.

Despite some remaining uncertainty arising from limitations that typically affect species – habitat association modelling exercises such as this, based on the outputs of our model we propose the following refinement of the general description of Macquarie perch habitat:

Macquarie perch is a riverine fish most abundant in reaches > 200m altitude. The species is heavily dependent on the availability of flowing mesohabitats (runs and/or riffles) and small complex rock piles (aggregations of 0.5 – 1 m diameter boulders) to provide cover. Extensive lengths of undercut banks in reaches with low coverage of flowing mesohabitats or limited small complex rock cover are detrimental. Depth, substratum type, riparian vegetation cover and aquatic macrophyte cover have little influence on the probability that Macquarie perch will occupy a reach.

Based on the predictions of our ANN model, the Abercrombie River provides the most consistent and least fragmented Macquarie perch habitat within the upper Lachlan catchment. At the opposite end of the spectrum, neither the Crookwell River nor Blakney Creek provide suitable habitat conditions. The upper Lachlan River provides habitat conditions intermediate between these two extremes, with isolated sections of suitable habitat fragmented by substantial stretches of unsuitable habitat. These include reaches in the vicinity of Gunning – Dalton, the Narrawa Bridge and downstream of the Crookwell River junction. The habitat values of these reaches should be maintained in order to sustain the remnant populations known to occupy all but one of these reaches. On the premise that rehabilitation of degraded habitats is particularly relevant when it facilitates reconnection of isolated remnant populations, rehabilitation of those reaches that fragment these areas is likely to result in the greatest conservation outcome.

The highest priority habitat rehabilitation activities to restore or improve habitat quality for Macquarie perch are enhancing the area of flowing water mesohabitats and/or increasing the number of small complex rock piles in reaches where they are deficient. Flowing water mesohabitats can be enhanced by ensuring sufficient environmental water allocations where possible and/or through the restriction of wetted channel width in heavily eroded, broadened and sediment affected reaches (via stabilisation and revegetation works) to maximise the flow velocity within a reduced portion of the channel.

1. INTRODUCTION

Habitat degradation (or loss in extreme cases) is considered the most significant threatening process for many fish species (Cadwallader1978; Allan and Flecker 1993; Faragher and Harris 1994; Maitland 1995; Richter *et al.* 1997; Wilcove *et al.* 1998; Kearney *et al.* 1999; Ricciardi and Rasmussen 1999). The persistence of threatened species and ecosystems will depend on protecting those viable habitats that remain and their recovery will depend on rehabilitating those habitats that have been degraded (Argent *et al.* 2003; Bond and Lake 2003; Welch and MacMahon 2005; Rosenfeld and Hatfield 2006; Morán-López *et al.* 2006; Westhoff *et al.* 2006; Knight and Arthington 2008). Rehabilitation of degraded habitats is particularly relevant when it facilitates reconnection of isolated remnant populations.

The majority of current aquatic habitat rehabilitation programs are dependent on the addition of a limited suite of habitat features such as instream woody structures, the exclusion of domestic livestock and re-vegetation of riparian buffer strips. However, different aspects of habitat are important for different species, and different life stages of the same species may be dependent on different habitat features. Therefore, in order for habitat rehabilitation activities to restore or improve habitat quality and connectivity for a particular target species, those habitat features that are most limiting for the species of interest are the ones that need rehabilitation (or enhancement). In addition, they need to be rehabilitated to an extent that ensures the needs of all life stages of the target species are met. As examples, it would be inefficient to introduce 100 items of woody structure per kilometre if only 10 would provide adequate cover for the target species. Similarly, it would be of limited long-term benefit to add habitat features that provide habitat for adult individuals if spawning or nursery habitats were absent or inaccessible. Because of these factors, habitat protection and rehabilitation activities need clear guidance on what habitat parameters are limiting species recovery in terms of the habitability of a location, as well as information on the optimum quantity of habitat required to promote the abundance and recruitment potential of the target species (Harig *et al.* 2000; Rosenfeld 2003). Species-habitat association models can provide this guidance (Wang *et al.* 2003; Rosenfeld 2003; McCleary and Hassan 2008). In addition, they can also be used to forecast the effects of habitat alteration and changing land-use patterns (Oberdorff *et al.* 2001), provide estimates of habitat suitability for identification and prioritisation of release locations for captive-breeding reintroduction programs (Evans & Oliver 1995) and reveal potential additional populations of threatened species in poorly surveyed regions within their range (Olden and Jackson 2002*a*; Rosenfeld 2003).

Analyses that assess the habitat needs of a target species, and mapping activities that describe the distribution and abundance of those habitat features should be an integral first step in targeted habitat rehabilitation projects (Bond and Lake 2003). Unfortunately, if the target species happens to be threatened, it is highly likely that many populations collapsed prior to anyone developing detailed species-habitat association models and that those populations that remain are sparsely distributed and have a low abundance. Further, it is not known whether the remnant populations that persist do so in ‘islands’ of ideal habitat, or whether they have been forced to persist only in sub-optimal habitat conditions (Filipe *et al.* 2004; Welch and MacMahon 2005; Barry and Elith 2006; Ferreira *et al.* 2007). Together, these factors can make it difficult to develop the species-habitat models that would facilitate effective management responses for threatened species.

Macquarie perch (*Macquaria australasica* Cuvier 1830) is a moderately sized (maximum total length (TL) = 495 mm, (Douglas *et al.* 2002)) freshwater percichthyid fish native to the Murray-Darling Basin (MDB) in south-eastern Australia. Translocated populations also exist in Cataract Dam (and river) in the Hawkesbury-Nepean catchment and the Mongarlowe River in the Shoalhaven catchment of the south-eastern drainage division (Faulks *et al.* 2010) (Figure 1). Genetic analyses (Dufty 1986, Faulks *et al.* 2010) and morphological analysis (Dufty 1986) indicate that these translocated populations are distinctly different from the undescribed endemic species of perch native to these coastal NSW catchments (but also currently known as Macquarie perch). Within the MDB, Macquarie perch were formerly present from the lower reaches of the Murray River ~ 30 m ASL (Reid *et al.* 1997; Hammer *et al.* 2009), common in reaches from ~ 100 m ASL (Cadwallader 1982), abundant above ~ 200 m ASL (Lake 1967; Trueman 2007) and collected up to a maximum altitude of 1,100 m in the Murrumbidgee River (I&I NSW unpublished data). The species was historically present in the Macquarie, Lachlan, Murrumbidgee, Murray, Mitta Mitta, Kiewa, Ovens, Broken, Goulburn, Campaspe and Loddon catchments (Cadwallader 1982). Populations in the MDB have declined substantially in range and abundance since the mid 1900s (Lake 1971; Pratt 1979; Cadwallader 1982; Ingram *et al.* 2000; Trueman 2007). By the 1970s, Macquarie perch were considered to be seriously threatened with extinction (Lake 1971; Cadwallader 1978). Lake (1971) considered them one of the four most seriously threatened Australian freshwater fish. The species has continued to decline, with populations considered viable as recently as 2001 having since declined or disappeared. As a result, the species is currently listed as endangered nationally as well as in the three states and one territory in which it is distributed.

Habitat degradation (inundation by dams, siltation, river regulation, clearing of riparian vegetation, fish passage obstruction, cold water pollution), interactions with salmonids, redfin perch and other alien species, overfishing, disease and pesticides have been proposed as threatening processes for Macquarie perch (Wharton 1968, 1973; Lake 1978; Cadwallader and Rogan 1977; Cadwallader 1978; Cadwallader 1979; Cadwallader and Backhouse 1983; Ingram *et al.* 1990; Pollard *et al.* 1990; Lintermans 1991; Harris and Rowland 1996; Ingram *et al.* 2000; Allen *et al.* 2002; Lintermans and Osborne 2002; Lintermans 2007). In particular, several authors have singled out siltation as one of the greatest threats (Lake 1971; Cadwallader and Rogan 1977; Cadwallader 1978; Cadwallader 1982; Cadwallder and Backhouse 1983; Battaglene 1988; Harris and Rowland 1996). Sediment fills in deep holes, smothers spawning substrata and changes benthic macro-invertebrate community composition (Waters 1995). With habitat degradation having been identified as one of the key threatening processes for this species, habitat protection at sites occupied by remnant populations, and the rehabilitation of degraded habitats in river reaches that isolate population fragments should be a central component of recovery plans for Macquarie perch.

Authors of general descriptions of the species have described Macquarie perch as a riverine fish inhabiting cool upland streams, with a preference for deep holes, but requiring the presence of shallow (0.4 – 0.75 m) riffles or gravel beds with water velocities of between 0.3 and 1.0 m s^{-1} for spawning (Lake 1967; Wharton 1968; Cadwallader and Rogan 1977; Lake 1978; Cadwallader 1982; Cadwallader and Backhouse 1983; Battaglene 1988; Allen 1989; Harris and Rowland 1996; Allen *et al.* 2002; Lintermans 2002; Lintermans and Osborne 2002; Lintermans 2007). Battaglene (1988) added the preference for rocky holes, well shaded reaches and substantial cover to the general habitat description. However, the only published quantitative Macquarie perch habitat assessment is provided by Cadwallader (1979). That study reported that in Seven Creeks, Victoria, Macquarie perch were found to inhabit sites from 0.4 – 4.4 m deep, 4 – 50 m wide, 120 – 460 m altitude, stream gradients from < 0.8 to 200 m km^{-1}, on sand, bedrock or boulder (occasionally mud and gravel) substrata in 4th and 5th order streams. Aquatic vegetation was usually present at sites occupied by Macquarie perch, particularly *Phragmites*, and to a lesser extent *Eleocharis*, *Myriophyllum*, and *Triglochin*. Cover included large boulders, snags, and occasionally undercuts. Cadwallader (1979) reported that the abundance of Macquarie perch was highest in deep holes and a weir pool. Despite the fact that these data are available on the habitat occupied by Macquarie perch, there are two reasons why further information is required. Firstly, there is insufficient detail in the generally qualitative habitat description to guide habitat rehabilitation activities, e.g., How deep is deep enough? What is the maximum acceptable distance between riffle and deep pool habitats? What coverage of which substratum is optimal? What coverage of aquatic vegetation is required? And what is the minimum number of large boulders or snags required before Macquarie perch will occupy a site? Secondly, Seven Creeks represents only a very small proportion of the total distribution of Macquarie perch, and the habitats present within Seven Creeks are not necessarily representative of the broader range of habitats available to the species across its range.

Unpublished data collected since 2000 (D. Gilligan, I&I NSW Freshwater Fish Research Database) suggest that the population of Macquarie perch upstream of Wyangala Dam in the Lachlan and Abercrombie Rivers is the most abundant, widespread and regularly recruiting remnant population within the New South Wales portion of the MDB (Figure 1). Therefore, the major problem limiting field studies of the biology of threatened species, namely the lack of available study animals, is minimised within this population. Further, the continuous length of river with uninterrupted fish passage available to the remnant population represents a broad range of values for most aquatic habitat variables and a broad range of levels of habitat disturbance, ranging from minimally disturbed to heavily degraded. Although not covering the full range of all the aquatic habitat variables available to Macquarie perch across its entire distribution, the upper Lachlan catchment provides the best available system in which to study the habitat associations of this endangered species.

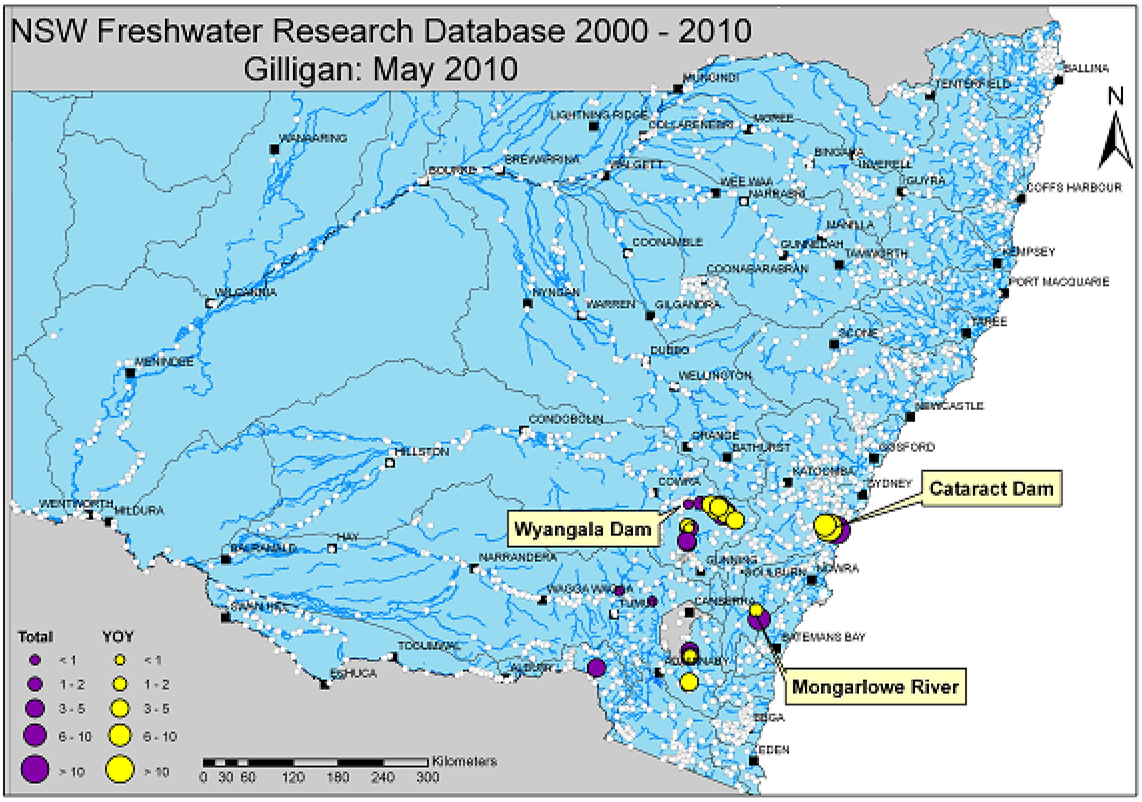

Figure 1. The catch per unit effort (catch per hour of electrofishing) of the Murray-Darling Basin form of Macquarie perch (*Macquaria australasica*) at sites within New South Wales between January 2000 and May 2010. White circles represent sites sampled where no Macquarie perch (Murray-Darling Basin form) were collected. Purple circles represent total abundance of all size classes of Macquarie perch and yellow circles represent abundance of young-of-year fish (smaller than 127 mm TL: Battaglene 1988). The size of the circle represents relative abundance as described in the legend at the bottom-left. Populations of the Murray-Darling Basin form of Macquarie perch in both the Hawkesbury (Cataract Dam) and Shoalhaven (Mongarlowe River) catchments are translocated (Faulks *et al.* 2010).

The development of a quantitative model to describe the species-habitat relationship for Macquarie perch within the upper Lachlan catchment allows us to move away from expert opinion and personal perceptions in describing their habitat requirements. Although conventional parametric multivariate linear or logistic regressions have been widely used to model species-habitat relationships (Manly *et al.* 2002; Morrison *et al.* 2006), they are limited in that only normally distributed and independent variables can be analysed (Rosenfeld 2003). Even commonly used non-parametric and multivariate analyses such as Principal Components Analysis (PCA) and Discriminant Function Analysis (DFA) are limited to modelling monotonic and smooth species-habitat relationships (Manly *et al.* 1993; Morrison *et al.* 2006). In contrast, newer multivariate modelling techniques based on machine learning, such as Classification And Regression Trees (CART)(De'ath and Fabricius 2000; Olden *et al.* 2008), evolutionary computation (D'Angelo *et al.* 1995; Olden *et al.* 2008) and Artificial Neural Network (ANN) analyses (Olden *et al.* 2008) can model non-linear relationships, threshold relationships and synergistic interactions between habitat variables. These characteristics make machine learning techniques particularly useful for modelling ecological systems and species-habitat relationships. Several published comparisons of these approaches with conventional modelling frameworks have found them to be more effective at predicting presence/absence based on a set of habitat variables (D'Angelo *et al.* 1995; Baran *et al.* 1996; Brey *et al.* 1996; Lek *et al.* 1996*a*; Lek *et al.* 1996*b*; Scardi 1996; Mastrorillo *et al.* 1997; Özesmi and Özesmi 1999). Further, Olden and Jackson (2002*a*) compared logistic regression, linear discriminant analysis, CART and ANN using simulated datasets exhibiting deterministic, linear and non-linear species response curves and the ANN approach out-performed the other modelling approaches, being better able to capture and model the complex non-linear patterns found in ecological data. ANN models have the added advantage that they are capable of modelling a dataset with a limited number of species records (Olden 2003; Barry and Elith 2006), as is typically the case for most threatened species. Although ANN models have been criticised for being 'black boxes' lacking explanatory power (Paruelo and Tomasel 1997; Lamouroux *et al.* 1999; Morrison *et al.* 2006), this has been largely dispelled by publications describing methods which allow inferences to be drawn regarding those habitat variables that drive the predictive outputs of the model, including neural interpretation diagrams, Garson's algorithm, sensitivity analysis and randomisation tests based on the product of axon connection weights (Lek *et al.* 1996*a*; Scardi 1996; Recknagel *et al.* 1997; Özesmi and Özesmi 1999; Olden and Jackson 2002*b*).

We aimed to develop a quantitative species-habitat model for Macquarie perch which would aid in the development of a habitat rehabilitation/enhancement program for the upper Lachlan catchment. We sampled fish communities at 42 sites dispersed throughout the Abercrombie and Lachlan Rivers within the Lachlan catchment upstream of Wyangala Dam. There were no fish passage barriers preventing perch from dispersing to any sampled location within the study system. Thirty-seven habitat variables were mapped along a continuous 125 km reach of the Abercrombie River, a continuous 156 km reach of the Lachlan River, a continuous 91 kms of the Crookwell River, a continuous 33 kms of Blakney Creek and at six discontinuous 1 km reaches within Lake Wyangala, a large impoundment flooding the confluence of the Abercrombie and Lachlan Rivers. Habitat variables were quantified at the 1 km reach scale. Macquarie perch-habitat associations were successfully modelled using an ANN approach using half of the fish sampling sites to train the ANN model and the other half of the dataset to validate the model outputs. Those variables which most influence the probability of Macquarie perch occupying a 1 km reach were identified using the product of axon weights method (Olden and Jackson 2002*b*). The ANN provides a predictive model of the probability of Macquarie perch occupying the 369 reaches that were mapped but where fish sampling data are unavailable.

2. METHODS

2.1. Study location

The Lachlan Catchment is a large drainage (84,700 km^2) located in central-western New South Wales, Australia (Figure 2). The Lachlan River rises at 700 m ASL near Breadalbane and terminates in the Great Cumbung Swamp near Oxley, 1,450 river km to the west. Wyangala Dam impounds the Lachlan River 200 km downstream of its source. The major tributary of the upper Lachlan River is the Abercrombie River. Both rivers have a similar climate, a similar stream order and have similar mean annual flows. However, the maximum altitude, aspect, gradient, geology, land-use and other catchment characteristics of the two rivers are very different. Within the Lachlan catchment, Macquarie perch historically existed as far downstream as Forbes, ~200 km downstream of Wyangala Dam, but no Macquarie perch have been reported downstream of the dam for many decades (Will Trueman, pers. comm.).

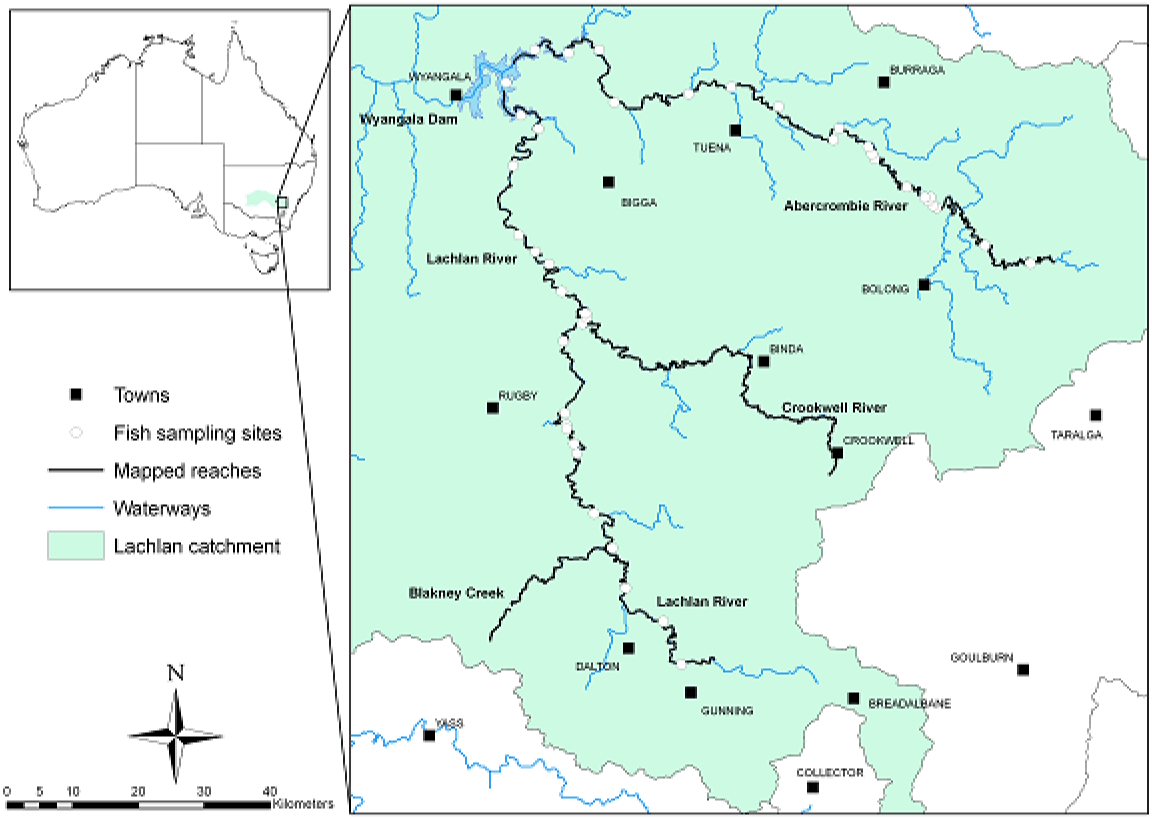

Figure 2. Map of the upper Lachlan study area with the locations of fish sampling sites and mapped reaches.

The study reaches were bounded by the Grabben Gullen Road bridge crossing the Lachlan River near Gunning (-34.7387S, 149.2986E) and the Goulburn – Oberon Road bridge crossing the Abercrombie River near the Abercrombie National Park (-34.1942S, 149.7375E) as the upstream limits and the Wyangala Dam wall (-33.974S, 148.950E) as the downstream limit. This equated to a 194 km reach of the Lachlan River and a 149 km reach of the Abercrombie River. When at capacity, the lower 24 km and 38 km of the Abercrombie and Lachlan Rivers respectively are impounded by Lake Wyangala. Major tributaries of the Lachlan River; the Crookwell River and Blakney Creek were also mapped, but no fish sampling data were collected. Each river was divided into 1 km units using ArcGIS 9.3 (ESRI Inc.) and each reach was assigned a unique identifier. These 1 km reaches formed the basis for quantification of aquatic habitat variables and fish sampling.

2.2. Quantification of habitat variables

Within the study area, aquatic and riparian habitat features were mapped continuously over the 405 km of un-impounded reaches of the upper Lachlan River (156 km), Abercrombie River (125 km), Crookwell River (91 km) and Blakney Creek (33 km). Aquatic habitat features were also mapped at six additional discontinuous 1 km reaches within the impounded waters of Wyangala Dam. Substratum, mesohabitat, physical cover, macrophyte beds, willows, eroded and undercut banks and depth were mapped in the field using hand-held PDA units (Dell Axim X51U and MIO Digi-walker pocket PC) with ESRI Arcpad 6.0.3 data acquisition software. Each PDA was linked to a Garmin 72 GPS unit via a bluetooth device (i.Trek Bluetooth Battery Adapter) to record positional data. Each PDA was loaded with the 1: 50,000 topographical map (GDA 94_MGA Zone 55) for that region as a background layer at a screen resolution of 1:2,000. Two technicians were each equipped with a mapping kit, and working in pairs, mapped all the habitat features within the bank-full river channel. Shallow and narrow reaches were mapped on foot. Deeper reaches were mapped from a canoe or kayak. The data capture system allowed for the recording of positional data in either of two formats, position dependent or position independent, depending on the habitat feature being recorded. All data were uploaded into a GIS for processing.

Substratum was mapped as the position of a transition from one type to another and defined as a position-dependent feature. Substratum transitions were mapped at the point considered to be the base-flow waterline, regardless of ambient flows on the day of mapping. Substratum categories were based on the classification of Platts *et al.* presented in Hamilton and Bergersen (1984): bedrock, boulders (> 512 mm), cobble (64 – 512 mm), gravel (2 – 64 mm), sand (62 µm – 3 mm), mud (< 62 µm and dispersible), clay (< 62 µm and pliable) or detritus (organic material). In instances where a mid-stream bed of a particular substratum occurred within a matrix of another substratum type, but did not reach the bank (i.e., a cobble bed in the centre of an otherwise sandy stream bed), the substratum that occupied the greatest proportion of that half of the stream bed was mapped. Meso-habitat transitions were also mapped as position-dependent features as for substratum, but at the current waterline. Meso-habitat categories were: pool (still or very slowly flowing water), run (flowing water with little or no surface turbulence), riffle (flowing water with a turbulent surface), rapid (very turbulent with the presence of one or more abrupt drops in surface water level) and dry (no surface water). Each time a pool was recorded, its maximum depth was recorded as a position dependent feature to 0.1 m accuracy. To calculate the area of each substratum or meso-habitat type, the river channel boundary was manually digitised within a desktop GIS using Spot 5 imagery as a template at a resolution of 1:3,000 to create a polygon representing the total area of the river channel. In cases where overhanging riparian vegetation obscured the underlying stream bank, the stream bank was recorded as the centre line of the row of riparian trees and/or the substratum transition points or locations of willows that had been recorded in the field. The resulting polygon was then manually split along its centreline in the GIS. These half-channel polygons were then cut (from bank to centre-line) at each substratum or meso-habitat transition point and the resulting polygons coded by substratum and meso-habitat type.

The start and end points of undercut and eroded banks were recorded as position-dependent features. Undercut banks were classed as those that overhang the water by at least 30 cm at a point where the water is at least 30 cm deep. The bottom of the overhang must be no more than 10 cm above the water surface. Actively eroding banks were defined as areas of stream bank where removal of material by surface wash, undercutting or slope failure was evident and unchecked by plant growth or showing signs of stabilising. These features were digitised by drawing a polyline connecting the start and end point of each feature along the outline of the channel polygon.

Individual woody habitats (snags), rocky habitats, macrophyte beds and willows were mapped as position-independent features. Woody and rocky habitats were further characterised as large or small, and simple or complex. The size of woody habitats was distinguished by having a maximum length of 2 m for small, or > 2 m for large. Simple structures were those with a single branch or trunk, whereas those with multiple branches, trunks with branches, trunks with hollows or root masses were classified as complex. An additional category of woody habitats; snag piles, was identified as dense accumulations of snags where the number of individual items contained within the pile could not be determined. The location of each woody habitat item was recorded as the position of the middle of the snag. Any individual item of simple woody habitat with a maximum dimension of < 1 m in length was not recorded.

Rocky habitat was considered to be any rocks classified as a boulder (or number of boulders > 512 mm diameter) that existed within an area of another substratum type (i.e., a single boulder surrounded by sandy or muddy substratum). Small rocks were those < 1,000 mm diameter and large ones were > 1,000 mm diameter. Simple rocky habitat consisted of isolated single rocks or rocks spaced widely amongst the dominant substratum. Complex rocky habitat consisted of closely spaced aggregations or piles of rocks.

The size, shape and area of macrophyte beds were mapped by drawing the outline of the macrophyte bed as a polygon onto the screen of the PDA in the field. The identity of macrophytes was recorded to genus level using Sainty and Jacobs (2003).

The position of each willow (*Salix* spp.) trunk (> 10 cm diameter at breast height) was marked as a position-independent feature.

Five additional aquatic habitat metrics; area of riparian canopy within a 100 m riparian buffer, altitude, mean daily flow, distance to the nearest riffle mesohabitat and distance to the nearest deep pool (> 2 m deep), were derived from existing spatial data layers. A 100 m buffer was generated for the stream from the digitised stream area polygon in ArcGIS. All riparian canopy cover within the buffer was manually digitised as polygons within ArcGIS from a Spot 5 satellite image (dated late 2004 – early 2005) at 1:3,000 scale resolution. Altitude data for each 1 km reach were extrapolated from a 100 m grid-cell DEM of NSW as the altitude ASL at the downstream limit of each segment. Average daily flow for each 1 km reach was derived from a stream network model developed by Stein *et al.* (2009). The distance to the nearest riffle and nearest deep pool (> 2 m deep) were derived by counting the number of 1 km reaches between each reach and the nearest reach where a riffle or deep pool was present, in either an upstream or downstream direction.

2.3. Fish sampling

Initially, 30 sites were spaced at semi-regular intervals along the length of the Lachlan and Abercrombie Rivers in an effort to achieve a broad spatial coverage of the system with the dual purpose of collecting data on the abundance of Macquarie perch for species-habitat association modelling and to map the distribution of the Macquarie perch population within the study area. Samples were collected in April – May 2006 and again in November 2006, with the intention that the two sampling events would provide sufficient data on both the 1+ population and of the young-of-year (YOY) cohort to enable separate species-habitat assessments of the two life stages. This turned out not to be the case, as although both YOY and 1+ Macquarie perch cohorts were collected, Macquarie perch of any size were only collected in small numbers and from only nine of the 30 sites and therefore all size classes were pooled. Because of the lack of Macquarie perch data upon which modelling could be undertaken, a further 12 locations were sampled in November –

December 2008 within mapped reaches proximal to those where Macquarie perch had been collected during sampling in 2006. Sampling protocols used were those developed for the Murray-Darling Basin Authority's Sustainable River Audit – Fish theme (MDBC 2007; Davies *et al.* 2008). These are based on standardised boat and/or backpack electrofishing, in addition to 10 un-baited concertina-type shrimp traps.

2.4. Data analysis

2.4.1. Training and test data

To ensure that sites with similar aquatic habitats were equally represented in both the training and test datasets, habitat data from the 42 fish sampling reaches were processed using hierarchical cluster analysis to group sites based on their overall habitat similarity using Primer 6.1 (Primer-E Ltd.). The 37 habitat variables were normalised prior to creation of a Euclidian distance similarity matrix and sites were clustered using the group-average algorithm. The resulting dendrogram was used to divide sites within each cluster into equally sized blocks of treatment and test sites (Table 1). When clusters contained sites with both Macquarie perch present and absent, we ensured that these were equally distributed among the treatment and test data sets. However, for those sites where subsequent or previous sampling for other projects had recorded Macquarie perch, but where they were not collected during sampling for this project (A22, A98, L43 and L77; Table 1), we deliberately excluded them from the 'training' dataset.

Table 1. Sites at which fish sampling was undertaken. Reach ID refers to the mapped reach that the sample was collected within. 'Original or Extra' refers to whether the site was one of the *a priori* systematically located sites, or one of the extra sites sampled to boost the quantity of Macquarie perch 'presence' data within the dataset. 'Training or Test' refers to whether the data from that site was used to train or test (validate) the ANN model. Within the final two columns, • indicates that Macquarie perch were recorded from that site during sampling for this project and * indicates that they have been sampled at these sites prior or subsequent to sampling for this project being completed (I&I NSW, unpublished data).

Waterbody name	Reach ID	Latitude	Longitude	Original or Extra	Training or Test	Macquarie perch present	YOY present
Abercrombie River	A5	-34.19471	149.73502	Original	Test		
	A22	-34.17179	149.66840	Original	Test	*	*
	A44	-34.12192	149.60238	Extra	Test		
	A45	-34.11434	149.59913	Extra	Training		
	A46	-34.11103	149.59057	Extra	Test		
	A47	-34.10557	149.58609	Extra	Training	•	
	A48	-34.10370	149.57992	Original	Training	•	
	A56	-34.08780	149.55104	Original	Test	•	•
	A64	-34.05274	149.52045	Extra	Training	•	
	A65	-34.04986	149.51373	Extra	Test	•	
	A66	-34.04279	149.51775	Extra	Test	•	
	A74	-34.01187	149.46860	Original	Test	•	•

Table 1 (continued)

Waterbody name	Reach ID	Latitude	Longitude	Original or Extra	Training or Test	Macquarie perch present	YOY present
	A77	-34.02724	149.45615	Original	Training	●	●
	A88	-33.98126	149.38426	Original	Training	●	●
	A98	-33.95240	149.32931	Original	Test	*	
	A107	-33.95945	149.26705	Original	Training	●	
	A122	-33.98139	149.17689	Original	Test	●	
Wyangala Dam	W1	-33.91393	149.14647	Original	Training		
	W2	-34.01950	149.05367	Original	Test		
	W3	-33.91056	149.09627	Original	Test		
	W4	-33.91734	149.05254	Original	Test		
	W5	-33.99097	149.03128	Original	Training		
	W6	-33.94926	149.01169	Original	Training		
Lachlan River	L7	-34.74420	149.25534	Original	Training		
	L20	-34.68831	149.22725	Original	Training		
	L30	-34.64104	149.17700	Original	Training		
	L43	-34.58523	149.15589	Original	Test	*	
	L53	-34.53956	149.14224	Original	Training		
	L73	-34.44412	149.11682	Original	Training		
	L74	-34.44315	149.11018	Extra	Test		
	L77	-34.42597	149.10580	Original	Test	*	
	L78	-34.42204	149.09645	Extra	Test		
	L82	-34.40327	149.08636	Original	Test		
	L96	-34.30788	149.09400	Original	Training		
	L102	-34.28309	149.11956	Extra	Test		
	L106	-34.27213	149.12590	Extra	Training		
	L107	-34.26559	149.11879	Original	Training	●	●
	L115	-34.23833	149.09518	Original	Training	●	●
	L126	-34.19404	149.06481	Original	Training		
	L130	-34.17774	149.05404	Extra	Test		
	L134	-34.15694	149.03059	Original	Test		
	L148	-34.06201	149.02067	Original	Training		

2.4.2. Combining variables

Despite the upper Lachlan catchment retaining the most abundant and widespread population of Macquarie perch remaining within the New South Wales portion of the MDB, the species was only collected from 13 of the 42 sites sampled. This low prevalence required that the number of predictor variables be reduced to enable a reasonable modelling capacity.

A Spearman rank correlation matrix of the 37 measured aquatic habitat variables was produced to identify any strong correlations and therefore redundant variables within the data. The only highly correlated variables were altitude and mean daily flow. Altitude was removed from the dataset as, out of these two variables, it was the least representative of the range of values occupied by the species in other catchments. To further limit the number of habitat variables it was necessary to combine the values for a number of variables, namely, the number of snag piles with the number of large complex snags and the area of lake mesohabitat with the area of pool mesohabitat. In addition, we combined the area of cover of each of the five macrophyte genera recorded into two growth-form categories described in Sainty and Jacobs (2003): ‘narrow emergent’ and ‘submerged and emergent feathery’. This resulted in a reduced set of 30 habitat variables.

Simple linear correlations between each of these variables and both Macquarie perch abundance and binary presence/absence data were undertaken in order to identify any variables that did not show any indication of a relationship and therefore could be omitted from further analysis. Correlations suggested that ten of the 30 habitat variables were less than weakly related ($r < 0.15$) to Macquarie perch abundance or presence/absence; small simple snags, large complex rocks, area of emergent/submerged feathery macrophyte beds, average daily flow, and area of bedrock, boulder, cobble, gravel, clay or detritus substrata. These could be removed from the modelling exercise with little risk of losing important information.

Finally, the raw values of the remaining 20 habitat variables were normalised and Principal Component Analysis (PCA) was used to produce a reduced set of linear combinations of the original variables. The PCA identified eight principal components which each explained more than 4% of the variance of the original data. These eight principal components explained a cumulative 84.5% of the total variance in the dataset.

2.4.3. Artificial Neural Network

The ANN model was developed using MATLAB’s Neural Network Toolbox (Version 6: 2009b release) (The Mathworks Inc.) (Demuth *et al.* 2009). Following experimentation with various neuron number and hidden layer combinations, a three layer feed-forward ANN model with three input neurons and two hidden layer neurons with tangent-sigmoidal transfer functions, and a single output neuron with a linear transfer function ranging from 0 (no Macquarie perch present) to 1 (Macquarie perch present), trained by the back-propagation algorithm using momentum and adaptive learning, was found to be the simplest model architecture that produced reasonable predictive outputs. ANN training was stopped when the mean standard error (MSE) fell below a threshold of 0.01. If the MSE of the check data-set was also below 0.13, the ANN was accepted. This somewhat large MSE threshold accounts for the uncertainty regarding whether perch should or should not have been present at four of the check data sites. This approach produced a superior model to others using either all 30 habitat variables or a further reduced set of 11 variables (those with linear correlation coefficients with Macquarie perch abundance or presence/absence of $r > 0.25$) pre-processed using PCA, or an 11 variable ANN using raw habitat variables. To assess repeatability of the ANN modelling outputs, 18 replicate ANNs were trained on the same dataset and using the same network architecture to obtain a 95% confidence interval on the model predictions.

2.4.4. Identifying important variables

Although PCA pre-processing produced a superior fitting model, the PCA procedure makes it impossible to apply subsequent analyses that identify the key driving habitat variables. Therefore, we developed a further ANN with the same model architecture described above, but using only the 11 habitat variables most correlated with Macquarie perch abundance or presence/absence and we did not apply PCA pre-processing (11 input variables).

The explanatory importance of each of the 11 environmental variables was quantified by calculating the product of the connection weights linking each habitat variable to the output neuron and then summing the products across all axons. This procedure is repeated for each environmental variable and the relative contributions of each variable was calculated by dividing the absolute value of each variable’s contribution by the grand sum of all variable contributions as described by Olden and Jackson (2002*b*). The ANN training procedure was repeated four times using the same dataset and network architecture in order to estimate error bars around the average percentage contribution for each habitat parameter.

Sensitivity analysis (Lek *et al.* 1996*a*; Scardi 1996; Recknagel *et al.* 1997; Özesmi and Özesmi 1999), which set all habitat parameters at a fixed value (usually their mean) and varied each of the habitat variables of interest from its maximum to its minimum, were used to assess the nature of the relationships for those variables that contributed more than ~10% to the model output.

2.4.5. Predictive modelling

Habitat values for the 369 mapped reaches where no fish sampling data were available were processed as per ‘test’ data in the 20 variable PCA pre-processed ANN to estimate the probability of Macquarie perch occupying each reach within the system. Predictions were derived from each of the 18 replicate ANN models in order to estimate error bars around the predicted probability of Macquarie perch being present within each reach. For those reaches with a mean probability of occurrence < 1, outputs from the sensitivity analysis were used to specify habitat rehabilitation requirements necessary to improve the reaches habitability for Macquarie perch.

3. RESULTS

Data on 37 habitat variables were compiled across 411 1 km reaches of the upper Lachlan River, Abercrombie River, Crookwell River and Blakney Creek upstream of Wyangala Dam (Table 2). For most aquatic habitat parameters, the average and range of habitat values present within the mapped reaches are reasonably well represented among those 42 reaches where fish sampling was undertaken, and upon which subsequent species-habitat association modelling was undertaken.

For just under half of the variables, the dataset used to develop the ANN contained the full range of habitat values present within the total dataset. Broad emergent macrophytes, submerged non-feathery macrophytes and attached floating macrophytes were the only three habitat variables that were completely absent from the 42 reaches used for model development and validation but were present at reaches where no fish sampling was undertaken.

3.1. Macquarie perch in the upper Lachlan catchment

A total of 44 Macquarie perch were collected from 13 of the 42 sites surveyed over a total of 71 sampling events (29 of the sites were sampled twice). Of those Macquarie perch captured, 46% were < 127 mm TL and were therefore assumed to be young-of-year fish. Although Macquarie perch were not abundant, they were the most common large native freshwater fish collected and the equal 2nd most widespread of ten native species (Table 3).

Macquarie perch were more abundant and widespread in the Abercrombie River than in the Lachlan River (Figure 3). In the Abercrombie River, the species was present at 11 of the 12 sites between reaches A47 and A122, and was most abundant in the mid reaches (A74 and A77). In contrast, Macquarie perch were found at only two of 19 sites in the Lachlan River (L107 and L115), both immediately downstream of the Crookwell River junction.

3.2. The Artificial Neural Network model

Eighteen replicate ANN models derived from the 20 aquatic habitat variables produced consistent models estimating the pseudo-probability that Macquarie perch are present at a 1 km reach scale (Figure 4a). ANN models were then (i.e., after training) able to accurately predict whether Macquarie perch were collected or not at 85 ± 0.6% of the reaches set aside to test the model. The three (of 17) reaches where the models incorrectly predicted the presence/absence of Macquarie perch were A44 and L82, where the models predicted an 0.9 ± 0.03 and 0.9 ± 0.07 pseudo-probability that Macquarie perch should be present, yet they were not collected during fish sampling, and A74 where the models predicted an 0.0 ± 0.01 pseudo-probability of Macquarie perch presence yet they were collected on both the occasions that this site was sampled.

Table 2. Aquatic habitat variables mapped or otherwise derived at the 1 km reach scale.

Habitat Variable	Unit of measure	Mean and range of habitat variables (all reaches) (per km)	Mean and range of habitat variables within reaches used to develop the ANN models (per km)
Altitude	Metres ASL	523 (370 – 890)	461 (370 – 665)
Small simple snags	Count	8 (0 – 153)	12 (0 – 153)
Small complex snags	Count	8 (0 – 53)	8 (0 – 33)
Large simple snags	Count	24 (0 – 162)	40 (0 – 162)
Large complex snags	Count	15 (0 – 78)	22 (0 – 78)
Snag Pile	Count	0.6 (0 – 19)	0.3 (0 – 12)
Small simple rocks	Count	5 (0 – 103)	8 (0 – 61)
Small complex rocks	Count	2 (0 – 36)	2 (0 –13)
Large simple rocks	Count	7 (0 – 87)	10 (0 – 87)
Large complex rocks	Count	5 (0 – 57)	5 (0 – 43)
Willows	Count	14 (0 – 212)	8 (0 – 48)
Eroded bank	Length (m)	119 (0 – 1,508)	60 (0 – 992)
Undercut bank	Length (m)	42 (0 – 871)	91 (0 – 871)
Narrow emergent macrophytes	Area (m^2)	1,043 (0 – 22,303)	856 (0 – 22,303)
Feathery emergent/submerged macrophytes	Area (m^2)	56 (0 – 1,872)	25 (0 – 1,064)
Broad emergent macrophytes	Area (m^2)	23 (0 – 3,299)	0
Submerged non-feathery macrophytes	Area (m^2)	212 (0 – 3,201)	0
Floating attached macrophytes	Area (m^2)	3 (0 – 409)	0
Riparian canopy within 100 m of the stream bank	Area (ha)	8.1 (0 – 28.5)	11.7 (0.4 – 28.5)
Riparian canopy within 10 m of the stream bank	Area (ha)	1.1 (0 –2.8)	1.5 (0.1 – 2.8)
Distance to nearest riffle	Kilometres	1.2 (0 –29)	3.2 (0 – 29)
Distance to nearest deep pool >2 m deep	Kilometres	13.3 (0 – 72)	14.7 (0 – 69)
Maximum pool depth	Metres	1.1 (0 – 21.5)	1.7 (0 – 21.5)
Average daily flow	ML per day	283 (5 – 873)	428 (83 – 873)
Rapid mesohabitat	Area (ha)	0.13 (0 – 4.64)	0.08 (0 – 1.67)
Riffle mesohabitat	Area (ha)	0.31 (0 – 5.05)	0.69 (0 – 3.14)
Run mesohabitat	Area (ha)	1.52 (0 – 23.39)	1.40 (0 – 4.64)
Pool mesohabitat	Area (ha)	0.55 (0 – 3.35)	0.40 (0 – 2.86)
Lake mesohabitat	Area (ha)	0.74 (0 – 138.67)	7.43 (0 – 138.67)
Bedrock substratum	Area (ha)	0.56 (0 – 23.39)	1.47 (0 – 23.39)
Boulder substratum	Area (ha)	0.29 (0 – 47.89)	1.60 (0 – 47.89)
Cobble substratum	Area (ha)	0.65 (0 – 30.17)	1.61 (0 – 30.17)
Gravel substratum	Area (ha)	0.70 (0 – 36.45)	1.39 (0 – 36.45)
Sand substratum	Area (ha)	0.64 (0 – 29.49)	1.06 (0 – 29.49)
Mud substratum	Area (ha)	0.82 (0 – 49.43)	3.28 (0 – 49.43)
Clay substratum	Area (ha)	0.006 (0 – 0.304)	0.004 (0 – 0.184)
Detritus substratum	Area (ha)	0.010 (0 – 1.248)	0.005 (0 – 0.179)

Table 3. The total catch of each fish species sampled and the proportion of the 42 sites sampled at which each species was found.

Species	Total catch	Proportion of sites
Carp-gudgeon species complex (*Hypseleotris spp*.)	1,776	0.67
Eastern mosquitofish (*Gambusia holbrooki*)	1,473	0.58
Common carp (*Cyprinus carpio*)	750	0.91
Flat-headed gudgeon (*Philypnodon grandiceps*)	464	0.16
Redfin perch (*Perca fluviatilis*)	275	0.12
Australian smelt (*Retropinna semoni*)	120	0.30
Goldfish (*Carassius auratus*)	44	0.21
Macquarie perch (*Macquaria australasica*)	44	0.30
Silver perch (*Bidyanus bidyanus*)	33	0.16
Golden perch (*Macquaria ambigua*)	26	0.19
Mountain galaxias (*Galaxias olidus*)	23	0.14
River blackfish (*Gadopsis marmoratus*)	16	0.02
Murray cod (*Maccullochella peelii*)	3	0.02
Rainbow trout (*Oncorhynchus mykiss*)	2	0.05
Freshwater catfish (*Tandanus tandanus*)	1	0.02

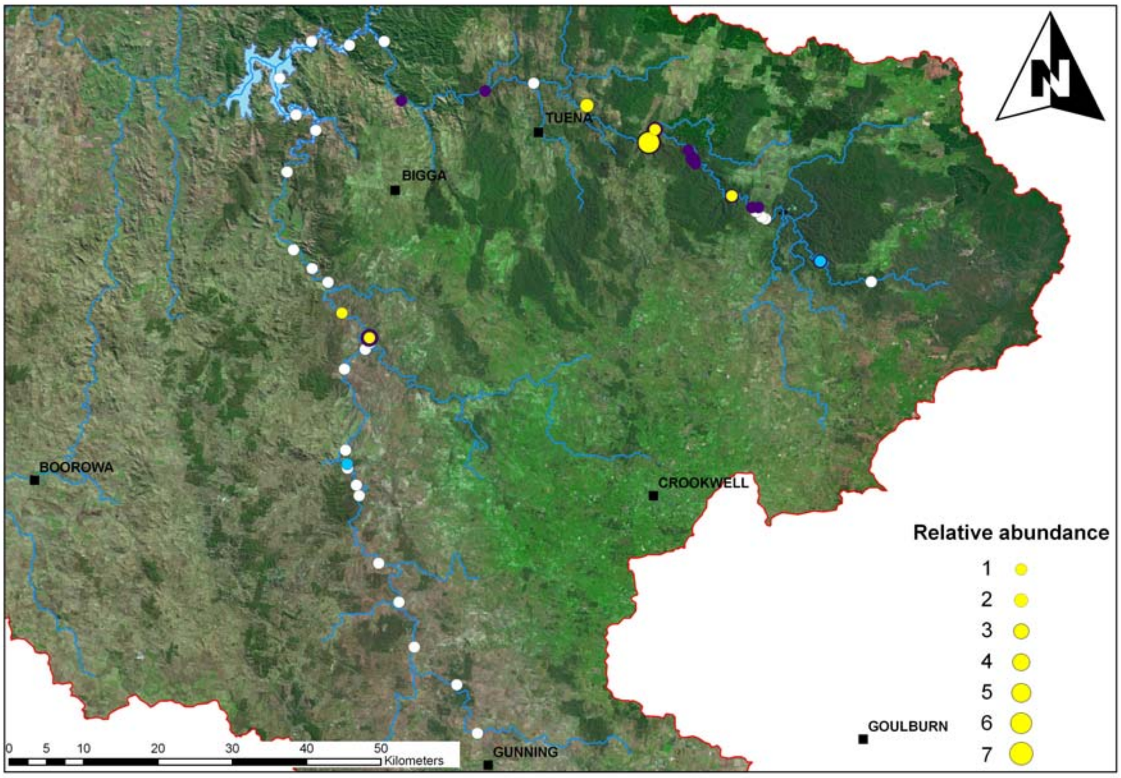

Figure 3. The distribution and abundance of Macquarie perch at sites sampled in the upper Lachlan and Abercrombie Rivers within the last three years (2006 – 2009). Data are standardised by the effort prescribed by the SRA sampling protocol for a single sample. White points represent sites where no Macquarie perch were collected, purple points represent the total catch of Macquarie perch, yellow points represent the catch of the young-of-year (YOY) size class and blue circles represent sites where Macquarie perch have been collected since sampling for this project has been completed, but where they were not sampled in this study.

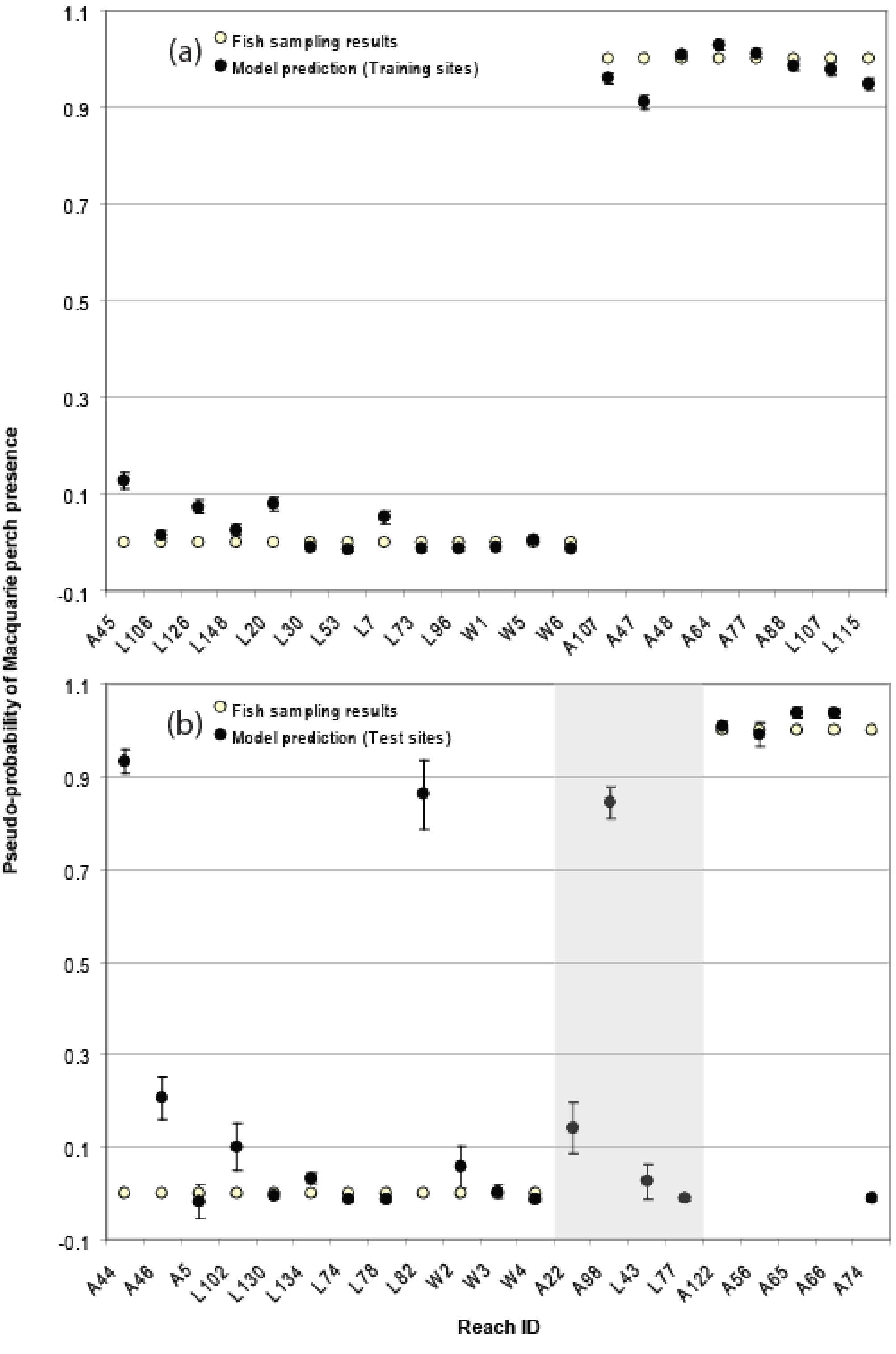

Figure 4. ANN predictions of Macquarie perch presence (closed circles) and observations based on fish sampling (open circles) at sites allocated to the training (a) and test (validation: b) data-sets. ANN predictions in each plot are the average (± SE) of 18 replicate model training runs using the same datasets and network architecture. The four test sites shaded in grey were not assigned a fish sampling result, as although we did not sample any Macquarie perch from these sites during fish sampling for this project, they have been sampled at these sites previously or since, and hence we are uncertain whether these sites should actually be considered 'perch present' despite none being collected by our sampling for this project.

Of those four sites deliberately excluded from the training dataset because of uncertainty about whether Macquarie perch were actually present or not (because they were observed at these sites prior to this study commencing or have been collected since this study concluded, but were not collected during this study), the ANN models concurred with our sampling observations that Macquarie perch should be absent at three of the sites (Reach IDs A22 (pseudo-probability of occurrence = 0.1 ± 0.05), L43 (0.0 ± 0.04) and L77 (0.0 ± 0.01), but were likely to have been present but un-sampled at reach A98 (pseudo-probability of occurrence = 0.8 ± 0.03) (Figure 4b).

3.3. Key habitat variables

An ANN model with the same network architecture, but using only the 11 habitat variables most correlated with Macquarie perch abundance or presence\absence rather than the eight principal components of 20 variables, also produced a robust predictive model of the probability of Macquarie perch being present in a 1 km reach, but with a slightly higher MSE than the model described in Section 1.3.2. Comparison of axon weights for each variable indicated that five of the habitat variables contributed more than 10% of the predictive power of the ANN model (Figure 5). Area of run mesohabitat was the most important variable determining reach occupancy by Macquarie perch, followed by the number of small complex rock piles and area of riffle mesohabitat, the length of undercut stream bank and the number of large simple snags.

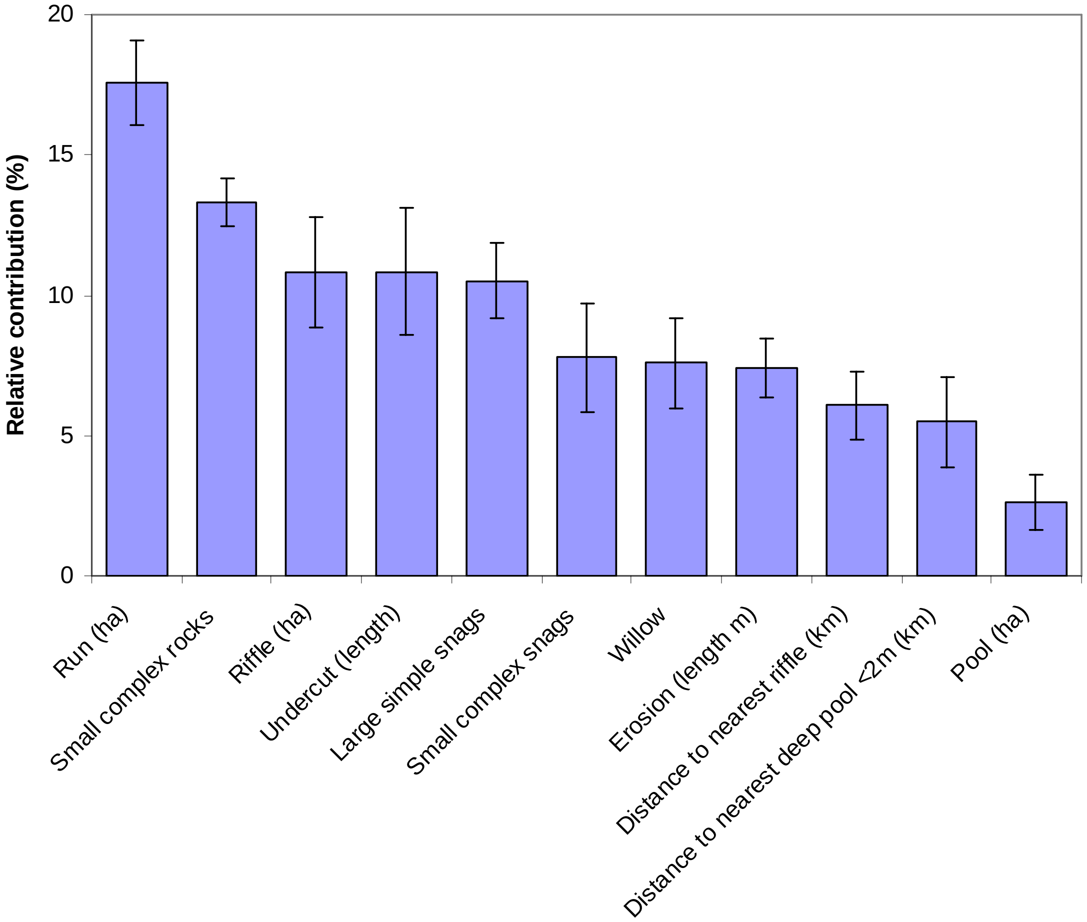

Figure 5. The relative contribution of each of the 11 habitat variables analysed to the prediction of the probability of occupancy of a site by Macquarie perch. Each bar represents the average (± SE) of four replicate models with the same network architecture and developed using the same dataset.

Sensitivity analyses were used to explore the nature of the relationship between the five most influential habitat variables and Macquarie perch occupancy (Figure 6). The outputs suggest that the top three key habitat variables; area of run mesohabitat, number of small complex rock piles and area of riffle mesohabitat are primarily important and that sufficient availability of any one of these three habitats is adequate to ensure a high probability that Macquarie perch will occupy a reach when all other variables are fixed at the catchment-wide average.

The area of run mesohabitat had a strongly positive relationship with the probability of Macquarie perch occupying a reach (Figure 6a). Sensitivity analysis suggests that Macquarie perch would not occupy any reaches with < 3 ha km^{-1} of run mesohabitat when the site had the catchment-wide average value for all other habitat variables. The analyses also suggest an asymptotic area of run mesohabitat of around 10 ha km^{-1}, above which no further increase in the pseudo-probability of Macquarie perch occupancy occurs.

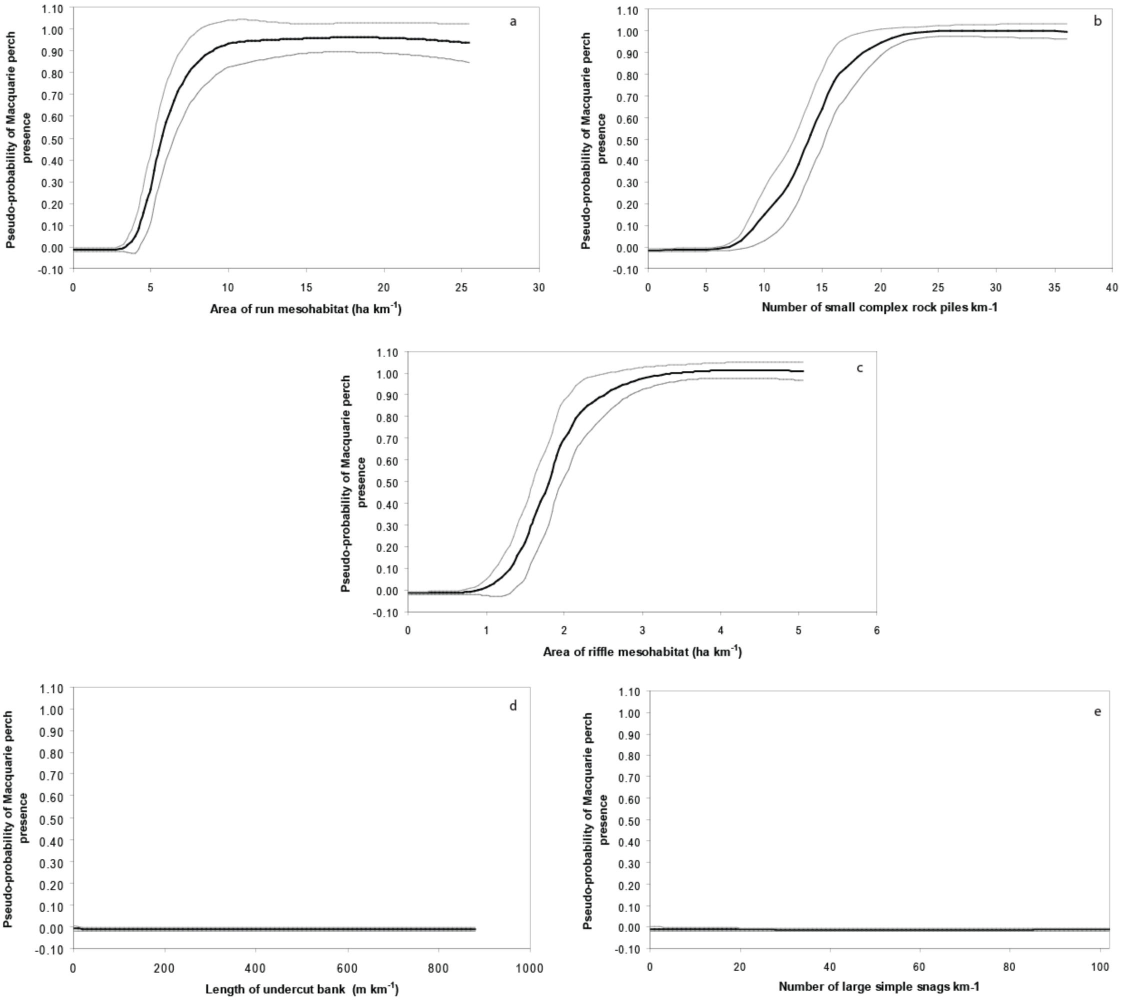

Figure 6. The relationship of the six most influential habitat variables to the pseudo-probability of occupancy of Macquarie perch as modelled by the ANN when all other habitat values are fixed at their mean. The dark line represents the mean prediction on 18 replicated ANN models and the grey lines represent the upper and lower 95% confidence limits.

Similarly, there was a strongly positive relationship between the second most influential habitat variable, the number of small complex rock piles per 1 km reach, and the probability of occupancy by Macquarie perch (Figure 6b). The results suggest that Macquarie perch would not occupy any reaches with < 8 small complex rock piles per kilometre when the site had the catchment-wide average value for all other habitat variables. Conversely, any reach that had > 24 small complex rock piles km^{-1} would almost certainly be occupied by Macquarie perch.

Like run mesohabitat, the area of riffle mesohabitat had a strongly positive relationship with the pseudo-probability of Macquarie perch occupying a reach (Figure 6c). Sensitivity analysis suggested that Macquarie perch would not occupy any reaches with < 1 ha km^{-1} of riffle mesohabitat when the site had the catchment-wide average value for all other habitat variables. The analyses also suggest an asymptotic area of riffle mesohabitat of around 3 ha km^{-1}, above which no further increase in the pseudo-probability of Macquarie perch occupancy occurs.

Sensitivity analysis utilising the catchment-wide mean value for all habitat variables was unable to illustrate the relationships between the length of undercut bank or the number of large simple snags and pseudo-probability of Macquarie perch occupancy. This was because at their catchment-wide means, the values for the three primary variables (run and riffle mesohabitat and small complex rocks) were below the minimum requirement for Macquarie perch occupancy. Consequently, varying the availability of these potentially important but not critical ‘modifier’ variables did not increase the pseudo-probability of Macquarie perch occupancy (Figure 6d-e). To explore these variables further, we ran additional sensitivity analyses by fixing the availability of the three primary variables at their optimum rather than mean values and found that the ANN predicted that Macquarie perch would occupy reaches with sufficient availability of primary variables irrespective of the availability of large simple snags or undercut banks. Therefore, by default, the number of large simple snags and length of undercut bank must only affect the pseudo-probability of occupancy by Macquarie perch when a minimum but suboptimal amount of the three primary habitat variables are available.

In a final attempt to explore the interactions between the availability of the two important modifier variables and sub-optimal availability of the three primary variables, we ran sensitivity analyses fixing the availability of run mesohabitat, small complex rock piles and riffle mesohabitats at the value which the initial sensitivity analyses suggest result in an intermediate (0.5) pseudo-probability of Macquarie perch occupancy. We found that when combined, the individually sub-optimal values for run, riffle and small complex rock habitats are sufficient to result in a high probability of occupancy by Macquarie perch. Under these conditions, the pseudo-probability of Macquarie perch occupancy is still independent of the availability of large simple snags (Figure 7a). However, in contrast, the relevance of length of undercut bank km^{-1} became evident (Figure 7b). When the area of run and riffle mesohabitats and the number of small complex rock piles km^{-1} are sub-optimal, the length of undercut bank per kilometre reach (summed over both banks) had a strongly negative relationship with the probability of Macquarie perch occupying a reach (Figure 7b). When the availability of primary habitat variables is sub-optimal, any more than 300 m of undercut bank km^{-1} will reduce the pseudo-probability of Macquarie perch occupancy and if > 650 m km^{-1} of undercut bank is present, Macquarie perch are unlikely to occupy that reach.

3.4. Predictive modelling outputs

Processing the habitat data from all mapped reaches through the PCA pre-processed ANN model determined that almost 10% of reaches (43 km) provide sufficient habitat conditions to ensure a high probability that Macquarie perch will occupy a reach, a further 15% (63 km) are generally suitable but not optimal habitat, 16% (67 km) provide marginal habitat (show at least some prospect of Macquarie perch occupancy) and 58% (238 km) do not provide the necessary habitat conditions for the species. However, the distribution of suitable habitat is not uniform amongst waterways. Blakney Creek does not provide any suitable habitat for Macquarie perch. Similarly, only one of the 91 mapped 1 km reaches of the Crookwell River provides suitable habitat for Macquarie perch. In contrast 56% and 20% of reaches in the Abercrombie and Lachlan Rivers respectively currently provide either ideal or suitable Macquarie perch habitat. As expected, the 1 km reaches providing either ideal or suitable habitat are clustered in series and are interspersed with sections of unsuitable habitat (Appendix 1 – 16). In the Abercrombie River, sections of suitable habitat are on average 3.3 km in length (range = 1 – 20 km) fragmented by 2.5 km stretches (range = 1 – 6 km) of unsuitable habitat. In the Lachlan River, the sections of suitable habitat are of a similar average length of 2.5 km (range = 1 – 8 km), but are fragmented by much longer stretches of unsuitable habitat (average = 11 km, range = 1 – 46 km).

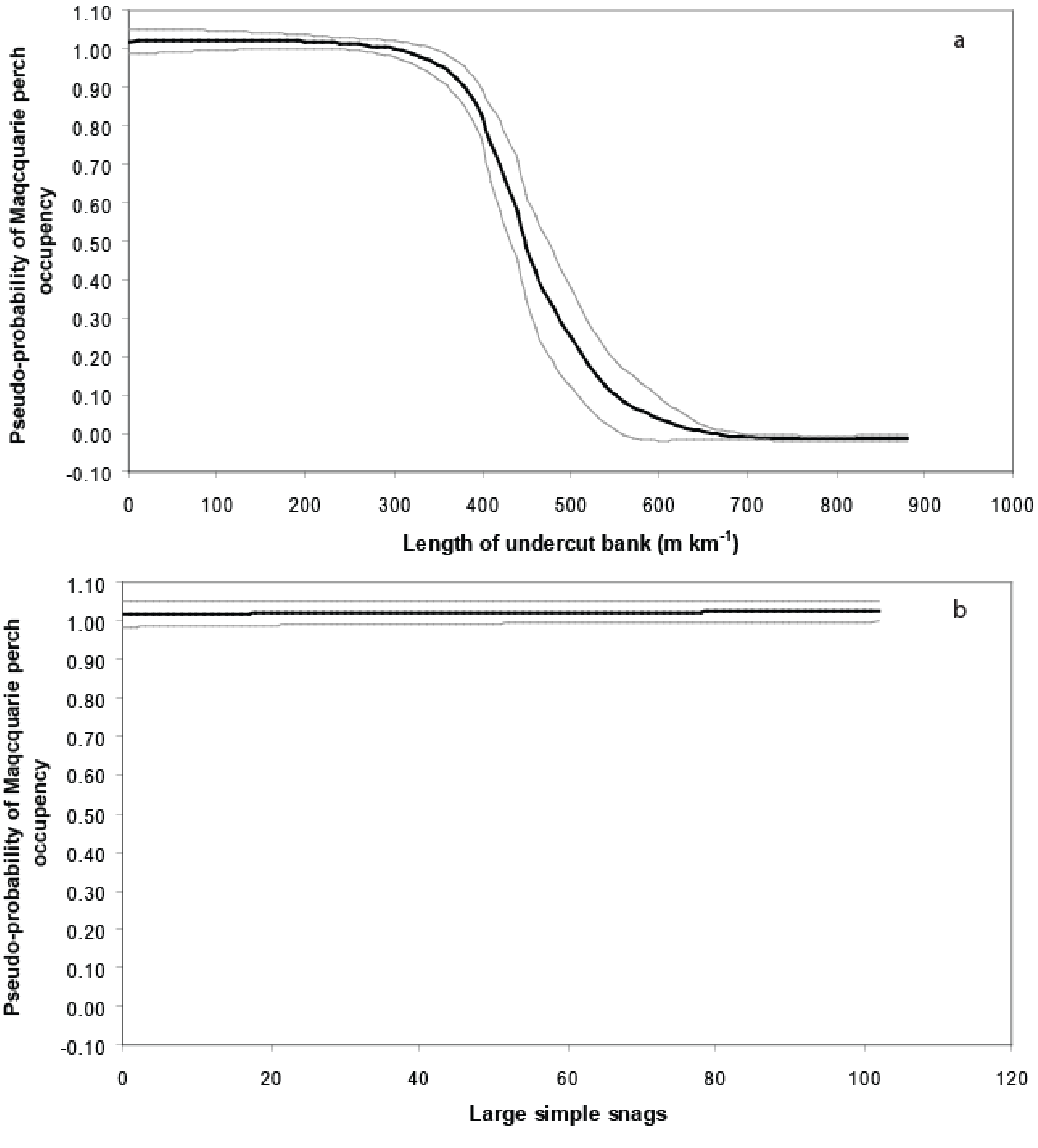

Figure 7. The relationship of the two ‘modifier’ variables to the pseudo-probability of occupancy of Macquarie perch as modelled by the ANN when the availability of all other habitat values are fixed at their mean apart from the availability of the three identified primary variables which are fixed at the value representing sub-optimal availability (pseudo-probability of Macquarie perch occupancy of 0.5). The dark line represents the mean prediction on 18 replicated ANN models and the grey lines represent the upper and lower 95% confidence limits.

4. DISCUSSION

Habitat protection and rehabilitation activities need clear guidance on what habitat parameters are limiting species recovery in terms of a location’s habitability, as well as information on the optimum quantity of important habitat features required to promote the fitness, abundance and recruitment potential of the target species (Harig *et al.* 2000; Bond and Lake 2003; Rosenfeld 2003). Species-habitat association models can provide this guidance (Wang *et al.* 2003; Rosenfeld 2003; McCleary and Hassan 2008). In this study, ANN analysis proved capable of developing a repeatable species-habitat association model for Macquarie perch within the upper Lachlan catchment with 85% predictive accuracy. This was despite the challenges of a data-set with only a relatively small number of capture records and, in many cases, potentially non-linear, correlated and interacting habitat variables. These limitations would preclude the development of equivalent models using more conventional approaches. This reinforces the value of ANN modelling in understanding species-habitat associations in aquatic environments. Several other studies have used ANN modelling of fish-habitat associations and have also reported 72 – 86% predictive accuracy (Lek *et al.* 1996a; Baran *et al.* 1996; Lek *et al.* 1996b; Mastrorillo *et al.* 1997; Boët and Fuhs 1999). The development of a quantitative model to describe the species-habitat relationship for Macquarie perch allows us to move away from expert opinion and personal perceptions in describing the species’ habitat requirements. Further, the model itself is a useful tool for identifying those reaches with good quality habitat that should be conserved and also those reaches in need of habitat rehabilitation or enhancement in order to improve their capacity to aid in the recovery of this endangered species.

Of the 37 habitat variables quantified at the 1 km reach scale, we identified that only three were primarily important correlates of whether Macquarie perch is likely to occupy a reach or not. These are the area of run mesohabitat, number of small complex rock piles and area of riffle mesohabitat. Our analyses suggest that either a minimum area of run or riffle mesohabitat, or a minimum number of small complex rock piles are required to satisfy the habitat needs of Macquarie perch. We also identified a further two habitat variables which, although not as influential as the three primary habitat parameters, influence the occupancy of Macquarie perch when the availability of the primary habitat variables is sub-optimal; large simple snags and length of undercut banks. The length of undercut bank had a negative effect on the pseudo-probability of Macquarie perch presence when run, riffle or small complex rock pile habitats are limiting. We were not able to decipher the effect of large simple snags from the model outputs.

These findings are only in partial agreement with published descriptions of the preferred habitat of Macquarie perch. While they support expert opinion and the limited existing quantitative data that Macquarie perch require the presence of riffle habitats, because our data are correlative rather than causative, we are unable to specify whether riffle habitats were required for spawning (as proposed), or simply provide the necessary habitat conditions for the species. Our model also confirms the importance of rocky habitats and substantial cover to Macquarie perch, but only in the form of aggregations of boulder-sized rocks (512 – 1,000 mm maximum dimension). In contrast to published habitat descriptions, we found no evidence that Macquarie perch have a preference for deep holes, as neither the area of pool habitat or the proximity to deep holes (> 2 m deep) were identified as important variables in the model. The lack of an observed association between Macquarie perch and deep pool habitats may be an artefact of the sampling technique used to survey for Macquarie perch, as electrofishing is less effective than nets at sampling benthic fishes from pools more than ~ 4 m deep. However, the deepest pool sampled within this study was 3.9 m and we collected Macquarie perch from that location. Similarly, our data do not support the suggestion that Macquarie perch ‘does well’ in impoundments (Cadwallader and Backhouse 1983; Harris and Rowland 1996; ACT Government 1999; Lintermans 2002, Tonkin *et al.* 2009) as no Macquarie perch were collected from any site within Lake Wyangala despite being present in adjacent riverine reaches. Although this may also be an artefact of our reliance on electrofishing as our sole sampling technique, netting data (Gilligan, unpublished) and accounts from recreational anglers support our observation that Macquarie perch are very rare or absent from the lake. Additionally we found no evidence that Macquarie perch required the presence of gravel beds in order to occupy a reach as we did not identify any relationships between the occupancy of Macquarie perch and the area of any particular substratum type. Our results do not support the observation that Macquarie perch prefer shaded streams as we found no relationship between the area of riparian canopy cover and Macquarie perch occupancy. And finally, we found no evidence that the area of aquatic macrophyte beds influenced the probability that Macquarie perch would occupy a site.

It is possible that these inconsistencies may have arisen through regional differences in the habitat requirements of the species, as our study was conducted wholly within the upper Lachlan catchment. However, we propose that the broad diversity of habitats and degrees of habitat disturbance, and the broad ranges observed for all variables assessed within our study system encompass the range of habitats within which other remnant populations persist elsewhere in the Murray-Darling Basin. On that basis, the species-habitat relationships observed in the Lachlan catchment should be transferable to other remnant populations. However, aspects of species-habitat association modelling studies (including this one) that require consideration before the model is utilised in either the Lachlan catchment or elsewhere in the Murray-Darling Basin are a) issues associated with the spatial scale of sampling, b) issues associated with the temporal scale of sampling, c) potential differences in the habitat requirements of different life-history stages, d) the influence of biotic effects, e) whether presence/absence models correspond to habitat quality, and f) that the relationships defined by the model are correlative rather than causative. The relevance of each of these issues to our model and its outputs are addressed below.

Aquatic ecosystems are strongly hierarchical, with large-scale features and ecosystem processes affecting the use of finer scale habitats nested within them (Frissel *et al.* 1986; Hawkins *et al.* 1993; Lamouroux *et al.* 1999; Pusey *et al.* 2000; Fausch *et al.* 2002; Magalhães *et al.* 2002; Wang *et al.* 2002; Wiens 2002; Boys and Thoms 2006). Consequently, species-habitat associations can be heavily affected by the spatial scale at which the relationships are investigated, with relationships apparent at one spatial scale potentially disappearing at others (Poizat and Pont 1996; Dunham and Vinyard 1997; Bult *et al.* 1998; Crook *et al.* 2001; Reichard *et al.* 2002; Wiens 2002). Therefore, the macrohabitat scale of our sampling frame limits interpretation of the results of our model to a similar spatial unit. We focussed on the macrohabitat scale, as Frissell *et al.* (1986), Labbe and Fausch (2000) and Fausch *et al.* (2002) suggest that it is at this spatial scale that most processes critical to fish populations and communities occur. Several previous studies have also emphasised the importance of landscape scale variables to aquatic habitats (Gordon *et al.* 1992; Richards *et al.* 1996; Allan *et al.* 1997; Pusey *et al.* 2000; Wang *et al.* 2003; Creque *et al.* 2005). For two reasons, we contend that the larger landscape scale is of lesser relevance to interpretation of our results. Firstly, those landscape scale factors that are relevant within the species natural range, such as land-use, climate and catchment morphology are represented at a macrohabitat scale by variables that correspond to their impact at local scales rather than inclusion of the landscape scale variables themselves (e.g., climatic data are represented by their local scale influence on average mean daily flow and land-use by its impact upon substratum type, riparian canopy cover and bank stability). Secondly, we only incorporated reaches nested within riverscapes known to be within the historical range of the species, so the effect of landscape scale drivers which determine whether Macquarie perch will occupy a reach or not are negated (Gorman and Karr 1978). In contrast, habitat associations at smaller spatial scales are not accounted for by models developed at macrohabitat scales and this has implications for interpretation of outputs. For example, Crook *et al.* (2001) present a reach scale analysis suggesting that golden perch (*Macquaria ambigua*) avoided reaches with woody habitat, but a microhabitat assessment undertaken within the same reach suggested a positive diurnal association. Similarly, Bult *et al.* (1998) found that, for a larger scale analysis (> 4 m), juvenile Atlantic salmon (*Salmo salar*) exhibited a strong preference for shallow regions of a

Canadian stream. However, analysis at a smaller scale (< 1 m) within these regions showed that the salmon avoided shallow microhabitats and were positively associated with small patches of deeper water within shallow reaches. At the macrohabitat scale of our study, the ANN model suggests that reaches with greater amounts of undercut bank are less likely to be occupied by Macquarie perch. However, when undercuts were available within occupied reaches, Macquarie perch were often sampled utilising them as cover. This suggests that perhaps it is not the presence of undercuts themselves that has a negative influence on Macquarie perch at a reach scale, but that the geomorphological conditions within the stream channel that lead to the creation of undercut banks are less favourable for the species. To gain a better understanding of how Macquarie perch utilise those microhabitats available within reaches providing suitable habitat, additional study of microhabitat scale habitat use is required (e.g., through the use of acoustic tracking technology). The fine-scale aquatic habitat maps developed as part of this project can be utilised as a basis for such assessments.

The temporal scale of sampling can also affect interpretation of the species-habitat relationships. Diel differences have the capacity to affect habitat assessments given that many species are likely to use different habitats during the day and at night (Crook *et al.* 2001). Macquarie perch are believed to be crepuscular or nocturnal (Lintermans 2007). Therefore, it is reasonable to assume that they are more likely to utilise cover habitats during the day and foraging habitats at night. As our fish sampling was only undertaken during the day, our model could possibly have over-emphasised the importance of cover variables and under-represent the importance of foraging habitats. However, diel differences are more likely to affect microhabitat scale assessments than macrohabitat scale ones. Unless Macquarie perch undertake > 1 km diel movements between cover and foraging habitats, diel variations in habitat use are unlikely to have affected our macrohabitat scale assessment. Seasonal movements between habitats may also affect interpretation of species-habitat relationships. Our ANN model is based on fish sampling data collected during late Autumn and late Spring. If movement studies determined that Macquarie perch undertake a population scale migration outside of these two periods, the model may not represent the habitat needs of the species during those periods. Limited movement data available for Macquarie perch in impoundment populations suggest that the only population movement is from lake environments into riverine spawning habitats in spring (at temperatures of 16.5^{o}C), over scales of only 2 km (Wharton 1968; Cadwallader and Rogan 1977; Cadwallader and Backhouse 1983; Cadwallader and Douglas 1986; Lintermans 2007, Tonkin *et al.* 2009). We are not aware of any data on seasonal movement patterns of Macquarie perch resident within riverine environments and therefore do not have the ability to postulate on the potential limitations of our biennial fish sampling strategy.

If the species of interest has a complex life history, different habitat association models may need to be developed for different life history stages. Size related shifts in habitat use have been observed in many freshwater fish (Reichard *et al.* 2002). Further, it may be that the habitat requirements of only one or two life stages create a limiting bottleneck on adult abundance (and hence recovery of the population) and it is the habitat requirements of that particular life-stage that are most relevant to habitat rehabilitation programs (Rosenfeld and Hatfield 2006). Unfortunately, despite Macquarie perch being the equal second most widespread native species and the most abundant large native fish in the Abercrombie and upper Lachlan Rivers, they were still only collected at 13 sites (31%). Although 46% of individuals collected were YOY, the total number of sites with Macquarie perch present was not great enough to split the dataset into separate new recruit (YOY) and 1+ to adult cohorts to model the species-habitat associations of these two life-stages separately. Therefore, this remains an unknown aspect of the species-habitat associations for Macquarie perch. This can be remedied with further sampling and re-analysis of the data.

Physical habitat requirements can be strongly modified by predation or other biotic factors, with biotic interactions leading to dissimilar fish assemblages even in similar macrohabitat types (Power *et al.* 1985; Labbe and Fausch 2000; Taniguchi and Nakano 2000; Pusey *et al.* 2000; Rosenfeld *et al.* 2000; Bond and Lake 2003; Martino and Able 2003; Robertson and Winemiller 2003).

Alternatively, the presence of predators can exclude prey species from preferred habitats (Rosenfeld *et al.* 2000). For some species, biotic effects may be substantially more influential than habitat availability (Rosenfeld and Hatfield 2006). Consequently, it is not unexpected that species-habitat association models that do not incorporate variables representing important biotic relationships will retain substantial unexplained residual variance. As expected, previous species-habitat association models have reported that the habitat variables analysed have only explained < 50% of the variance in modelled fish variables (Godinho *et al.* 2000; Rosenfeld *et al.* 2000; Morán-López *et al.* 2006). Despite the obvious importance of biotic interactions, our ANN model was capable of modelling the presence/absence of Macquarie perch based on habitat variables alone with 85% predictive accuracy. This may suggest that biotic interactions are potentially relatively less important than habitat variables for Macquarie perch in the upper Lachlan catchment. However, the illegal introduction of alien redfin perch (*Perca fluviatilis*) at several locations in the upper Lachlan catchment in late 2005 (I&I NSW, Freshwater Fish Research Database) has potential to reverse this pattern, as redfin are predicted to have substantial negative biotic interactions with Macquarie perch through predation, competition and disease transmission.

Although presence/absence of individuals in habitats is a simple metric, it can be misleading as it provides no information of the variation in quality of occupied habitats and fails to distinguish source and sink habitats. Abundance data may be better, as under the Ideal Free Distribution Theory (Fretwell and Lucas 1970), organisms should select habitats that maximise their fitness resulting in highest densities in high quality habitats. However, there are risks that conspecific interactions such as territoriality can influence results, with a majority of individuals displaced to sub-optimal habitats by a smaller number of dominant individuals (Rosenfeld 2003). Direct assessment of individual fitness (condition, growth, survival etc.) would be the most reliable indicator of habitat quality, but is much more difficult to measure (Rosenfeld 2003; Rosenfeld and Hatfield 2006). Distinguishing between source and sink populations is particularly critical as failure to distinguish them may result in the inappropriate protection of sink habitats rather than sources (Rosenfeld and Hatfield 2006). Although we intended to partly address this issue by analysing the species-habitat associations of new recruits and older individuals separately (under the assumption that sites occupied by recruits are source populations), we were limited in doing so by the small sample size. Consequently, there is a slight risk that our study may have used data from both source and sink populations to model the species-habitat association of Macquarie perch.

Although the relationships we identified are well supported, it is impossible to infer that the link between the habitat variables in question and the probability that Macquarie perch will occupy the reach is a causative one, rather than a reflection of an underlying correlated variable that was not recorded as part of the study (Crook *et al.* 2001; Rosenfeld 2003). The clearest possible example of how this may be an issue is for the unexpected negative relationship inferred between the length of undercut banks and pseudo-probability of Macquarie perch occupancy. In Seven Creeks, Cadwallader (1979) observed that Macquarie perch were occasionally associated with undercut banks. Similarly, those undertaking field sampling for this project also noted that when undercuts were available within occupied reaches, Macquarie perch were often sampled utilising them as cover. In contrast, the species-habitat model suggests that reaches with greater amounts of undercut bank are less likely to be occupied by Macquarie perch. Together, these points suggest that perhaps it is not the presence of undercut banks themselves that has a negative influence on Macquarie perch at a reach scale, but that the geomorphological conditions within the stream channel that lead to the creation of undercut banks are less favourable for the species, perhaps because shallow gravel bars favoured as foraging habitat are less likely to occur in reaches with steep and undercut banks. Without any supporting data, this hypothesis is purely conjecture, but this example illustrates that given the complexities associated with drawing definitive conclusions from correlative relationships, our results should not be used as direct evidence that run mesohabitats, number of small complex rock piles or riffle mesohabitats themselves are the critical habitat requirements of Macquarie perch, only that reaches that have sufficient quantities of these habitat features create an ecological niche that supports Macquarie perch populations. Similarly, our results should not be used to suggest that the presence of undercut banks is necessarily detrimental to Macquarie perch populations. Only that reaches that have undercut banks are indicative of niches that are less suitable for Macquarie perch, or are indicative of less favourable broader landscape processes.

Despite the uncertainties arising from these potential limitations, based on the outputs of our model, we propose the following refinement of the general description of Macquarie perch habitat: *"Macquarie perch are a riverine fish most abundant in reaches > 200m altitude. They are heavily dependant on the availability of flowing mesohabitats, requiring at least 3 ha of run habitat or 1 ha of riffle habitat per kilometre of stream. They are also heavily dependant on availability of small complex rock piles (aggregations of 512 – 1,000 mm diameter boulders) as cover, preferring reaches with 8 – 24 or more rock piles per kilometre of stream. Extensive lengths of undercut banks within reaches with low coverage of flowing mesohabitats or little small complex rock cover are detrimental. Depth, substratum type, riparian vegetation cover and aquatic macrophyte cover has little influence on the probability that Macquarie perch will occupy a reach".*

4.1. Implications for a Macquarie perch habitat rehabilitation program in the upper Lachlan catchment

Based on the predictions of our ANN model, the Abercrombie River provides the most consistent and least fragmented Macquarie perch habitat within the upper Lachlan catchment. At the opposite end of the spectrum, neither the Crookwell River nor Blakney Creek provide suitable habitat conditions. The upper Lachlan River provides habitat conditions intermediate between these two extremes, with suitable habitat fragmented by substantial stretches of unsuitable habitat. Those reaches that currently provide suitable macrohabitats to support Macquarie perch populations in the Lachlan include reaches in the vicinity of Gunning – Dalton (Appendix 10), Narrawa Bridge (Appendix 13) and downstream of the Crookwell River junction (Appendix 14). The habitat values of these reaches should be maintained in order to sustain the remnant populations known to occupy all but one of these reaches. No fish sampling has been undertaken in those reaches in the vicinity of Gunning-Dalton that provide suitable habitat. Therefore, targeted sampling of the high quality reaches should be undertaken in order to determine whether a remnant population remains at this location before resources are invested in rehabilitating adjacent reaches.

On the premise that rehabilitation of degraded habitats is particularly relevant when it facilitates reconnection of isolated remnant populations, rehabilitation of those reaches that fragment the areas of suitable habitat within the Lachlan River is likely to result in the greatest conservation outcome. In particular, rehabilitation of reaches L3 – L21 (-34.742S, 149.291E to -34.683S, 149.214E) would facilitate recovery of any possible isolated Gunning-Dalton population. Rehabilitation of reaches L68 – L126 (-34.467S, 149.114E to -34.194S, 149.070E) to restore or enhance connectivity between the isolated Narrawa Bridge and Crookwell River junction population fragments should be high priorities. The next most significant outcome would be the reconnection of the Macquarie perch populations in the Abercrombie and Lachlan Rivers, but this would be difficult given the logistical challenges of fluctuating water levels within the impounded waters of Wyangala Dam. Once preferential rehabilitation has been completed at the above reaches, effort can be concentrated on the less significant sections of unsuitable habitat in the Abercrombie River, and then finally the rehabilitation or enhancement of reaches with in the Crookwell River and/or Blakney Creek.

The ANN model identified the area of both run and riffle mesohabitats and the number of small complex rock piles as primarily important correlates of the pseudo-probability that Macquarie perch will occupy a reach. Therefore, the highest priority habitat rehabilitation activities to restore or improve habitat quality for Macquarie perch are enhancing the area of flowing water mesohabitats and/or increasing the number of small complex rock piles in reaches where they are deficient.

The ANN model suggests that over 3 ha of run habitat, or 1 ha of riffle habitat per kilometre of river are required to result in a reasonable probability that Macquarie perch will occupy a reach. These flowing water habitats can only be rehabilitated or enhanced by increasing flow velocity within the river channel. Given that the upper Lachlan catchment is an unregulated system, there is little potential to obtain or allocate additional environmental flows to the system. Therefore, it is likely that the only achievable means of increasing the availability of run and riffle mesohabitats is by undertaking channel restriction works, bed stabilisation and revegetation in heavily eroded, broadened and sediment affected reaches, so that flow is concentrated into a narrower portion of the channel. However, the most viable targeted rehabilitation or habitat enhancement option for Macquarie perch in most reaches of the upper Lachlan River remains the addition of small complex rock piles. Small complex rock piles are aggregations of boulder sized rocks (512 – 1,000 mm), each with an area of 2 – 5 m^2. The ANN model suggests that even when limited run or riffle mesohabitat is present, a total of 24 small complex rock piles per kilometre is sufficient to result in a high probability of occupancy by Macquarie perch, with the number of rock piles required decreasing as the area of flowing mesohabitats increases. Although the ANN model has not been configured to specify the number of additional rock piles required per reach to maximise its habitability, the ANN can be used to simulate the likely response to addition of specified numbers of rock piles within any reach of interest once target reaches have been established. As an estimate, based on the count of existing small complex rock piles, and accounting for availability of existing boulder substratum within reaches, approximately 1,500 small complex rock piles would need to be added to 86 priority reaches within the Lachlan River in order to provide connectivity between regions of suitable habitat. These are reaches: 5 – 16, 18 – 21, 69 – 79, 81, 84 – 103, 105 – 106, 109 – 110, 113, 115 – 116 and 118 – 148.

5. CONCLUSIONS

The probability that Macquarie perch occupy reaches of the upper Lachlan catchment was predominantly determined by the availability for flowing water mesohabitats (riffles and runs) and the availability of small complex rock piles as cover. The ANN model developed suggests that the remnant population should be almost continuous throughout much of the Abercrombie River, that populations in the upper Lachlan River are fragmented by lengthy stretches of degraded or otherwise unsuitable habitat and that few Macquarie perch are likely to occur with the major tributaries of the upper Lachlan River; Blakney Creek and the Crookwell River. Because the Macquarie perch population within the upper Lachlan catchment is one of the largest remaining populations of this threatened species, aquatic habitat values within the Abercrombie River should be protected at the same time as degraded reaches within the upper Lachlan River channel are rehabilitated or enhanced to facilitate reconnection of the three known fragments of suitable quality habitat. Rehabilitation activities should include the maintenance of environment flows to ensure retention of flowing mesohabitats, undertaking channel restriction works, bed stabilisation and revegetation in heavily eroded, broadened and sediment affected reaches to enhance the availability of riffle and run mesohabitats and the addition of small complex rock piles in those reaches where few flowing water mesohabitats are present.

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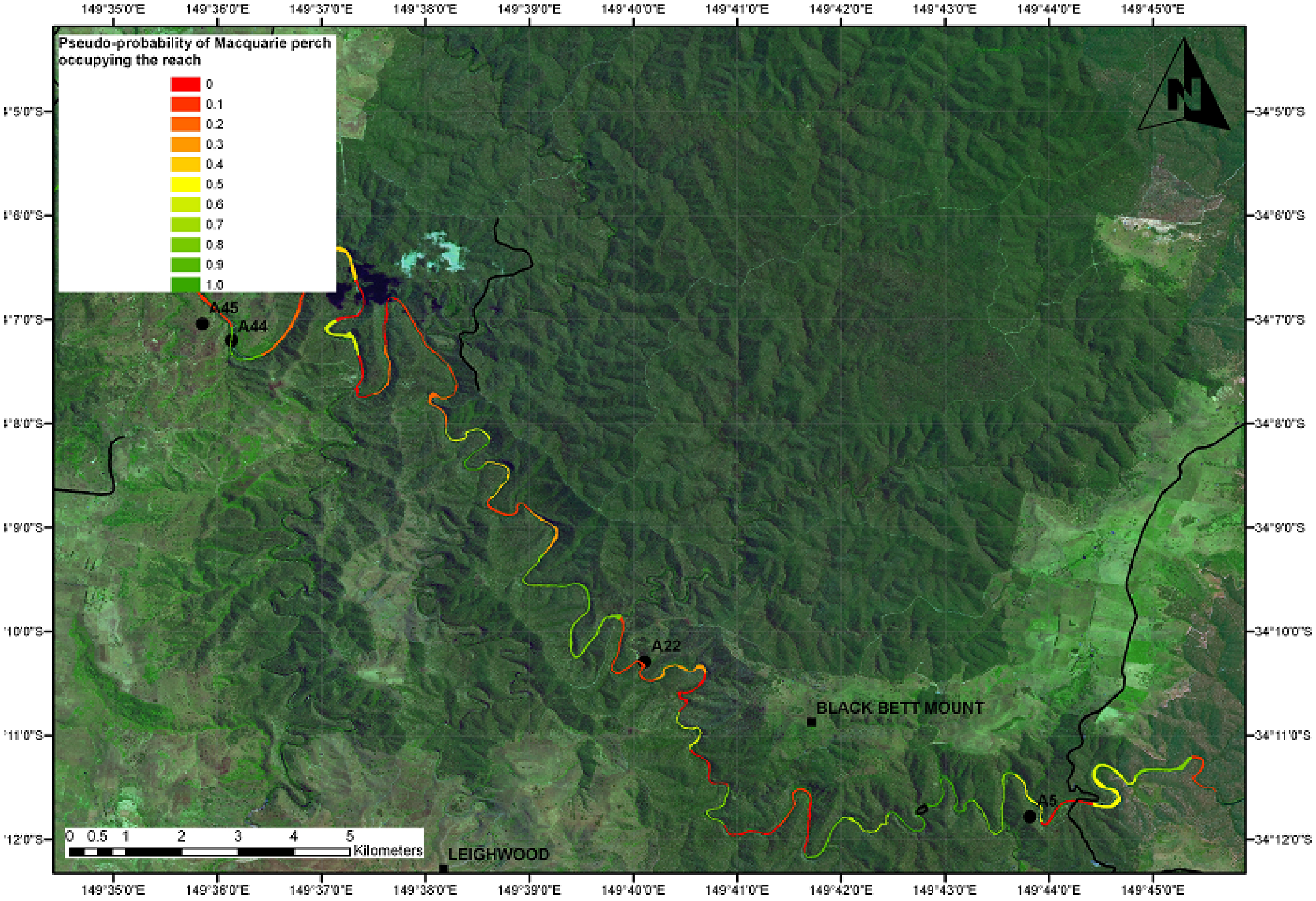
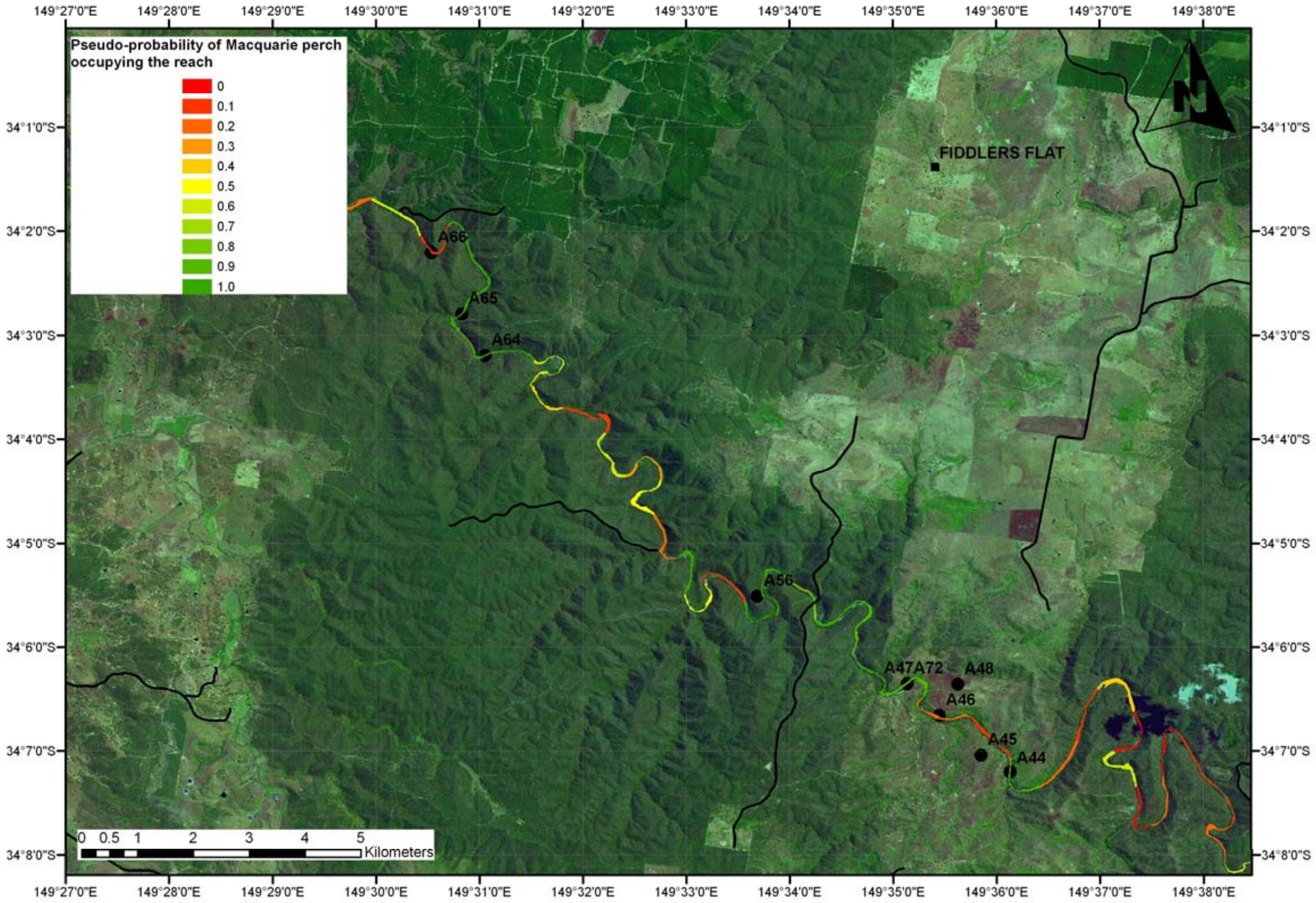
7. APPENDICES

Maps presenting the modelled pseudo-probability that Macquarie perch will occupy each 1 km reach of the Abercrombie River, Blakney Creek, Crookwell River and upper Lachlan River based on the availability of aquatic habitat features.

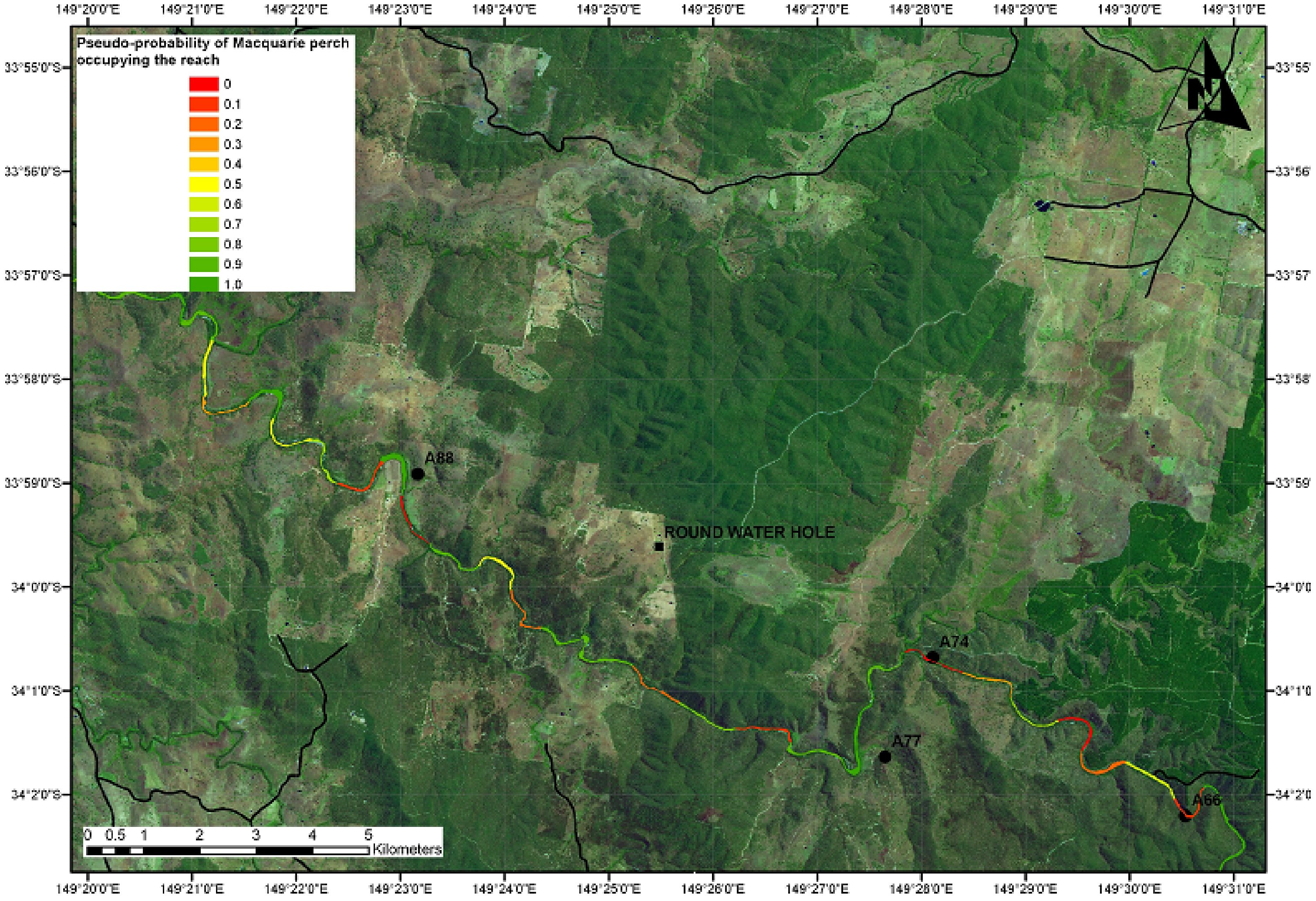
Appendix 1. Predicted pseudo-probability of Macquarie perch occupancy of reaches A1 – A40 of the Abercrombie River.



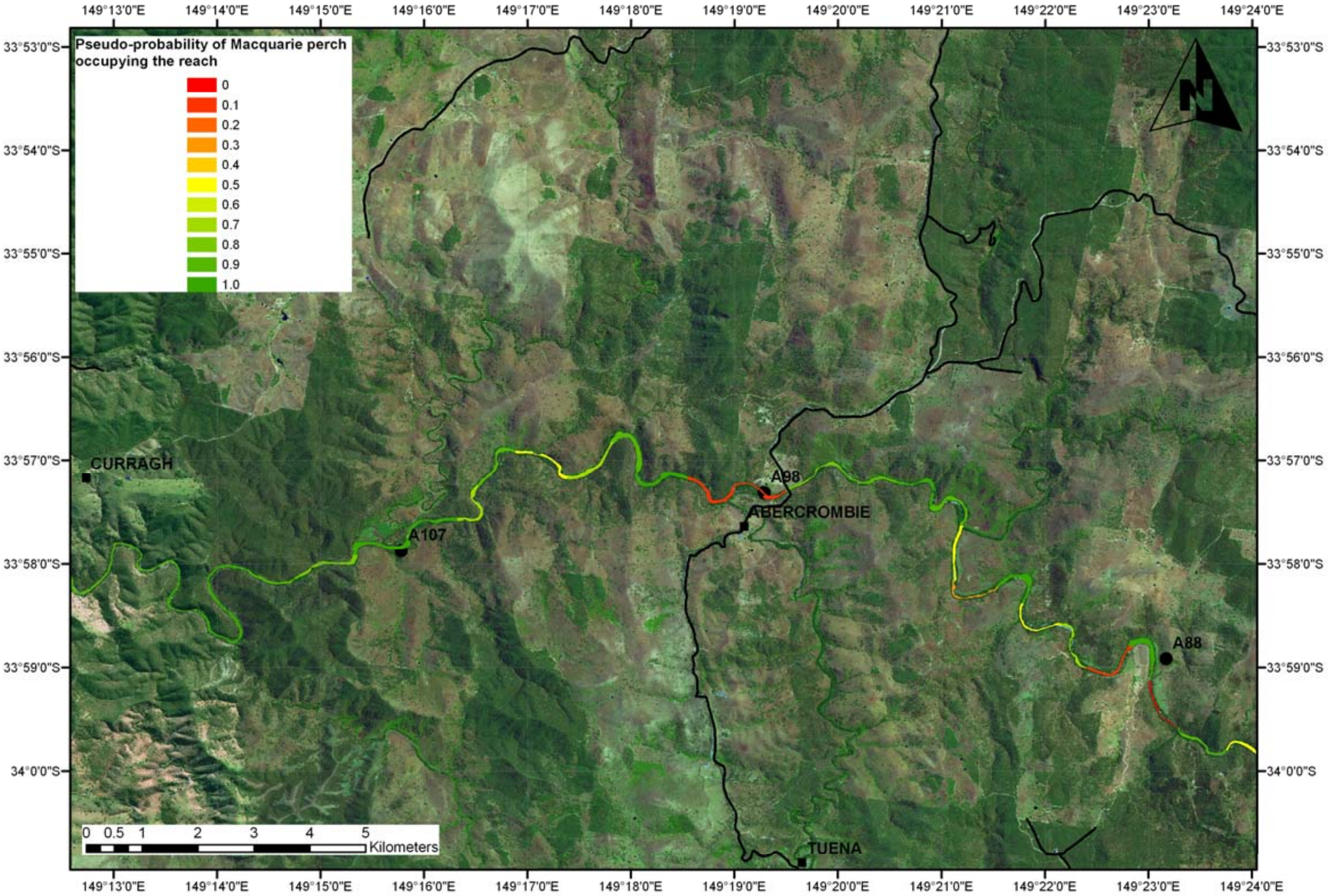
Appendix 2. Predicted pseudo-probability of Macquarie perch occupancy of reaches A35 – A67 of the Abercrombie River.



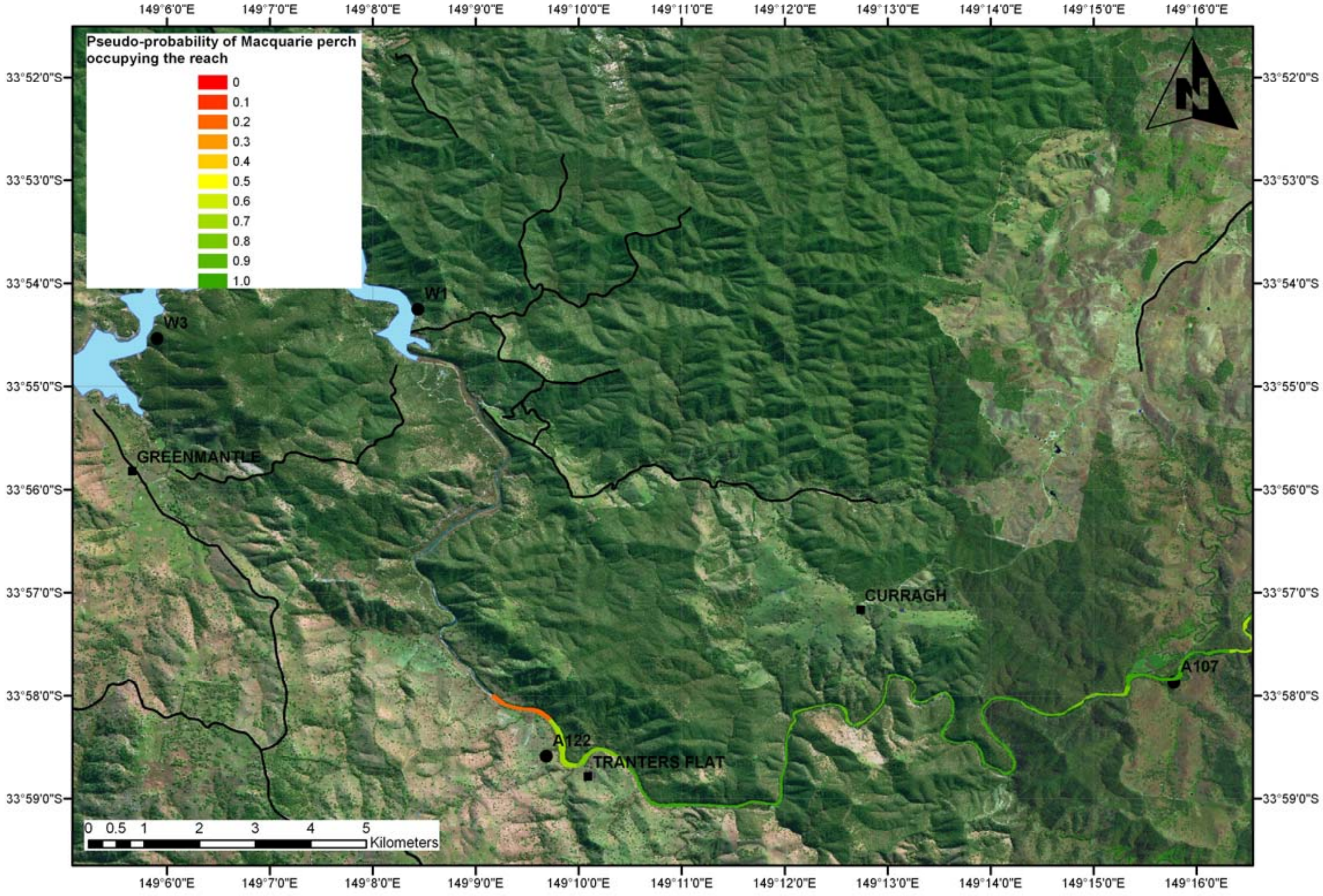
Appendix 3. Predicted pseudo-probability of Macquarie perch occupancy of reaches A65 – A94 of the Abercrombie River.



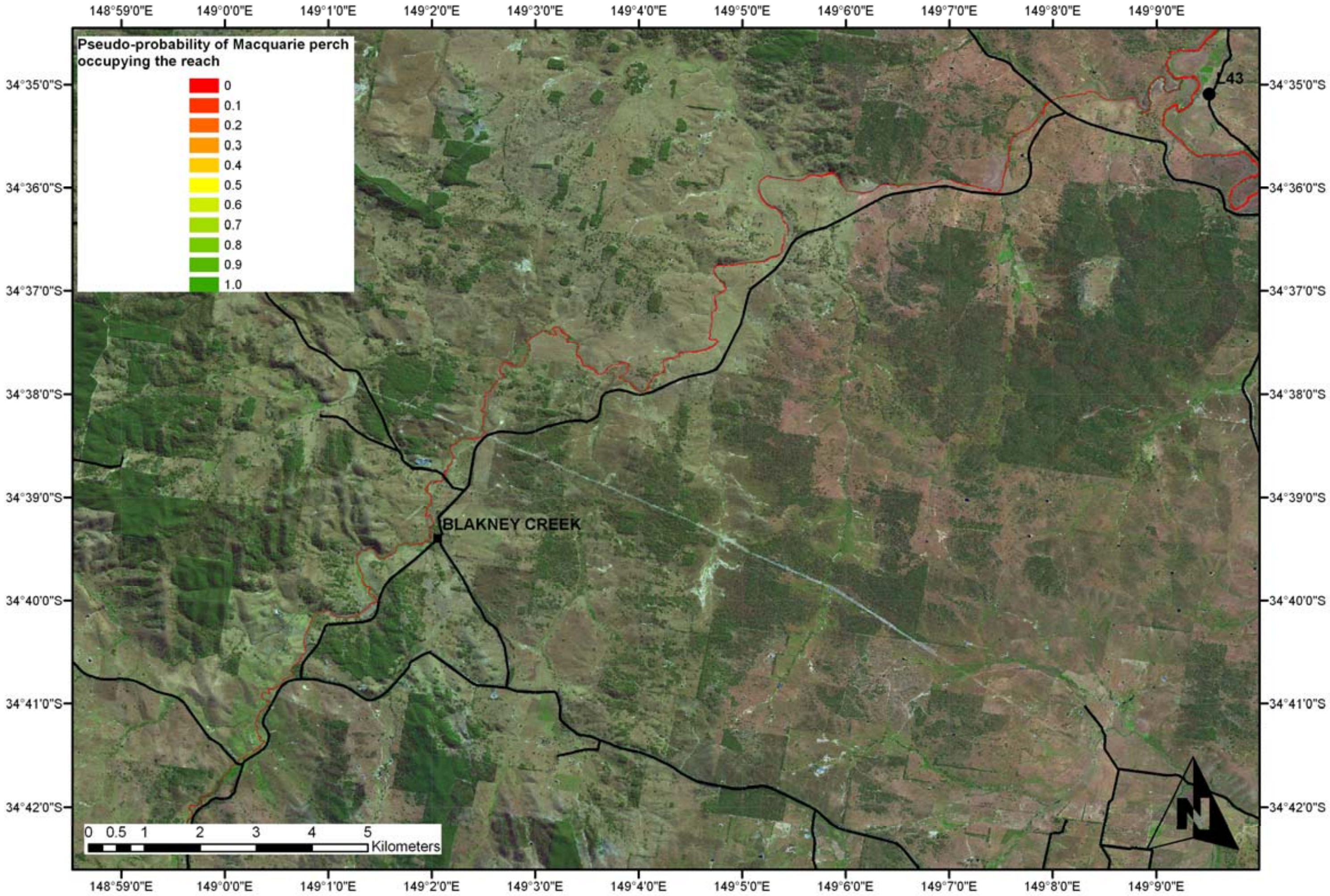
Appendix 4. Predicted pseudo-probability of Macquarie perch occupancy of reaches A86 – A113 of the Abercrombie River.



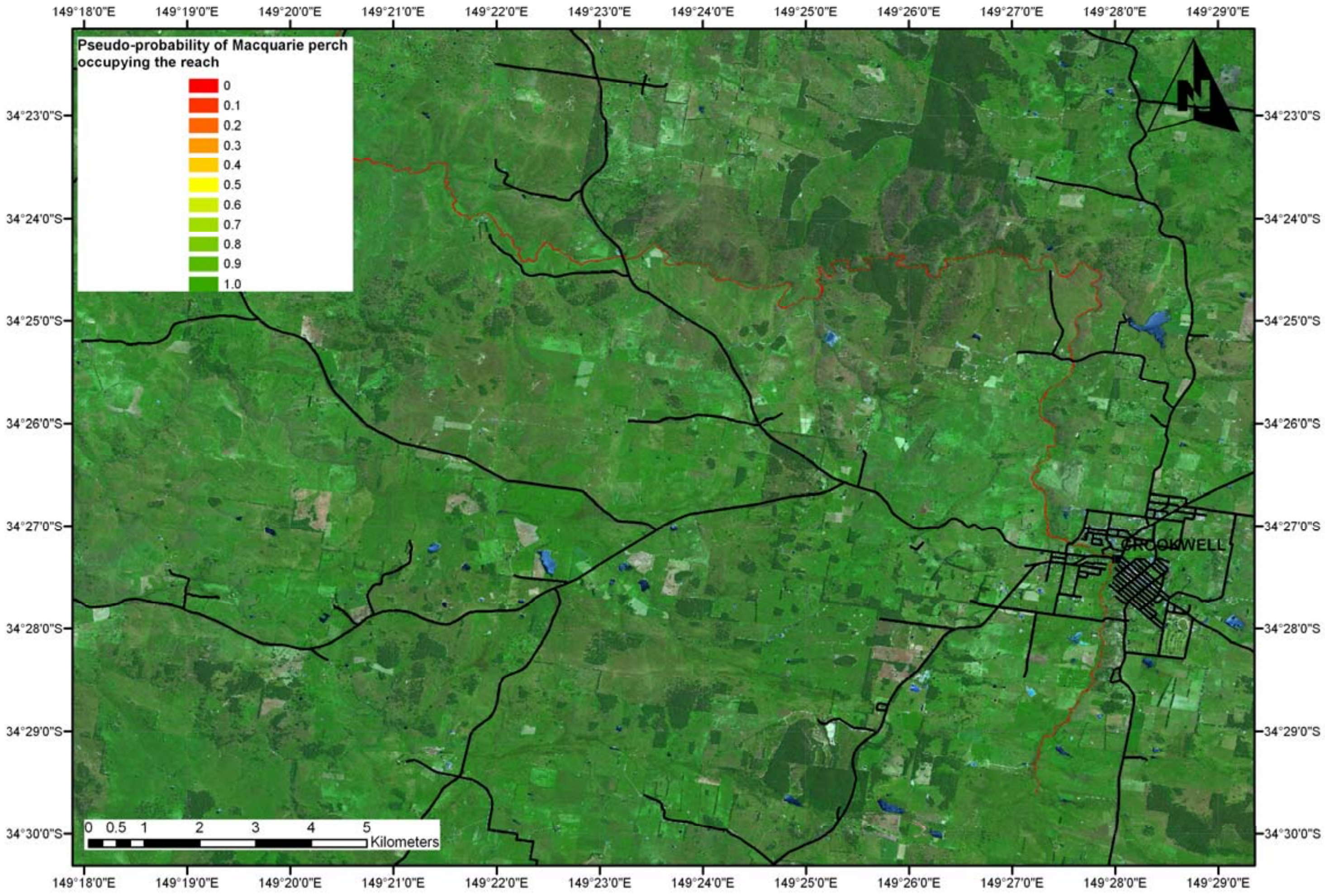
Appendix 5. Predicted pseudo-probability of Macquarie perch occupancy of reaches A107 – A125 of the Abercrombie River.



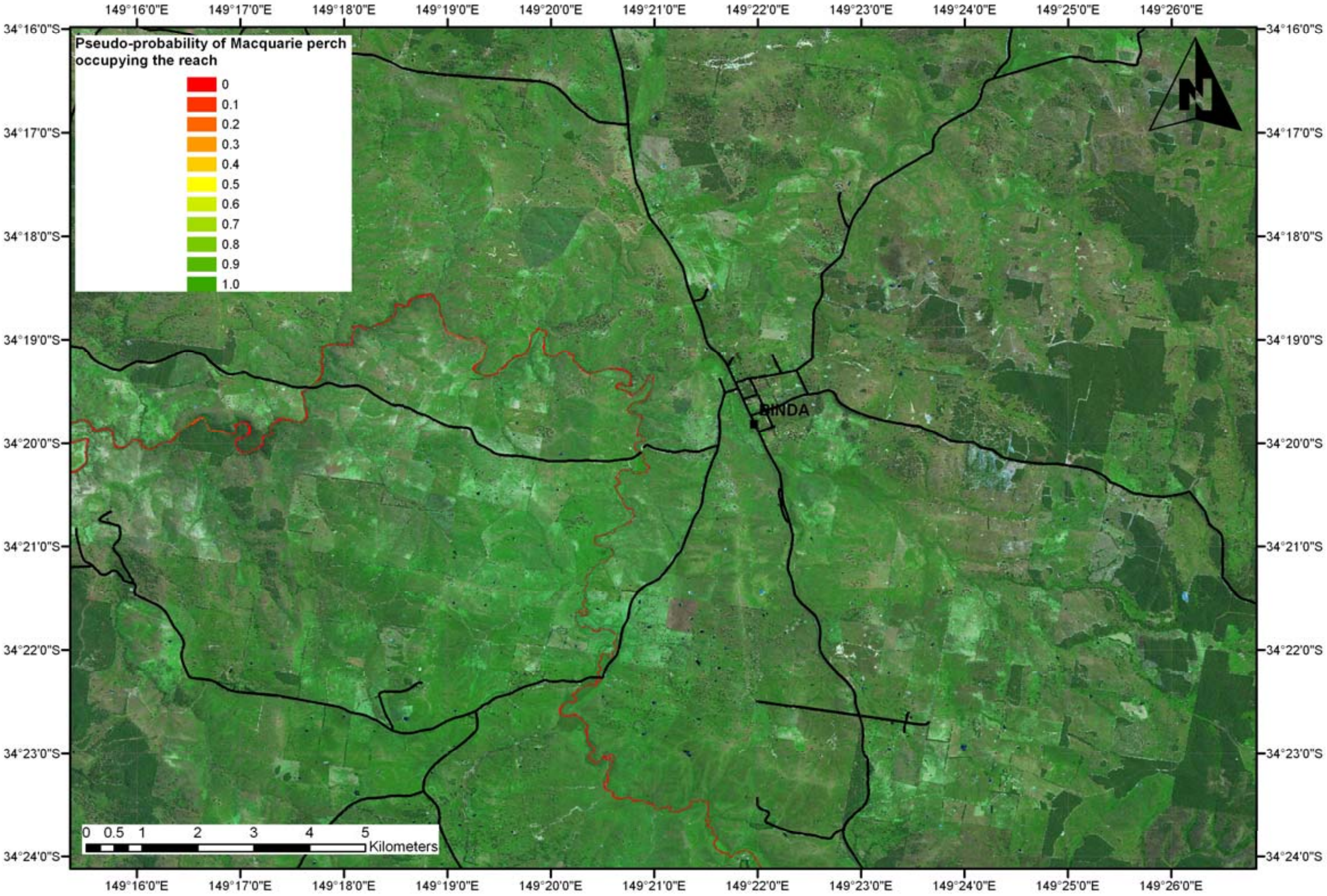
Appendix 6. Predicted pseudo-probability of Macquarie perch occupancy of reaches B1 – B33 of Blakney Creek.



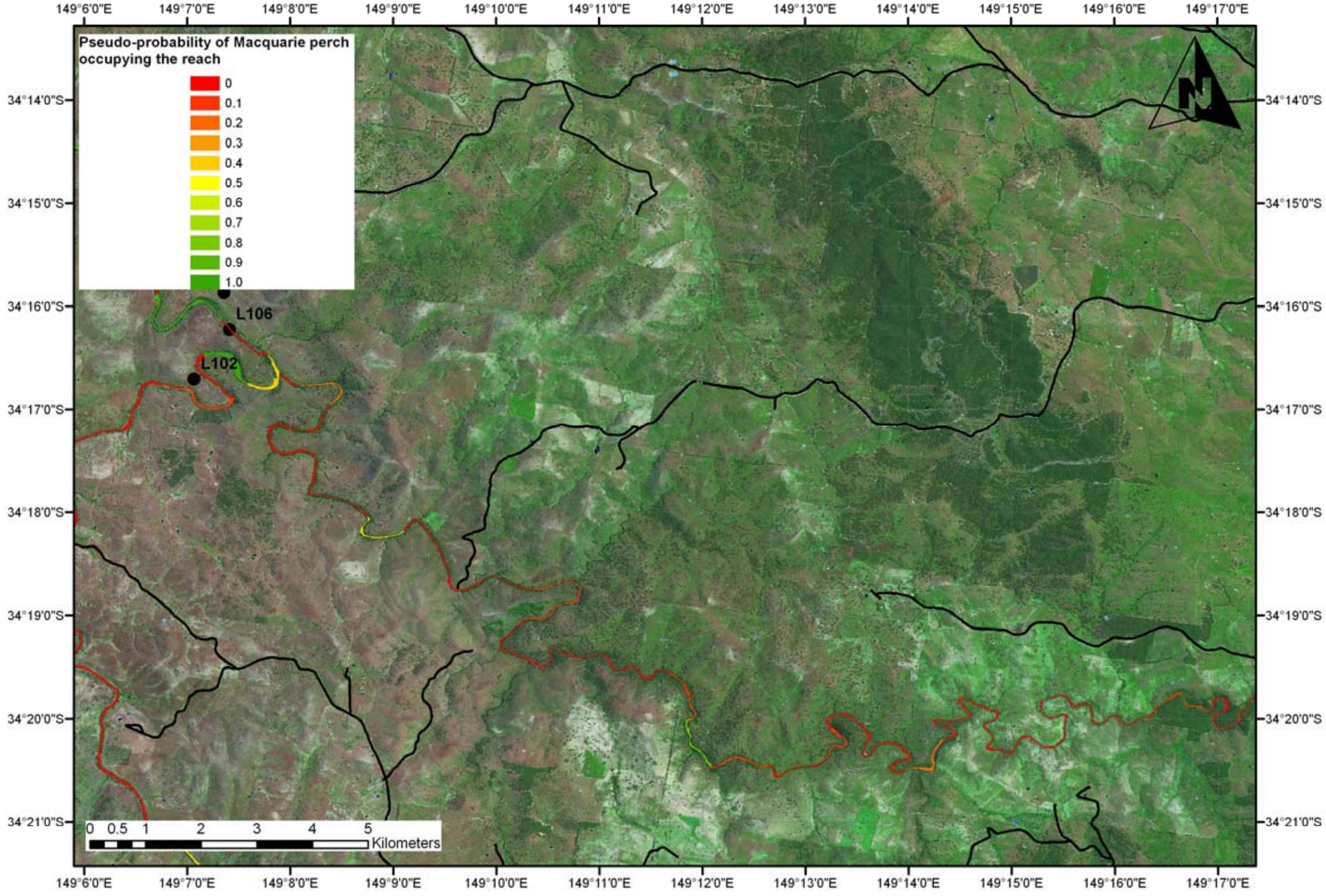
Appendix 7. Predicted pseudo-probability of Macquarie perch occupancy of reaches C1 – C28 of the Crookwell River.



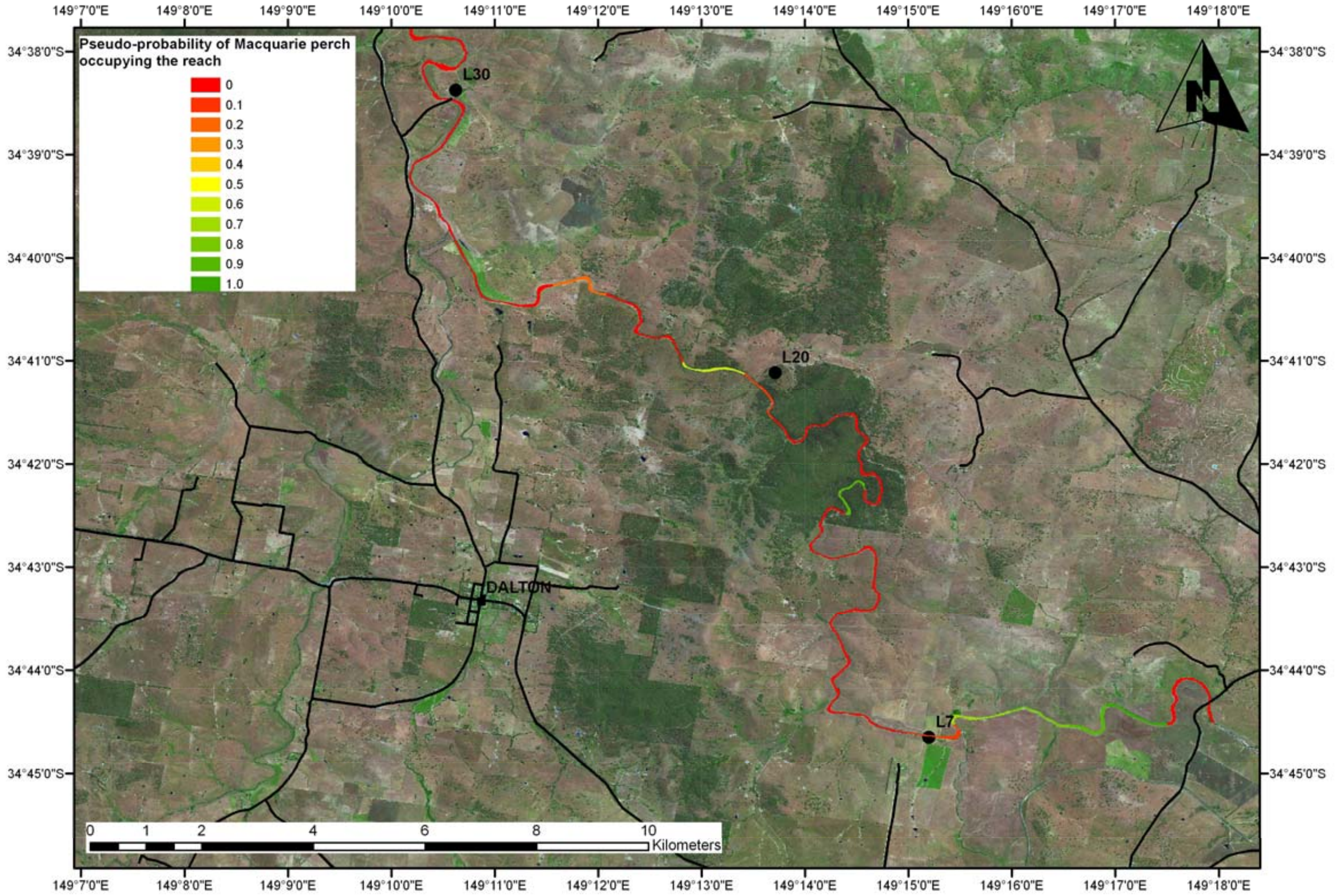
Appendix 8. Predicted pseudo-probability of Macquarie perch occupancy of reaches C28 – C58 of the Crookwell River.



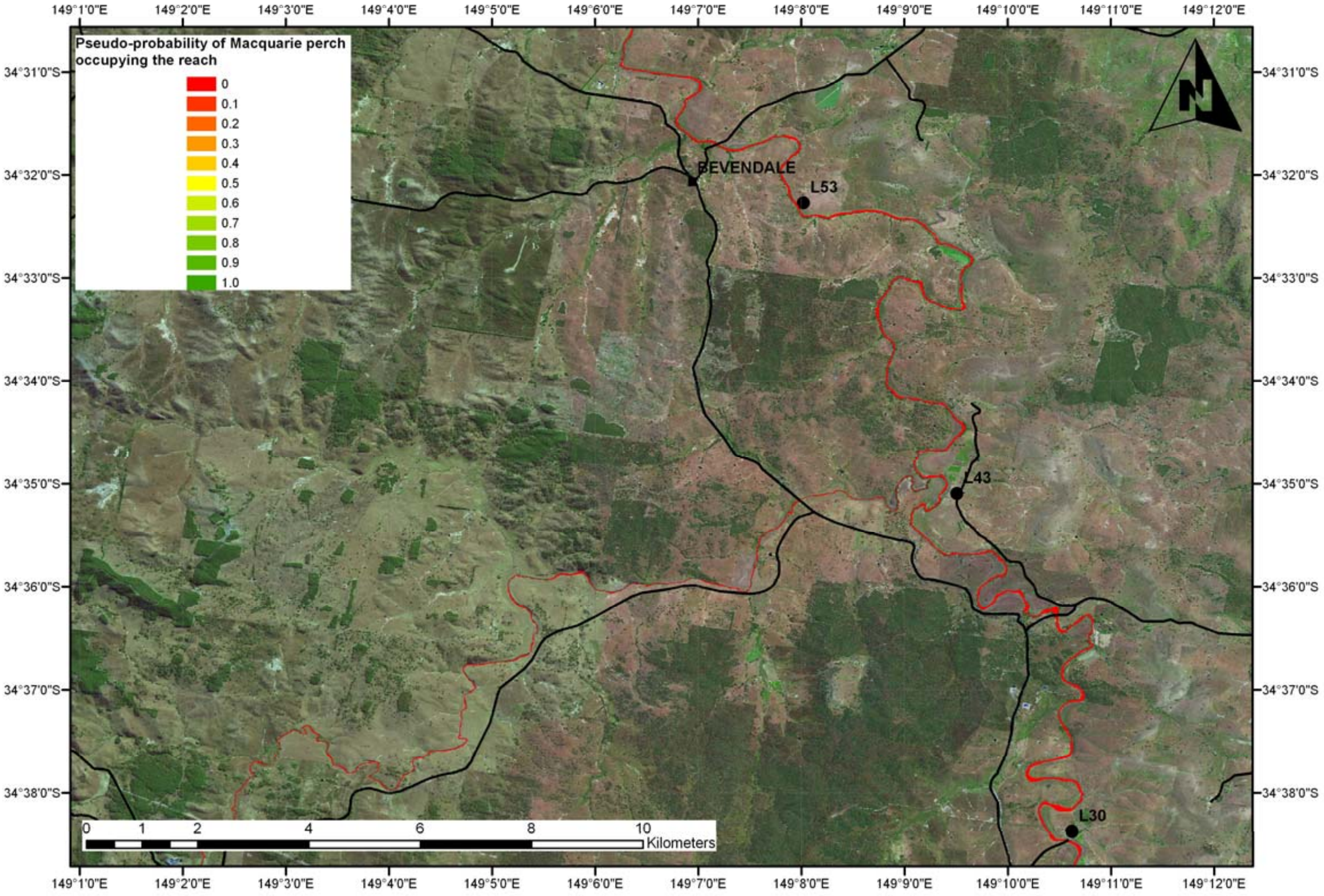
Appendix 9. Predicted pseudo-probability of Macquarie perch occupancy of reaches C58 – C91 of the Crookwell River.



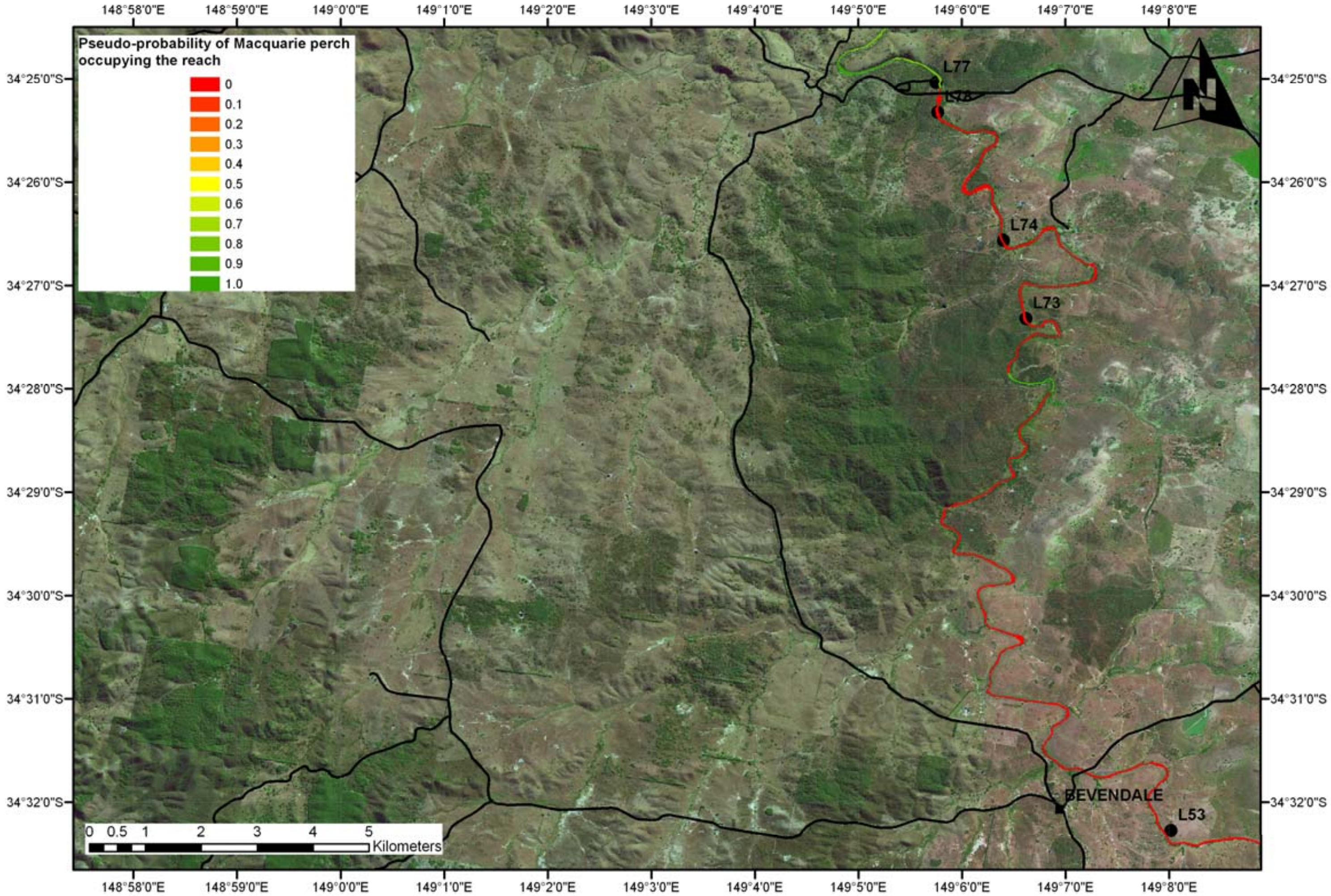
Appendix 10. Predicted pseudo-probability of Macquarie perch occupancy of reaches L1 – L30 of the Lachlan River.



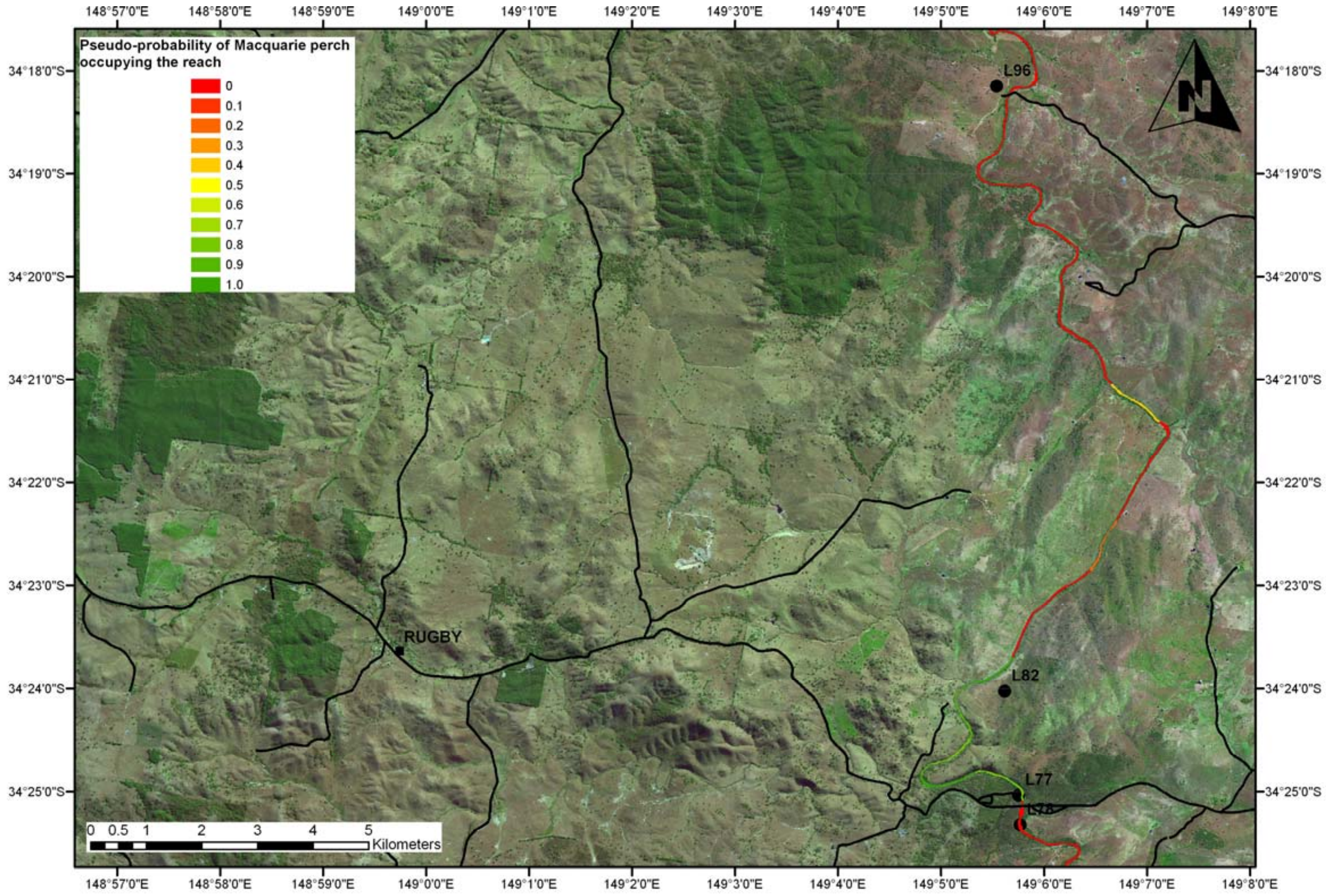
Appendix 11. Predicted pseudo-probability of Macquarie perch occupancy of reaches L30 – L59 of the Lachlan River.



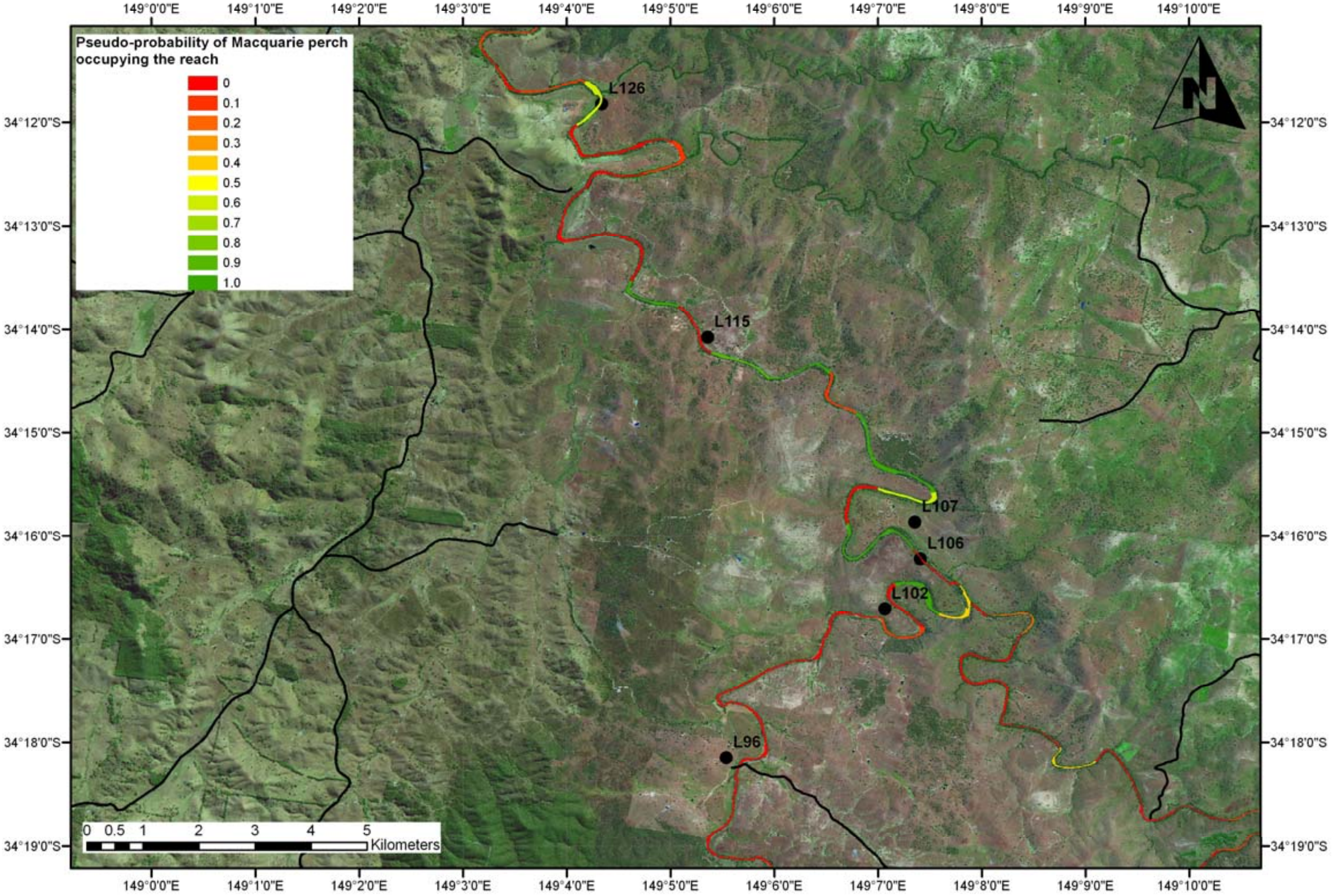
Appendix 12. Predicted pseudo-probability of Macquarie perch occupancy of reaches L53 – L77 of the Lachlan River.



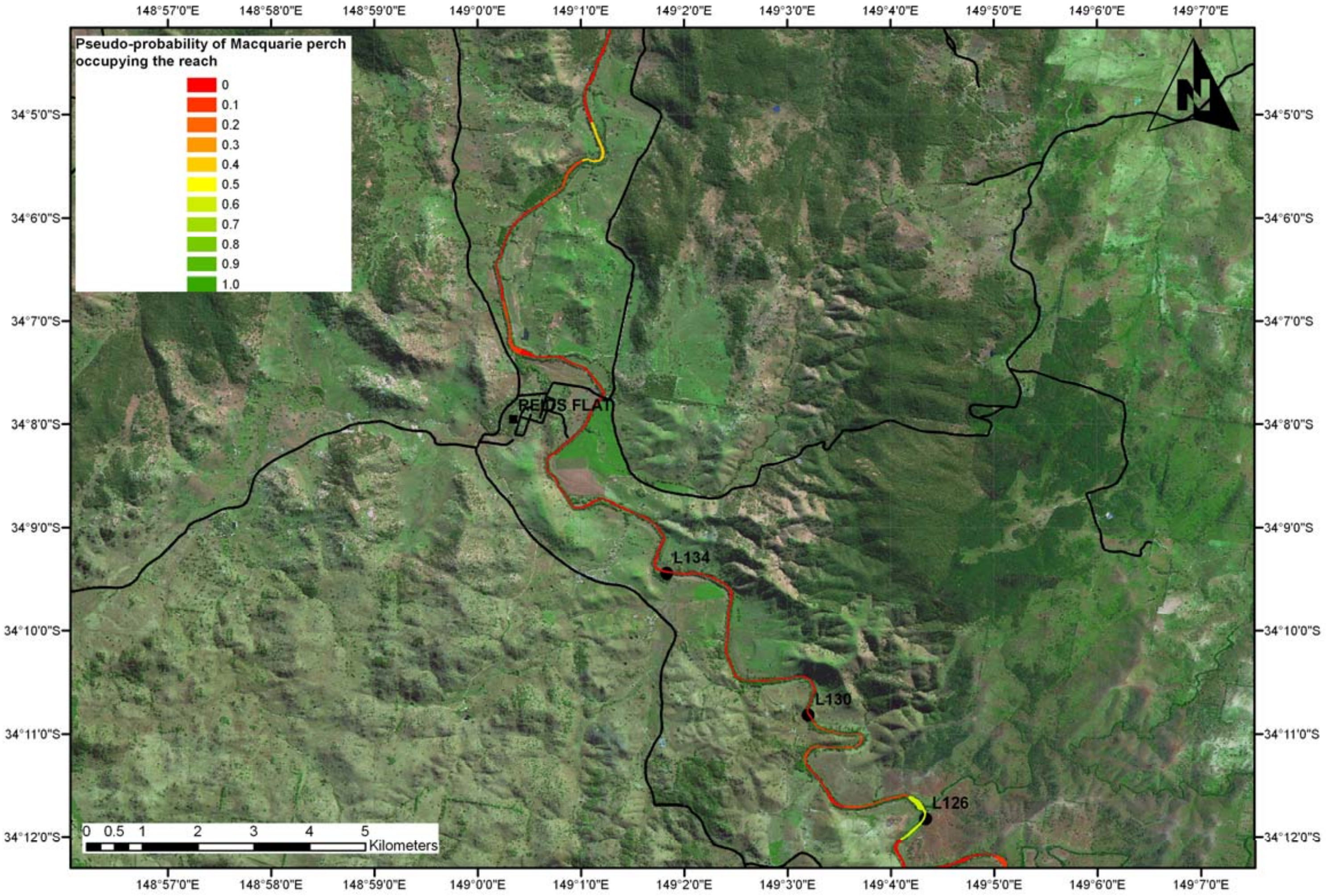
Appendix 13. Predicted pseudo-probability of Macquarie perch occupancy of reaches L76 – L96 of the Lachlan River.



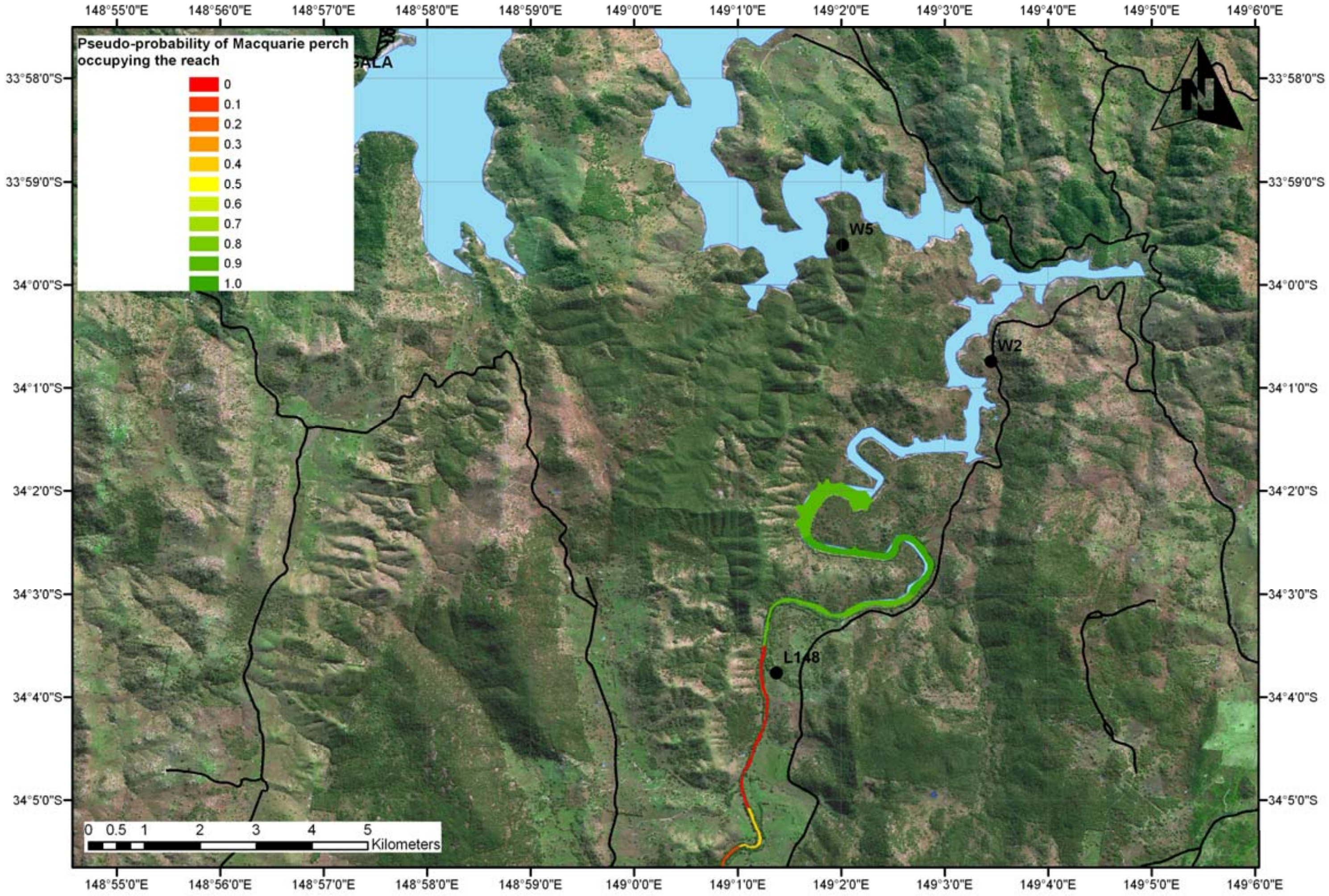
Appendix 14. Predicted pseudo-probability of Macquarie perch occupancy of reaches L94 – L127 of the Lachlan River.



Appendix 15. Predicted pseudo-probability of Macquarie perch occupancy of reaches L126 – L145 of the Lachlan River.



Appendix 16. Predicted pseudo-probability of Macquarie perch occupancy of reaches L144 – L156 of the Lachlan River.



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