Exploratory GIS: Modelling Past Land Use and Occupancy with Functional Connectivity, Willandra Lakes Region World Heritage Area, NSW, Australia

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ABSTRACT

Exploratory GIS models present multiple different conceptual versions of space. This article focusses on the landscape level pathways between areas defined as suitable for land use and occupancy within the Willandra Lakes Region World Heritage Area (WLRWHA), New South Wales (NSW), Australia. Models of the potential connections between ecologically significant land use patches and key hydrology provide iterative networks of functional connectivity, highlighting salient pathways of past land use and occupancy of Country. The shape of the connections between places is important to understanding Country from the inside. Outputs from these network models are a powerful visualisation tool because they display areas where contact with the 19thc Europeans, particularly through fence construction and ground water appropriation, caused greater levels of exploitation and damage than currently recognised. Concomitantly, the benefit of situating these network techniques within an exploratory framework cannot be understated. The iterative nature of the exploratory design allows for multiple presentations of the connectivity between the spaces within the WLRWHA and therefore multiple ways of knowing and seeing space. Modelling the potential pathways between suitable patches opens the door to discussions about the diverse possible corridors of activity within pre-European settlement of Country and the corollary discussion of how European settlement substantially impacted upon these connections and continues to impact on a living Country.

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INTRODUCTION

Exploratory Geographic Information Systems (GIS) model the potential pathways between areas as a range of possibilities and erode the idea of a single path or a single presentation of suitability. This is a study of connectivity and past land use and occupancy in the Willandra Lakes Region World Heritage Area (WLRWHA) in rural NSW, Australia (Figure 1). European fences, Travelling Stock Routes (TSRs) and wells altered the vegetation and hydrological zones by placing barriers, creating voids, and altering the internal connections (Bates 2013; Benson 1991; Fiege 2005). Exploratory GIS modelling is the key to understanding why the initial functional connections within Country are important and why European settlements caused deep, lasting, chaotic effects upon a living Country. In addition, exploratory GIS design for functional connectivity modelling also highlights the need to explore more diverse data sources and methods in our modelling of the deep geographic footprint of human occupancy of Country. The archaeological record of material traces does not represent the totality of human land use and occupancy and the archaeological record should not be employed in isolation to model the biocultural record of past activity. Exploratory GIS in this study provides a way of presenting other areas of Country that may have been actively traversed or settled through modelling possible links and signatures of connectivity between past land use zones and potential water sources.

Exploratory GIS modelling incorporates the multifaceted impacts of salience assessments of a node, network, or area as a range of possibilities and a series of options. Understanding and modelling complexity with an exploratory approach adds the appreciation of the vagaries of human agency and impetus within GIS modelling past land use and occupancy (Maschner & Bentley 2008; Warren & Seifert 2011). There are three main types of salience assessments that are significant within GIS modelling. These are visual, structural, and cognitive salience (Caduff & Timpf 2008; Nuhn & Timpf 2016; Sorrows & Hirtle 1999). Exploratory GIS provide alternative parameters to communicate the differing presentations of visual and structural salience within GIS modelling.

The work presented in this article is of the exploratory functional connectivity GIS models within the Willandra Lakes Region World Heritage Area (WLRWHA). Exploratory GIS network models are part of a larger project which investigated the applications of exploratory GIS in land suitability modelling and the necessity of including testimonies from Traditional Owners into a Participatory

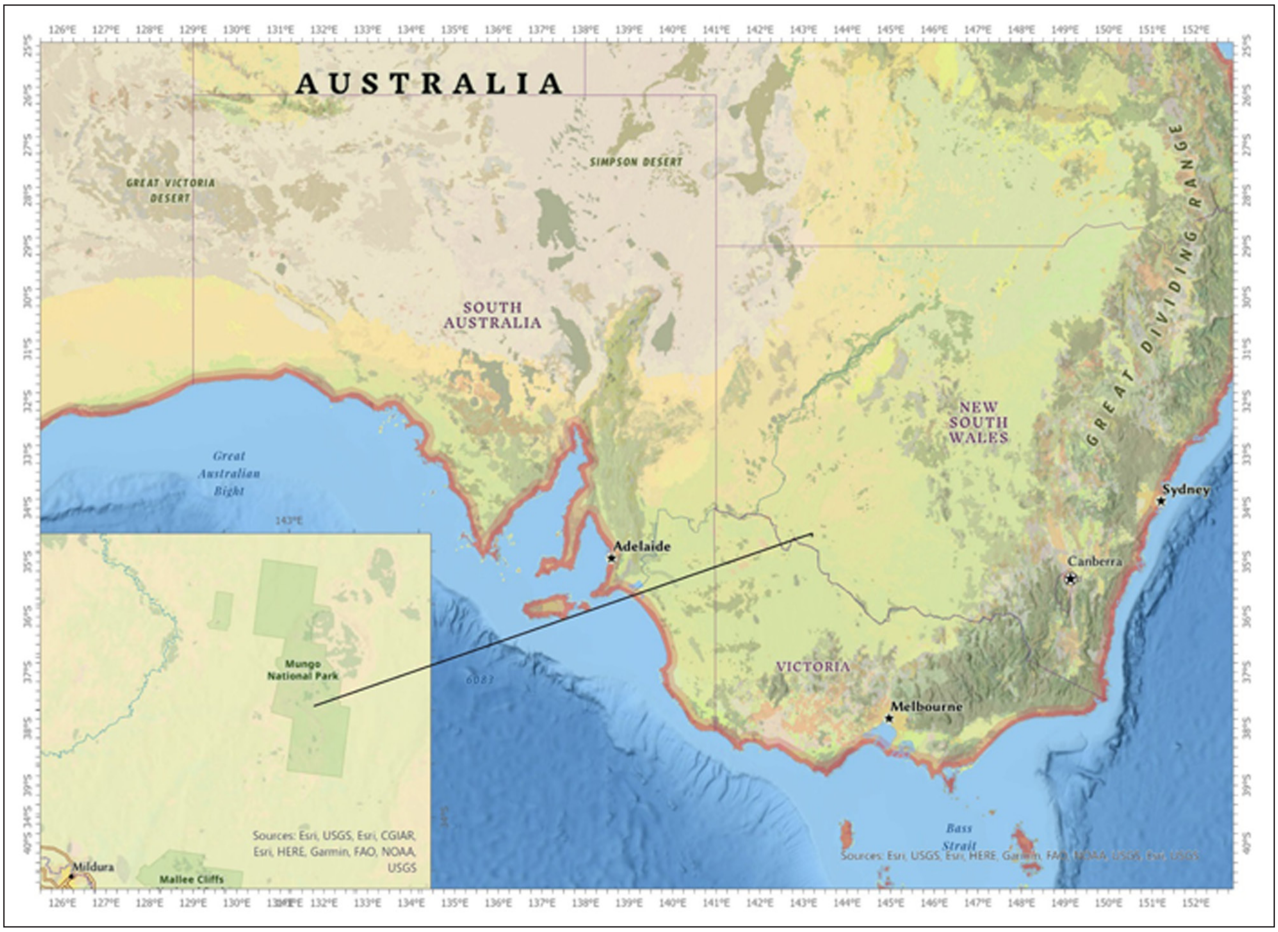

Figure 1 Location of the research.

GIS (pGIS). There are no current models of the pre-pastoral landscape of the WLRWHA that adequately display the fluidity of the landscape and appropriately represent the concepts of salience from a Traditional Owner perspective. Exploratory GIS, coupled with pGIS, presents truly comprehensive models of the material records of past land use and occupancy and the nuanced intangible cultural signatures of the Mutthi Mutthi, Ngyiampaa, and Paakantji (Barkindji). This paper, however, is designed to explore just one facet of the entire methods and methodologies applied to a holistic GIS exploration of pre-European Country within the WLRWHA. As such, this paper represents a subsection of a larger project that formed the basis of PhD research encompassing exploratory GIS and pGIS within the WLRWHA with the First Nations community members (Thomas 2019, 2018). Below, we will examine the need for exploratory GIS design within environmental network modelling to demonstrate the possible impacts of European settlement to the multiple pathways of human agency.

BACKGROUND

CULTURAL FRAME

Cultural frames are ways of defining space that are derived from cultural boundaries and attachment to Country instead of European generated map areas (Byrne & Nugent 2004; Goggin et al. 2017; Howard-Grenville, Hoffman, & Wirtenberg 2003; Walton & Bailey 2005). The cultural frame of the project centres on Lake Mungo which overlaps the Mutthi Mutthi, Paakantji and Ngiyampaa areas (Hercus 1969; NSW National Parks and Wildlife Service 2006; Tindale 1974a). The WLRWHA Aboriginal Advisory Group is comprised of these three communities. Traditional Owner land use areas should not be viewed in European or Euclidian geometric terms as definitive conceptions of space or as a definitive absolute statement on the boundaries of Traditional Lands. The Ngyiampaa centre around the Willandra Creek and the land use zones within proximity to this water source, moving westward to Mungo Lake; the Paakantji centre around the Darling and come eastward to Mungo; the Mutthi Mutthi centre around the Murrumbidgee and Box Creek and travel in movement lines northwestward to Mungo (Allbrook & McGrath 2015; NSW National Parks and Wildlife Service 2006; Tindale 1974a, 1974b). This paper models the underlying environmental functional connectivity in relation to the main rivers, ecotonal areas, and flowing water sources.

CULTURAL CENTROID

The WLRWHA acts as the central point within the cultural frame (Graham & Healey 1999). A central point is a centroid. Mungo National Park, specifically the dry lake beds, bordering dunes, and lunettes, has been and continues to be a central place for the Traditional Owners: Mutthi Mutthi, Paakantji and Ngyiampaa (Goggin et al. 2017; Howard-Grenville, Hoffman, & Wirtenberg 2003, pp. 71–72). Furthermore, Lake Mungo, within Mungo National Park, has also been a focus area for researchers due to the discovery of Mungo Man and Mungo Lady in the Mungo lunette (Fitzsimmons et al. 2014, pp. 349–350; Bowler et al. 2003; Allbrook and McGrath, 2015). The Willandra Lakes continues as a place of deep significance for the Traditional Owners. Continuing attachment to Country by the Traditional Owners is the reason that the WLRWHA is the centre of the exploratory GIS modelling. Thus, this is how the cultural frame, and the centroid were defined. Exploratory GIS models of the functional connections between land use and occupancy patches, with a centroid defined by cultural framing, takes depth of attachment to the WLRWHA of the Traditional Owners (Lewicka 2011; Walton & Bailey 2005). Thus, the salience of the centroid and the edges of the GIS model are set by cultural framing instead of the GIS technician, or a research agenda, for this project.

Pathways across Country

Landscape level pathways between areas defined as suitable for land use and occupancy within the Willandra Lakes Region World Heritage Area (WLRWHA), NSW are structurally salient connections, criss-crossing Country. Land use and occupancy or use and occupancy mapping (UOM) has had a revival under the work of Tobias (2000, 2009) and the overarching work within this project includes some of the theoretical concepts of mapping the cultural acts as well as the material cultural record (Smith 2006; Wilkinson et al. 2016).

The complex land use signatures within the WLRWHA are influenced by the occupation and travels of the Traditional Owners, explorers, drovers, and pastoral families. In detail, the Mungo National Park's timeline travels through Indigenous ownership to pastoral leases and soldier settlement blocks, and then the transfer of the lease to the NSW National Parks and Wildlife in 1979. In subsequent years (2002, 2005), the adjacent leasehold blocks of Leaghur, Garnpang, Balmoral, Pan Ban, and Joulni joined to create the area of Mungo National Park (NSW National Parks and Wildlife Service 2006, p. 4).

IMPACTS ON THE PATHWAYS OF LAND USE AND OCCUPANCY

Impacts from European settlement on the pre-contact Indigenous community pathways of land use and occupancy are manifold. These impacts include, but are not limited to, depletion of the topsoil, climate change, water table alteration, grazing impacts, and generalised degradation of the environment (Allen & Holdaway 2009; Bowler & Magee 1973; Clark 1987; Dare-Edwards 1979; IPCC 2020; Pickard 1991; Verstraete & Schwartz 1991). This leads to changes in the environmental record which results in differential preservation of the material archaeological record and the networked cultural signatures. Additionally, the differing layers of human occupation and travels all impact and compact the model of the internal functional connectivity between land use and occupancy patches.

ENVIRONMENTAL RECORD

From an ecological perspective, the WLRWHA spans the sub-bioregions of *South Olary Plains/Murray Basin Sands* and it is proximal to the *Murray Scroll Belt* (IBRA7 (Cummings & Hardy 2000)). Hydrologically, the area is an endorheic basin which means water drains inward instead of outward (De Deckker 2019, 1983). Therefore, many areas within the WLRWHA are very dependent on seasonal rainfall and the ground water, which flows predominately in lines westward within the Ivanhoe block and deeply affected by the pulses coming from the snow melts in the Lachlan (Kemp 2010; Odins et al. 1991). The Willandra Lakes are regional discharge zones. The area is geologically rich and filled with varied landforms, semi-arid vegetation communities, and high levels of endemism, which have been mapped and recorded at different times and scales (Bowler & Magee 1978; Genty et al. 2003; Haslem et al. 2010; Hesse 2011; Westbrooke & Miller 1995).

As a closed semi-arid ecological basin with high levels of flora and fauna endemism, it is particularly important to model the baseline of the pre-contact landscape to establish what areas were most impacted by pastoral settlement. It has been shown that these areas of high endemism and high isolation are the most fragile and susceptible to large scale change when faced with contact with foreign plants and animals (Keith 2002; Keith et al. 2022; White 1997). In particular, biogeographic and botanical studies on vegetation within pastoral blocks in western NSW illustrate that the effect of the pastoral frontier on these areas of rangeland were discernible and degrading (Graz, Westbrooke, & Florentine 2012; Pickard 1991; Westbrooke 2012; Westbrooke & Miller 1995). In addition, exploratory GIS modelling of the past landscape connectivity can be employed to inform future climate change modelling for this fragile ecosystem and also be retrofitted to past environmental states, including the Last Glacial Maximum (LGM) by establishing possible vulnerabilities within the connected biocultural landscape.

EXPLORERS AND DROVERS

The next layer of land use and occupancy of the WLRWHA is the pathways from the early explorers and drovers that crossed through the area of Western NSW. From the first main expedition by Sturt in the late 1830s onwards, there were a series of expeditions to follow rivers to their sources and to assess the agricultural potential of the land (Sturt 2004). The early explorers left a minimal imprint on the land use zones because they were transients, focussed on gathering information, rather than settling the area. However, their travels left their mark in the form of slaughter by microbes, child removals, and massacres – a genocide (Burke et al. 2016; Joyce et al. 2011; Tatz 2016; Wolfe 2006). A full summary of all the early explorers and drovers within the Darling basin can be found in Harry Allen's comprehensive PhD thesis (Allen 1972, p. 24) and in the earlier writings of Burke and Wills, Hawdon, Mitchell, and MacCabe (Hawdon 1838, reprinted 1952; Joyce et al. 2011; Mitchell 1848, reprinted 2014; Joyce, E.B. & McCann, D.A. 2011, p. 290; MacCabe Francis P Surveyors' Letters 1822–1855, 2/1554.1(Reel 3075), 2/1554.1A (Reel 3076), 6 Dec 1841–Dec 1848).

Many of the early expeditions were focussed on the rivers because water was a key route for travel for explorers, especially those hoping to find an inland sea (Deloria 2017; Judd 2019; Watts 2020). Mitchell's expedition in 1836 along the Murray, Murrumbidgee, and Lachlan rivers was followed by Bonney and Hawdon's 1838 droving expedition along the Murray. Hawdon's journal has several observations about the local inhabitants and the vegetation, including descriptions of what food was being gathered and hunted. He makes reference to wild yams, emus, and fish being a staple near the Murray-Darling junction (Hawdon 1838, reprinted 1952, p. 41). From Mitchell's expedition, there are also countless observations, including the transfer of knowledge from the Traditional Owners to the explorers regarding ground water, forbes, and food (Mitchell 1848, reprinted 2014). Lastly, the surveyor MacCabe conducted a series of expeditions in 1848–1853 along the Lachlan to the Darling. These journeys are a rich primary source filled with observations about the vegetation and inhabitants of the area (MacCabe Francis P Surveyors' Letters 1822–1855, 2/1554.1(Reel 3075), 2/1554.1A (Reel 3076), 6 Dec 1841–Dec 1848). These snippets of information add to background of the GIS model because they provide primary source observations for the contact period, and they illustrate the crossover of information from the Traditional Owners to the early explorers and drovers.

PASTORAL FAMILIES

The next wave of land use and occupancy came in the settlement of the back blocks of the Lower Darling from the 1850s onwards. Predominately settled for sheep rearing, these back blocks of the WLRWHA drastically changed the Country for the Traditional Owners by removing the initial pathways. As Bobbie Hardy recounts, '...a monstrous tragedy made by white man...the disaster area was the [Paakantji] Barkindji's homeland, the last vestige of their link with a meaningful past...In their land was neither work to be had nor game to hunt,' (Taylor 1978, p. 177). Conclusively, the movement and settlement of the WLRWHA into the blocks of Gall Gall and then the further subdivision into Garnpung, Arumpo, Gol Gol, and Turlee marked a huge change in the land use and occupancy of the area.

Several families were part of the settlement of the WLRWHA. However, for the purposes of this project, the main written record sources were of the Patterson family archives of Gol Gol station (University of Melbourne Archives; (Patterson family 1838)) and the detailed plans and letters within the Pastoral Lease files and Run Boundary files of Gol Gol, Turlee, Arumpo, and Garnpung stations (NSW State Archives, Pastoral Holdings – Western Division, NRS 8368; NSW State Archives, Run Boundary Register – Darling, 8/2205). These sources, like the diaries of the explorers, provided detailed information on vegetation, clearing, stocking rates, and rainfall. Whereas the explorers and drovers' journals were useful primary sources for assessing the connectivity between areas, the primary source data in the Pastoral Lease files and the Patterson family archives provided contextual information for the level and type of impacts that the imposed agrarian economy had on the WLRWHA.

Without straying into a declentionist environmental history narrative, the exploratory GIS methods within this article substantiate the assertion that the pastoral frontier caused deep change to the initial functional connections of land use and occupancy for the Aboriginal communities of the WLRWHA (Chakrabarty 2009; Potter 2013). The introduction of fences caused significant impact to the area because of the clearing of the significant hardwoods and the division of the land, breaking apart traditional routes (Instone 1999; Pickard 1997). The exploratory GIS models in the ensuing sections provide multiple iterations of potential environmental connectivity across Country and highlight the areas of greatest impact by the pastoral frontier on the internal structures of a living biocultural Country.

METHODS

FUNCTIONAL CONNECTIVITY

Connectivity science within ecological network analysis can take many forms, from graph trees to circuit theory to functional connectivity assessments (Dickson et al. 2018; Gibaja, Marreiros, & Mazzucco 2020; Goicolea et al. 2022; Laliberté & St-Laurent 2020; Leming et al. 2019; McRae et al. 2008). Adopted into this exploratory GIS modelling is the concept of functional connectivity (Vogt et al. 2009; Wainwright et al. 2011). Functional connectivity is the concept that even remote areas of land are connected through networks within a matrix of zones and areas. This idea of visualising corridors of activity and connections between zonal areas is derived from applied ecology and neural network mapping in the human brain (Friston, Frith, & Frackowiak 1993; Vogt et al. 2009). A landscape that is functionally connected is one through which humans can move between habitat patches because the entire network supports land use and occupancy (Poniatowski et al. 2016). This is a concept derived from spatial ecology (Bélisle 2005; Moilanen & Nieminen 2002; Saura & Rubio 2010). Habitats and the land (or matrix) that lies between them displays functional connectivity at a landscape scale. The functional network modelling potential pathways that may represent connections to water sources and ecological zones, crucial elements for past land use and occupancy. Modelling the internal connections allows for a window into the past biocultural landscape. This also is echoed in Somerville and Bates' work showing the importance of water and water pathways (Somerville & Bates 2013). The nature of the land cover, including potential water sources, is critical and can be either a barrier or a conduit for land use and occupancy.

Functional connectivity has been expressed within GIS through least-cost path modelling, graph trees, and variants of the Voronoi diagrams (Edelsbrunner, Kirkpatrick, & Seidel 1983; Gustas & Supernant 2017; Radke 2015; Thomas 2000; Toussaint 2015). These add another view to the Euclidean distance measurements that form the basis of the land suitability modelling of zones. This is important because Euclidean distance measurements are heavily criticised for not representing internal structures appropriately due to not being able to cope with the impact of relative relationships between the loci (Gutiérrez & García-Palomares 2008; McLean & Rubio-Campillo 2022; Nicholls 2001). This work builds on land suitability modelling, which centers on modelling the external shapes of space – the exohulls of space (i.e. zones, Delaunay triangulations). Functional connectivity models the endohulls of space (i.e. connections, Voronoi tessellations)(Goodman, Pollack, & Aronov 2003; Radke 2015; Toussaint 2015; Wang et al. 2022). Modelling the internal and external connections of Country allows for a deep understanding of the biocultural landscape by modelling space holistically.

Within archaeological GIS applications, the attempt to map and model internal connections or internal shape descriptors has taken the form of core-periphery modelling, least-cost path modelling, raw material provenancing, and transhumance route modelling (Bintliff 1996; Duke & Steele 2010; Field, Glowacki, & Gettler 2022; Moreno-Meynard et al. 2022; Savary, Foltête, & Garnier 2022; Taliaferro, Schriever, & Shackley 2010; Van Leusen 1999). Recent work by Gustas and Supernant depicts how to better situate these scientific modelling techniques within an intuitive framework (Gustas & Supernant 2017). Recent work by Field et al. (2022) depicts how to better develop more nuanced models of time versus energy as a prime movers for pathway selection. Functional connectivity science within an intuitive framework of exploratory GIS provides the structural salience for a connected landscape; this provides the basis for modelled hypothetical versions of past land use and occupancy.

EXPLORATORY GIS

Exploratory GIS challenges the single output GIS mapping for the past record of land use and occupancy. GIS should be a modelling 'process' and the many decisions and inferences that impact on the outputs from GIS modelling should be transparent (Downs & Stea 2011; Fleming 2006; Schmoldt, Mendoza, & Kangas 2001). It is not appropriate to create a single cartographic output and uncertainty needs to be built into the modelling designs (Brouwer Burg 2017; Burg, Peeters, & Lovis 2016; Hunsaker et al. 2001; Leusen, Millard, & Ducke 2009; Pánek, Pászto, & Marek 2017). Exploratory functional connectivity GIS models the relationships between the points and areas of potential water availability and resource locations as ranges of functionally connected corridors of land use and occupancy. The outputs from connectivity science are both models of the functions of the landscape and the analysis techniques employed; exploratory GIS or experimental design allows for ranges of presentations and will be discussed below.

The way space is measured is the most important factor in defining a network within an exploratory GIS connectivity model. Categorisation of the base data set, applying thresholds, averaging, and systemisations of human pathways have many compounded errors when network modelling is employed in a single output fashion. Many assessments of land networks are dependent upon the way space is divided and measured between the underlying point set or base areas. Therefore, exploratory design is crucial within GIS network modelling because a range of options and visualisations can be explored instead of an ill-fitting single option route model. Space is either measured in an absolute way by employing Euclidean geometric measurements of end-to-end distances between loci or space is measured in a relative way where all of the different loci are brought into the modelling to create a network model with interdependencies (Radke 2015, p. 110; Thomas 2000). The areas, and the ways that they are categorised, are important to the creation of the network.

Corollary to this concern is the issue of scale. Specific to network analysis, scalar judgements on which loci to include within the network greatly affect the outcomes. Irrelevant outliers to the network, if included within the graph structure, may distort the network. Conclusively, failure to attribute differential weights of importance to the nodes in the absolute measurement techniques also distorts the outcomes. Setting different thresholding values for both land use and occupancy zones and potential movement pathways is a benefit of exploratory GIS design. Finally, the concept of the averaging and systemisation of human movements and the corollary suggestion that these human movements can be mapped into a functional space implies a level order to cultural space that is not substantiated by any investigation into randomness of human agency. Thus, it is even more crucial to bring exploratory GIS into connectivity modelling because normative pathways are not the only pathways (Leming et al. 2019; Vogt et al. 2009; Wainwright et al. 2011).

Circuit theory modelling starts to address the concerns of multiple random path options reducing the importance of singular routes and pinch points (like mountains) as barriers (Dickson et al. 2018). However, as Dickson et al. note, circuit theory's advantages are less pronounced in areas where the landscape is a known area and works best where a landscape is unknown to a species (Dickson et al. 2018, p. 6). Exploratory GIS goes further than circuit theory approaches to GIS analysis because the conceptual framework of multiplicity is at the base of the model. This means that the complexity of the inferences within a decision tree is within the theoretical design of the research and not just embedded in the method. Thus, with these focussed concerns on categorisation, thresholding, averaging and systemisation, this article explores the benefit of employing an iterative network model of the connections within zones as an exploratory GIS.

TECHNICAL DESCRIPTION OF THE METHOD – CONEFOR

There are several ways of establishing functional connectivity within GIS models. The method employed in this paper was developed by Pascual-Hortal and Saura (2006). Their program, *Conefor Sensinode*, was developed to establish the relative significance of habitat zones or patches for the entire functionally connected landscape. The relative significance of habitat patches within the total matrix of landscape connectivity is modelled through network graphs and habitat availability indices (e.g. Integral Index of Connectivity (IIC) and Number of Links (NL)) (Pascual-Hortal & Saura 2006; Saura & Rubio 2010). Habitat patches are viewed as discrete locations, termed 'nodes' in a graph tree. These graph trees are similar conceptually to relative neighbourhood graphs which represent through connections the 'region of influence' for points. Graph trees are superior to absolute Euclidean distance measurements between two habitat zones because the weight of the entire network is considered as a functional whole (Dodge, Kitchin, & Perkins 2009; Holdaway et al. 2015; Laliberté & St-Laurent 2020; Wainwright et al. 2011).

As stated above, network modelling employing a graph, with minimum and maximum spanning 'trees' of the network, develops out of the relationship between Voronoi diagrams and Delaunay triangles. These applications can also be explained within the terminology of Set Theory, Venn diagrams, or Boolean logic (Böther, Kißig, & Weyand 2022; Hunsaker et al. 2001; Moilanen & Nieminen 2002; O'Quinn & Mao 2020; Pop 2020). Within *Conefor Sensinode*, the degree of how connected the points or patches are to one another is dependent on the movement or dispersal distance. Thus, if a person can travel 5km then that is set as the maximum distance two patches can be from one another. The indicators or indices can be utilised to show the 'connectivity' of the area and the importance of each patch within the whole landscape graph (Edelsbrunner, Kirkpatrick, & Seidel 1983; Radke 2015).

Pascual-Hortal and Saura (Pascual-Hortal & Saura 2006, p. 962) recommend employing the Integral Index of Connectivity (IIC) to establish a baseline for connectivity. The IIC takes account areas where breaks in landcover might be an artefact of the GIS base data as opposed to actual breaks (Pascual-Hortal & Saura 2006, p. 964). The other index to assess functional connectivity was the Number of Links (NL) index. These indices are binary indices. The *Conefor Sensinode* program can use binary and probabilistic indices. A binary index requires the user to specify a species dispersal value as an absolute distance measurement threshold whereas a probabilistic index also considers the probability of the species travelling the specified distance.

The IIC index of connectivity models the significance of a habitat patch by assigning a numerical value of node importance, deriving from the composite influence of the graph. Patches that have a higher delta value (dI) are classed as more significant nodes for maintaining landscape connectivity. This means that the loss or interruption of the functional network at these nodes of higher delta values is more detrimental to the entire functionally connected landscape. Therefore, nodes (or areas) with the highest dI values are the areas that should be considered as priority areas for maintenance and preservation. The NL index of connectivity provides a comparative benchmark for the recommended IIC index, as Pascual-Hortal and Saura's investigations determine that it has the advantage of remaining the most stable index when facing changes (Pascual-Hortal & Saura 2006, p. 963).

Hydrology and Ecotones

Areas that are classified as highly suitable for locating water resources with relative ease are areas that are less structurally salient than the rarer ground water soaks in otherwise dry landforms. The definition of the ecotonal areas and the hydrological sources is a reflexive process, incorporating data analysis and oral history collation with the Traditional Owners as part of a larger PhD research project within the WLRWHA (Thomas 2019). The water resource zones and ecotonal areas were defined through satellite image analysis, oral testimonies within the pGIS work with the Barkindji/Paakantji, Mutthi Mutthi, and Ngyiampaa communities, ground truthing, vegetation quadrat surveys, primary source analysis of European settlers and original records of pastoral lease files, and GIS analysis of geomorphological features and ground water (Thomas 2019). These geometric primitives of water types and ecotonal areas formed the basis of the exploratory GIS for this phase of analysis of the possible functional connections between zones and areas, irrespective of whether there was a visible material archaeological record.

Within the functional connectivity analyses employing *Conefor Sensinode*, the graph trees were assessed for the binary indices of connectivity, NL and IIC, to iterative thresholds and classifications of water availability. In this stage of the exploratory GIS, the hydro-suitability maps were vectorized and the water patches were transformed into an ordinal classification system. From these water patches, nodes and distance files were created for areas of greater and lesser size. Changing the size and structure of the network clearly shifted the balance of structural salience of water resources across the WLRWHA. In addition to this, altering the standard deviations and/or natural break classifications of the ordinal ranking created vastly different results for areas of hydro-suitability.

In detail, this type of geometric modelling supports inferences about the structural salience of localities. The modelled areas of potential water locations will be discussed first. In Figure 2, the interpatch areas are the areas where the water resources are the most structurally salient with thresholds set to half a standard deviation from the mean. The areas that are in red equate to these areas of structural salience and these areas include zones that are outside of the lakebed floors within natural breaks. Experimenting with the thresholding, categorisation, and averaging of the hydrological data layers allowed for the identification of areas that were key nodes/patches of structural salience. In Figure 3, these red areas are the most clearly represented when the distance from water resources was incorporated into the model with 1 standard deviation from the mean as the classification threshold.

From a narrow and binary GIS perspective, the modelling indicates that if water was found (i.e. ground water soak, ephemeral wetland) in these areas of high structural salience, then that water feature would be a key node in the pathway. There are many issues however with the way that the water layers are classified and developed for these models – the main issue is that structural or visual salience assessments are only part of the model. Cognitive salience provides the holistic exploratory model. Therefore, additional work incorporating the Traditional Owner testimonies indicates where the potential water locations were on Country (Thomas 2019). PGIS provides the more meaningful model of the cognitive functional connections and past land use and occupancy. The results section below is

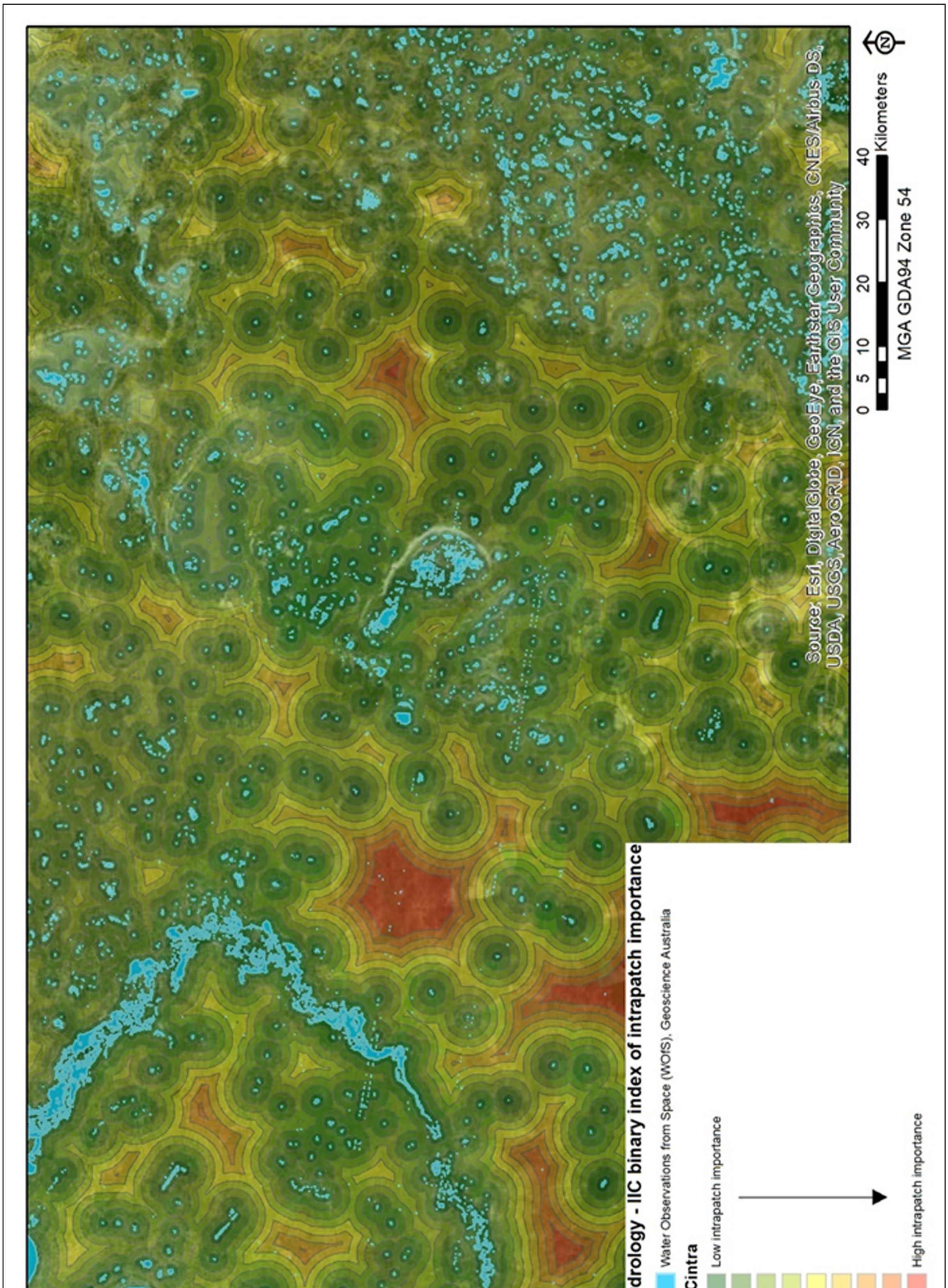

Figure 2 Intrapatch structural salience, ½ standard deviation, Hydrology.

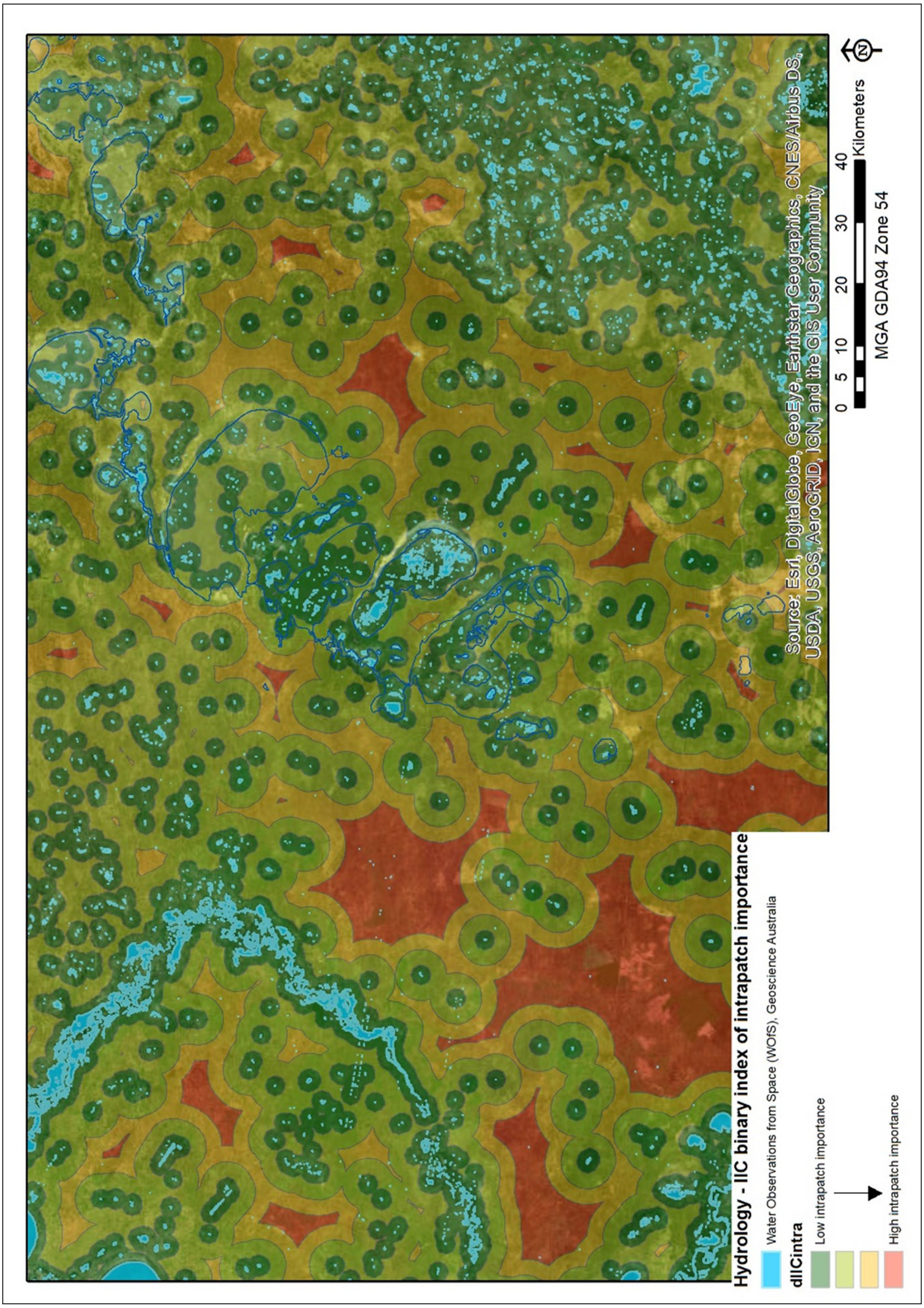

Figure 3 Intrapatch structural salience, 1 standard deviation, Hydrology.

an important first step in modelling past land use and occupancy on a biocultural landscape.

RESULTS

The models in this section are functional connectivity models of the range of structurally salient environmental links within the current presentations of hydrology and ecotonal areas within the WLRWHA. This section is structured to assess the possible connections and pathways between the hydrology and ecotonal areas through assessing the structural salience of the functional connectivity (Kattenbeck 2017; Röser, Krumnack, & Hamburger 2013). Structural salience is as important as visual salience in assessing the predictive GIS models of key zones within the cultural landscape (Caduff & Timpf 2008; Götze & Boye 2016; Röser et al. 2012). Structural salience can be measured with respect to how important an area or zone is in maintaining the entire connectivity of an area. With reference to an ecological feature, it is the patches that are in zones that are classified as inhospitable or unsuitable for land use and occupancy that are highlighted as being highly structurally salient. Functional connectivity analyses through graph trees provide the mathematical computational framework to explore what are essentially the geometric theorems of land suitability that are offered up by the spatial analyses in a Generalised Additive Model (GAM) (Delangre, Radoux, & Dufrêne 2018; Hastie 2017; Hopkins 1977).

NETWORK MODELLING: ECOTONES AND HYDROLOGY

Water alone cannot be utilised to define the GIS model of the structurally salient areas in the WLRWHA. Utilising the neural network vegetation mapping of Haslem et al. (2010), the internal connections between the resultant ecotonal land suitability areas are presented below. As discussed above, altering the thresholds for water availability and ecotonal distance altered the presentation of the data. The same results are apparent when the GIS model is repeated for the functional connectivity between potential habitation zones defined by ecotonal datasets. Exploratory GIS illustrates conclusively that different methods or different thresholds equates to different models.

In the following figures, the potential pathways between areas were identified as suitable based on ecotonal and hydrological layers. With the weighting of the ecotonal areas set at a ratio of 90:10 (ecotone: hydrology), the connections between the areas ranked as highly suitable are compared to the connections between the less suitable areas. Figure 4 and Figure 5 show that the red areas between the ecotonal areas surrounding the lakebed floors are highly structurally salient and crucial from an environmental perspective to the habitat network of the WLRWHA. Focus should be placed on the western area of the Willandra Lakes because this area has corridors of land use zones that are highly structurally salient within the internal network of the Willandra Lakes. These areas are salient for both connectivity (dIIC) and intrapatch importance (dIICintra). However, shifting the perspective and focus on the network nodes between inter- and intra-patch salience does change the symbolisation of the GIS output because different areas become more crucial to preserving the integrity of the structure of the habitat corridors. These exploratory GIS models were developed with a distance threshold set to 5km. Further iterations and building into the model other factors (such as elevation and other least-cost variables) would also alter the outcome. To reiterate, however, these models serve as a check on the previous modelling and as an indication of where the most vulnerable areas within the regions surrounding Willandra Lakes are from a structural salience perspective. In addition, these models highlight the implicit internal structure of the relationship between areas that are ecologically similar.

DISCUSSION

The above modelling has identified areas that are structurally salient and key within hydrological and ecotonal frameworks in the current landscape. Exploratory GIS modelling is theoretically determined and defined by the precepts in behavioural ecology and methodologically determined by the limits of the ecological data sets. In this section, exploratory GIS models will be presented as areas where structural salience modelling has been impacted by the human record of land use and occupancy. Untangling anthropogenic impacts from each wave of settlement after the Traditional Owners leaves us with exploratory GIS models of where the underlying functional network was weakened, or obliterated, by the waves of European settlement. Thus, this section will examine the voids, the barriers and disruptors, and the attractors within an exploratory GIS model of the landscape in the WLRWHA (Allen, Green, & Zubrow 1990; Zubrow 1994).

The impact of anthropogenic changes on the environment is a challenge within many disciplines. With GIS connectivity models, efforts to measure the human impacts upon the environment have resulted in modelling indices such as the HFI (Human Footprint Index) that use a composite of variables to assess the levels of human disturbance on a particular ecosystem and SHFI (Spatial Human Footprint Index) (Sanderson 2013; Correa Ayram et al. 2017). Such an approach for the Willandra Lakes would enable quantification of the levels of impact from the pastoral settlement on the local ecosystems. Unfortunately, the acquisition of this level of detailed

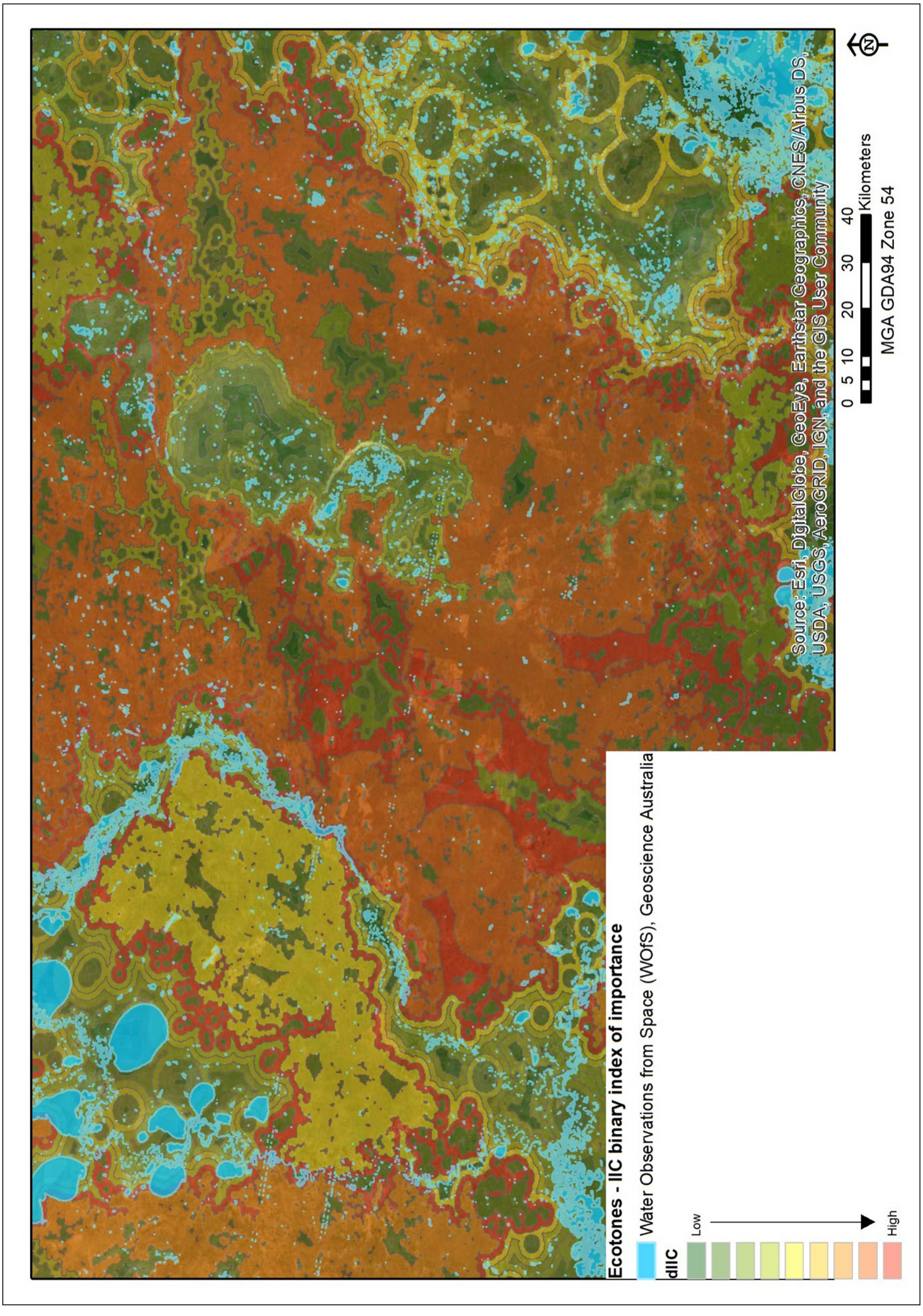

Figure 4 IIC binary index – delta value (dIIC), natural breaks threshold, ecotonal areas.

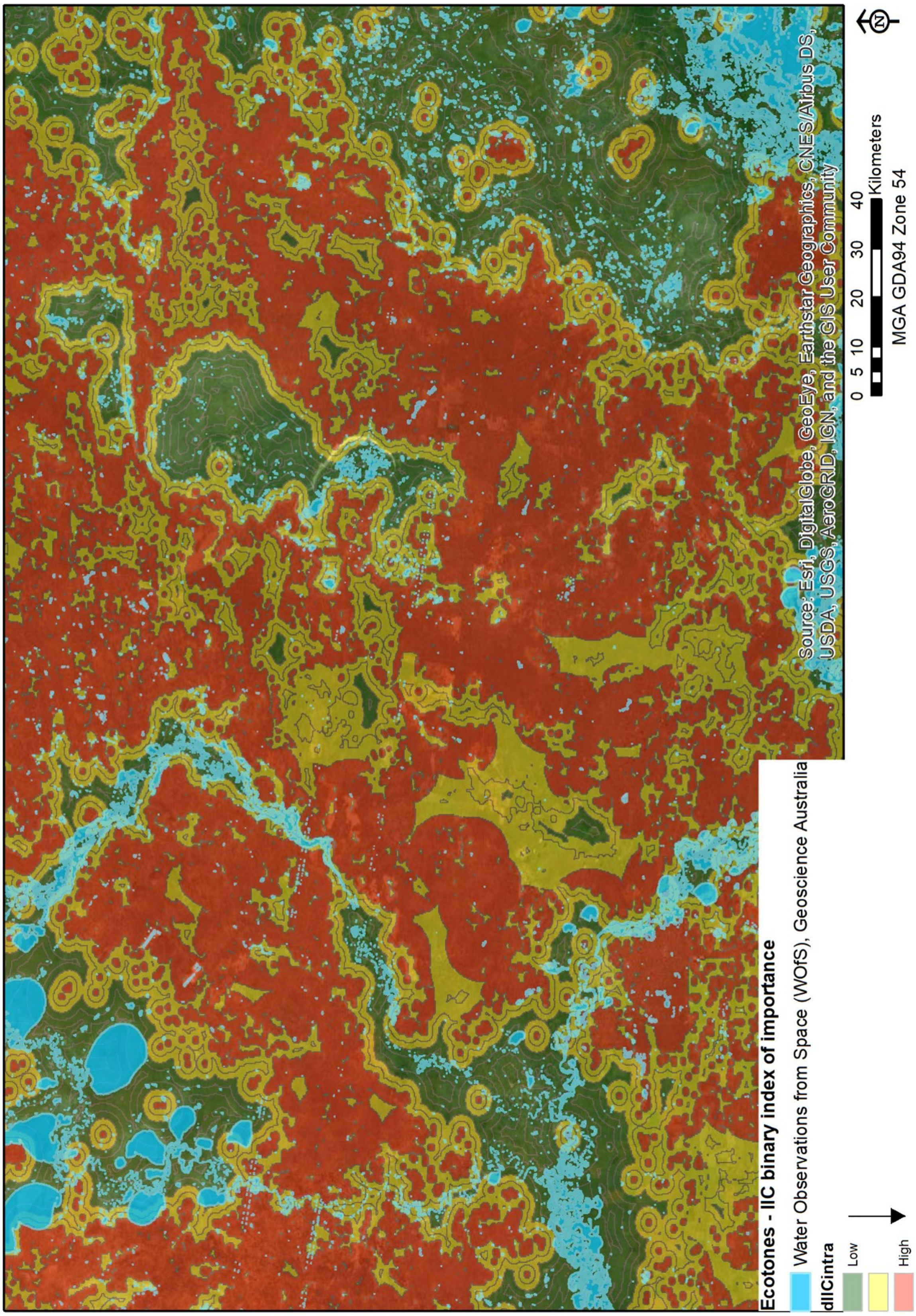

Figure 5 IIC binary index – delta value intrapatch (dIICintra), natural breaks threshold, ecotonal areas.

data is outside of the scope of this project. However, the principles from this circuit theory approach of modelling disruptors into the model of structural salience or functional connectivity are applicable. This section focusses on how to include anthropogenic impacts into a functional exploratory GIS model as a way of targeting areas where archaeological traces might be removed or absent due to purely anthropogenic impacts and where the network node is missing from the connectivity tree. Working step by step through the logical sequences and assumptions of the premises of the GIS model within an exploratory design, allows for analysis of each step of the model development.

Within the Willandra Lakes, the impacts from the pastoral settlement onto the model can be viewed as barriers and disruptors. Apart from the widespread impacts of grazing and tree felling, the other two main disruptors and barriers are the construction of tanks and the creation of fences. These two anthropogenic changes dramatically altered the landscape of the Willandra Lakes because this new deeper footprint of human activity shifted and squashed the fragile arid ecosystem. GIS models without pastoral impacts are 'blind to history' (Rowlands 2005, p. 28). Including some of the impacts into the model from the pastoral leases allows for some of the hindsight to be restored (Kerr 2013). Furthermore, European settlement in some areas created artificial voids in a GIS model. This section outlines the areas where the GIS model would be most affected by anthropogenic changes brought on by the pastoral settlement from a hydrological and environmental viewpoint on the impact areas surrounding tanks, fences, and pathways.

VOIDS: TANKS AND BORES

The location of the availability of ground water through wells, tanks and bores in areas that the GIS model has flagged as areas of low suitability for water are important ways to help refine the search for hydrologically structurally salient areas and are therefore part of the development of a meaningful GIS model. In addition, those areas are places where the structural salience of the ephemeral wetland areas (as captured by the Water Observations from Space (WOfS)[1] Landsat dataset) are less important because ground water is accessible. By this rationale, the tanks and bores in the red areas should be the most structurally salient and important tanks within the network (Figure 6, Figure 7). By extension, the tanks, wells and bores in the areas highlighted as structurally salient by the GIS model in ecotonal areas, should be the most critical resources and the resources for which conflict between the settlers and the Traditional Owners over the water is higher. The most vulnerable resources are the tanks and bores in the red and orange areas in Figure 8.

Plotting the Department of Primary Industries (DPI) NSW water features data set[2] within the Lower Darling run shows several tanks, bores, and wells puts the background information as separate layers into the exploratory GIS. The available modern bore data show no trends with ground water depth, but this is due to inconsistencies in the data set (Figure 9). Seismic explorations detailed by Odins et al. (1991) define the hydrogeography of the study area as to be primarily defined by the pre-Tertiary geological basement. For the ground water, this means that the conclusions from their studies show that the geometry of NNE troughs (Willandra trough, Iona Ridge, Balranald Trough) constrain the flow of ground water into a parallel flow alongside the Willandra trough and restrict the flow westward (See Figure 6) (Odins et al. 1991). This also results in higher salinity in areas where the fresh ground water is unable to reach (areas to the west of the Willandra Trough and to the south). Thus, although explorations to develop wells and tanks were key to the pastoral settlement, the depth of the water and the salinity was particularly constricting in the areas to the west of the Willandra Lakes.

Including an awareness of the situation and type of ground water tank or well from the pastoral settlement into the GIS model highlights areas where modelling the structural salience of standing water from Landsat data could be particularly flawed. In addition, it also highlights areas where the vegetation structure and ecological vegetation classes are more affected by weediness and the introduction of non-native vegetation near tanks. Comprehensive surveys within the Mungo National Park, Nanya, and Mallee Cliffs by Westbrooke, Morcom and Miller cite the alteration of the vegetation structure around tanks with higher proportions of weeds near tanks within the study area due to the artificial water source, grazing pressures from native and introduced animals, and general impacts from the pastoral settlement (Graz, Westbrooke, & Florentine 2012; Westbrooke 2012; Westbrooke & Miller 1995; Westbrooke & Morcom 1990, p. 157). Furthermore, the pastoral impacts to the vegetation around tanks have been described by Graz et al. as the cause for microbiomes or piospheres due to the extensive nature of the changes to the vegetation around waterpoints and fences at Nanya station, NSW (Graz, Westbrooke, & Florentine 2012, p. 187).

Tanks and the availability of non-saline ground water coupled with the pastoral impact of these water sources alters the GIS model of vegetation and hydrology. Mapping the areas where tanks are present as a pastoral impact illustrates the issues of the GIS modelling of the environment or archaeological record in a period where the historical record can contribute to the model. This also brings to the fore the manifold issues of retrofitting an environmentally determined GIS model, without an exploratory design, into a discussion of the biocultural landscape of the Willandra Lakes or anywhere else.

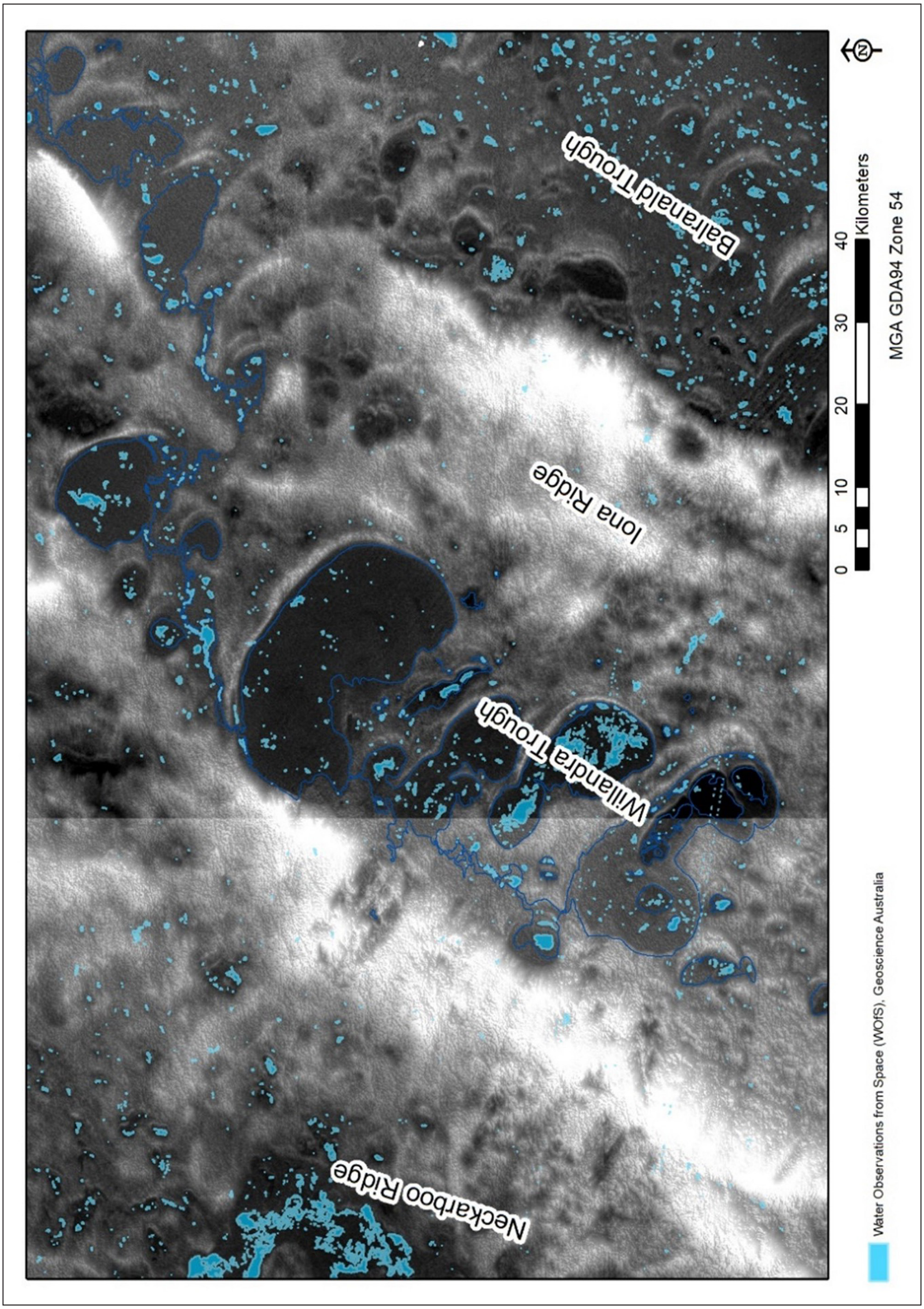

Figure 6 Ridges and troughs in the study area.

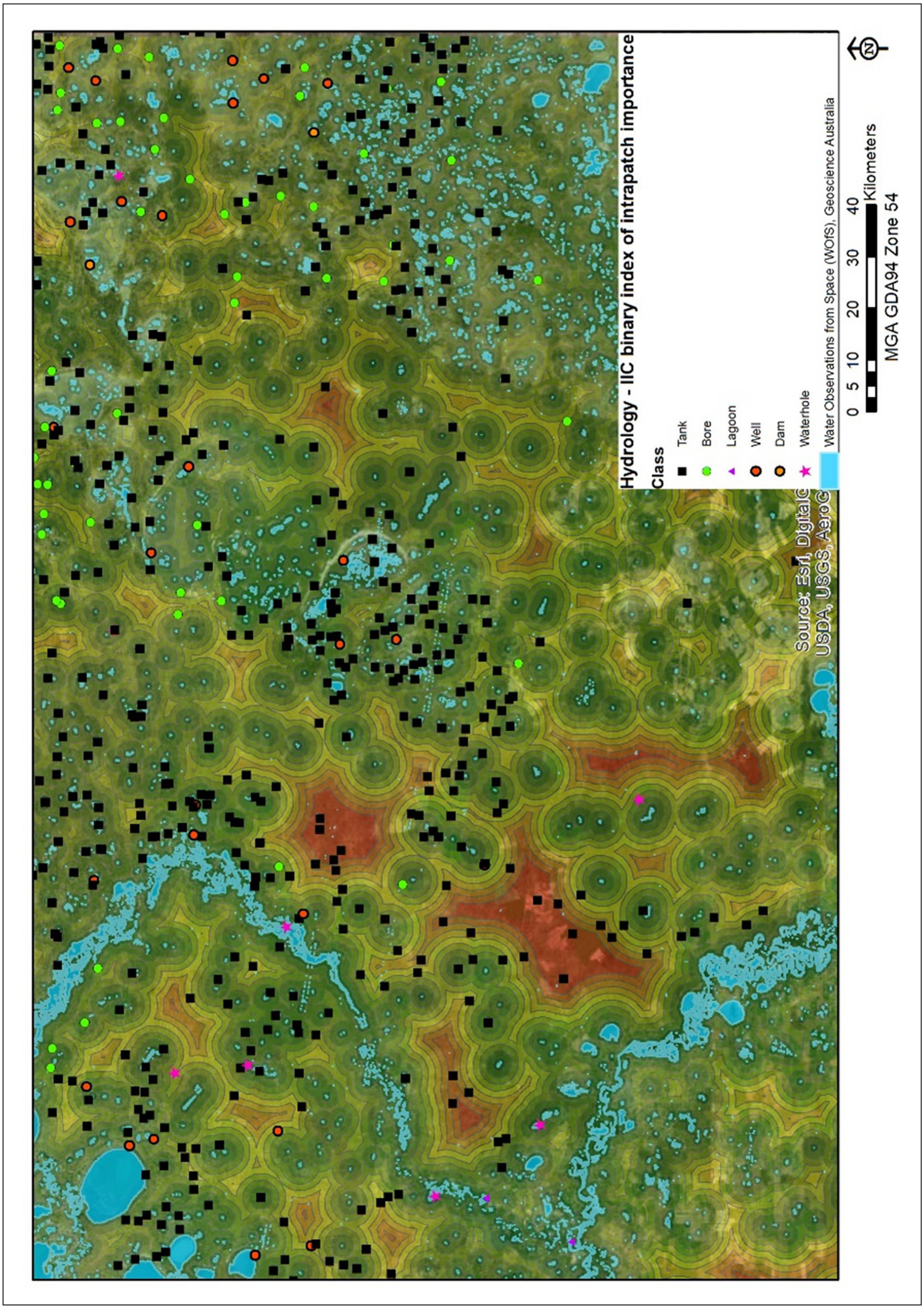

Figure 7 Available ground water and derived structural salience.

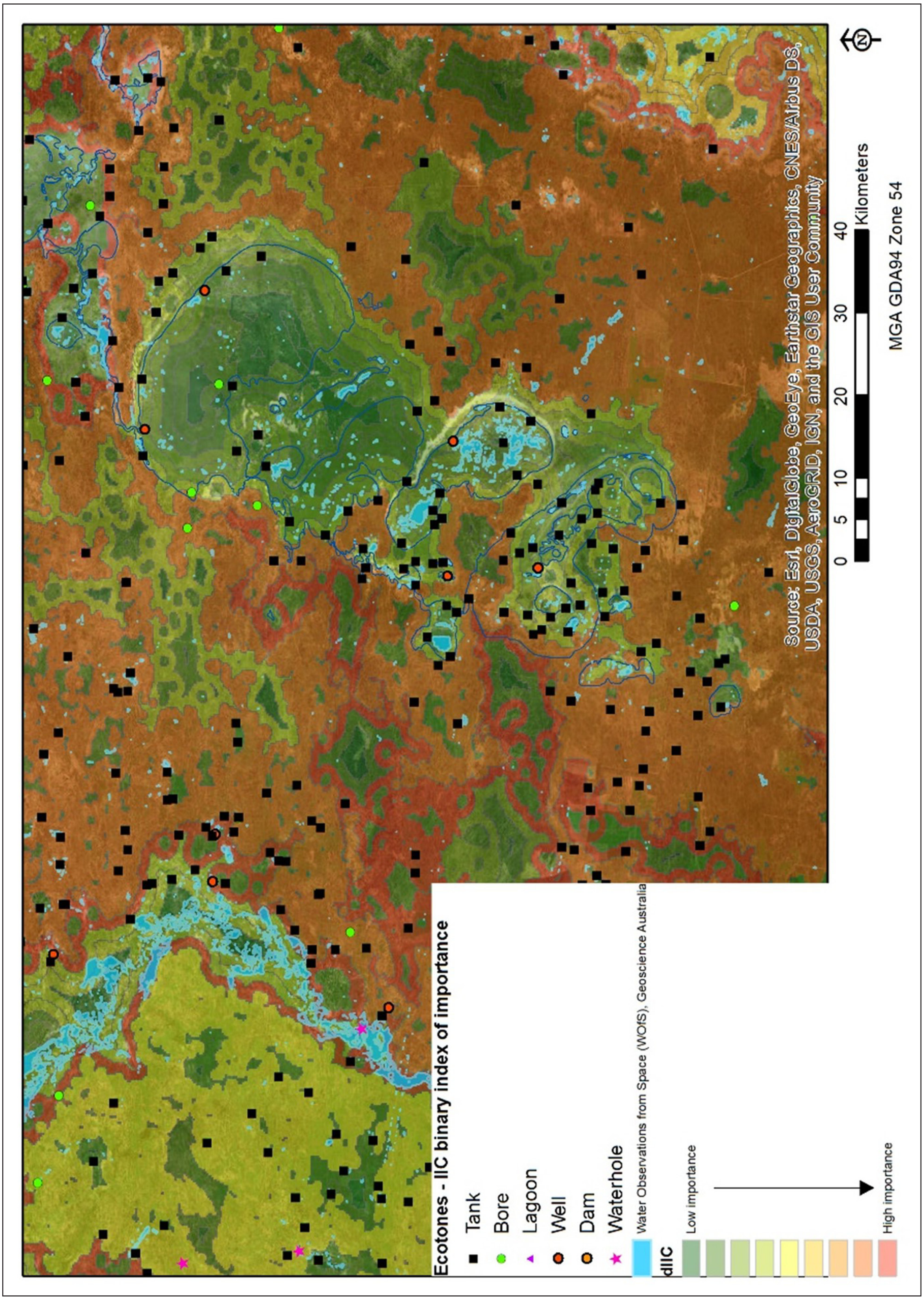

Figure 8 Available ground water and ecotones, structural salience.

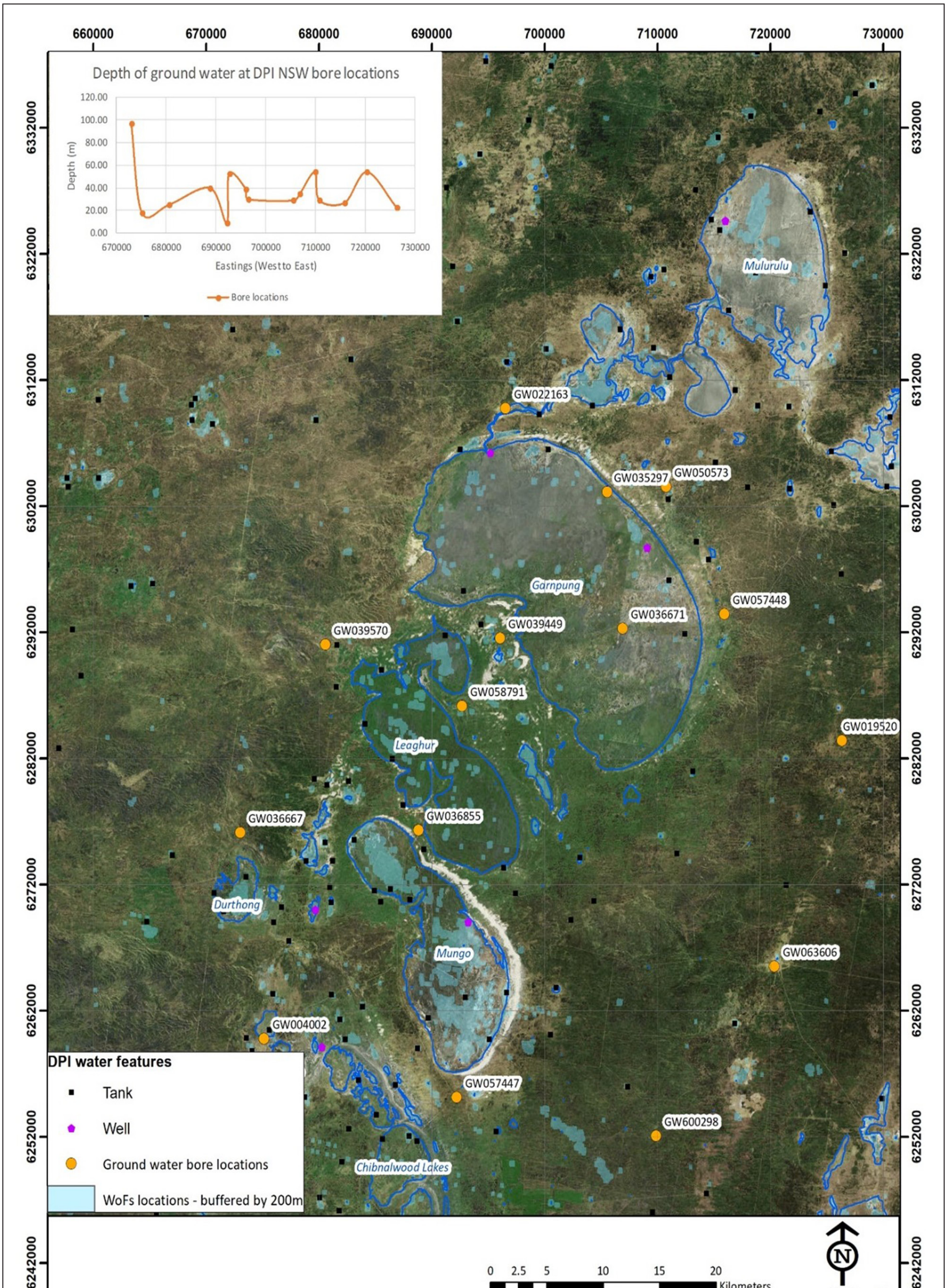

Figure 9 Ground water locations, DPI bores.

BARRIERS: FENCES

From a GIS modelling perspective, this is an issue of scale and regional versus local modelling of resource zones. Tanks and fences both cause the development of microbiomes and are places where ground-truthing of a large-scale model would reveal quite different outputs with respect to vegetation structure and ultimately the visual or structural salience of land use zones. Tanks require a buffer area around them as they result in these piospheres and alter the direction of not only animal but also human traffic around a network. Fences, however, require not only a buffer around them because they create a microbiome, but they also apportion the land in a way that puts artificial barrier into space that was previously constrained by the underlying geometry of the rivers, hills, and valleys. This is apparent in Figure 10, where the fence lines from the 1884 Lower Darling Division mapping show the fences bisecting rivers and cutting through ridges, troughs, and lakebed floors.

Centering here on a strict interpretation of the geometric primitives within GIS modelling, the GIS exploratory model has focal points for places of significant change with the fence, tank, and pathway locations. These map features provide points of reference for where edge effects should be the most prominent, conflict over resources, break points in the initial networks. From a basic GIS modelling perspective, the geometric features that can be placed into a secondary model to identify the best places to conduct fieldwork to ground-truth the model. In addition, there are the issues connected to the aggressive organisation of rural space or the impacts connected to live, wooden, or steel fence alterations (Philo 1992, p. 197; Prout & Howitt 2009, p. 397), but these are nearly impossible to assess comprehensively within a GIS model of this scale.

ATTRACTORS: TRAVELLING STOCK ROUTES (TSRS)

The pastoral impacts of TSRs onto the initial internal connections and pathways of the pre-European landscape need to also be considered in the exploratory GIS model. Summarised by Lennon in the 'Long Paddock', the TSRs are places where Indigenous and settler cultural landscapes intertwine and tend to follow water courses and/or pathways of Indigenous communities (Lennon 2014, p. 58). From a GIS modelling perspective, these pathways are indicators of where the functional connectivity model between ecotones and water resources should also be strongest. These pathways are defined by the record of human-environment interaction instead of by computational analysis. Thus, these pathways provide a check on the functional connectivity modelling outputs. Furthermore, these pathways are attractors or indicators of where the pGIS models of cognitive salience might overlap.

In this format, these places are the liminal spaces that point the GIS model to the internal network of past land use and occupancy prior to pastoral settlement. Models that ignore these pathways and focus on hydro-suitability, ecological values, or mapping areas of the archaeological record, are dismissing the cornerstone of structural salience for network route modelling. The cornerstone of GIS modelling should be human agency and the footprint of human-environment interaction. To a certain extent, the TSRs and early roads are the endo-hulls of space that the modelling with *Conefor Sensinode* (or other circuit theory approaches) is trying to build through identifying patch salience. Including this layer into the design provides the structure to the modelling that is missing in network modelling based on just environmental or hydrological variables.

Figure 11 shows where the tracks and routes were in the latter part of the 1880s and these lines were digitised from the pastoral lease files from the Western Sydney Records Office, Kingswood (NSW State Archives, Pastoral Holdings – Western Division, NRS 8368; NSW State Archives, Run Boundary Register – Darling, 8/2205). In Figure 11, it is apparent that the fences disrupt the initial routes, that there is a centralisation of routes to the middle of Lake Mungo and to the north-east of Paika block, converging on Box Creek. It is only through Participatory GIS (pGIS) that the cognitive salience of this internal network is properly comprehended, especially with respect to Box Creek (Thomas 2019). The tracks and routes of the early settlers show potential attractors for the functional connectivity modelling of the Aboriginal communities due to the appropriation of these pathways. Adding the TSRs shows that modelling the water and the ecotones at this scale illustrates that the routes do not directly connect areas that are flagged as highly suitable for hydrology or ecotones.

A more appropriate way to model the connectivity (structural salience) and land suitability (visual salience) for building a picture of the land use and occupancy of Country is to utilise the network provided by the TSRs as a base for a further exploratory GIS model. It is this cultural frame that provides an additional internal skeleton between places and it is this internal skeleton of connectivity that was disrupted by the fences and tanks of the pastoral settlement. In addition, modelling other routes, such as the route that the explorers Burke and Wills travelled by or the pathways that the early surveyors (e.g. MacCabe) traversed are better ways to establish likely connections between land use and occupancy zones because these pathways also often followed along Aboriginal pathways (Burke et al. 2016).

CONCLUSION

Exploratory GIS design within this project has illustrated that the current practice of using either the extant archaeological record or hydrological/ecological data sets to model the functional connections between past potential land use and occupancy zones has several flaws. These flaws are

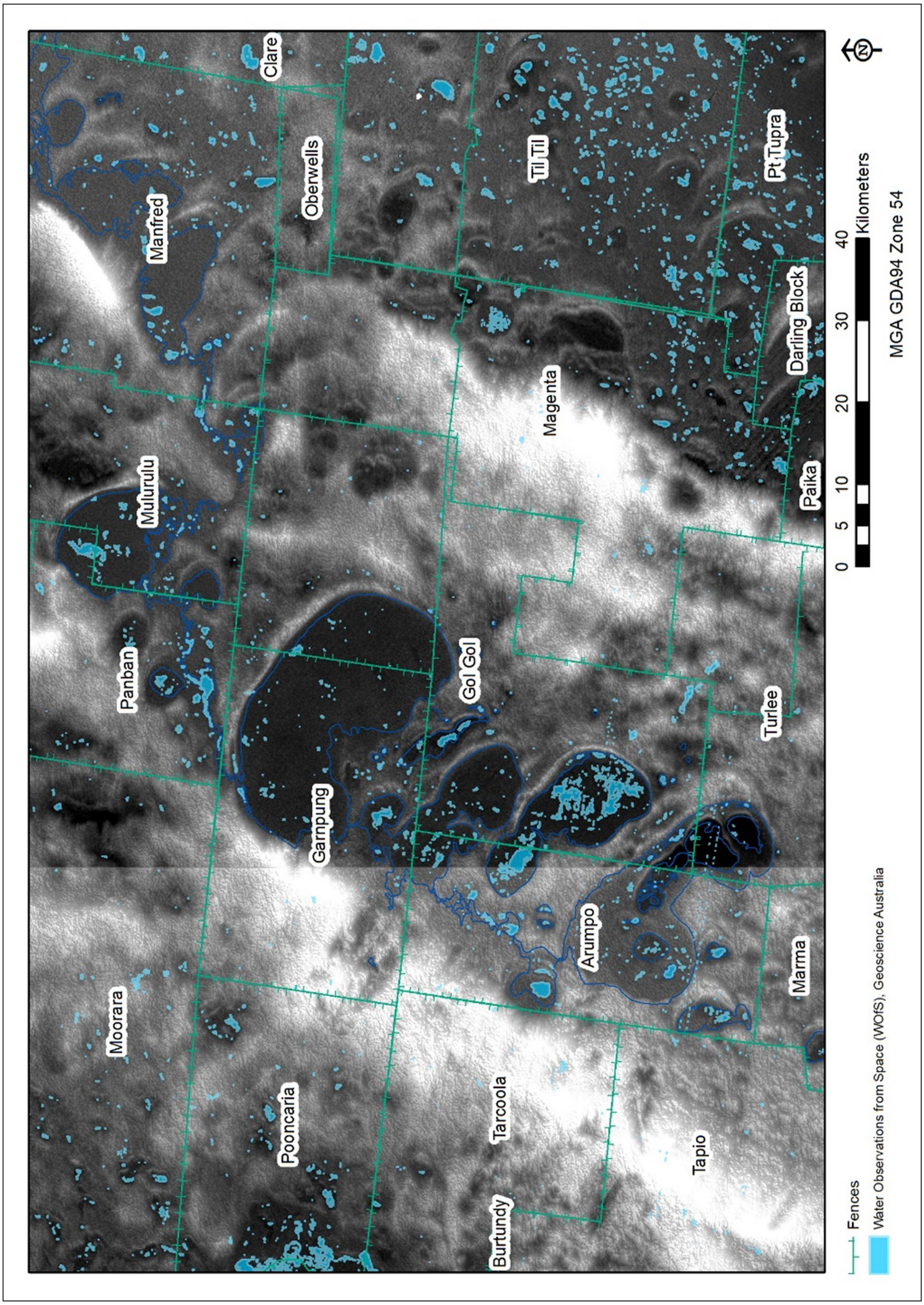

Figure 10 Fences bisecting land features.

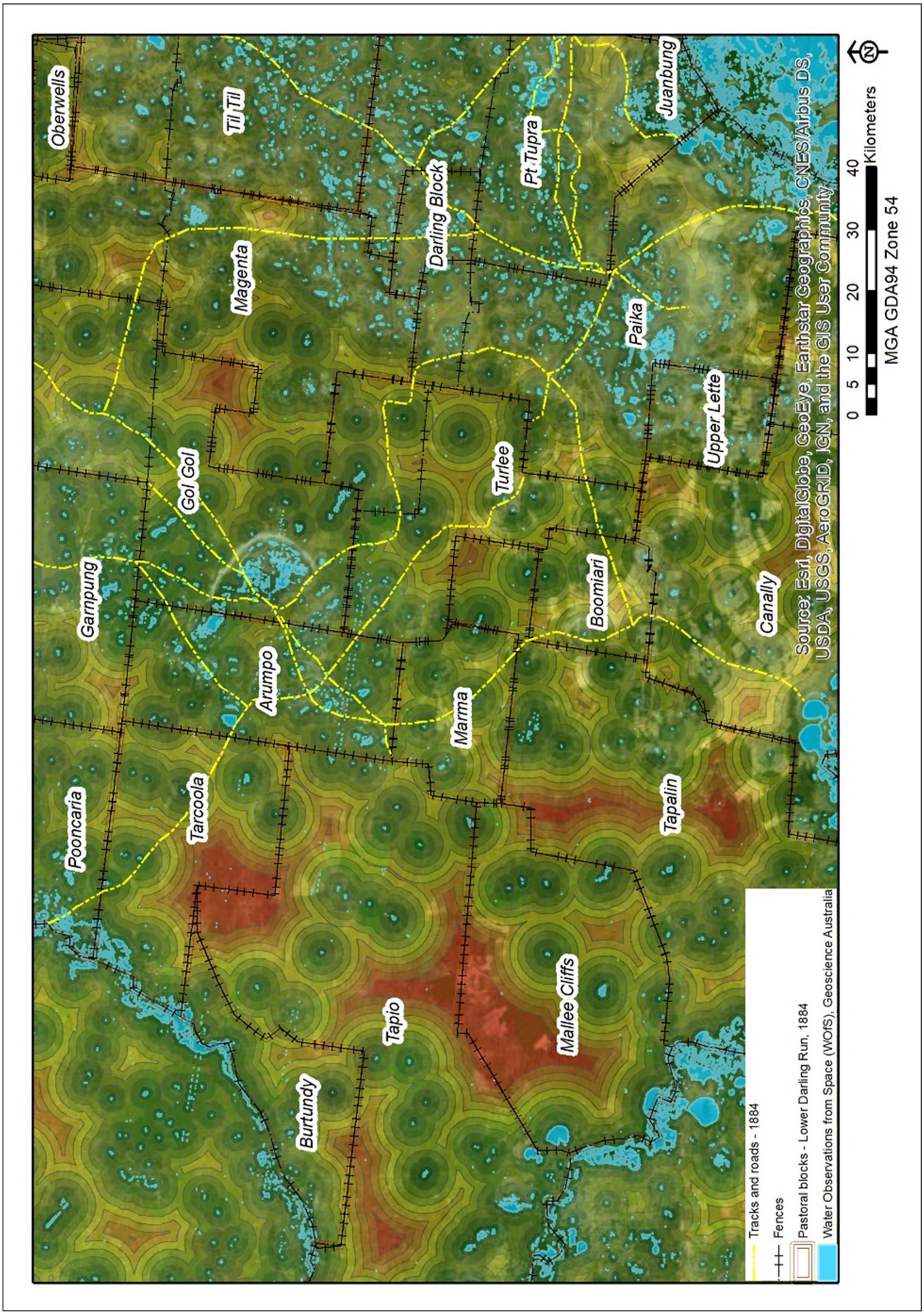

Figure 11 Pastoral features, fences and pastoral blocks, Western Division 1884.

connected to the misidentification of structural, visual, and cognitive salience of both the internal networks and the classification of key areas of the biocultural landscape. This step-by-step approach to the exploratory GIS model has demonstrated the need to incorporate more exploration and experimentation into modelling the past connections across the biocultural landscape. Identification of voids, barriers, and attractors within the WLRWHA network furthermore highlights the issues of ignoring the waves of European settlement on modelling the past networks of functionally connected land use zones.

The GIS modelling outputs above follow the common practice of using available hydrological and environmental data to map both land suitability and internal connections within resource zones. Exploratory design allows for multiple presentations of the data and helps plan fieldwork and visualise potential suitable contexts. However, the GIS models are not useful without the pastoral impacts. Also, this type of modelling includes only visual or structural salience of features and ignores the cognitive salience of a land use or occupancy zone. Cognitive salience is only brought into the picture or map with Participatory GIS (pGIS) work with the Mutthi Mutthi, Ngyiampaa, and Paakantji communities (Brown, Raymond, & Corcoran 2015; Byrne & Nugent 2004; Goggin et al. 2017; Lewicka 2011; Thomas 2019; Zubrow 1994). Additional mapping of the liminal spaces of human-environment interaction through pathways, TSRs, and exploration routes also adds the necessary cognitive salience element to the exploratory GIS.

The exploratory functional connectivity GIS models in this article are not representative of the totality of the biocultural record of the Traditional Owners of the Willandra Lakes. Instead, these models are conceptual models to help understand the underlying environmentally salient networks of a living Country within the Willandra Lakes. This article is an opening point to assess the level of impact the construction of fences, tanks, and pastoral settlement had on the internal connections between land use and occupancy zones. Ultimately, exploratory GIS models should start to develop the deeper footprints and pathways across the lakebed floors and arid zones of the Willandra Lakes – so that we might be able to see and hear from the Traditional Owners, past and present, what we might need to do in all our efforts to preserve and protect Country, from the inside out.

DATA ACCESSIBILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Dr Katherine Thomas, upon approval from the Willandra Lakes Region World Heritage Area Aboriginal Advisory Group. Restrictions apply to the availability of these data, which were used under strict Indigenous Cultural Intellectual Protocols (ICIP) for this study.

NOTES

1 https://www.ga.gov.au/scientific-topics/earth-obs/case-studies/water-observations-from-space.

2 https://data.nsw.gov.au/.

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COMPETING INTERESTS

The author has no competing interests to declare.

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