

Aggregate Opportunity Modelling for New Zealand

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GNS Science Report 2021/10
May 2021

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BIBLIOGRAPHIC REFERENCE

Hill MP. 2021. Aggregate opportunity modelling for New Zealand. Lower Hutt (NZ): GNS Science. 106 p. (GNS Science report; 2021/10). doi:10.21420/1RKC-QB05.

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This project is supported by funding from the New Zealand Infrastructure Commission, Te Waihanga.



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ABSTRACT

Efficient utilisation of New Zealand's aggregate resources is critical to supporting infrastructure development as well as reducing operational and transport costs related to extraction of the raw materials. A mineral potential modelling approach has been used to identify places with opportunity for future hard rock and gravel extraction across New Zealand. Geographic information system (GIS) software has been used to build a spatial model of the critical components of aggregate opportunity using digital geological, land-use, statistical and geographic data. Model components include source rocks, land use, future demand, supporting infrastructure and cultural sensitivity that use 23 mappable criteria layers. These are combined using the fuzzy logic expert-weighted spatial modelling technique to qualitatively rank aggregate resource opportunities at a national scale. The resulting maps and their GIS-based equivalent datasets of gravel and hard rock aggregate opportunity can be used to manage aggregate resources, generate targets for exploration activities and provide insight into future resources.

KEYWORDS

Aggregate, aggregate opportunity concept, spatial modelling, fuzzy logic, hard rock, gravel, sand, resource planning

1.0 INTRODUCTION

The development of built infrastructure in New Zealand requires large quantities of aggregate material for roading and construction, and these materials are ideally extracted in close proximity to minimise the cost of transportation and emissions. Regions such as Auckland, Wellington and Christchurch, require new and existing quarries to meet their future high demand for aggregate resources. Planning for future aggregate supply is essential for our country's economic development, and knowledge of potential aggregate resources can be used for decision-making around land use, as well as exploration for future quarry sites.

Aggregate is extracted based on its physical properties (strength, durability, cohesiveness, size), chemical properties (beneficial or lack of deleterious minerals) and its homogeneity and volume at a site. As well as these petrophysical properties and volume of resource, social and cultural aspects (proximity to urban areas, landscape values, areas of cultural significance), environmental (water, air and noise pollution) and resource economics (quality and distance to market) play a key role in the economic success of a quarry. Future explorers and resource planners need to carefully consider all of these parameters when developing new quarry sites.

In 2018, the domestic production of aggregate was 41 million tonnes (Mt) per year (AQA c2021) with more than 75% of this aggregate typically utilised in the North Island (Christie et al. 2001). Much of this aggregate is consumed by New Zealand's road networks (Black 2009), and large roading projects need to plan well ahead to ensure that there is a suitable and timely supply of material for the project. Demand for aggregate will continue increasing as future demand scenarios indicate major growth in high population areas (O'Brien 2006) and large roading and other infrastructure projects.

Ideally, aggregate resources are extracted close to their markets; the cost of transporting aggregate doubles approximately every 30 km, so local sources are favoured to minimise the cost of new infrastructure projects. However, with many of the high-demand aggregate consumers near urban or city areas, operating a quarry close to the proximity of the end user can become problematic. The proximity of aggregate extraction operations to each other also needs to be considered; too many operations in close proximity can adversely affect local communities or the environment, so planning production to meet ongoing and surges in demand is critical.

Future opportunities for resource supply can be guided by databases of geological map and rock property information, but land use, demand, infrastructure and cultural criteria also need to be considered to find the most suitable areas for quarrying activities. This study uses digital map data that classifies geology, land use, critical infrastructure, estimates of future high-demand locations and factors that are culturally sensitive. This data is combined using spatial modelling to create maps to help identify the best locations for future aggregate opportunities. Many of the features that determine the suitability of a quarry site and its economic potential are mapped using freely available spatial data. By using geographic information system (GIS) computer software to analyse the data, we can quickly assess large volumes of information over the entire landmass of New Zealand.

To understand feature relationships that represent the best locations for a quarry, concepts regularly used in the mineral exploration industry have been adapted, termed here the 'aggregate opportunity concept'. The aggregate opportunity concept describes a multitude of critical or highly important features that must be present for a quarry to succeed (e.g. the correct rock type) but also, importantly, contra-indicator features that affect the suitability of a quarry (e.g. high-value conservation land that should not be disturbed or a long distance

from the quarry site to the end user). Some of these features may not be mappable, i.e. are conceptual only; however, and fortunately for the modelling here, many of the critical positive and negative features can be represented by map data proxies that are currently available. The aggregate opportunity concept supporting this model and the spatial modelling techniques used to create it have been revised over several years (Christie 2007; Christie et al. 2011; Hill 2018a, b; Hill et al. 2019; Hill and Chilton 2020) with the help of aggregate industry experts and spatial modelling professionals.

The resulting final model of aggregate opportunity is represented as a map of areas that are ranked (coloured based on numerical value) in terms of their potential to be a future aggregate resource. The model layers and maps can be used as part of an exploration programme for a new quarry to eliminate large areas of unsuitable land and focus on areas with the most potential for detailed ground-based exploration and rock quality testing. They can also be used to determine potential aggregate sources close to a city or large roading project so they can be protected in the urban planning processes or used to avoid transporting material from other, more distant, quarries. The results are also useful for determining the relative quantities of aggregate material types (sandstone, gravel, basalt, limestone) or assessing the type of land use that future aggregate extraction opportunities are currently being used for (e.g. native vegetation, wetlands, open farmland, etc.).

The modelling undertaken in this study is easily updated as data versions are revised (e.g. land-use maps), if new data are made available (e.g. physical rock property data) or if there are major new developments proposed that change the future demand in some locations. New aggregate opportunity maps can be easily created to reflect these and used to make future assessments of aggregate opportunity.

2.0 NEW ZEALAND AGGREGATE RESOURCES

New Zealand is fortunate to have large areas of well-indurated (hard) rock and deposits of gravel throughout the country that can be utilised for aggregate to support infrastructure development. Over much of the country, this material is only weakly weathered and exposed at or near the surface, providing access to good-quality resources of rock. Both in situ hard rock and unconsolidated boulder, gravel, sand and clay deposits are quarried around the country, and a wide range of rock types are mined, including greywacke, sandstone, basalt, andesite and limestone, for a variety of purposes.

Aggregate resources in New Zealand can be largely grouped into two classes: **hard rock**, e.g. greywacke (Figure 2.1), sandstone, basalt (Figure 2.2) and limestone; and **gravel**, e.g. unconsolidated deposits such as river gravels (Figures 2.3 and 2.4), sand (Figure 2.5) and boulders. These deposit types are distributed throughout New Zealand (Figure 2.6), but quarries that extract them are typically located close to major cities and roads and clustered to meet demand. Hard rock quarries are usually located in areas of steeper terrain where un-weathered and indurated material can be accessed more easily from beneath unsuitable covering material, such as weathered overburden (e.g. Figure 2.1). Gravel quarries are typically located in river valleys and alluvial plains. Most gravel aggregate operations are limited in the depth they can extract material to by the local groundwater level, with only some exceptions where gravels are harvested from the active river channel (e.g. Figure 2.4).



Figure 2.1 Waitohu Quarry near Otaki extracting greywacke hard rock aggregate with the contact between the weathered (brown) and un-weathered (blue-grey) material visible. (Photography by Matthew Hill, GNS Science.)



Figure 2.2 Pukekawa Quarry near the Waikato River extracting basalt hard rock aggregate. Basalt columnar jointing visible in exposed face. *(Photography by Matthew Hill, GNS Science.)*



Figure 2.3 Rangitikei Quarry located next to the Rangitikei River west of Palmerston North. Gravel is excavated at this site for roading, drainage and concrete components. *(Photography by Matthew Hill, GNS Science.)*



Figure 2.4 Waimakariri Quarry operating near the active river in Christchurch harvesting river gravel material for local roads, drainage and concrete components. *(Photograph courtesy of Road Metals Ltd.)*



Figure 2.5 Quarry at Otaihanga on the Kāpiti Coast extracting sand from an old sand dune inland from the modern-day coast. *(Photography by Matthew Hill, GNS Science.)*

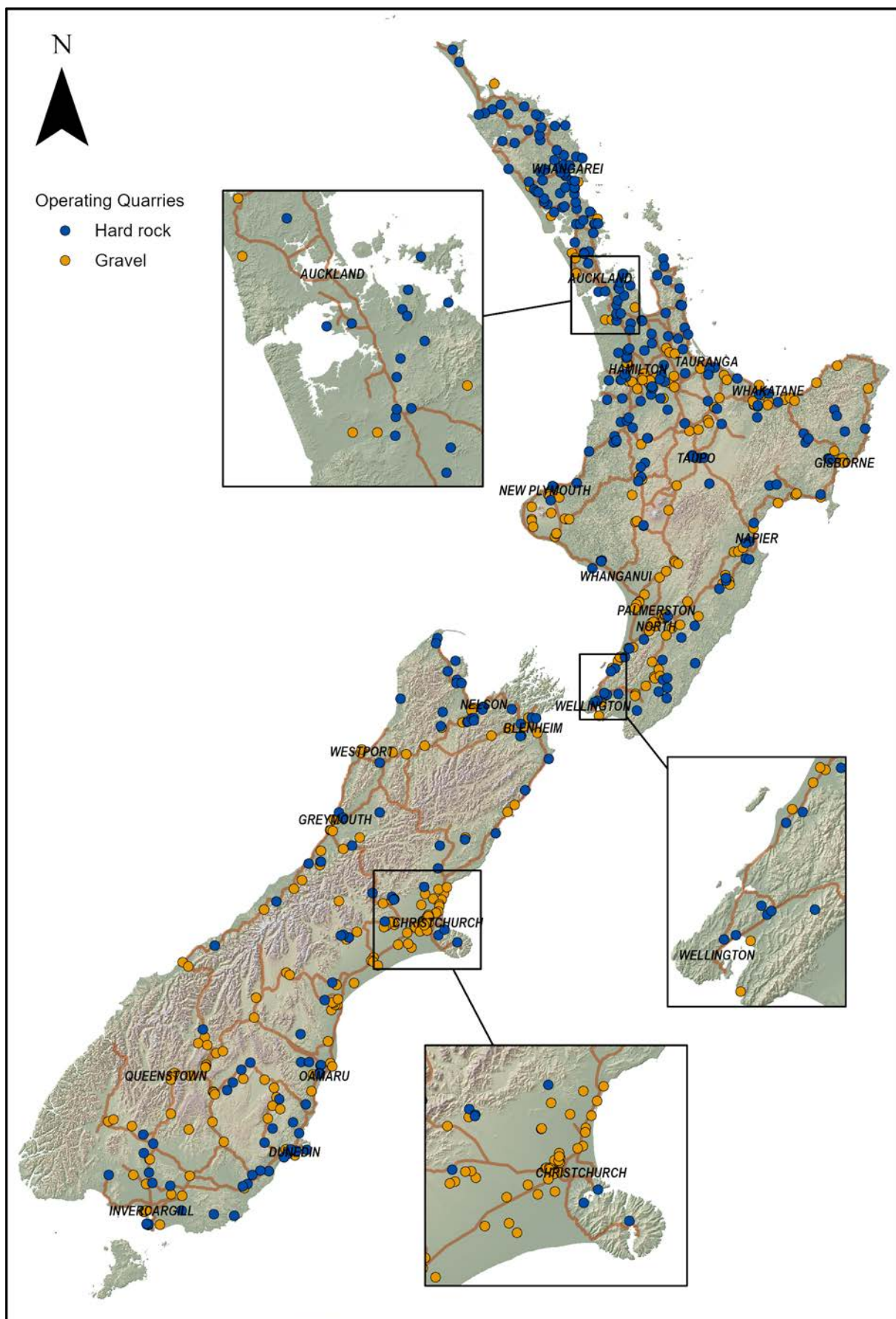


Figure 2.6 New Zealand operating quarries as reported by Freeman Media in 2020. Quarries are divided into either hard rock or gravel material types, and locations have been updated for this study using satellite imagery.

3.0 SPATIAL MODELLING

This project has adapted similar spatial modelling approaches used for previous critical mineral potential models (nickel-cobalt, Durance et al. 2018; rare earth elements, Morgenstern et al. 2018; lithium, Turnbull et al. 2018, 2019) and aggregate resource models (Christie 2007; Christie et al. 2010, 2011) to understand the **aggregate opportunity concept**, that is, determining the extent to which factors critical to aggregate extraction occur in the same place throughout New Zealand.

The aggregate opportunity concept in this study is divided into five **predictive model components**: (1) source material, (2) land use, (3) future demand, (4) supporting infrastructure and (5) cultural sensitivity (Figure 3.1). For each of the components, **mappable criteria layers** have been created; these are GIS layers that summarise spatially varying information for a range of features; for example, supporting infrastructure includes proximity to roads, railways and electrical supply. For spatial modelling, it is important that the predictive model components are mappable, i.e. can be visualised on a map using digital data. Some features may not be mappable, i.e. are conceptual only; however, and fortunately for the aggregate opportunity concept, many of the critical positive and negative features can be represented by map data that is currently available.

The aggregate opportunity model uses openly available data. Data have been sourced from Land Information New Zealand (LINZ), the Department of Conservation (DoC), Manaaki Whenua Landcare Research, GNS Science, the Ministry for the Environment and Statistics New Zealand (Stats NZ). Mappable criteria representing the factors that are critical or desirable for establishing a future quarry operation have been developed from these open data, with a preference for uniform, national coverage that can be used with GIS software.

The predictive maps have utilised GIS spatial modelling techniques such as area classification, distance analysis, zonal statistics and fuzzification formula. Classification of the map data ranges or values that realistically reflect aggregate opportunity were made by considering advice from New Zealand industry experts using thresholds determined from overseas examples (e.g. Robinson et al. 2004; Blachowski 2014; Blachowski and Buczyńska 2020) and from spatial statistics generated from 200 operating quarries selected as training data in the model (see Appendix 6). The training data points were selected from operating quarries with a range of suitable source rock and locations relatively close to an end user. The training data are used along with all the operating quarries in New Zealand to understand the trends in quarry sites (e.g. distance from residential areas) and support the expert opinions used to weight the maps in the modelling process.

The aggregate opportunity consists of GIS-based models and layers at three levels: Level 1, mappable criteria layers; Level 2, predictive model component layers; and Level 3, the final models (Figure 3.1). The Level 1 layers are created from classification or analyses of the source data. For example, geological rock types are classified into one of the key aggregate source rock types, or a distance function is used to model location relative to a major road. The Level 1 layers are associated with one of the mappable criteria components in the aggregate opportunity concept, e.g. demand or land use, and they are given a prefix of 'L1' in the file name to delineate that they are from the first level of modelling. Five Level 2 predictive model component layers representing the aggregate opportunity components are created from combinations of the Level 1 mappable criteria layers.

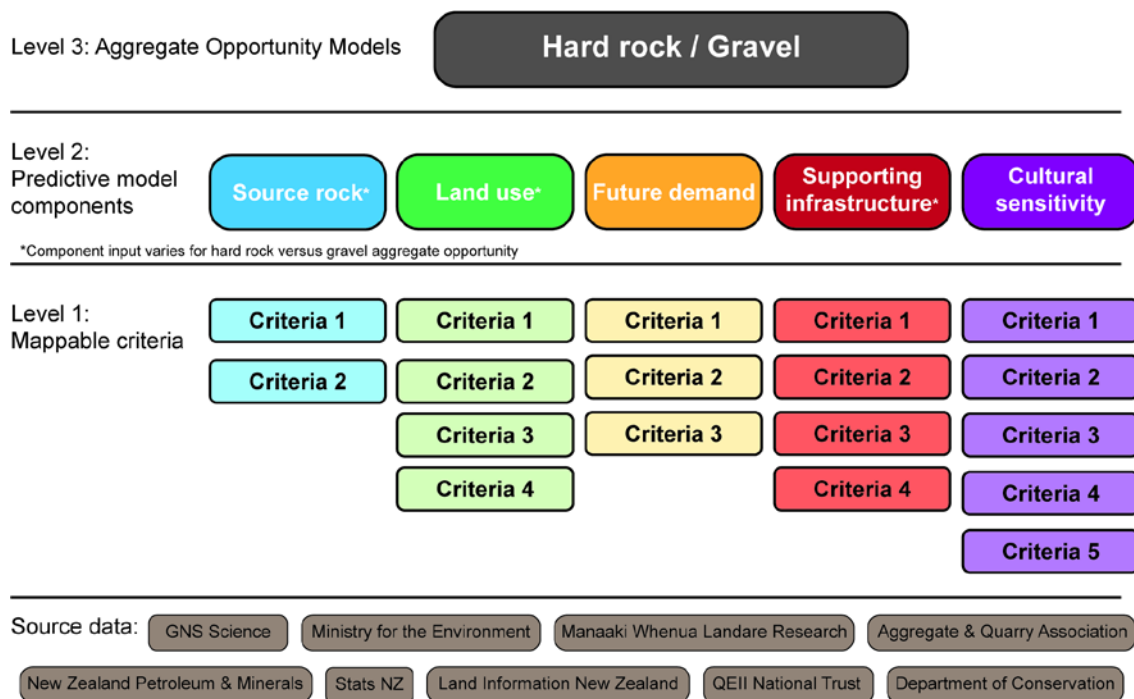


Figure 3.1 Overview of the spatial modelling process for aggregate opportunity. Mappable criteria representing the predictive model components are combined to create the final model for hard rock and gravel opportunity.

The final Level 3 hard rock and gravel aggregate opportunity models combine the Level 2 maps. Due to differences in the exploration for and operation of hard rock versus gravel aggregate, two final Level 3 maps have been created for this project that represent these two aggregate types. Although the two models utilised many of the same Level 1 mappable criteria layers, their classification differs for some elements such as rock type, waterway proximity and terrain. The final models show where areas have overlapping component parts of the aggregate opportunity concept. As the Level 1 and Level 2 components are semi-quantified and show differing spatial variations in suitability, the Level 3 maps and models are also semi-quantified in terms of opportunity and show where there is the most opportunity for aggregate extraction.

Twenty-three mappable criteria maps were selected for the final model that best represented the predictive components and did not repeat existing map patterns or have multi-collinearity. Continuous rather than discrete datasets were preferred to minimise gaps in data coverage; for example, GIS-calculated distance from existing quarries or roads creates a spatially continuous gridded dataset from discrete location data. This means that fewer areas of the map were missing data or had an unknown classification in the model. Emphasis was also placed on creating maps sourced from uniform coverage of geological, land-use, demand and infrastructure and cultural sensitivity data where possible.

This study uses knowledge-driven (expert) fuzzy logic membership values and operators to combine the maps into the aggregate opportunity model. Fuzzy logic is a widely used and conceptually simple method for combining spatial data and maps that represent various parts of the aggregate opportunity concept. This approach is guided by recent models in New Zealand for critical mineral modelling (see Durance et al. 2018; Morgenstern et al. 2018; Turnbull et al. 2018, 2019 for a more detailed outline of the fuzzy logic approach in mineral potential modelling) and has worked well in this study, as the model is able to include expert knowledge of future exploration priorities and important map features such as land-use classification and future demand calculations.

The mappable criteria layers used in the modelling are 100 m x 100 m cell size integer grids over the entire area of New Zealand generated by classification of the various data sources. Each class in those layers (e.g. different rock types, distances from infrastructure or ranges of future production) were assigned a fuzzy logic membership value between 0 and 1 that represents an expert opinion-derived numeric weight or relative importance for each classification in the layer. For initial ranking, integer values between 0 and 100 were used as **class weights**; they are then converted to **fuzzy membership values** for the fuzzy logic process by dividing them by 100 to give values between 0 and 1.

These classification weights are expressed as a continuous scale between 0 (full non-membership) and 1 (full membership), with 1 being definitely true and 0 being untrue or impossible (Bonham-Carter 1994). In this study, most values fall between 0.1, which is a contra-indicator for quarry opportunity (e.g. a high-value conservation land use), and 0.9, which is strongly positive indicator (e.g. an area of highly desirable rock type). A value of 0.5 has been used where there is neutral value in terms of quarry opportunity (e.g. the distance from a road that is neither desirable nor un-economic). This allows the break between the favourable and unfavourable conditions to be tracked and appropriately attributed in the modelling process.

After the Level 1 mappable criteria layers were combined into Level 2 predictive model component layers, fuzzy membership values were recalibrated. This process determines what the equivalent 0.5 fuzzy membership value would be in the Level 2 maps. The Level 2 predictive layers are then reclassified using natural breaks in the data to create classes above and below this value. New fuzzy membership values are assigned to each of these classes and retain 0.5 as the neutral value.

Level 1 layers are combined using the fuzzy GAMMA, fuzzy AND or fuzzy OR operators to create the five Level 2 layers representing the aggregate model components. The fuzzy gamma operator is an averaging process where the gamma parameter in the function indicates the degree of nearness to the fuzzy AND (minimum value) or fuzzy OR (maximum value) operator (Zimmermann 2001). In this study, a gamma value of 0.8 was chosen to combine the data because its additive effect reflects the decision-making thought process (An et al. 1991). The fuzzy gamma function has been used to retain a positive result in areas that are unfavourable in one component of the opportunity concept but favourable in the other four. Theoretically, there should not be aggregate opportunity at a site without all five components of the aggregate opportunity concept present, but most geoscience data are incomplete, so missing information or a negative factor that could be mitigated during quarry operation should not entirely rule out an area as having no potential. The fuzzy gamma function handling of missing data does not negatively impact on the opportunity modelling.

As an alternative to the fuzzy logic modelling approach, machine learning techniques such as random forest, weights of evidence and logistic regression were attempted in this study. These techniques yielded poor model results. Training data, which is required for these techniques, was compiled from quarries that are operating today, have high-quality products and are large producers. Although these features by all accounts represent ideal quarry locations, they would not necessarily be granted operating permits under current or future legislation. Therefore, the models were being trained on historic quarry placements that may be in a unsuitable environmental location, near a current market or sensitive to a changing culture. The fuzzy logic technique allows model weights to be applied using expert knowledge, a subjective but valid and flexible approach that better reflects future quarry requirements and ideal site conditions.

4.0 SOURCE MATERIAL

A spatial dataset of source material for both hard rock, gravels and volcanic deposits is a critical component for assessing the aggregate opportunity in New Zealand. Material composition or lithology is broadly well known from published geological maps, but these maps do not convey fine-scale variation in rock properties within individual geological units. Information on measured rock property data (e.g. rock density, degree of weathering, etc.) would benefit the modelling, but this information is rarely available and, where present, is typically insufficient for characterising more detail within geological map units. However, at a national scale, these geological units can be qualitatively generalised in terms of their suitability for aggregate. This study has used the digital QMAP 1:250,000-scale geological map database of New Zealand (Heron 2018), as it is consistent in interpretation and classification of rock types and is a continuous dataset across the entire study area. Data from this map has been reclassified to create mappable criteria layers for both hard rock and gravel lithology types.

The ***hard rock source mappable criteria layer*** is formed of 11 rock classes that are most commonly quarried in New Zealand:

- Sandstone (Mesozoic age greywacke)
- Sandstone (younger Cenozoic sandstones and greywacke)
- Limestone
- Marble
- Basalt
- Scoria
- Andesite and dacite
- Rhyolite
- Granite
- Mafic plutonic (e.g. gabbro and diorite)
- Other rock types (e.g. young Quaternary sediments or unsuitable rock types).

The layer is an extract based on the MAINROCK field in the QMAP database (see Table 4.1), and the SUBROCK field was also used to find areas where a source rock type might not be the primary lithology but is still present in the geological unit. The SUBROCKS classification was only used in places where the MAINROCK class was one of the 'other sediments' rock types. The mappable criteria layer was numerically weighted based on their MAINROCK (Figure 4.1) with a lower weight contribution from the SUBROCKS (see Table 4.1 for rock class weights). The class weight is a value between 0 and 100 that represents the importance of the rock type in the model. Rock types suitable for aggregate extraction were assigned class weights >50, with unsuitable material types (e.g. Quaternary sediments) assigned values <50. The predictive model component layer of hard rock source types has been created from the combination of the mappable criteria layers for the MAINROCK and SUBROCKS lithologies (Figure 4.3a).

Table 4.1 Lithological rock classes used in the modelling, the GIS queries used to combine MAINROCK and SUBROCKS QMAP polygons and the assigned class weight.

Rock Class	Query (of the QMAP Database using ArcGIS Software)	Class Weight MAINROCK	Class Weight SUBROCKS
Mesozoic (MZ) and Palaeozoic (PZ) sandstone greywacke	(MAINROCK = 'sandstone', 'greywacke', 'psammite', 'metasandstone', 'quartzite') AND (TZONE = 'I', TZONE = ' ', TZONE = '') AND ABSMIN_MA >= 65	94	78
Cenozoic (CZ) sandstone greywacke (excluding Quaternary rocks)	(MAINROCK = 'sandstone', 'greywacke', 'psammite', 'metasandstone', 'quartzite') AND (TZONE = 'I', TZONE = ' ', TZONE = '') AND (ABSMIN_MA >= 2.5 AND ABSMIN_MA <65)	82	66
Limestone	MAINROCK = 'coquina', 'limestone', 'algal limestone', 'micrite', 'travertine'	80	64
Marble	MAINROCK = 'marble'	72	56
Granite	MAINROCK = 'granite', 'monzogranite', 'granodiorite', 'granitoid', 'porphyry', 'syenogranite', 'trondhjemitite', 'tonalite', 'quartz diorite', 'quartz monzodiorite', 'quartz monzonite', 'syenite'	69	53
Gneiss	MAINROCK = 'gneiss', 'granulite', 'orthogneiss', 'paragneiss', 'migmatite'	62	51
Mafic plutonic	MAINROCK = 'gabbroic,orthogneiss', 'ultramafics', 'anorthosite', 'clinopyroxenite', 'diorite', 'dioritic,orthogneiss', 'dolerite', 'dunite', 'microdiorite', 'gabbro', 'gabbroiorite', 'lamprophyre', 'peridotite', 'olivine nephelinite', 'norite', 'monzodiorite', 'hornblendite', 'harzburgite', 'pyroxenite', 'epidiorite'	73	57
Rhyolite	MAINROCK = 'trachyte', 'rhyolite'	70	54
Basalt	MAINROCK = 'olivine basalt', 'metavolcanics', 'spilite', 'basaltic andesite', 'basalt', 'keratophyre', 'hawaiite'	77	61
Scoria	MAINROCK = 'scoria'	84	68
Andesite and dacite	MAINROCK = 'phonolite', 'andesite', 'dacite', 'rhyodacite'	75	59
Other sediments (not Quaternary [Q])	(MAINROCK = 'breccia', 'melange', 'broken formation', 'metaconglomerate', 'volcanic conglomerate', 'conglomerate', 'gravel', 'boulders', 'volcanic sandstone', 'sand') AND STRATAGE Not Like '%Q%'	65	52

Some rock types are not suitable for hard rock aggregate material. These are either specifically queried in the 'Other sediments' class or excluded by age or other classification. Rock types such as breccia, melange and conglomerates are not often suitable due to their heterogeneous nature. Schist rock is excluded from the model by higher textural zone (TZONE) classification, as the mica mineral in schist makes the rock type unsuitable for many hard rock aggregate uses (Reyes et al. 2003).

The **gravel aggregate source mappable criteria layer** uses the QMAP digital geological data to map areas of unconsolidated sediments suitable for quarrying and includes data from the Ministry for the Environment (Snelder et al. 2010) to include large river systems that are more likely to contain well sorted and more indurated clasts. The gravel source map is classified into five different sediment types:

- River gravels (classified into five types by river order [size] or mapped deposit area).
- Sand.
- Beach gravels.
- Volcanic sediments (e.g. pumice).
- Other unconsolidated Quaternary material.

These classifications were made through extracts of the QMAP database and the river environment database (Table 4.2). River lines were buffered by an area 250 m on either side of the river, and all data were assigned class weights as listed in Table 4.2. The mappable criteria layer of gravel source types used in the modelling is created from the maximum of all gravel source material class weights (Figure 4.2). The layer also represents gravel source rocks as the Level 2 predictive model component (Figure 4.3b).

Table 4.2 Lithological gravel and river classes used in the modelling, the GIS queries used to combine the river ORDER lines and the MAINROCK and SUBROCKS QMAP polygons and the class weight for each area of that gravel class used in the model.

Rock Class	Query (of the QMAP or Ministry for the Environment Database using ArcGIS Software)	Source	Class Weight
Dune sand	MAPSYMBOL Like '%dns%', '%dnp%', '%dnu%', 'IPIQ.snd'	QMAP	83
Beach deposits	MAPNAME LIKE '%beach deposits%'		79
River alluvium from QMAP	MAPNAME LIKE '%river%', '%congl%'		71
Ignimbrite, tuff and pumice	MAINROCK = 'pumice', 'pyroclastics', 'pyroclastic breccia', 'ignimbrite', 'tuff', 'lapilli tuff', 'vitric tuff', 'volcanic breccia', 'tephra'		67
Other Quaternary rocks	STRATAGE Like '%Q%'		40
4 th Order in river alluvium	ORDER_ = 4	Ministry for the Environment	74
5 th and 6 th Order in river alluvium	ORDER_ = 6 OR ORDER_ = 5		76
7 th Order in river alluvium	ORDER_ = 7		81
8 th Order in river alluvium	ORDER_ = 8		88

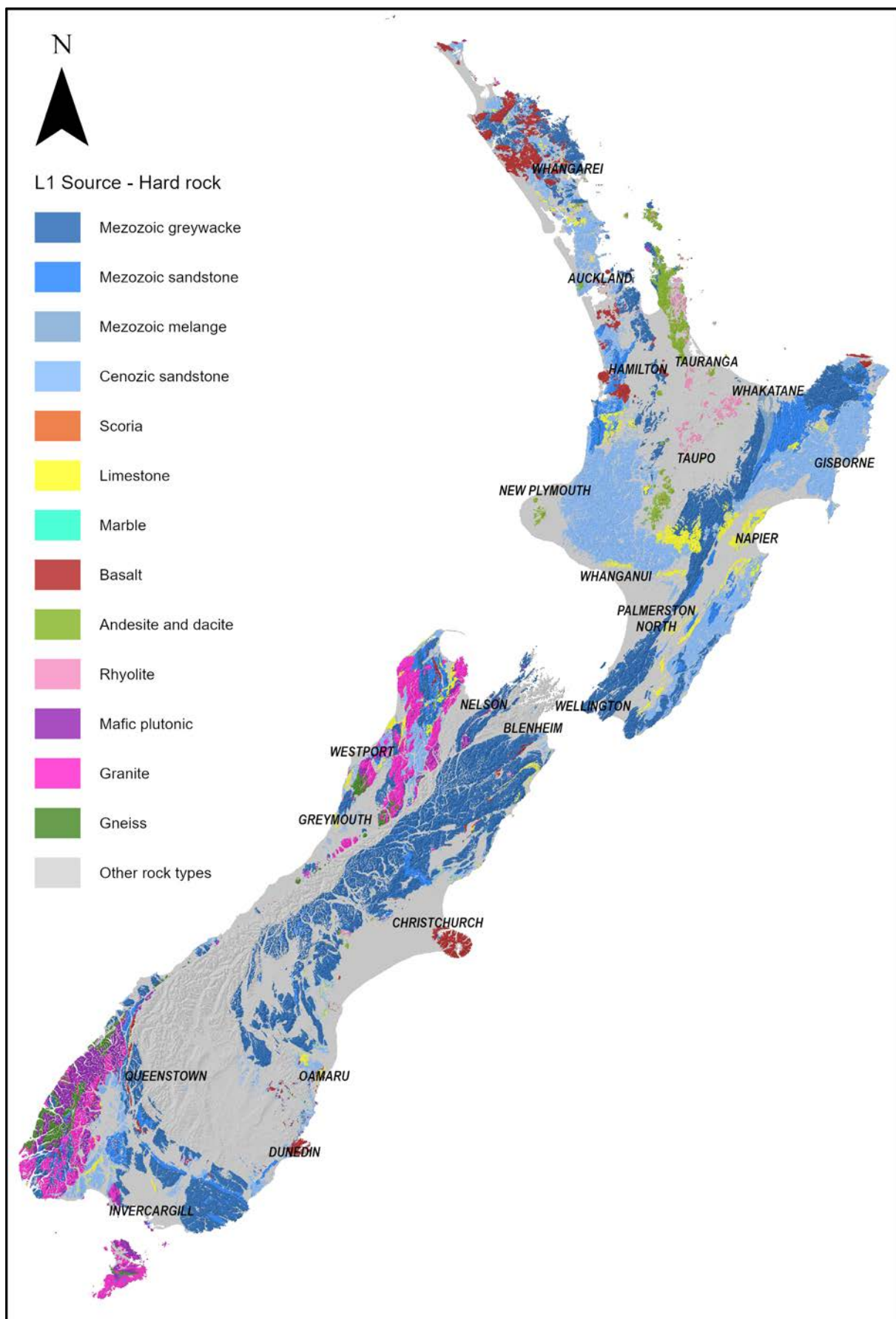


Figure 4.1 Map of lithological rock classes combined to create the Level 2 (L2) predictive model component layer used to define the source material for the hard rock aggregate opportunity model. Combined from L1_SOURCE_MAINROCK_FM and L1_SOURCE_SUBROCKS_FM (see Appendix 3).

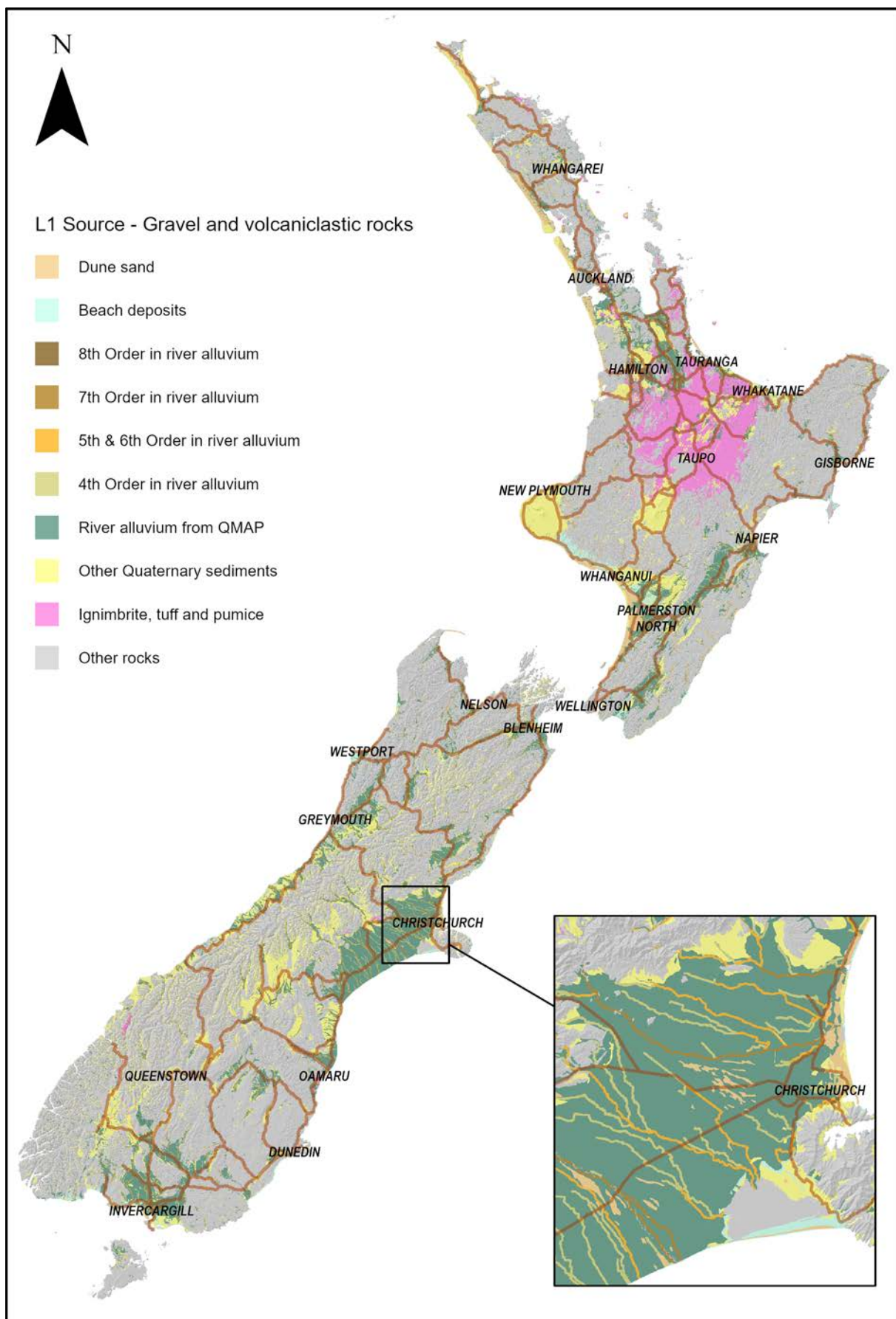


Figure 4.2 Map of lithological and river classes combined to create the Level 2 (L2) predictive model component layer L1_SOURCE_GRAVEL_FM used to define the source material for the gravel aggregate opportunity model (see Appendix 3).

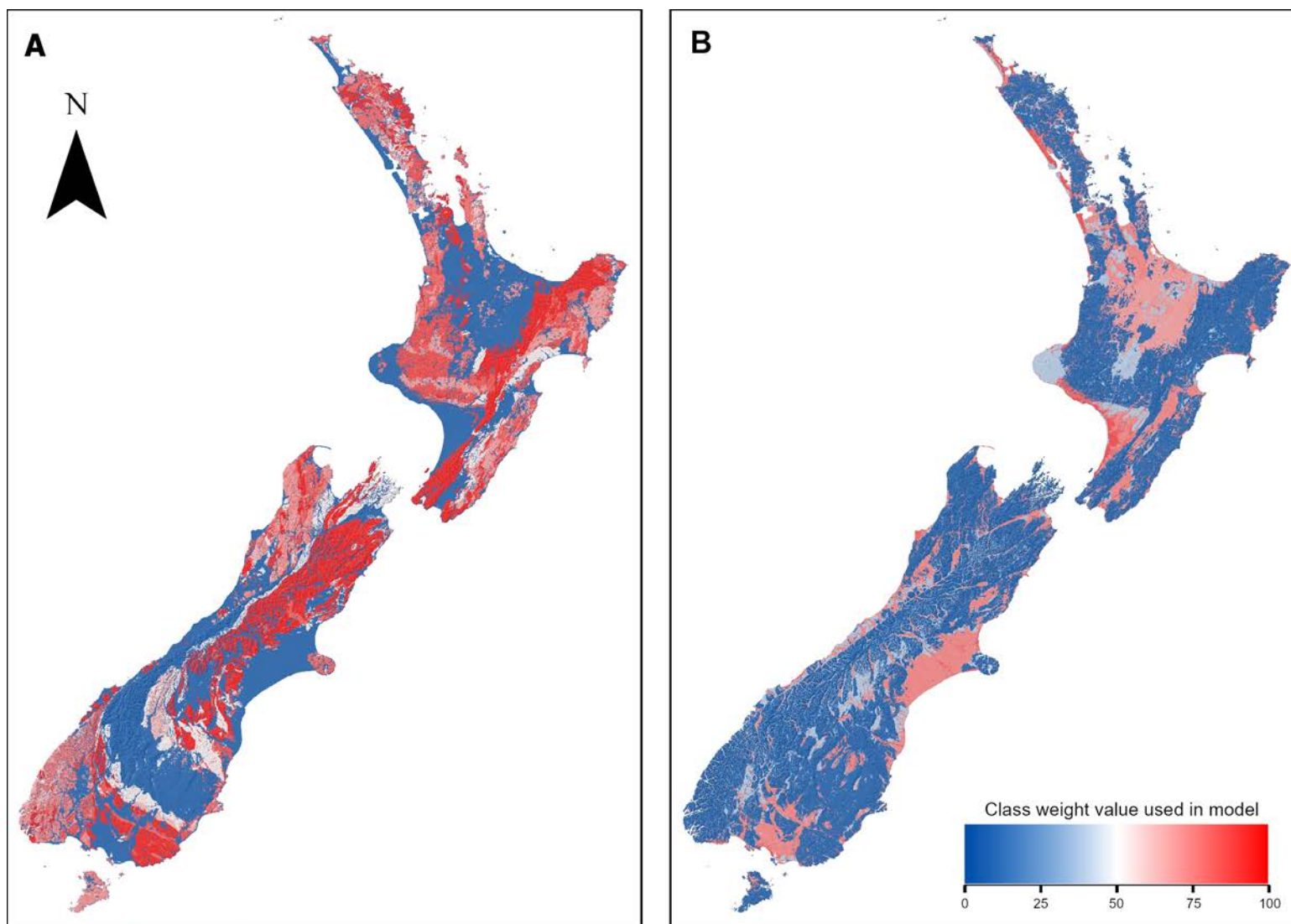


Figure 4.3 Maps of Level 2 source material predictive model component layers for hard rock (A) lithological classes and (B) gravel classes. Values are shown in class weights, where the red regions are more ideal than the blue for aggregate sources. Maps from datasets L2_SOURCE_GRAVEL_FM and L2_SOURCE_HARDROCK_FM (see Appendix 3).

An analysis of the operating quarries in New Zealand and the source rock classes is illustrated in Figure 4.4. Sandstone (old Mesozoic [MZ] and Paleozoic [PZ], and younger Cenozoic [CZ]), limestone and basalt are the most common source rocks for hard rock quarries with river gravels away from the active channel ('River alluvium (QMAP)'), and 5th and 6th order river areas are the most common for gravel quarries.

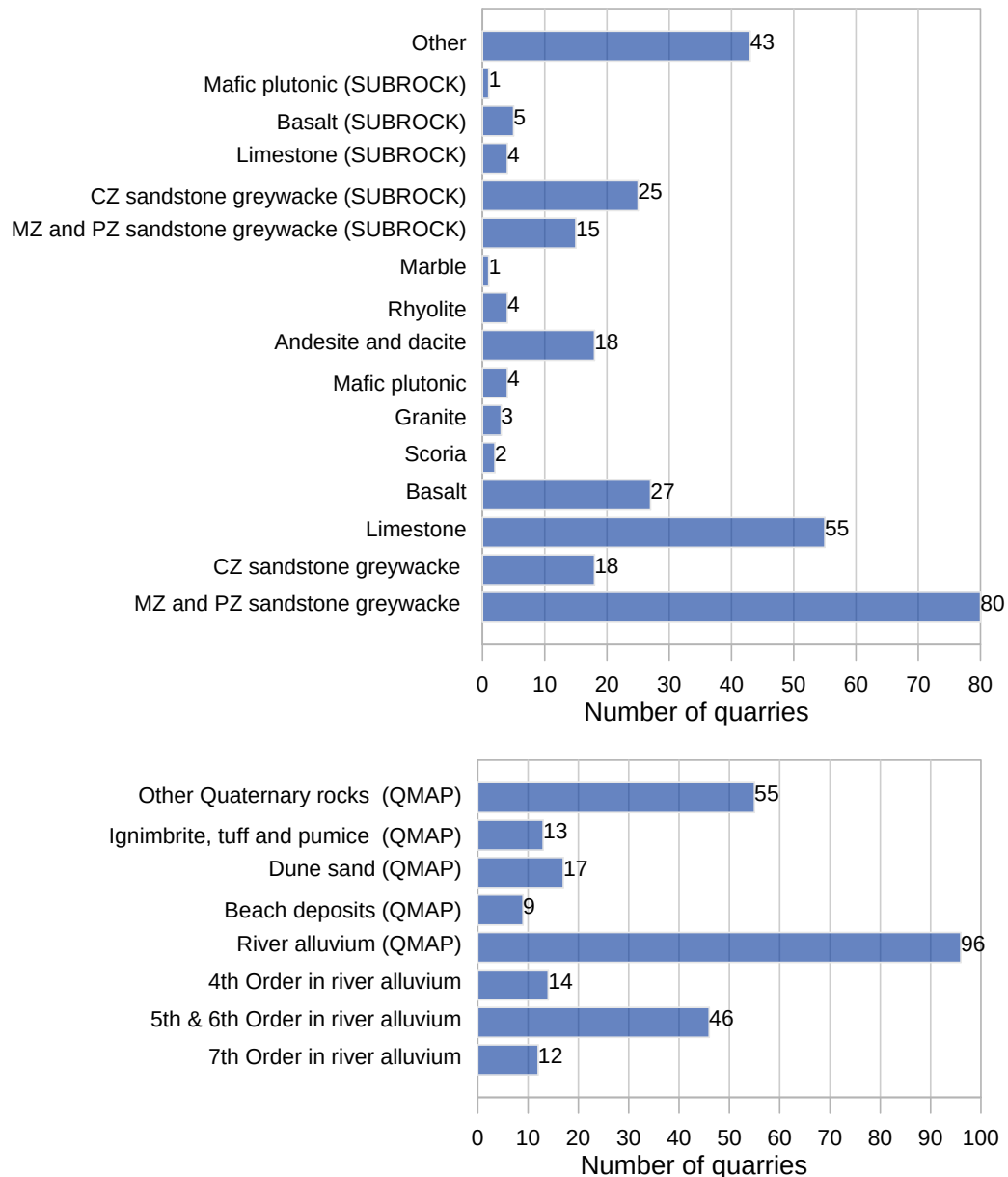


Figure 4.4 Histograms of the mapped lithology rock and gravel classes that operating quarries in New Zealand are working. MAINROCK and SUBROCK classes of hard rock lithologies (top chart) and gravel lithologies and river size (bottom chart).

The model does not include any engineering or chemical qualities of the rock (e.g. Black 2009) or local lithological variation, e.g. argillite-rich versus sandstone-rich zones in the greywacke. Acquiring these data would substantially improve the source rock predictive model component layer. In some areas, cover rocks obscure hard rock resources just below the surface and small outcrops of suitable source material may not be mapped within the national-scale 1:250,000 QMAP geological database. Integration of detailed maps at a regional scale would also enhance future models.

5.0 LAND USE

Land use is one of several non-geological predictive model components needed for assessing the aggregate opportunity. The land-use layer combines information from several digital databases that classify land, including areas that are incompatible with quarrying. The modelling has included areas of restricted land where mining activities are prohibited or where access restrictions apply, such as Schedule 4 Crown-owned conservation land (see the Crown Minerals Act 1991), Department of Conservation (DoC) public conservation areas, QEII National Trust land, and waterways (flowing rivers and active river braids) and waterbodies. We have also used version 5 of the Land Cover Database (LCDB; LRIS Portal 2020) that maps areas of different vegetation and other land uses, including areas of significant indigenous native vegetation that typically have high conservation value.

The LCDB classifies all areas of New Zealand into 34 different land-use types using satellite data. For this study, those classifications have been simplified into six classes to use in the modelling, which are listed in Table 5.1. Each class is assigned a numerical class weight value that defines the suitability of the current land use for establishing a new quarry. For example, exposed sand, gravel and rock areas are highly suitable for new quarry locations. Areas of indigenous vegetation and settlements or infrastructure are not suitable for new quarry locations. The LCDB classifications clearly define large areas of indigenous vegetation and crop land in New Zealand (Figure 5.1).

Data for the DoC-managed public conservation areas are available in a publicly accessible database. The land areas are divided into 19 'SECTION' classifications (Table 5.2). For this study, those classifications have been simplified into five classes, and each class is assigned a numerical class weight value that defines the suitability and access potential for quarrying activities on public conservation land. For example, areas of national parks are highly unsuitable for extractive activities and are therefore given a very low class weight. However, there are some parts of the stewardship land areas that are suitable for quarrying so that land class has been given a higher class weight. Figure 5.2 illustrates the large area of land managed by DoC in New Zealand, which is approximately 32% of the land area in this model.

Three other datasets are also included in the land-use analysis: the Schedule 4 listed land areas, areas of land managed by the QEII National Trust and a map of waterways and waterbodies. Schedule 4 and QEII National Trust land areas are located throughout New Zealand (Figures 5.3 and 5.4) and are inappropriate for quarrying activity, so therefore have very low class weights (

Table 5.3). Hard rock aggregate extractability is down-weighted where there are nearby waterways or lakes (

Table 5.3), and water areas near a hard rock quarry site are a complication that can be mitigated; however, avoiding these areas, where possible, would remove the difficulty of managing and protecting the water resource. A layer of waterways and waterbodies has been created from the LINZ Topo 50 river lines (buffered by 100 m) and Topo 50 lakes and lagoons (Figure 5.5; LINZ 2019).

Gravel aggregate extraction is commonly very close to rivers where unconsolidated river gravels have naturally accumulated in abandoned river channels or, in some cases, directly from active channels (Figure 2.3). The waterways mappable criteria layer is therefore not used in the land-use predictive model component for the gravel aggregate opportunity model.

Table 5.1 Land Classification Database (LCDB v5) classifications combined to create the six LCDB classes for the land-use predictive model component, with their assigned class weights.

Land Cover Class	LCDB Classifications (Grid Code and Name)	Class Weight
Settlements and infrastructure	1 – Built-Up Area (settlement) 2 – Urban Parkland / Open Space 5 – Transport Infrastructure	21
Crop/grassland	30 – Short-Rotation Cropland 33 – Orchard, Vineyard or Other Perennial Crop 40 – High-Producing Exotic Grassland 41 – Low-Producing Grassland 43 – Tall Tussock Grassland 44 – Depleted Grassland	82
Exotic vegetation	51 – Gorse and/or Broom 56 – Mixed Exotic Shrubland 68 – Deciduous Hardwoods 71 – Exotic Forest	71
Indigenous vegetation	15 – Alpine Grass/Herbfield 45 – Herbaceous Freshwater Vegetation 46 – Herbaceous Saline Vegetation 47 – Flaxland 50 – Fernland 52 – Manuka and/or Kanuka 54 – Broadleaved Indigenous Hardwoods 55 – Sub-Alpine Shrubland 58 – Matagouri or Grey Scrub 69 – Indigenous Forest 70 – Mangrove	55
Sand, gravel or rock	6 – Surface Mine or Dump 10 – Sand or Gravel 12 – Landslide 16 – Gravel or Rock 64 – Forest – Harvested	85
Water or ice	14 – Permanent Snow and Ice 20 – Lake or Pond 21 – River 22 – Estuarine Open Water	14

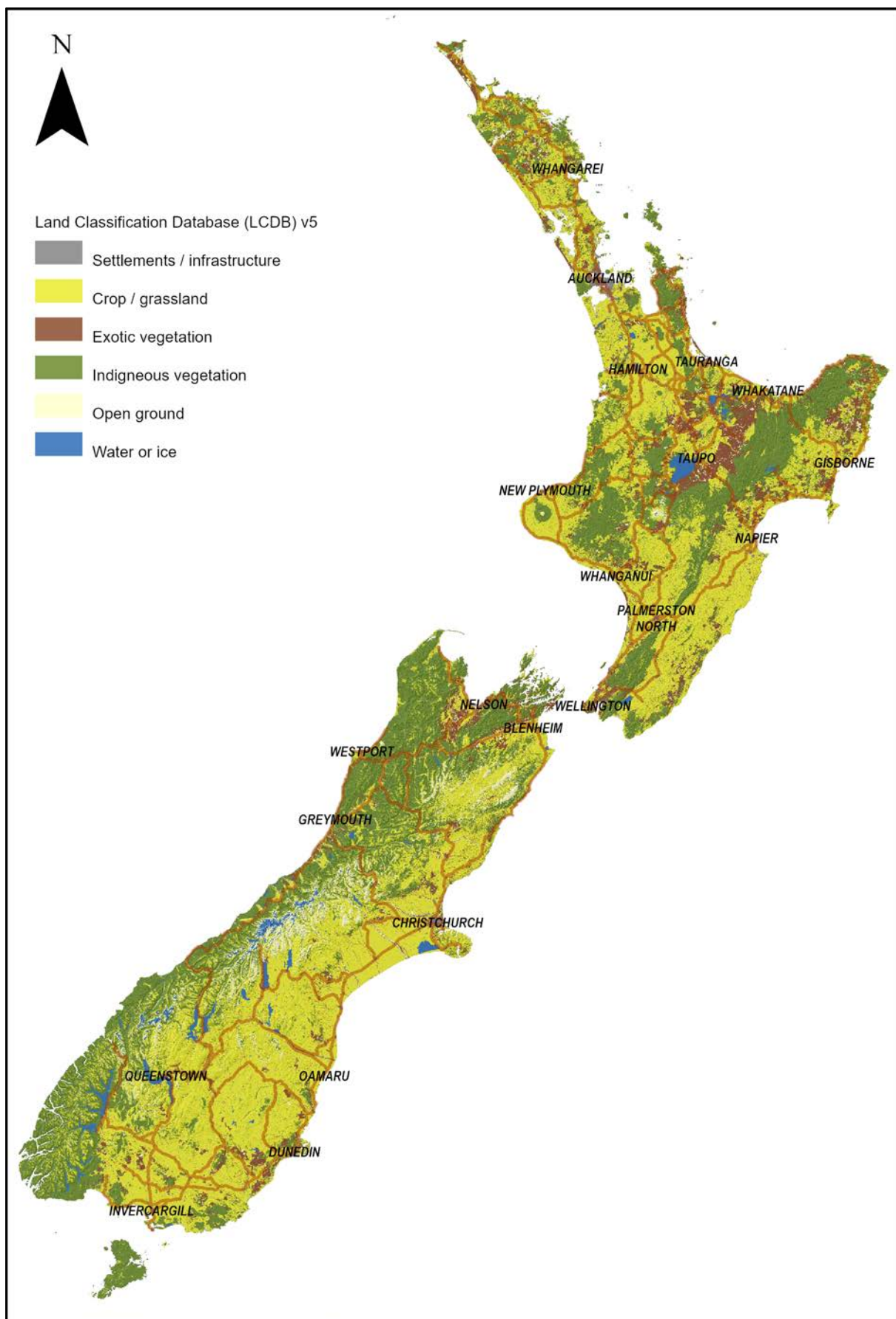


Figure 5.1 Map of land cover classes in L1_LANDUSE_LCDB_FM created from the Land Classification Database (LCDB) classifications and used in the land-use predictive model component layer (see Appendix 3).

Table 5.2 Department of Conservation public conservation land sections combined to create five map classes for the land-use component of this modelling and the class weights each class is assigned.

Conservation Land Class	Public Conservation Land 'SECTION' Classification	Class Weights
National Parks	S4_NATIONAL_PARK	10
Scenic reserves, conservation parks, scientific reserves and sanctuary areas	S19_1_A_SCENIC_RESERVE S21_SCIENTIFIC_RESERVE S22_SANCTUARY_AREA S19_1_B_SCENIC_RESERVE S19_CONSERVATION_PARK S2_WAITANGI_ENDOWMENT_FOREST	15
Wilderness, historic, nature, ecological, government, wildlife and fixed marginal areas	S24_3_FIXED_MARGINAL_STRIP S22_GOVERNMENT_PURPOSE_RESERVE S18_HISTORIC_RESERVE S20_NATURE_RESERVE S21_ECOLOGICAL_AREA 20_WILDERNESS_AREA	20
Recreation, local purpose and amenity areas	17_RECREATION_RESERVE S23_LOCAL_PURPOSE_RESERVE S23B_WILDLIFE_MANAGEMENT_AREA S23A_AMENITY_AREA	25
Stewardship areas	S25_STEWARDSHIP_AREA	40

Table 5.3 Class weights for map areas of the QEII National Trust, Schedule 4 and waterways maps used in the land-use component of this modelling.

Land Use Class	Land Classification	Class Weights
QEII National Trust	QEII National Trust covenant land areas.	6
Schedule 4	Areas listed in Schedule 4 of the Crown Minerals Act.	5
Waterways and water bodies (hard rock aggregate only)	Waterways (rivers and creeks) and water bodies (lakes)	35

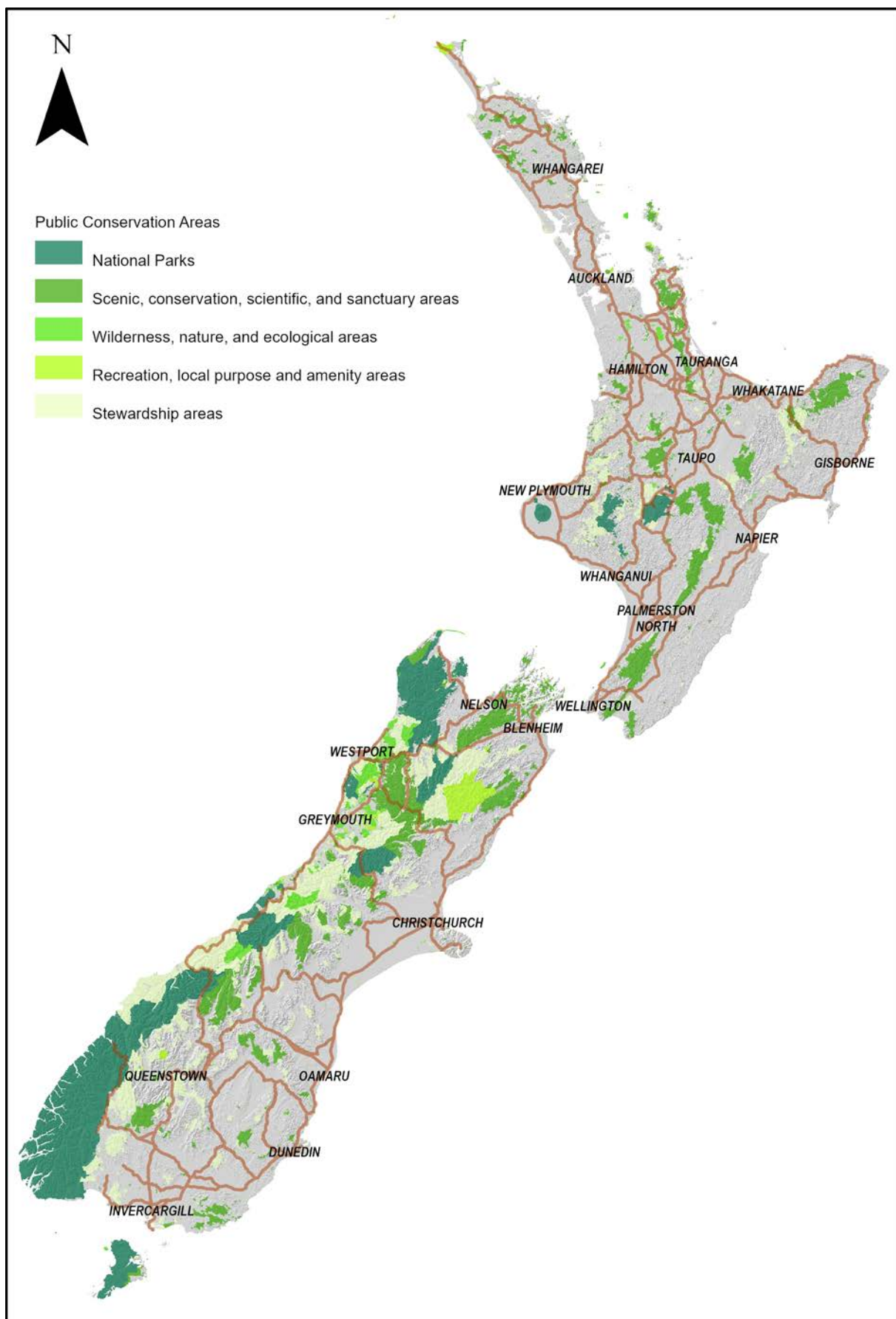


Figure 5.2 Map of conservation land classes based on combined Department of Conservation public conservation land section classifications used in the land-use predictive model component layer. Map from dataset L1_LANDUSE_DOC_FM (see Appendix 3).

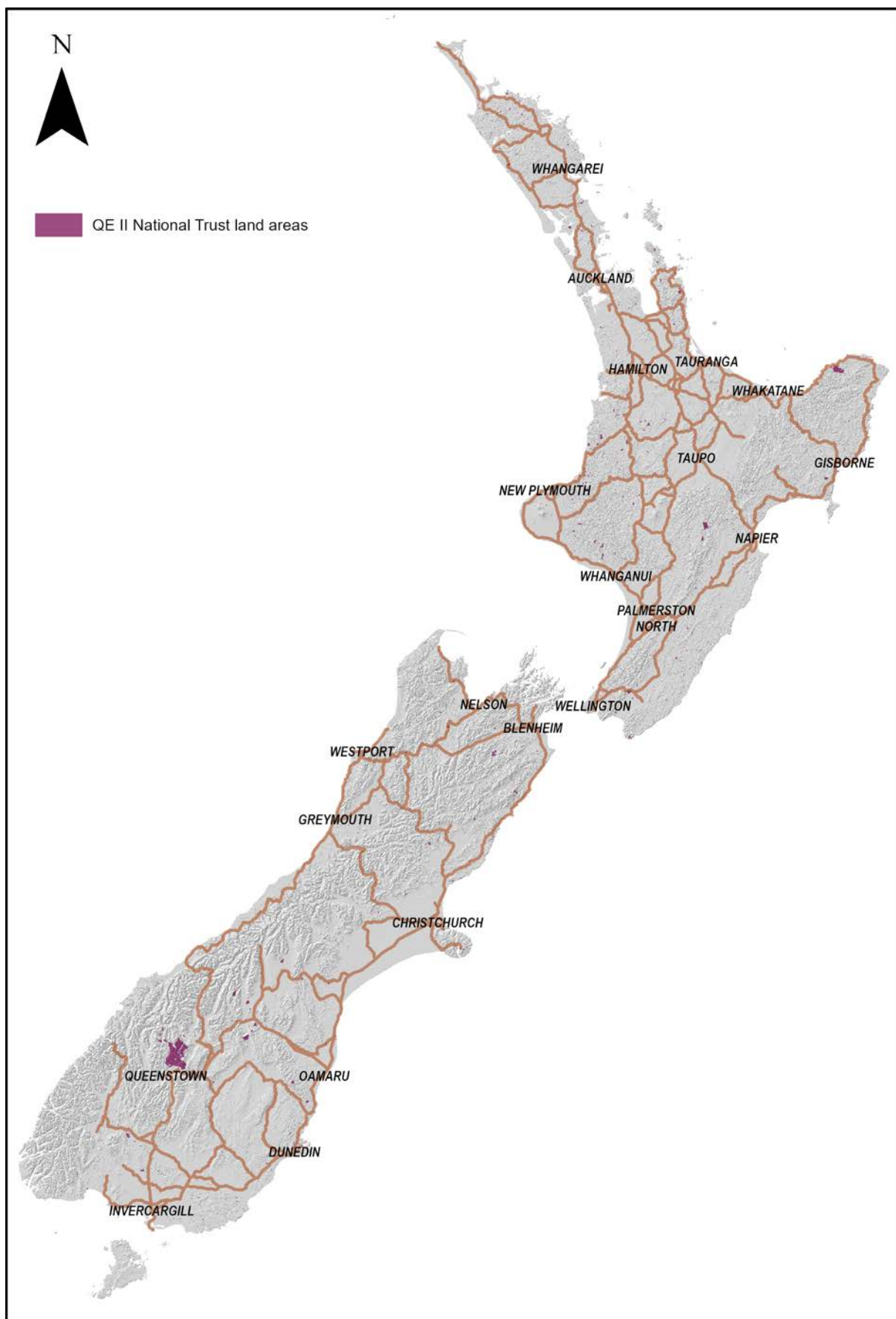


Figure 5.3 Map of QEII National Trust land covenant areas in New Zealand. These land classes in L1_LANDUSE_QEII_FM are used in the land-use predictive model component layer (see Appendix 3). Many areas are very small and not visible at the scale of this figure.

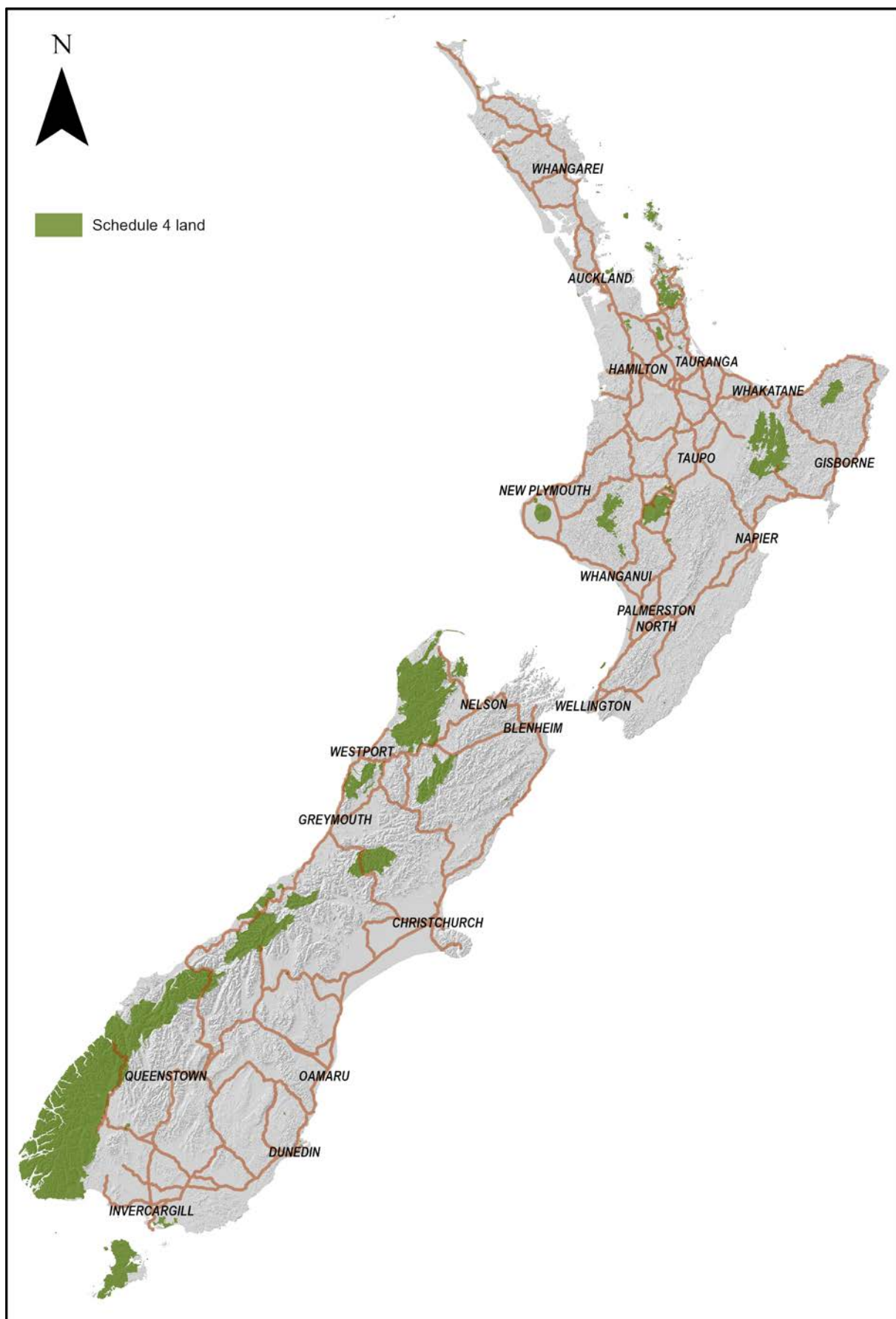


Figure 5.4 Map of areas listed in Schedule 4 of the Crown Minerals Act in New Zealand. These land classes in L1_LANDUSE_S4_FM are used in the land-use predictive model component layer (see Appendix 3).

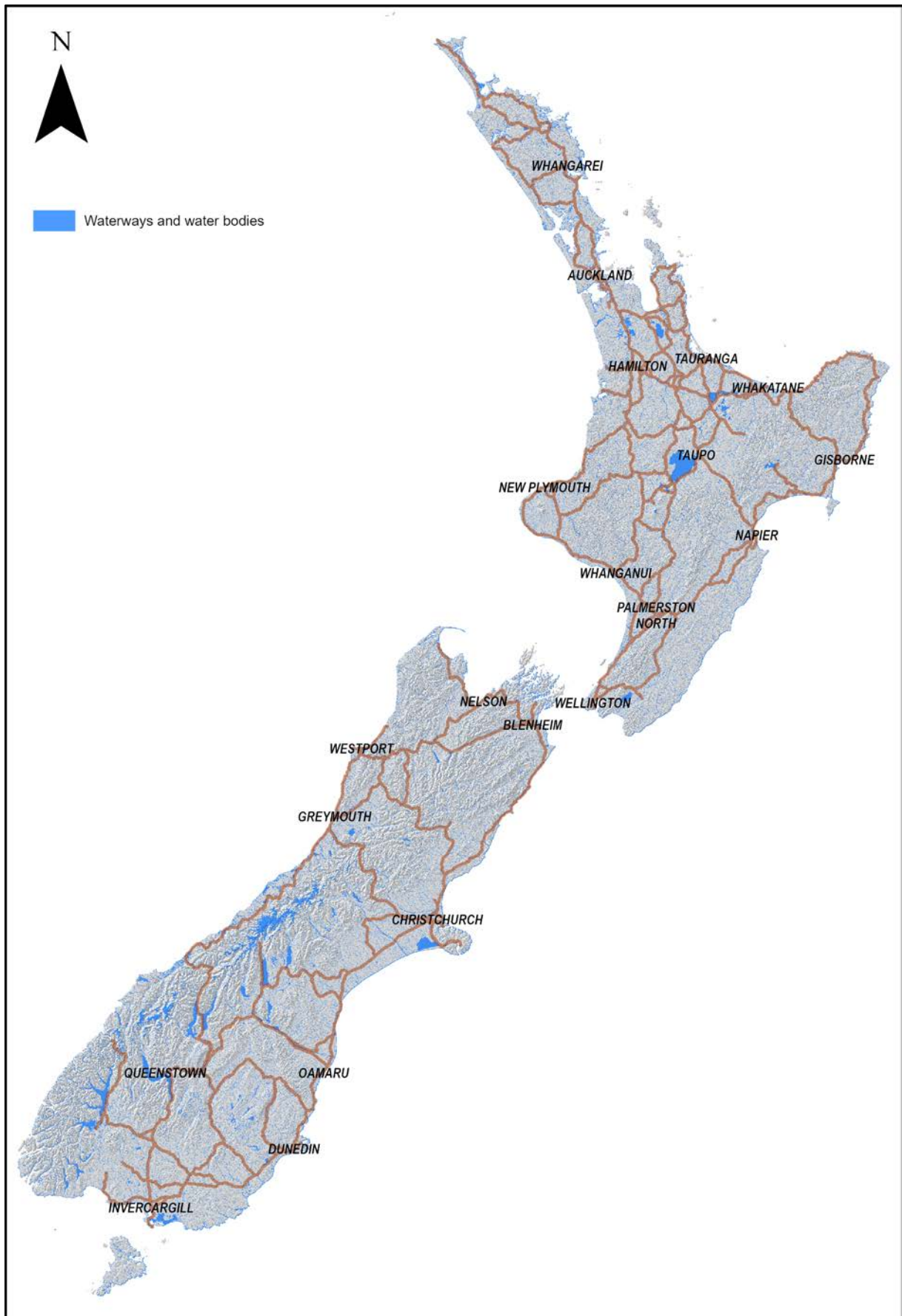


Figure 5.5 Map of river and lake areas in New Zealand. These land classes in L1 LANDUSE_WATER_FM are used in the land-use predictive model component layer (see Appendix 3) and are only used for hard rock aggregate opportunity modelling, not for the gravel modelling.

Two Level 2 predictive model component layers are created for land use; one for the hard rock aggregate opportunity model, where DoC, LCDB, QEII, Schedule 4 and waterways are combined; and one for the gravel model, which excludes the waterways mappable criteria layer (Figure 5.7). The maps are combined using the fuzzy AND function (finds the minimum value of the combined maps for each cell site), which prioritises those areas of high conservation value in the resulting map.

An analysis of the operating quarries in New Zealand and the land-use classes is illustrated in Figure 5.6. Most of the operating quarries are currently located in sand, gravel or rock areas or crop/grassland areas. Few are near indigenous vegetation or are in areas classified as conservation land.

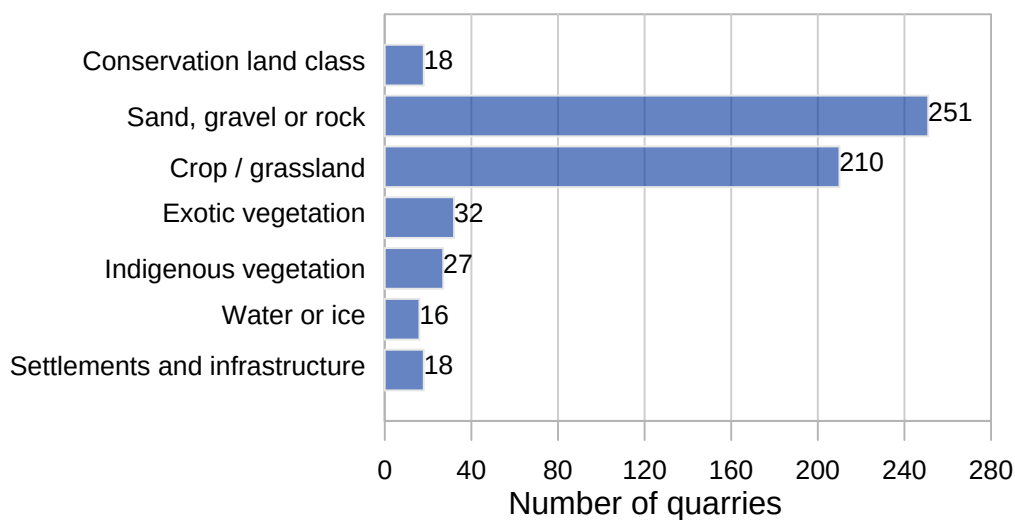


Figure 5.6 Histogram of land-cover class for operating quarries in New Zealand. The 'Conservation land class' combines results for areas of Schedule 4, QEII and Department of Conservation land.

Follow-up studies would benefit from including data from local and regional councils for parks and reserves that are currently not in an easily accessible national database.

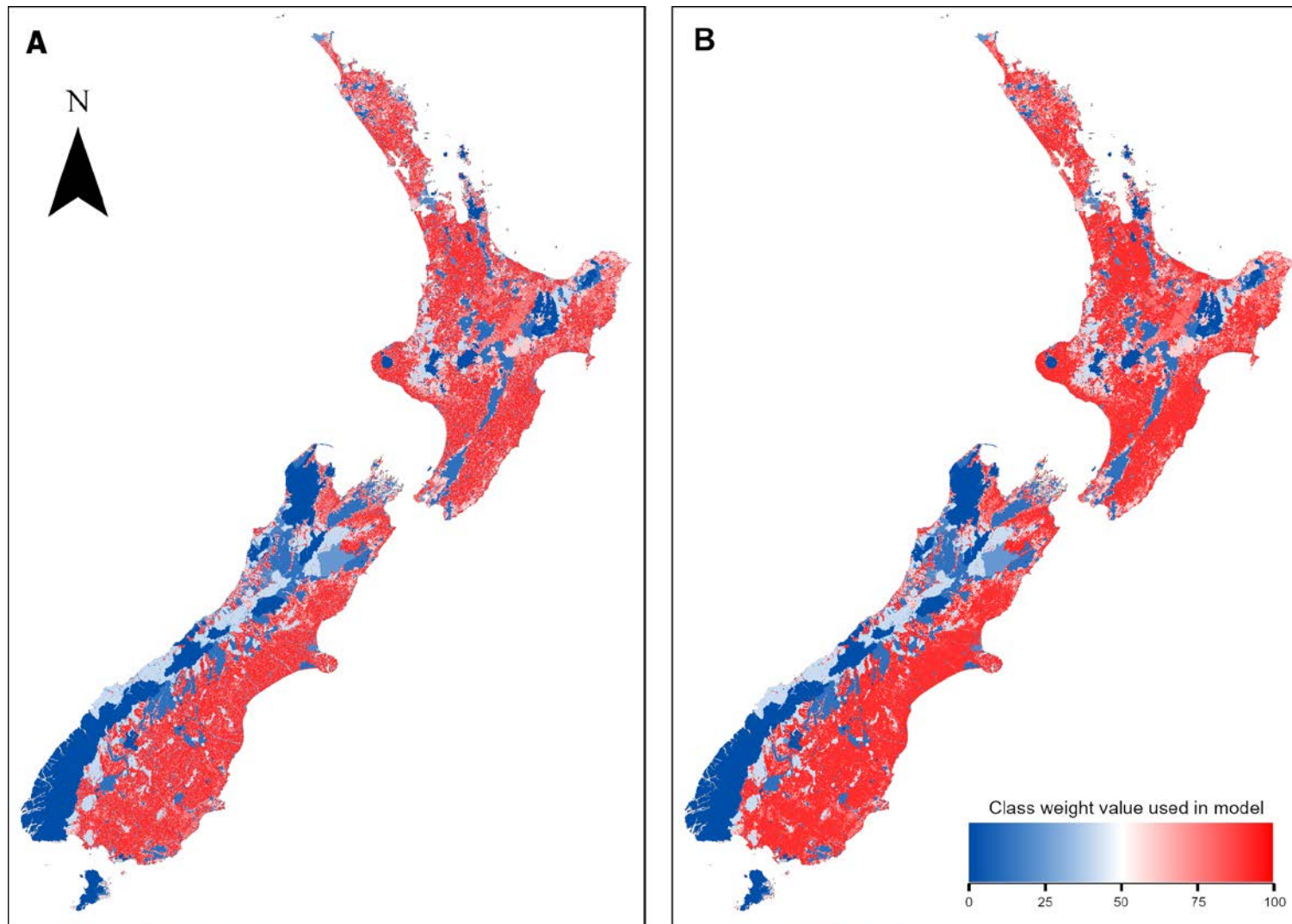


Figure 5.7 Maps of the Level 2 land-use predictive model component layer for the hard rock (A) and gravel (B) aggregate opportunity models. Values are shown in class weights, where the red regions are interpreted as more ideal for aggregate extraction than the blue areas. Derived from datasets L2_LANDUSE_GRAVEL_FM and L2_LANDUSE_HARDROCK_FM (see Appendix 3).

6.0 FUTURE DEMAND

Proximity to high-demand aggregate markets and roading projects is critical for the economic viability of quarries. The model has used several data sources to represent these markets, which include the distance from highly populated areas, the distance from roads classified by size and use, estimates of future construction and building and the predicted future aggregate production. All of these data provide insight into the end use of aggregate and are a forecast of future demand.

The regional aggregate demand is not always directly correlated to the production in that area. For example, production in the Auckland Region does meet the demand; however, aggregate from the Waikato and Northland regions is transported to Auckland to satisfy the much higher construction and building activity. A summary of the regional production (NZP&M 2018), construction and building activity (BRANZ and Pacifecon 2020) and regional population (Stats NZ 2020) are illustrated in Figure 6.1 and show the decrease in construction activity forecast between 2018 and 2023, the increase in population predicted for the same period and that, in some cases, production must be servicing demand outside of the region.

Although construction and building activity overall is forecast to decrease in the coming years, the infrastructure component (e.g. roads, rail, bridges, tunnels, groundworks and energy services) in many areas is forecast to increase (BRANZ and Pacifecon 2020). Of the total rock, sand and gravel aggregate currently produced in New Zealand, only 27% is for building; 1% for reclamation and protection; and 10% for fill; whereas 62% is utilised for roading (NZP&M 2018). The high volume used for road development and maintenance highlights the importance of that infrastructure for future aggregate demand.

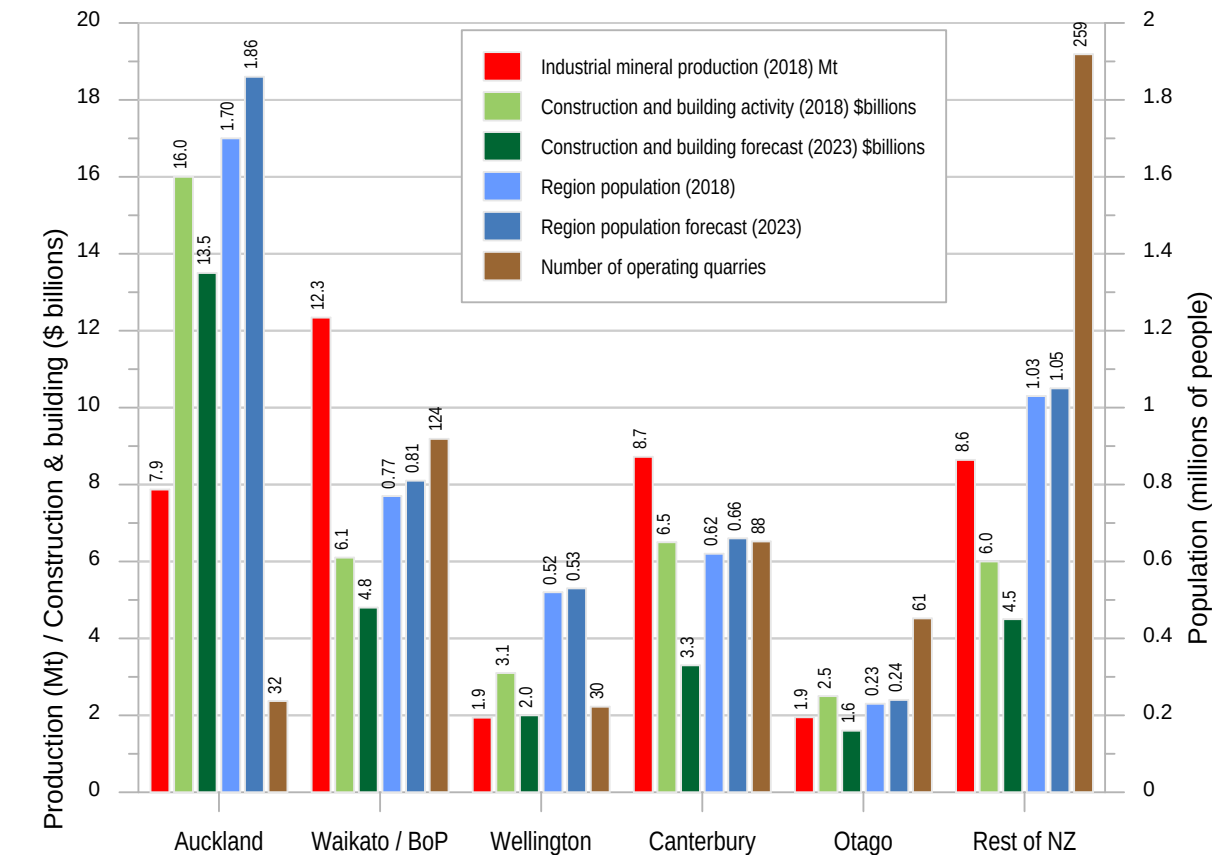


Figure 6.1 Industrial mineral production (2018), construction and building activity (2018 and 2023), population (2018 and 2023) and the number of operating quarries for major regions of New Zealand. Data sourced from NZP&M (2018), BRANZ and Pacifecon (2020) and Stats NZ (2020).

To map the demand, it is important to represent the final market location but also the distance from them that the supply may have to travel. Therefore, maps in this predictive model component all include a distance function to represent this. To create the proximity to populated areas and roads mappable criteria layer, a function was used to model increasing distance away from the features. For populated areas, a distance from statistical mesh blocks with a population >50 people per km² was calculated; for roads, distances from major roads (highways or having ≥3 lanes), local roads (sealed roads with <3 lanes) and metalled roads (gravel roads) were calculated. In this modelling, we use a distance from existing roads that require aggregate for maintenance; new roads planned for future builds would be a dataset that could be compiled for future iterations of this study.

To determine class weights from the distance calculations, a fuzzification function was used. In places where low values need to have a strong spatial association with aggregate opportunity, the small fuzzification function (Equation 6.1, Almasi et al. 2017) can be used to represent the distance values as fuzzy membership values; that is, low values where map area is closer to the feature will have higher fuzzy membership values, and high values where the map area is more distal to the feature will have lower fuzzy membership values. We have used this function to create fuzzy membership values for the proximity to populated areas (Figure 6.3), distance from major roads, distance from local roads and distance from metalled (gravel) roads (Figure 6.4) in this modelling.

$$\mu_x = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{f_1}} \quad \text{Equation 6.1}$$

where x is the spatial grid value (e.g. distance from the feature), μ_x is the fuzzy membership value, f_1 is the spread of the transition and f_2 is the midpoint in the dataset of values and assigned a fuzzy membership value of 0.5. The small fuzzification functions used in the demand modelling for this study are plotted in Figure 6.2.

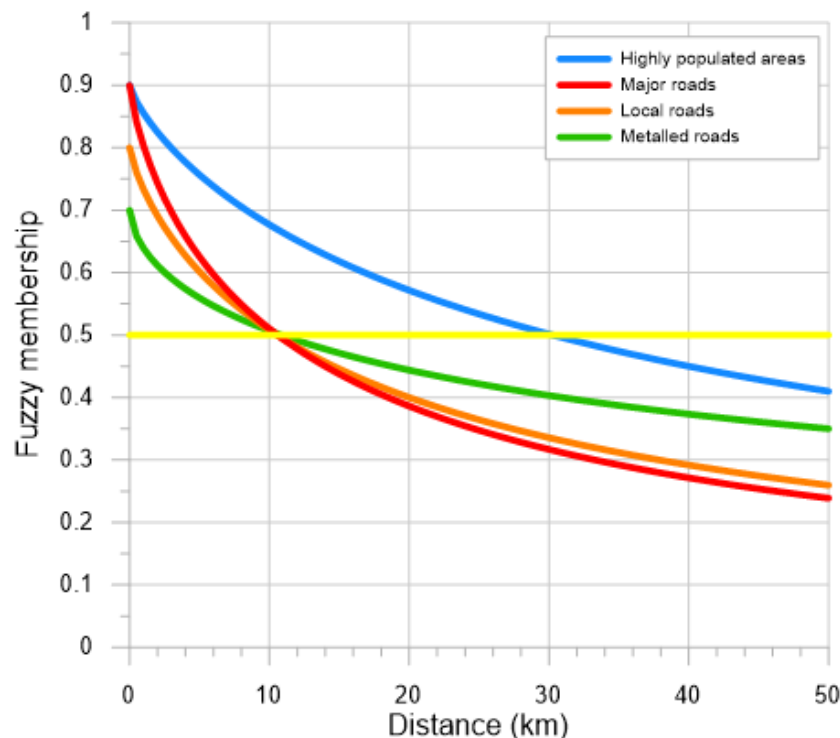


Figure 6.2 Chart of fuzzy membership values based on distance from a feature, determined using the small fuzzification formula. Lines are plotted for the fuzzification formula used to create the maps for the distance from highly populated areas, major roads, local roads and metalled roads.

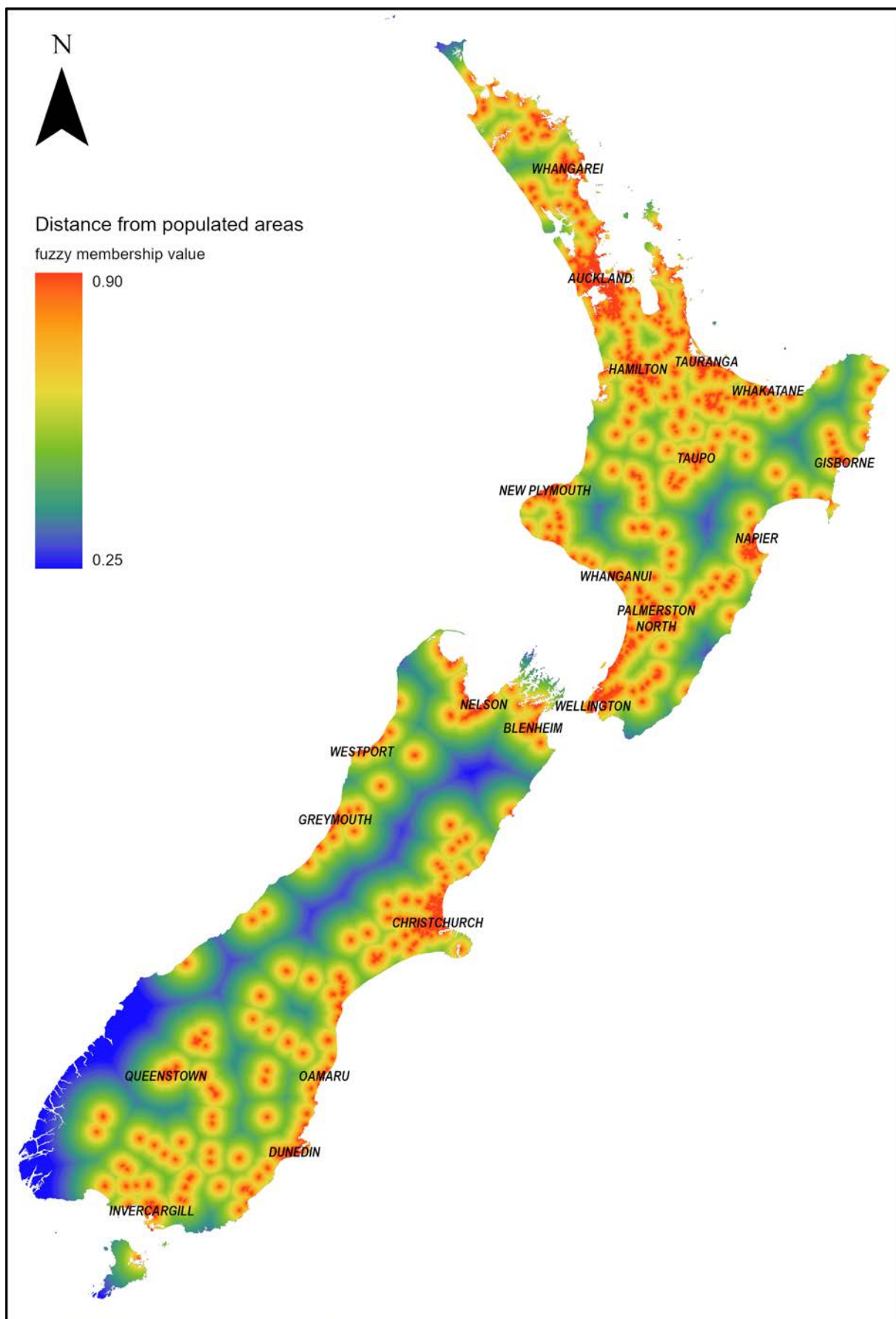


Figure 6.3 Map of the fuzzy member value representing the proximity to populated areas. The map was created using the Euclidean distance from statistical mesh blocks with a population >50 people per km². Map derived from dataset L1_DEMAND_POPULDEN_CR (see Appendix 3).

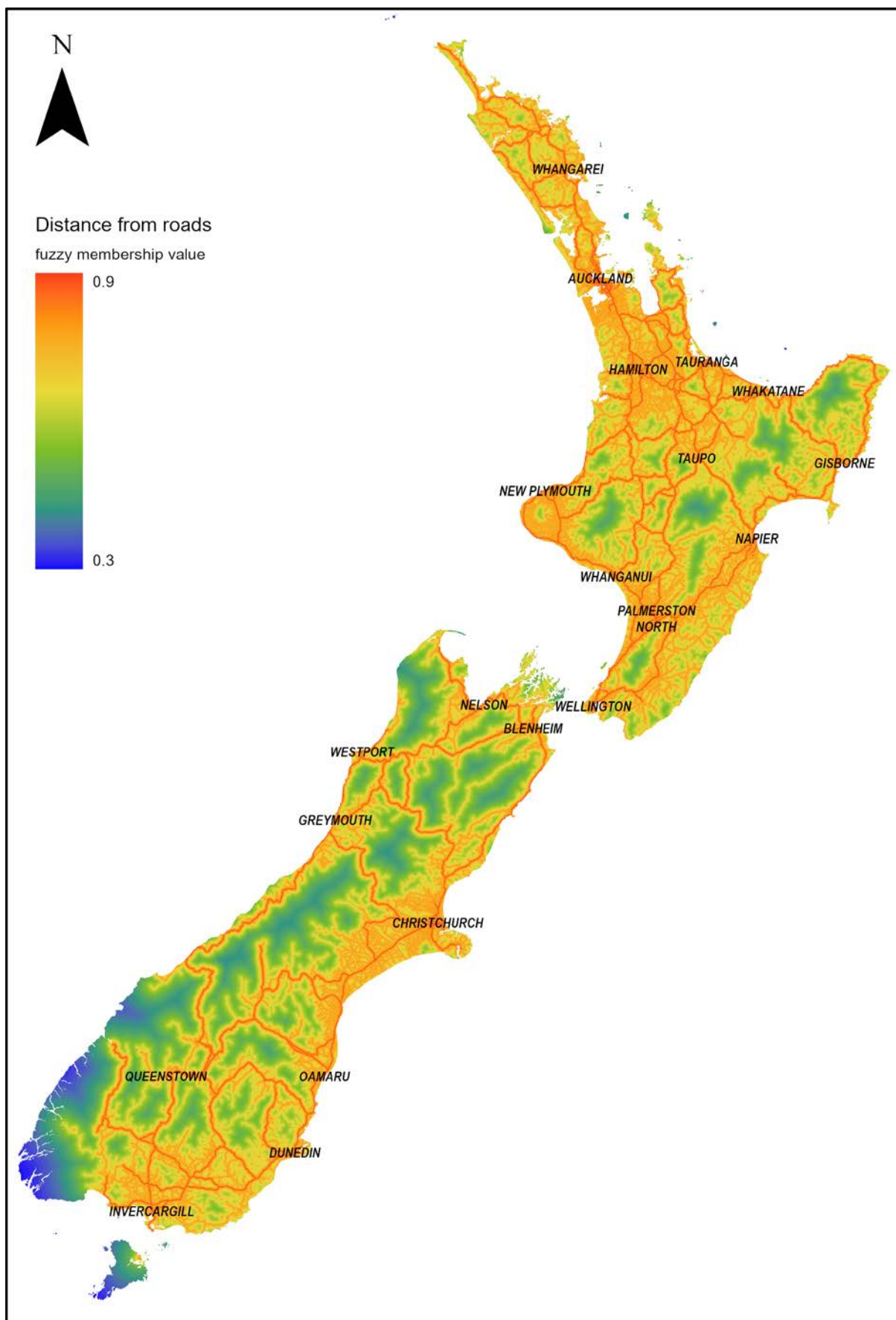


Figure 6.4 Map of the fuzzy member value representing the distance from major, local and metalled roads. The map was created using the Euclidean distance from major roads, local roads and metalled roads (gravel roads) that were combined, taking the maximum small fuzzification value for each cell. Map derived from dataset L1_DEMAND_ROADS_CR (see Appendix 3).

Anticipating future aggregate demand based on end-use activity in New Zealand is also critical to the planning and location of future quarry sites. This study has modelled it using two different techniques and datasets; from current production data and from forecast construction and building activity. Future demand from current production data is based on a population estimate, a per-person rate of aggregate production and a future demand increase factor. The current rate of aggregate production per capita is a good proxy for future production and can be calculated from the population and production values for regions around New Zealand. This rate can then be applied to future population estimates to calculate production volumes needed.

The production values for each region from 2017 published by the Aggregate and Quarry Association (AQA c2021) and the Stats NZ population estimate published for the nearest census year, which was 2018 (Table 6.1), were used to determine an average production value of 8.4 tonnes per person each year. A map of future production per territorial authority (city council area) can then be made using the population estimates for 2028 from Stats NZ and the average production rate. Mapping by territorial authority provides a more detailed spatial model than a regional council area map that the per capita rate was derived from.

Table 6.1 Regional aggregate production values from the AQA used with population from Stats NZ to determine the current rate of aggregate production per person.

Region	Production in 2017 (tonnes)	Population Estimate (number of people)	Production per Person (tonnes)
Northland	3,169,419	179,700	17.6
Auckland	9,291,320	1,736,200	5.4
Waikato	8,957,218	476,600	18.8
Bay of Plenty	1,586,874	310,200	5.1
Gisborne	435,066	49,500	8.8
Hawke's Bay	910,489	167,500	5.4
Taranaki	532,547	121,700	4.4
Manawatu/Whanganui	2,114,646	245,600	8.6
Wellington	1,532,936	526,300	2.9
Tasman/Nelson	1,014,805	105,400	9.6
Marlborough	98,120	47,000	2.1
West Coast	239,095	33,300	7.2
Canterbury	8,547,894	641,100	13.3
Otago	2,127,162	230,800	9.2
Southland	753,229	101,300	7.4
Average: (tonnes per person per year)			8.4

To factor in future increases in regional demand and large infrastructure projects, a survey of industry professionals was undertaken at a recent Quarry NZ conference (2019) regarding regional demand change in New Zealand over the next ten years (Figure 6.5). This data was used to create a subjective rate of forthcoming demand change in each of New Zealand's main regions. A future-growth factor was determined for each region from a subjective analysis of the survey results (Table 6.2) and mapped by applying these values to the regional council boundaries.

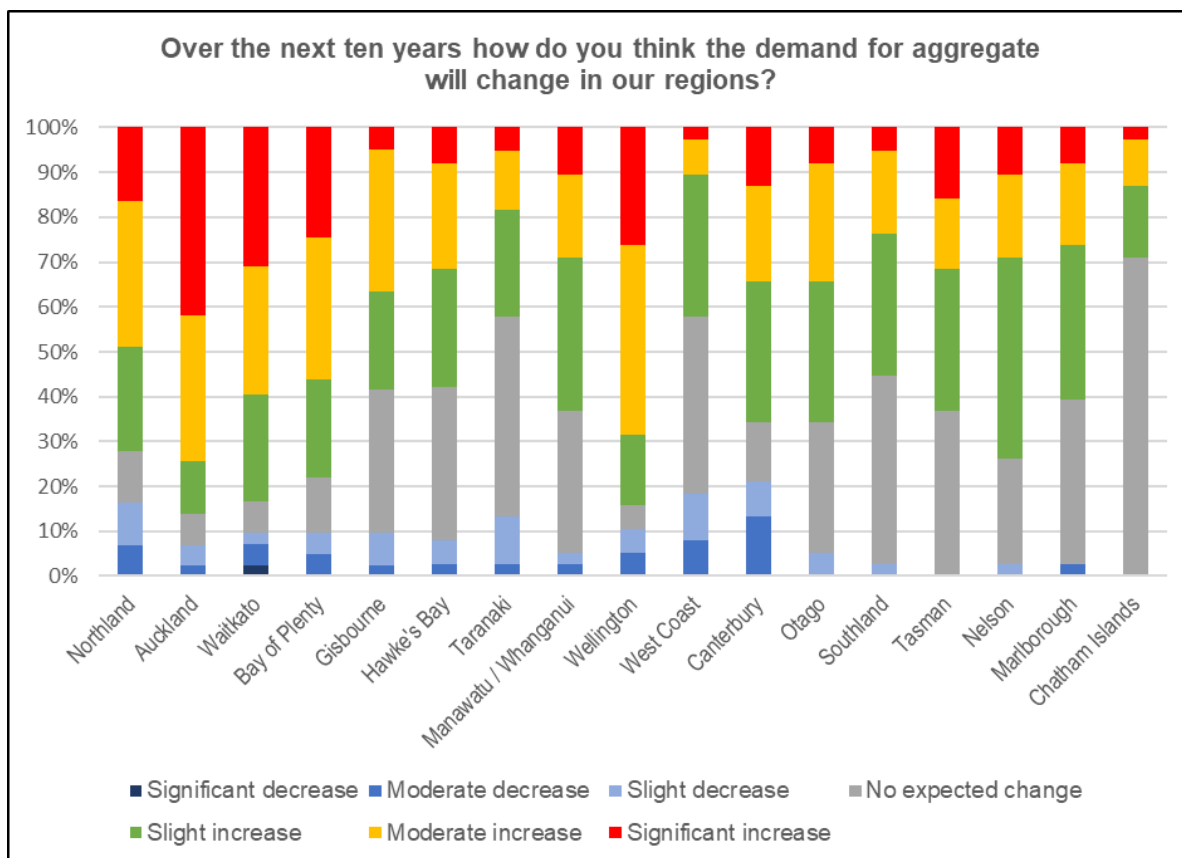


Figure 6.5 Results of 121 surveyed industry professionals at the 2019 Quarry NZ conference, asking their opinion of future aggregate demand change in New Zealand regions over the next ten years. Bars are plotted as a percentage of total respondents and into seven categories of change estimate.

Table 6.2 Future-growth factor for each region determined from survey results, where future-growth factor <100, reduction; = 100, no change; >100, increase.

Region	Future-Growth Factor
Northland	118
Auckland	125
Waikato	120
Bay of Plenty	122
Gisborne	110
Hawke's Bay	112
Taranaki	105
Manawatu/Whanganui	110
Wellington	120
West Coast	105
Canterbury	112
Otago	110
Southland	105
Tasman	105
Nelson	110
Marlborough	105

The future demand mappable criteria layer has been created using the population of each territorial authority in 2028 (*Pop2028_TA*), a production rate of 8.4 tonnes per person a year (the current average) and the future-growth factor (*FGF*). The map used in the model is then calculated using Equation 6.2 below.

$$\text{Future demand estimate} = [\text{Pop2028_TA}] \times 8.4 \times \left(\frac{\text{FGF}}{100}\right) \quad \text{Equation 6.2}$$

The future demand mappable criteria layer is divided into 10 classes of aggregate demand and assigned a class weight (Table 6.3), where higher weights are in areas where there is an expected high demand for aggregate. The map is plotted as values of tonnes per km² each year (Figure 6.6).

Table 6.3 Future aggregate demand classifications used in the future demand predictive model component layer and the assigned class weights.

Demand (tonnes per km ² per year)	Class Weight
>25,000	90
5000–25,000	85
2000–5000	80
1000–2000	75
500–1000	70
250–500	65
100–250	60
50–100	50
25–50	47
<25	45

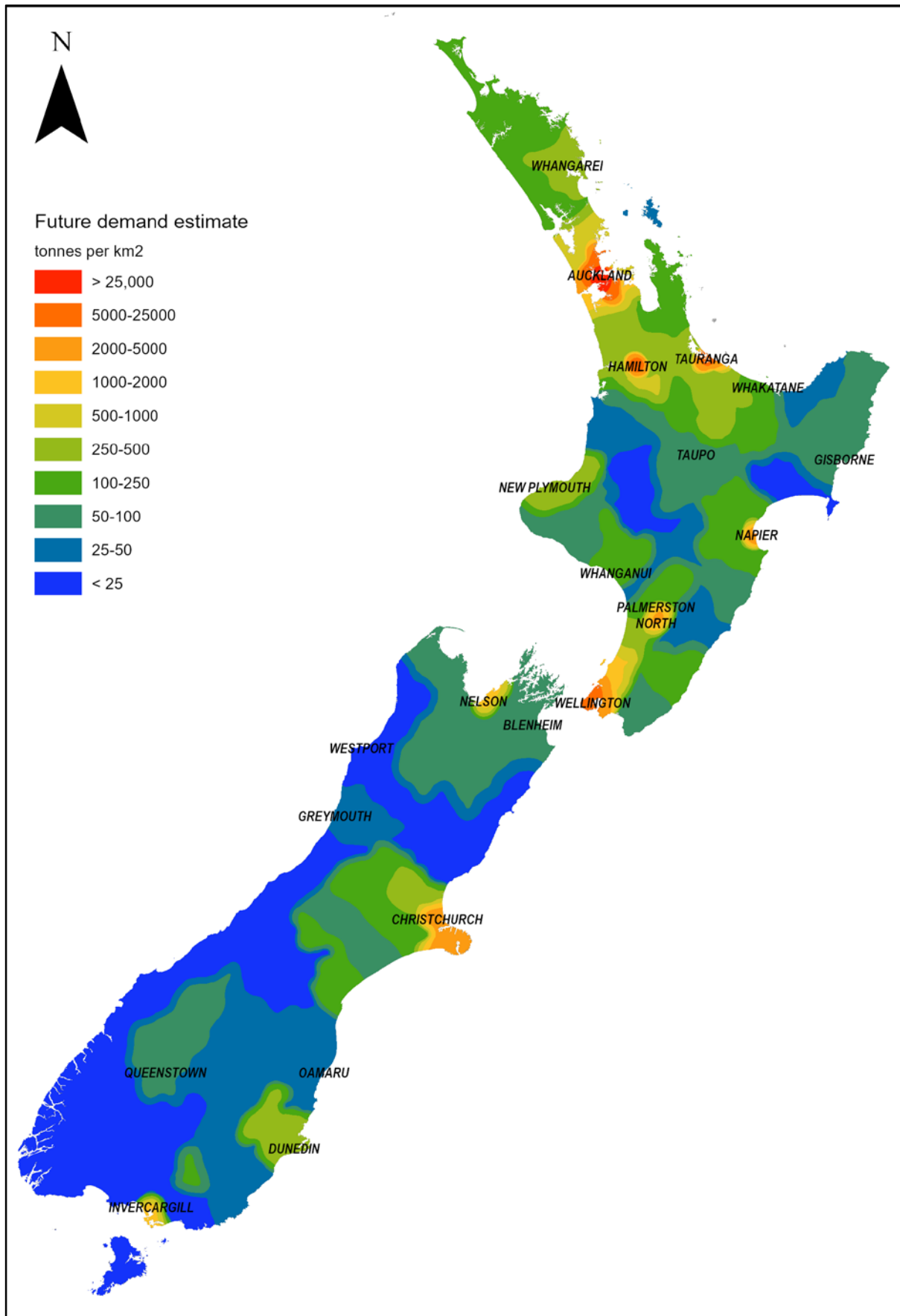


Figure 6.6 Map based on the estimated future demand mappable criteria layer L1_DEMAND_FUTURESQKM_FM. The layer was created using a future population estimate for each territorial authority (city council area), an average aggregate consumption value per person and a future-growth factor from a survey of industry professionals (see Appendix 3).

As well as utilising estimated future production values to map the aggregate demand, a forecast of building and construction activity from the National Construction Pipeline Report (BRANZ and Pacifecon 2020) is also a useful guide to future aggregate demand. The report includes building and construction from residential building, non-residential building and infrastructure such as roads and other civil works so that the forecast of spending from these activities can be correlated well to aggregate demand. The forecast building and construction spending in New Zealand is expected to decline slightly in most regions over the next five years; however, Auckland will still account for approximately 40% of the national total.

To create the mappable criteria layer of forecast construction and building activity, the financial spending value for the major New Zealand regions has been assigned to the populated urban and rural area extents in each region. As the forecast only provides spending data for the Auckland, Waikato / Bay of Plenty (combined), Wellington, Canterbury and Otago region, the other regions of New Zealand were derived from the 'Rest of NZ' category and values determined proportionally to the population in each region (Table 6.4). The forecast activity year of 2023 was used so that it matched the same Stats NZ forecast population census year. The forecast expenditure value for each region was mapped more concisely to the areas of urban and rural population boundaries (Stats NZ) and then subjectively allocated by the percentage of spending estimated in each boundary type (Table 6.5). To account for spending outside of these boundaries, and the fact that quarry sites may be located outside the boundaries but servicing a nearby urban demand, zones extending in 2 and 10 km buffers were also included. Within these buffer zones, the percentage of spending reduced by 40% and then 60%, respectively.

Table 6.4 Forecast construction and building expenditure for regions of New Zealand in 2023 from the National Construction Pipeline Report (BRANZ and Pacifecon 2020).

Region	Forecast of Building and Construction Spending in 2023 (millions of dollars)
Northland	\$783
Auckland	\$13,500
Waikato*	\$2917.6
Bay of Plenty*	\$1882.4
Gisborne*	\$211
Hawke's Bay*	\$715.1
Taranaki*	\$523.3
Manawatu-Whanganui*	\$1044.9
Wellington	\$2000
Tasman*	\$226.4
Nelson*	\$229.4
Marlborough*	\$200.4
West Coast*	\$138.8
Canterbury	\$3300
Otago	\$1600
Southland*	\$427.6

* Value determined from the 'Rest of NZ' category and proportionally to the region population.

Table 6.5 Relative percentage of construction and building spending based on the urban and rural area type of Stats NZ.

Area Type	Percentage of Spending
Major urban	50
Large urban	25
Medium urban	20
Small urban	4
Rural settlement	1

The mappable criteria layer for the construction and building activity includes several assumptions (e.g. the percentage of spending in urban and rural area types); however, the map created represents the demand for aggregate well (Figure 6.7). With the spending constrained to the urban boundaries rather than evenly across the region, the map more concisely identifies the areas with high forecast construction activity. Areas of very high demand, such as Auckland, are clearly anomalous in this layer. The mappable criteria layer is created from the spending map after division of the values by 10 natural breaks in the dataset and assigning a class weight to each (Table 6.6).

Table 6.6 Ranges of mapped forecast construction and building activity (spending in millions of dollars) used in the predictive model component layer, with assigned class weights.

Forecast Construction and Building Activity (\$ millions)	Class Weight
\$4050 – \$6750	80
\$2700 – \$4050	75
\$1012.5 – \$2700	70
\$600 – \$1012.5	68
\$261.3 – \$600	65
\$96 – \$261.3	62
\$29.2 – \$96	60
\$7.2 – \$29.2	57
\$0.4 – \$7.2	55
<\$0.4	45

The Level 2 future demand predictive model component layer is created by combining the distance from road, distance from populated areas and future aggregate demand maps using the fuzzy GAMMA operator, with a GAMMA value of 0.8. The combined layer resulting from the GAMMA operator is then divided into 17 classes above the calculated 0.5 fuzzy membership value (the resulting gamma function value for an input of 0.5 in each mappable criteria layer) and 8 classes below the value, using a natural breaks analysis. These classes are mapped in Figure 6.8, where red areas are likely to be high aggregate consumers in the future and require nearby quarries to meet the demand.

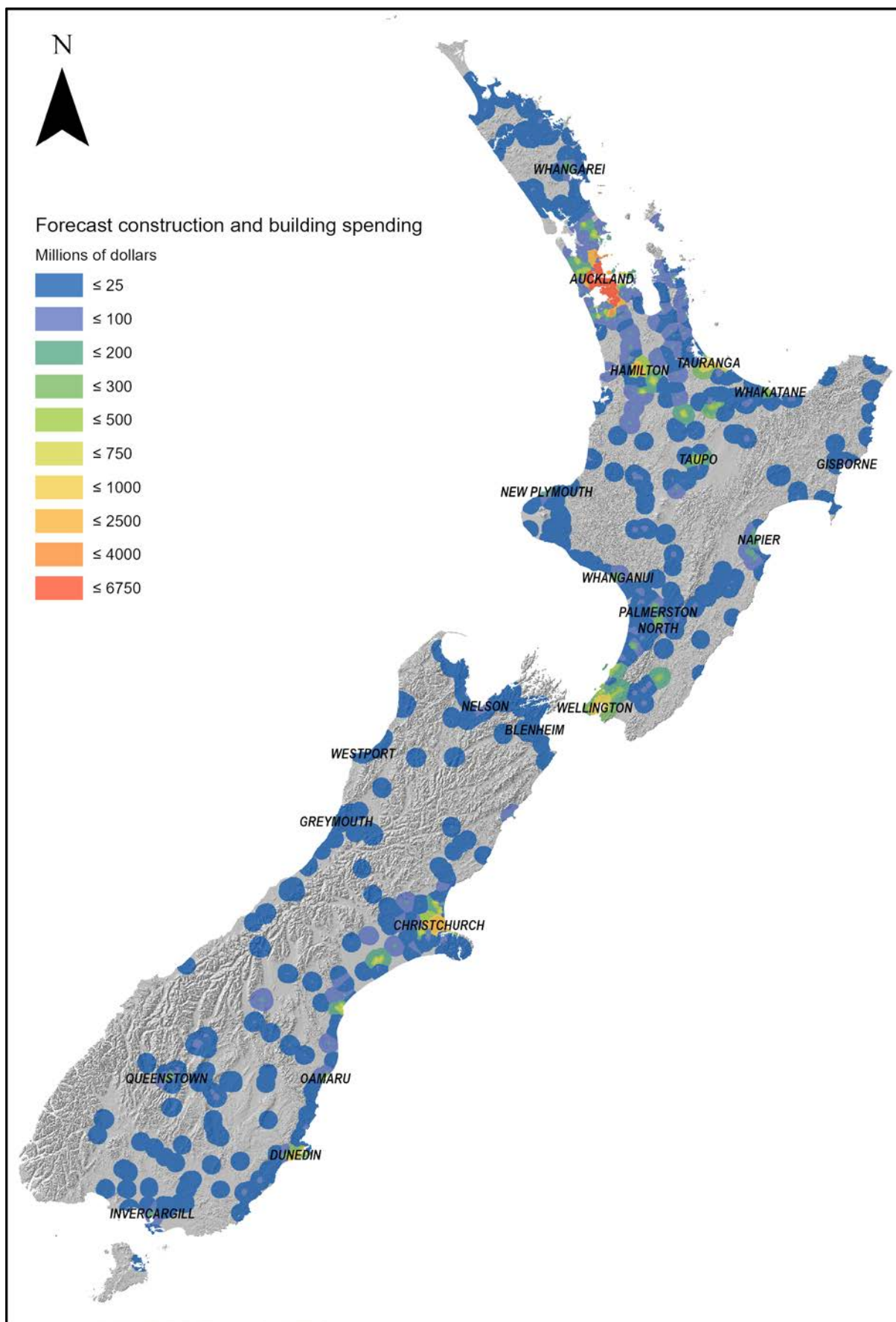


Figure 6.7 Map based on the estimated future demand mappable criteria layer L1_DEMAND_CONSTRUCTION_FM (see Appendix 3). The layer was created using forecast construction and building activity for 2023 in regions of New Zealand and areas of urban and rural populations. Inset map shows examples of urban and rural area types mapped by Stats NZ.

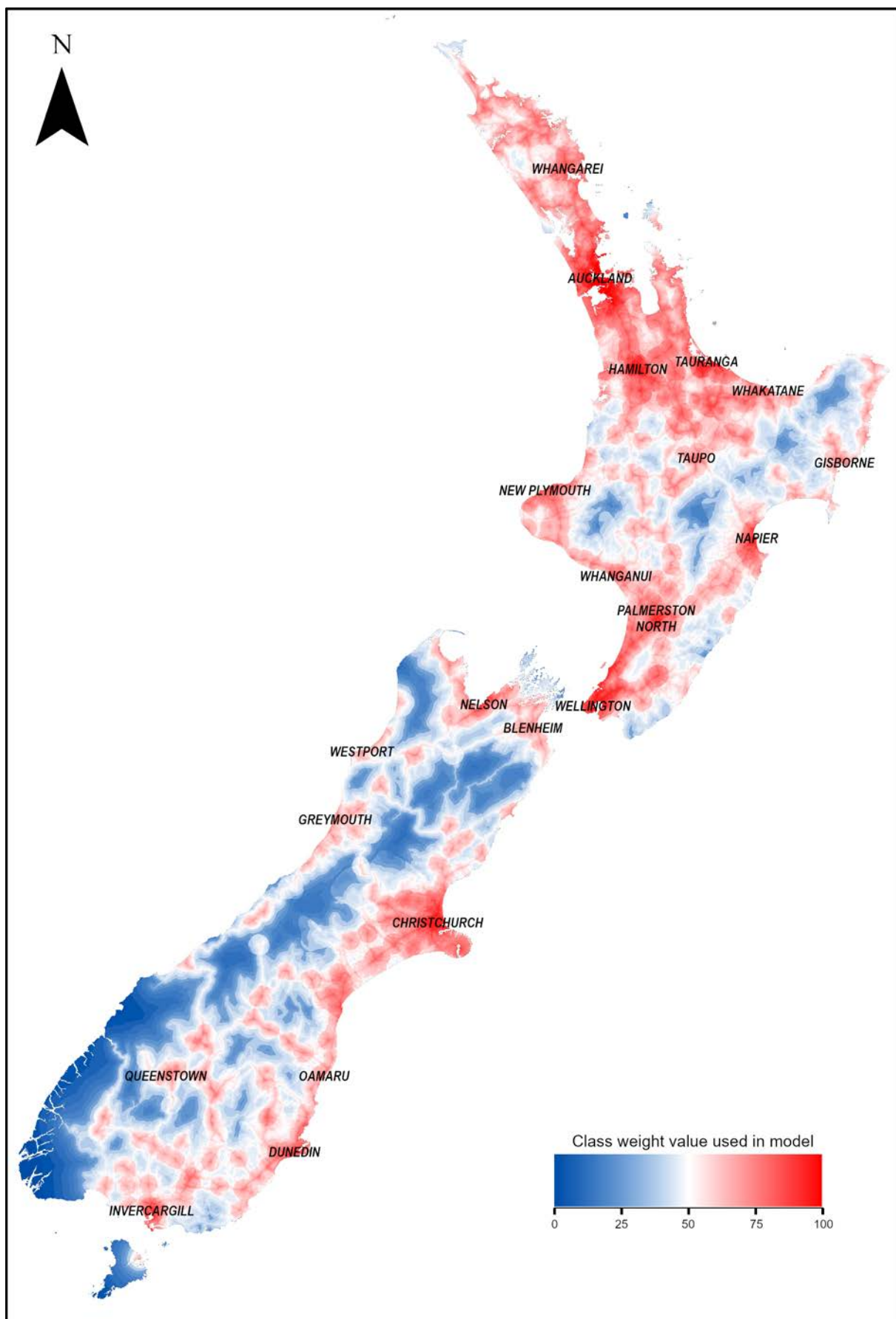


Figure 6.8 Map of the Level 2 future demand predictive model component layer L2_DEMAND_FM. Values are shown in class weights, where the red regions are interpreted as having a higher aggregate demand than the blue areas (see Appendix 3).

7.0 SUPPORTING INFRASTRUCTURE

Development of a quarry is ideally close to existing infrastructure, such as large roads and the railway network, for transport of aggregate; near to electricity transmission to supply enough energy for low-emission processing plants and mining equipment; and proximal to labour markets. It should also be in suitable terrain for the style of extraction activity and deposit type.

Future quarry sites need to have access to highways and railways to transport the aggregate; these highways are mapped from the LINZ Topo 50 road and railway data, and a function is used to calculate the distance from those features throughout the study area. Although a mappable criteria layer representing roads is already included in the future demand component of the model, just the large highways are used here, as they are prioritised for transporting material. The distance from LINZ Topo 50 powerline features is also calculated using the same function. To create class weights, a small fuzzification function has been used (see Section 6) to calculate a fuzzy membership value (class weight divided by 100) dependent on the distance from the mapped features (Figure 7.1). To guide the small fuzzification function curves, this study has analysed the distances from the current operating quarries to highways, railways and powerlines (Figure 7.1 histograms) so that resulting maps in the model reflect those statistical trends (Figures 7.2, 7.3 and 7.4).

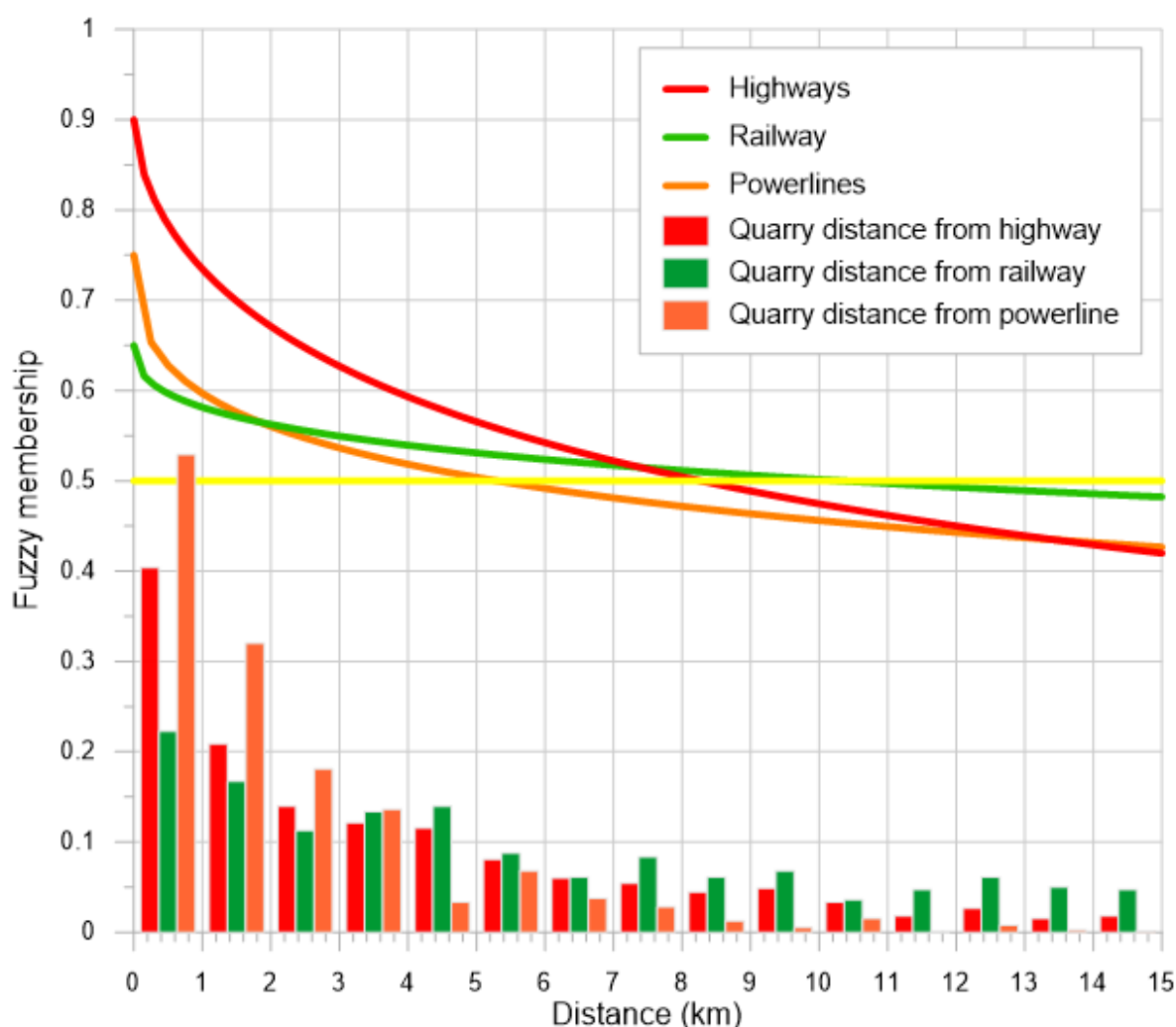


Figure 7.1 Chart of fuzzy membership values based on distance from a feature determined using the small fuzzification formula and histograms of statistical data from operating quarries (1 km bins plotted as a percentage of total operating quarries – no y-scale). Lines are plotted for the fuzzification formula used to model distance from highway, railway and powerline infrastructure. The small fuzzification function developed to represent these statistical trends.

In this study, the unemployment rate has been used as proxy of available labour with data mapped from Stats NZ 2018 census data per territorial authority in New Zealand. The distribution of unemployment percentage values has been smoothed across authority boundaries to account for market potential that may be in an adjacent area (Figure 7.5). Ranges of unemployment percentage are numerically weighted to create the map for the model. The class weights used for this layer are lower and smaller in range than other mappable criteria; this illustrates that unemployment, although a consideration, is not as important as other layers in this model component.

Table 7.1 Unemployment percentage classifications used in the modelling and their assigned class weights.

Unemployment Percentage	Class Weight
>6.5	75
5.8–6.5	72
5.1–5.8	70
4.4–5.1	68
4.1–4.4	65
3.7–4.1	62
3.2–3.7	60
2.7–3.2	50
2.2–2.7	45
1.4–2.2	40

The elevation and steepness of terrain is included as part of the infrastructure model component, as terrain affects the style of extraction at a given site. In general, hard rock quarries favour steeper sites to access less weathered material and to minimise the overburden (stripping) that must be removed. Gravel quarries typically occur in low-lying terrain where materials have been deposited by modern river systems. Using these characteristics, this study has used geomorphon modelling (Jasiewicz and Stepinski 2013) to map 10 geomorphic terrain types (Figure 7.6, Inset 2) and create numerically weighted classes where the terrain is most suitable for hard rock or gravel quarrying (Table 7.2, Figures 7.6 and 7.7).

Table 7.2 Geomorphon classes used in the modelling and their assigned class weights.

Model	Geomorphon Class	Class Weight
Hard rock	Slope	80
	Ridge	75
	Spur	72
	Shoulder	70
	Other	30
Gravel	Flat	80
	Foot slope	75
	Valley	70
	Hollow	60
	Other	30

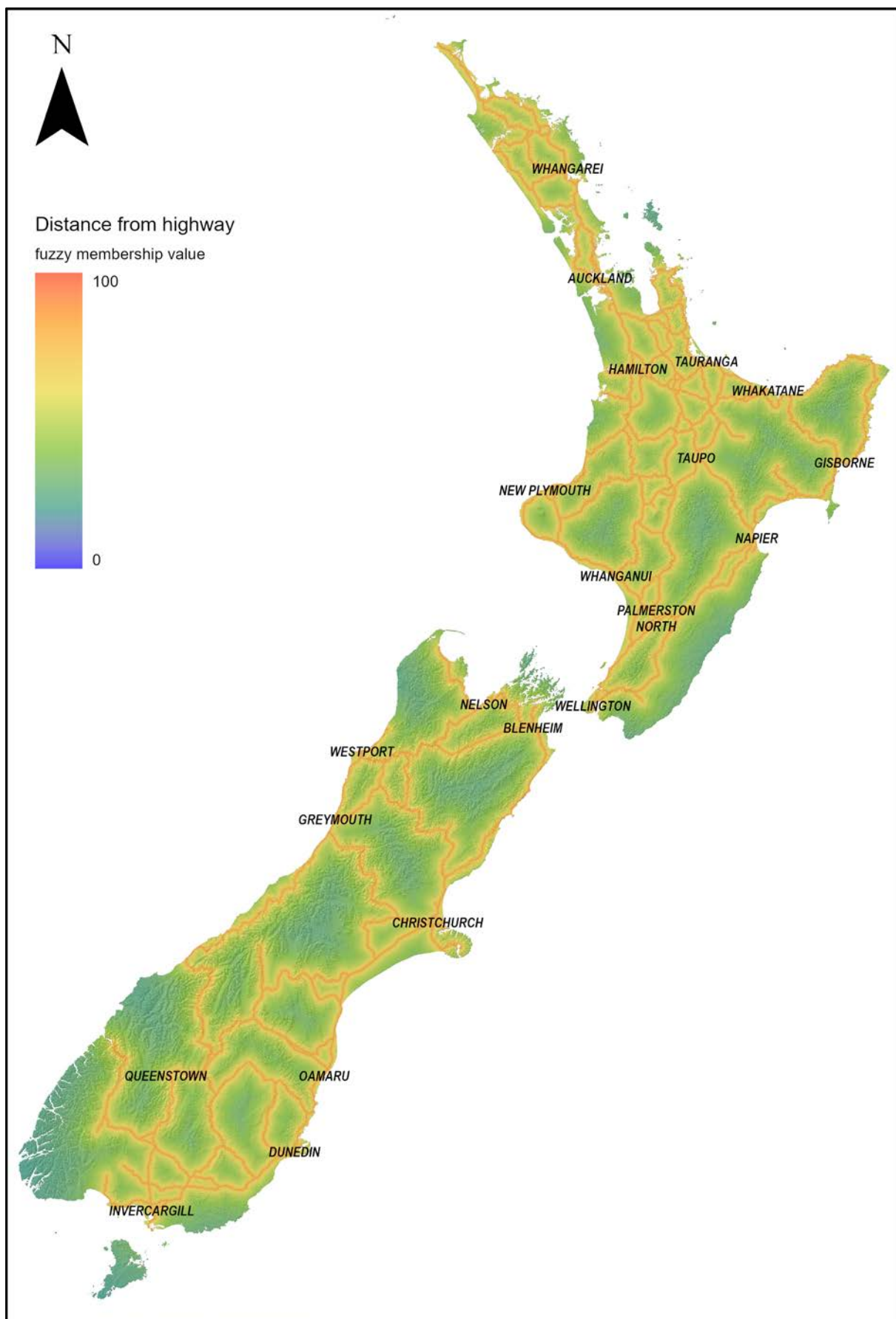


Figure 7.2 Map of the fuzzy membership value representing the distance from highways in New Zealand. The mappable criteria layer L1_INFRA_HIGHWAY_CR was created using the Euclidean distance from highways and the small fuzzification function (see Appendix 3).

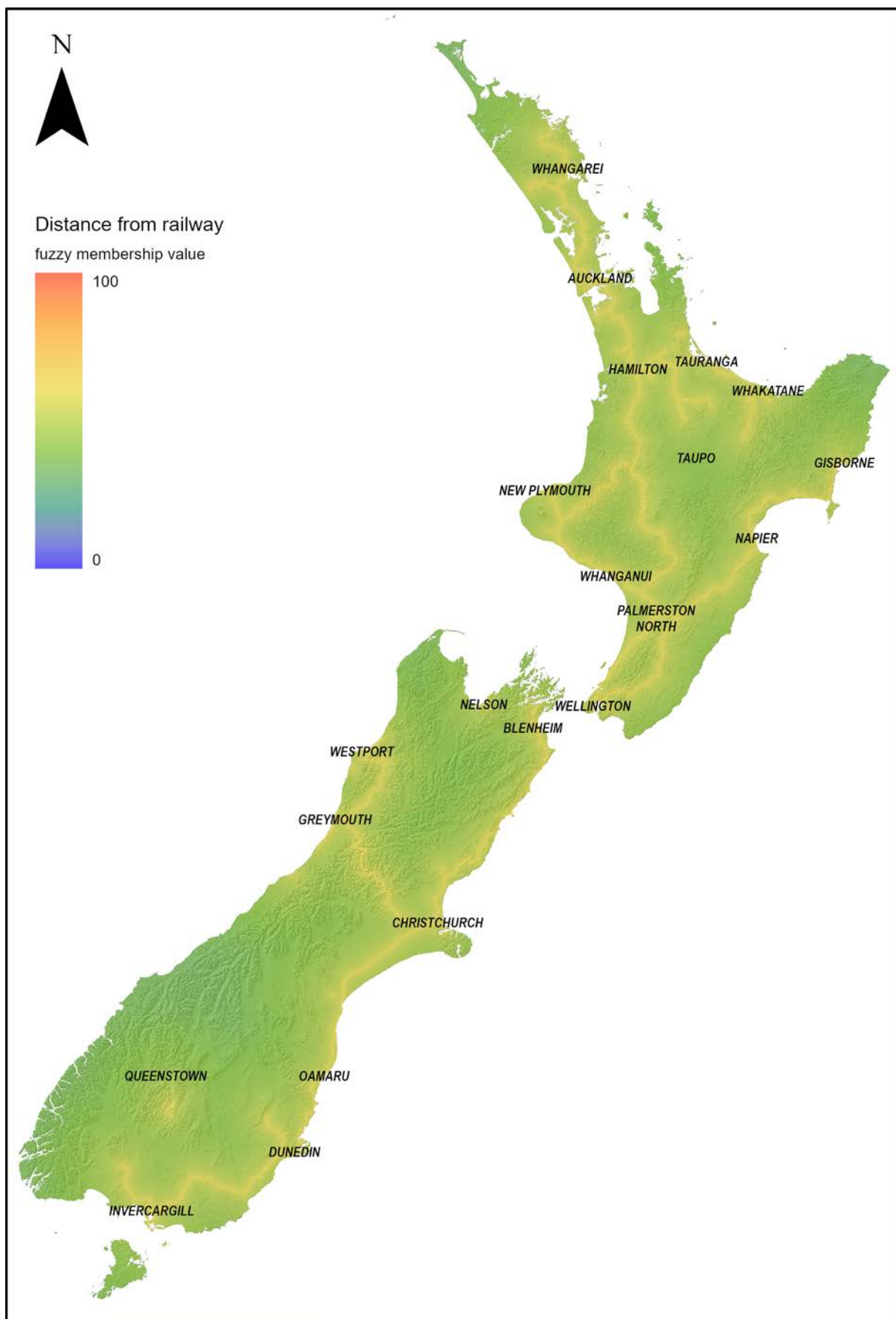


Figure 7.3 Map of the fuzzy membership value representing the distance from the railway network in New Zealand. The mappable criteria layer L1_INFRA_RAILWAY_CR was created using the Euclidean distance from railway lines and the small fuzzification function (see Appendix 3).

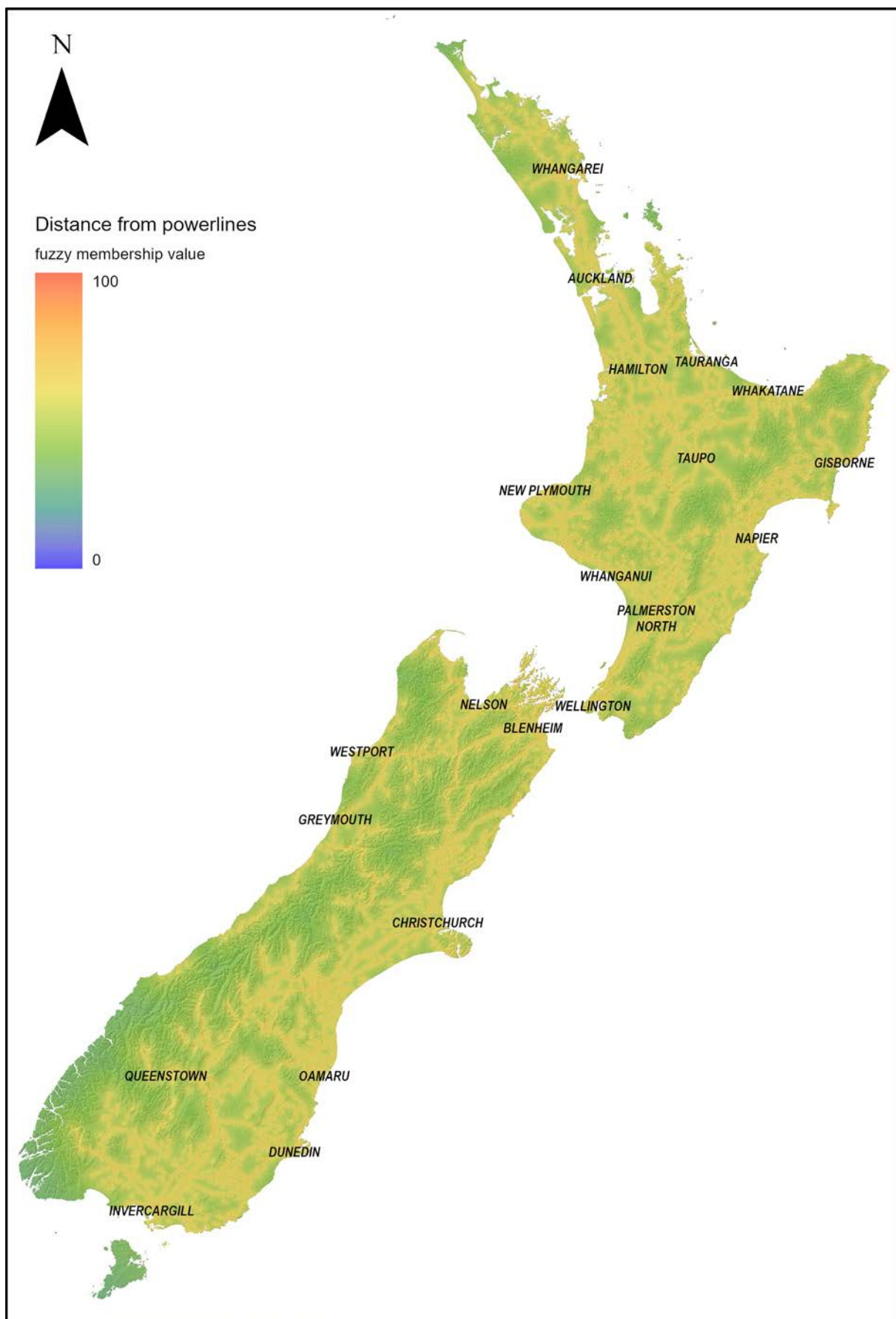


Figure 7.4 Map of the fuzzy membership value representing the distance from the power network in New Zealand. The mappable criteria layer L1_INFRA_POWER_CR was created using the Euclidean distance from powerlines and the small fuzzification function (see Appendix 3).

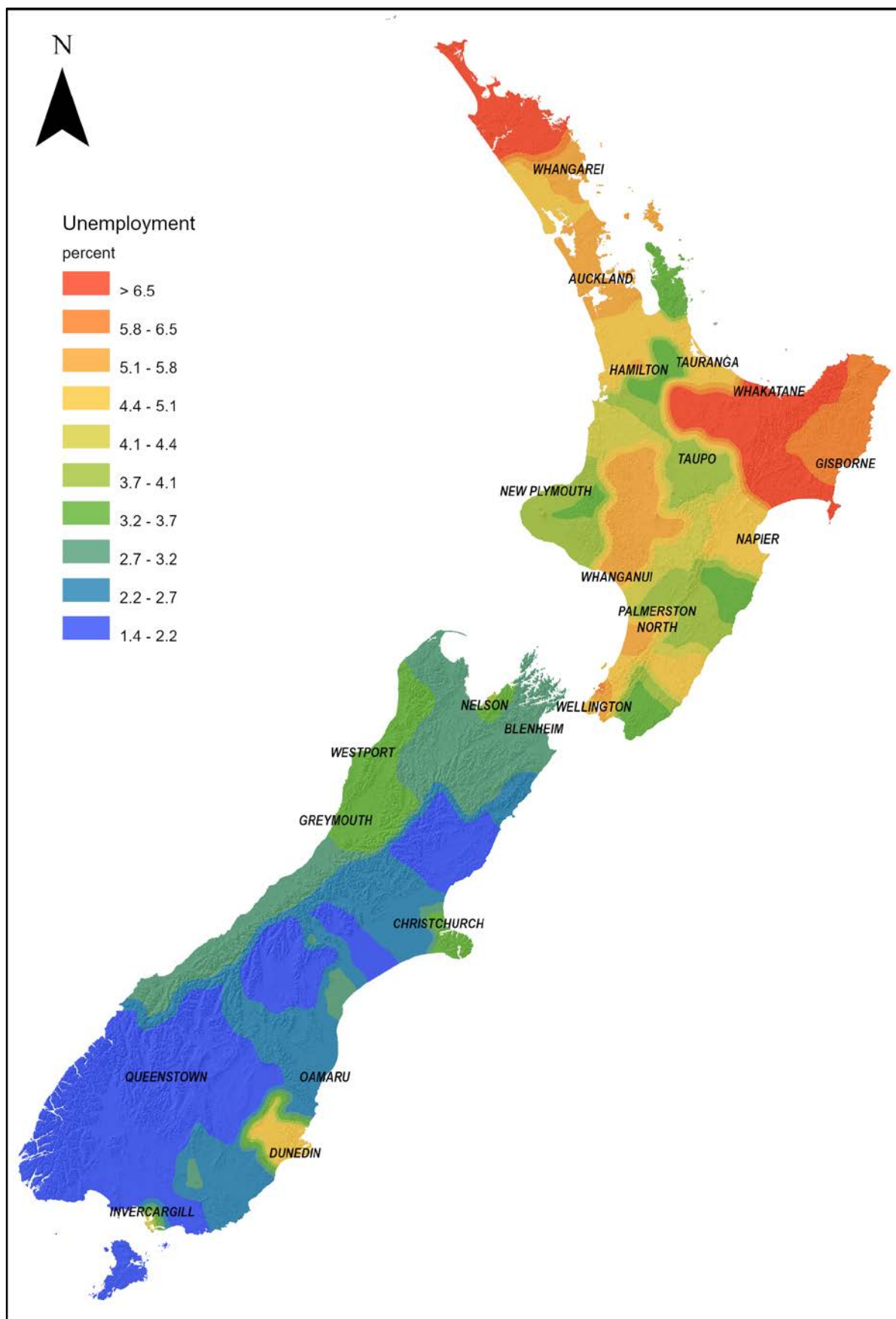


Figure 7.5 Map of unemployment as a percentage in New Zealand, used as a proxy for an available labour market that can work in a new quarry or aggregate-processing-related facilities. The mappable criteria layer L1_INFRA_UNEMPLOYMENT_FM is based on unemployment statistics for each territorial authority and then smoothed across authority boundaries to allow for migration of a near-boundary workforce (see Appendix 3).

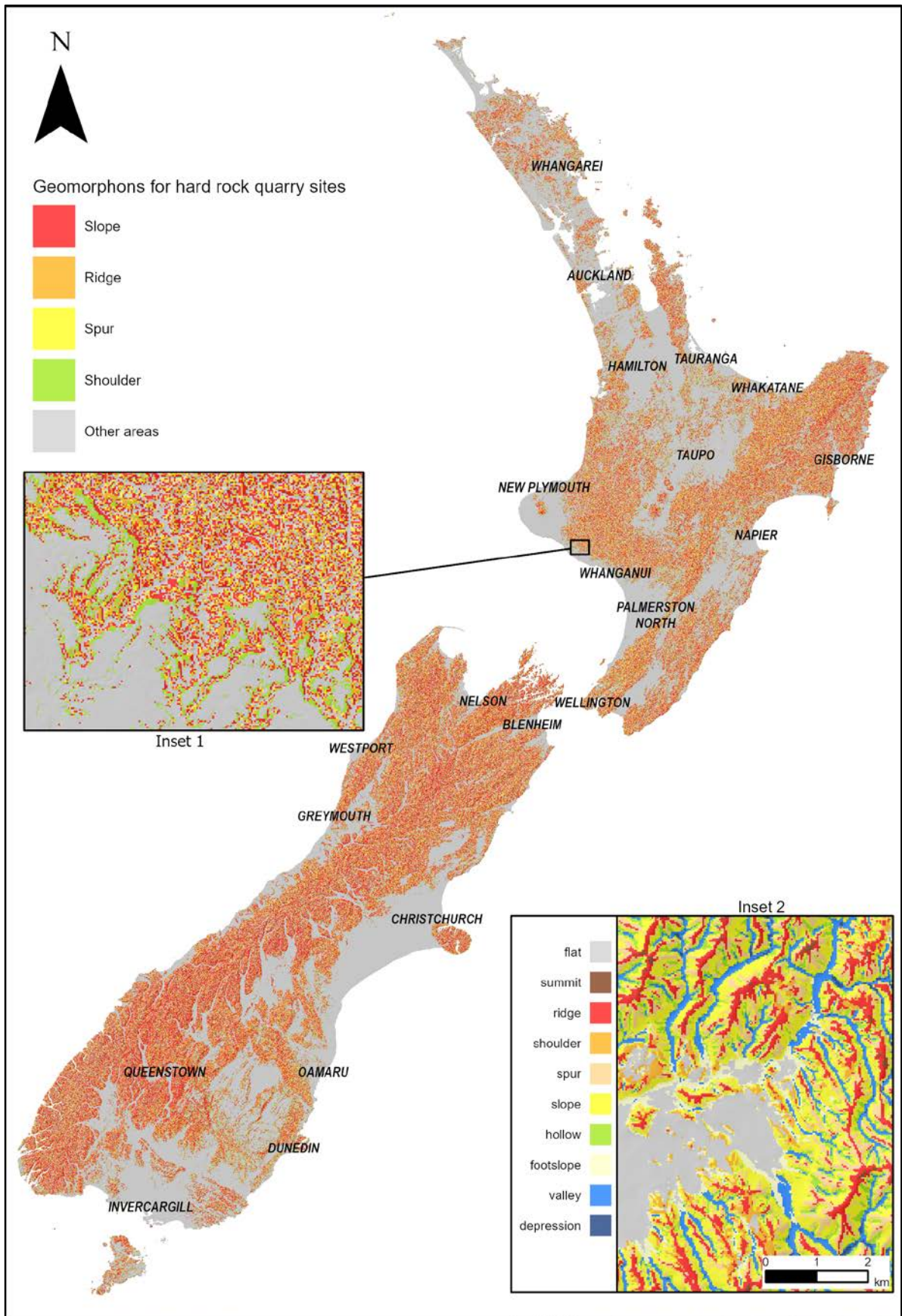


Figure 7.6 Map of geomorphon classes most suitable for hard rock quarry operations (slopes, ridges, spurs and shoulders). Inset 1 illustrates the geomorphon classes in the Taranaki region, highlighting the steeper hill terrains. Inset 2 is an example of the 10 geomorphon classes calculated for New Zealand and used in this study. The mappable criteria L1_INFRA_GEOMORPH_HR_FM is weighted for these hard-rock-quarry-specific geomorphon classes (see Appendix 3).

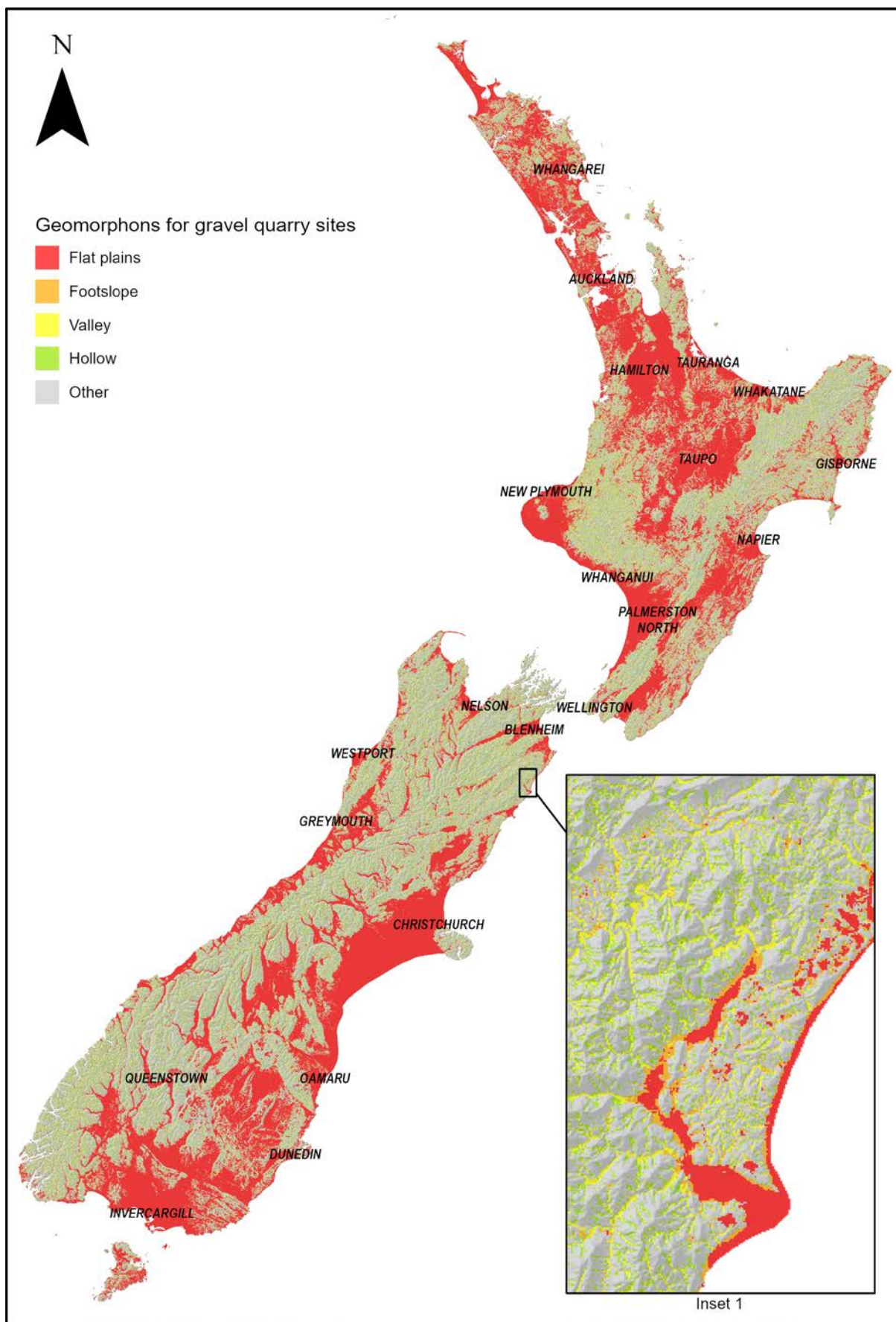


Figure 7.7 Map of geomorphon classes most suitable for gravel quarry operations (flats, foot of slopes, valleys and hollows). Inset 1 illustrates the geomorphon classes in the Kekerengu area, highlighting river valley and flat river terrace deposits. The mappable criteria layer L1_INFRA_GEOMORPH_GR_FM is weighted by these gravel-quarry-specific geomorphon classes (see Appendix 3).

Two Level 2 predictive model component layers are created for infrastructure; one for the hard rock model where highway, railway and powerline proximity are combined with classes of unemployment percentage and steeper, more elevated, geomorphic terrains (Figure 7.8a); and one for the gravel model that uses the same proximity and unemployment maps but instead uses a map of the flatter and valley geomorphic terrains (Figure 7.8b).

These Level 2 predictive model component layers combine, contributing mappable criteria layers using the fuzzy GAMMA operator with a GAMMA value of 0.8. The combined map from the GAMMA operator is then divided into 17 classes above the calculated 0.5 fuzzy membership value (the resulting gamma function value for an input of 0.5 in each map) and 8 classes below the value, using a natural breaks analysis. These classes are mapped in Figure 7.8, where red areas are likely to have more infrastructure that will support future quarries and have the most suitable terrain for either gravel or hard rock aggregate.

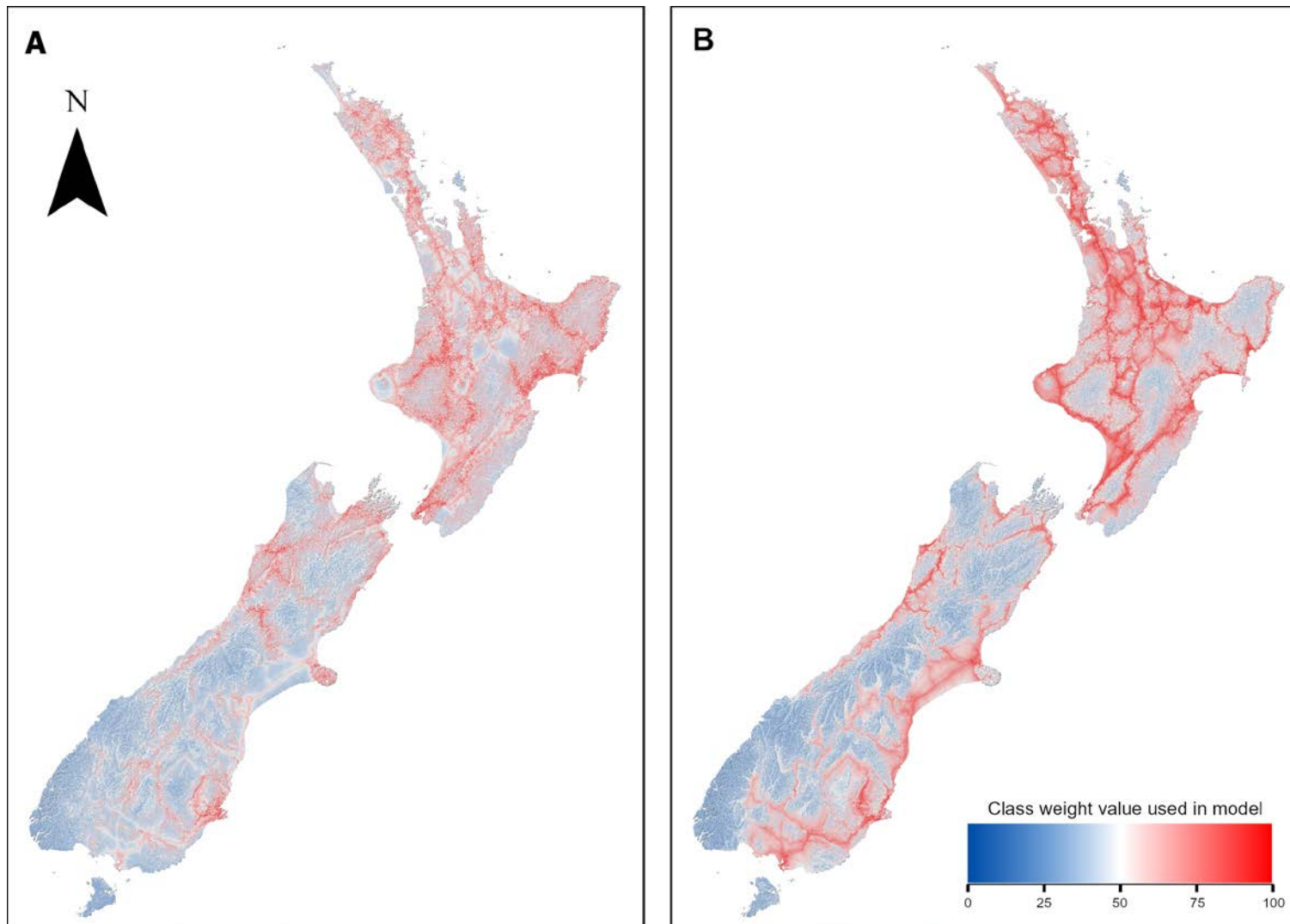


Figure 7.8 Maps of the Level 2 supporting infrastructure predictive model component layer for (A) hard rock (L2_INFRA_HARDROCK_FM) and (B) gravel (L2_INFRA_GRAVEL_FM) aggregate. Values are shown in class weights, where the red regions are modelled as having more infrastructure support for aggregate extraction than the blue areas (see Appendix 3).

8.0 CULTURAL SENSITIVITY

For all extractive activities, social licence to operate is very important for consenting new operations or extending existing quarry operations. Consenting is commonly protracted and litigious; this is usually a reflection of cultural sensitivity to quarry operations. Ideally, quarries should be located close to their markets, but residents near quarries and their transport routes are sensitive to their operations due to the resulting dust and noise pollution. This model includes mappable criteria layers for residential areas, population density developed from census data, cadastral parcel size (a proxy for populated areas) and mapped cultural artefacts to avoid places of importance to people and communities. Also included is a mappable criteria layer for quarry sites to determine areas where historic acceptance of quarry activity has occurred. The cultural sensitivity aspect of the modelling also includes a visibility model to determine which parts of the landscape quarrying might be visible to the public.

Cadastral parcel size is used in this model as a proxy for where houses and other populated areas are located, as well as infrastructure such as roads (see Christie 2007; Christie et al. 2010). Cadastral data from LINZ is classified into four parcel size groups and assigned numerical class weights (Table 8.1, Figure 8.1). Areas of small cadastral parcels are less favourable for quarry activities, as it is likely they are populated, and areas of larger land areas are more likely open ground and less densely populated, and therefore more suitable for quarry development. Another, more direct, measurement of where highly populated areas are located is population density, calculated from the ratio of residents to the area of the statistical mesh block (Figure 8.2). This mappable criteria layer is assigned numerical class weights based on population density (Table 8.1), where low density is deemed more suitable for quarrying activities.

A third proxy for populated areas is LINZ Topo 50 polygons of residential areas. Mapping distances from these areas is important; too close to the areas can cause dust and noise problems that operators need to mitigate, but too far away can be problematic if the quarry becomes too remote and the quarry operators need to travel large distances from nearby residential areas (partly an infrastructure criteria reflecting labour market preferences to a work site, but utilised in this cultural sensitivity component). An analysis of operating quarries and their distance from residential areas showed that 75% of operating quarries in New Zealand are within 10 km of a residential area; and most of these occur within 7 km. These statistics are reflected in Table 8.1 and Figure 8.3, showing the numerical class weights for each distance range.

Acceptance of quarrying activity can also be associated with existing and historic activity in an area. Locations where current quarry activity is dense, possibly overwhelming the community with activity, or where quarrying has not occurred in the past, may make new sites unfavourable. However, some current or historic activity may indicate that the area is favourable to extractive activities. A quarry density mappable criteria layer has been modelled from a count of quarries within a 2 km search radius (Figure 8.4), and these have been assigned numerical class weights (Table 8.1) that represent societal tolerance for quarrying activity. Quarrying activity should also be distanced from cultural locations such as historic sites, Māori pā, cemeteries (urupā) or infrastructure such as airports or vineyards. These examples and others are mapped from the LINZ Topo 50 data, buffered by 250 m, and assigned a numerical class weight for the model (Table 8.1, Figure 8.5).

Cultural sensitivity is also manifest in the visibility of quarry operations. A visibility analysis has been undertaken for the study area, which results in a mappable criteria layer that shows how much of the land area can be visibly seen within 10 km of a residential area and therefore identifies locations where quarries would be less visible to communities. Numerical class weights for these data (Table 8.1) reflect the number of 250 m spaced points within residential and city areas that can be seen from any grid point in the digital elevation model used for the analysis. The classes with lower point counts are more favourable to quarry activity, as they are less likely to be seen from residential areas (Figure 8.6).

Table 8.1 Class weights used for the cadastral parcel size, population density, distance from residential areas, quarry density and cultural artefact mappable criteria layers.

Mappable Criteria Layer	Class	Class Weight
Visibility	Not visible or out of 10 km range	80
	<10 residential points visible	70
	10–20 residential points visible	65
	20–50 residential points visible	55
	50–100 residential points visible	45
	100–150 residential points visible	35
	>200 residential points visible	30
Cultural artefacts	Cultural artefact in LINZ Topo 50	25
	Other areas	75
Quarry density	No quarries in search distance (2000 m)	70
	1 quarry in search distance	75
	2 quarries in search distance	65
	3 or more quarries in search distance	40
	Historic quarrying activity mapped from GERM	60
Distance from residential areas	Distance 1 – too close (<500 m)	35
	Distance 2 – getting a bit close (500–2000 m)	65
	Distance 3 – best (2000–7000 m)	85
	Distance 4 – getting a bit far away (7–20 km)	70
	Distance 5 – too far away (>20 km)	60
Population density	>200 people per km ²	20
	100–200 people per km ²	60
	50–100 people per km ²	75
	Less than 50 people per km ²	80
Cadastral parcel size	Parcels <1000 m ² and roads	25
	Parcels 1000–5000 m ²	40
	Parcels 5000–10,000 m ²	55
	Land >10,000 m ²	80

The Level 2 cultural sensitivity predictive model component layer combines the mappable criteria layers using the fuzzy GAMMA operator, with a GAMMA value of 0.8. The combined layer from the GAMMA operator is then divided into 17 classes above the calculated 0.5 fuzzy membership value (the resulting gamma function value for an input of 0.5 in each map) and 8 classes below the value, using a natural breaks analysis. These classes are mapped in Figure 8.7, where blue areas are likely to be unsuitable for gravel or hard rock extraction due to cultural sensitivity.

Future modelling should also consider land value to iwi groups, places of high scenic or tourism value, high-value agriculture zones and where future population expansion may encroach upon existing aggregate resources and quarries.

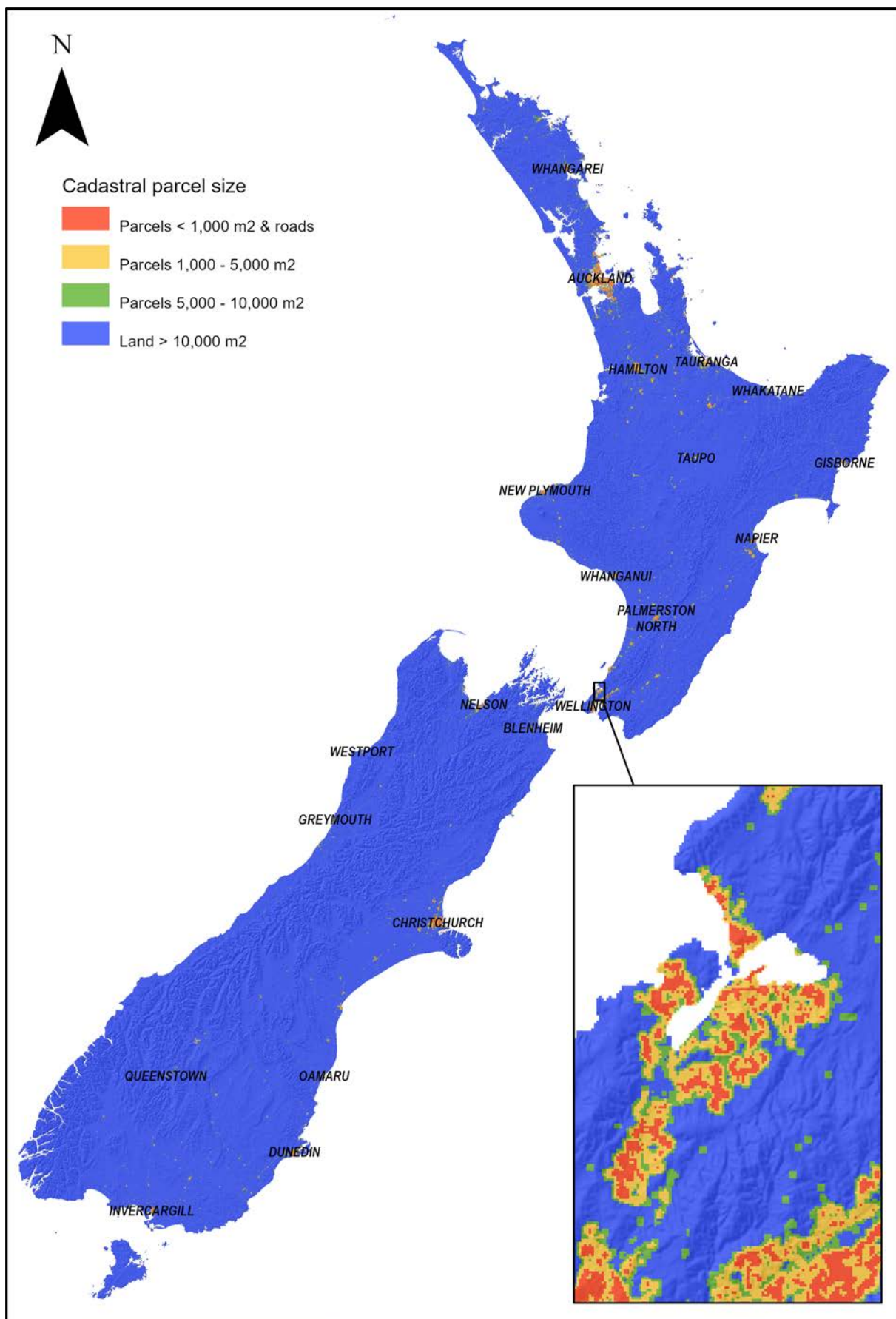


Figure 8.1 Map of cadastral parcel sizes used as the L1_SENS_CADASTRA_FM proxy for populated areas and land areas that would support a quarry. Cadastral parcels are classified into four size ranges for the model and smoothed using a mean value from a 300 m diameter counting circle (see Appendix 3).

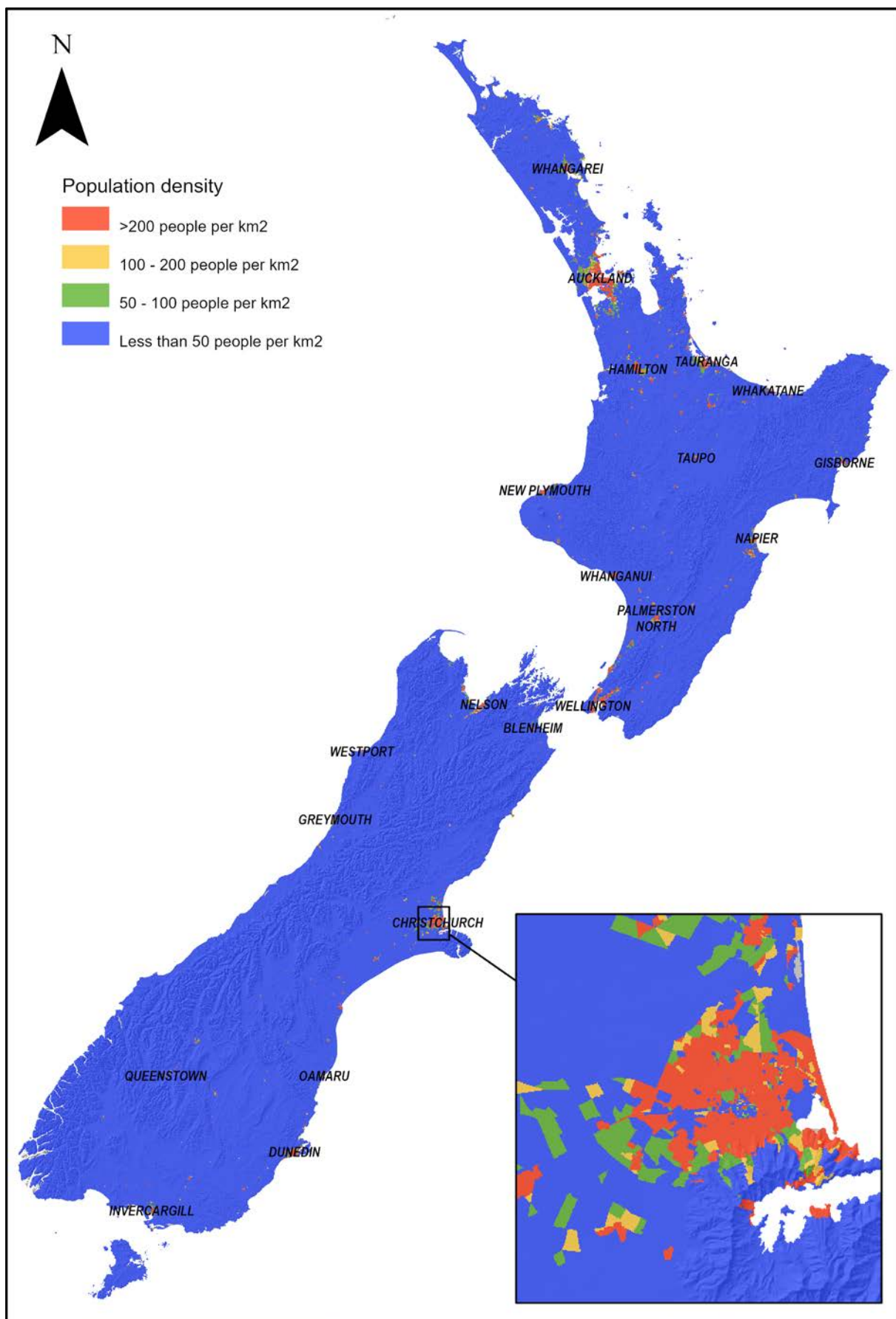


Figure 8.2 Map of population density in New Zealand created from the number of people per km² in each statistical mesh block as mappable criteria layer L1_SENS_POPULDEN_FM, classified into four ranges of population density (see Appendix 3).

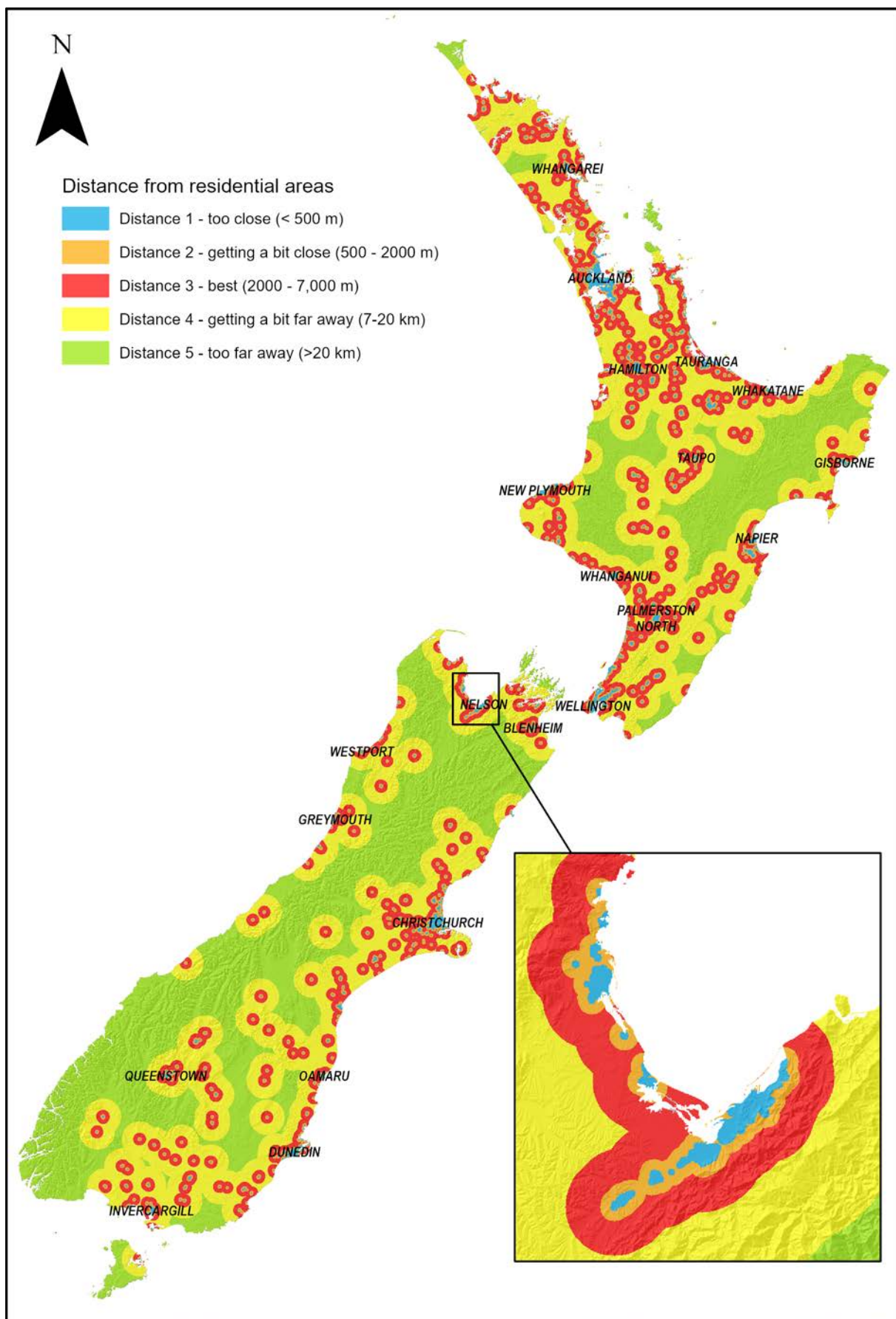


Figure 8.3 Map of distances from residential areas. Five distance classes are used in the mappable criteria layer L1_SENS_DIST2RES_FM (see Appendix 3).

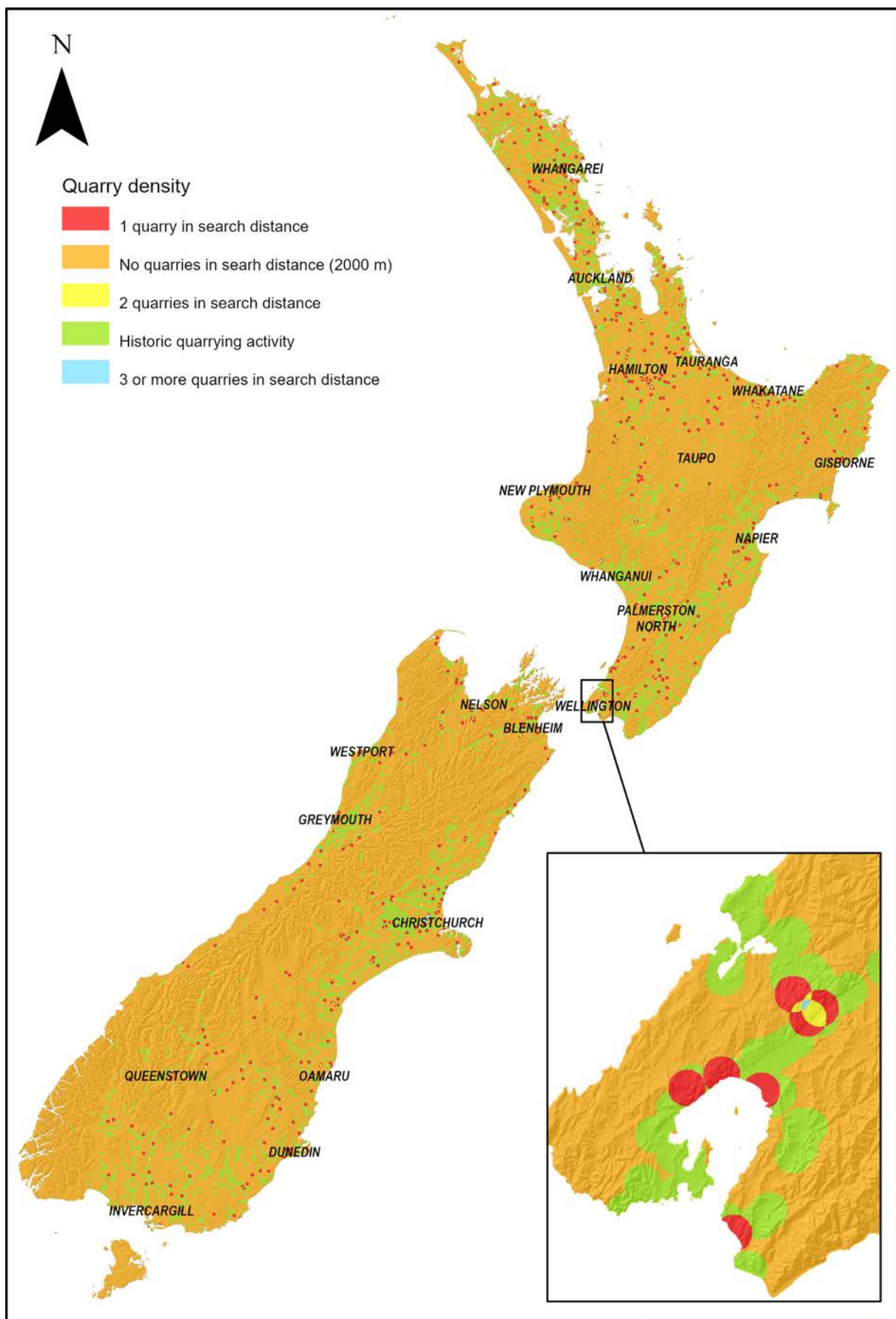


Figure 8.4 Map of operating quarry density and historic quarry locations. The mappable criteria layer L1_SENS_QUARRYDEN_FM is based on a density calculation for a 2 km search radius of operating quarries and the occurrence of historic quarry sites from the GERM database (see Appendix 3).

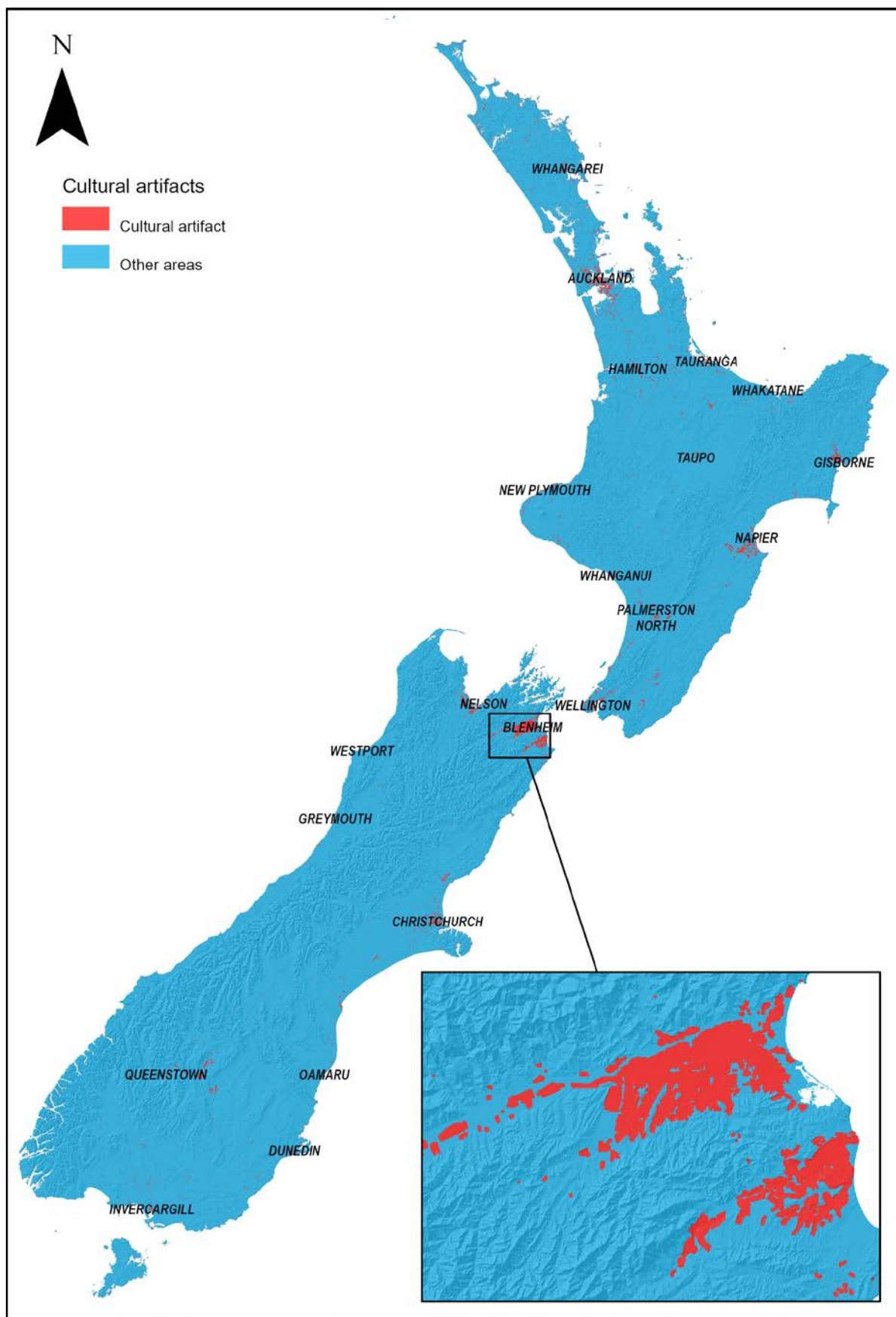


Figure 8.5 Map of significant cultural sites. The mappable criteria layer L1_SENS_CULTURAL_FM is based on the occurrence of airports, pā sites, windmills, large buildings, sports fields, showgrounds, racetracks, historic sites, golf courses, cemeteries and vineyards from the LINZ Topo 50 vector data. The inset map illustrates the unfavourable area for quarries in Marlborough where vineyards occupy areas of gravel alluvium (see Appendix 3).

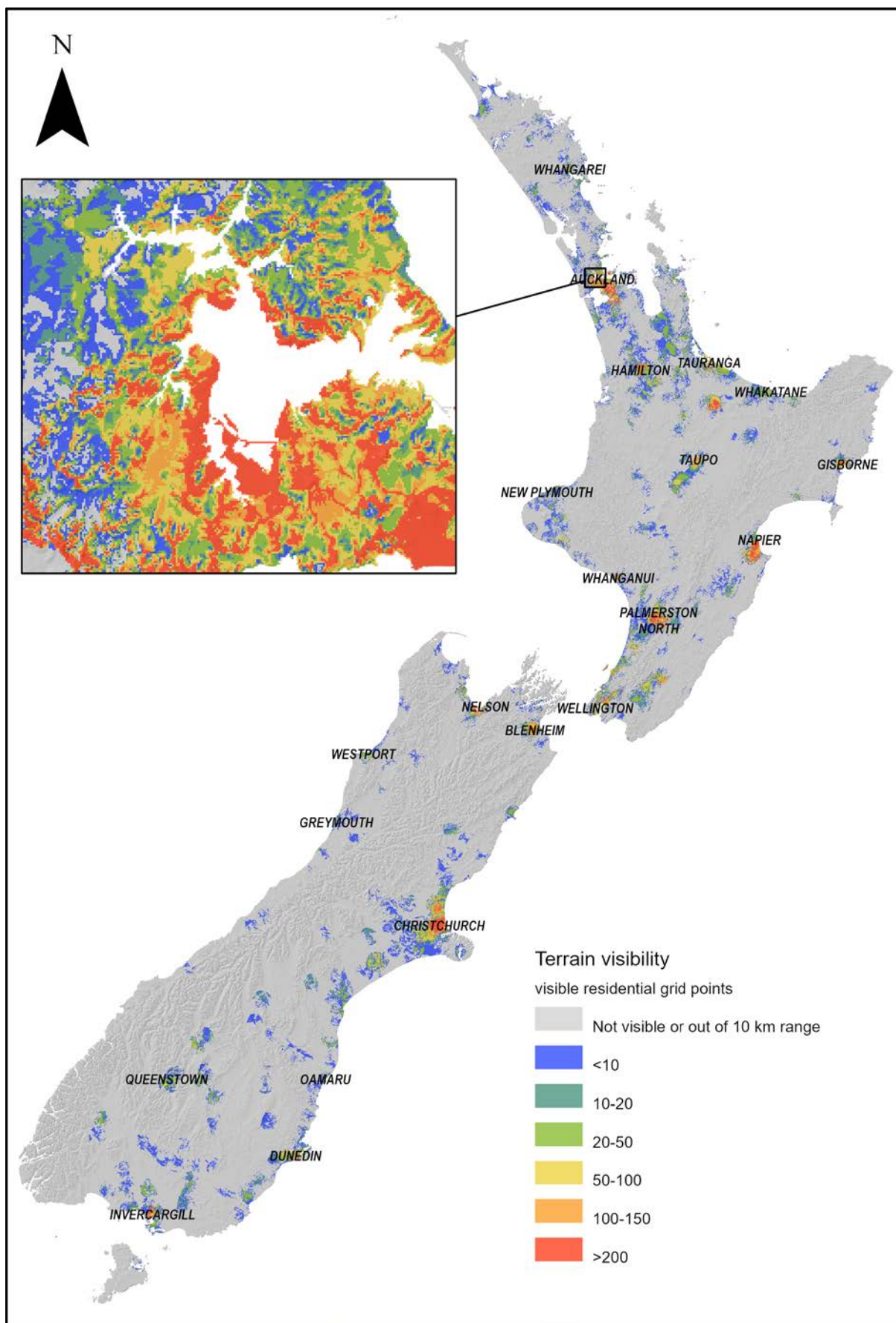


Figure 8.6 Terrain visibility analysis for New Zealand. The mappable criteria layer L1_SENS_VIEWSHED_FM is based on a visibility calculation using a digital elevation model and points representing the distribution of residential areas. The analysis determines the number of those residential points visible within 10 km for each grid cell in the model area (see Appendix 3).

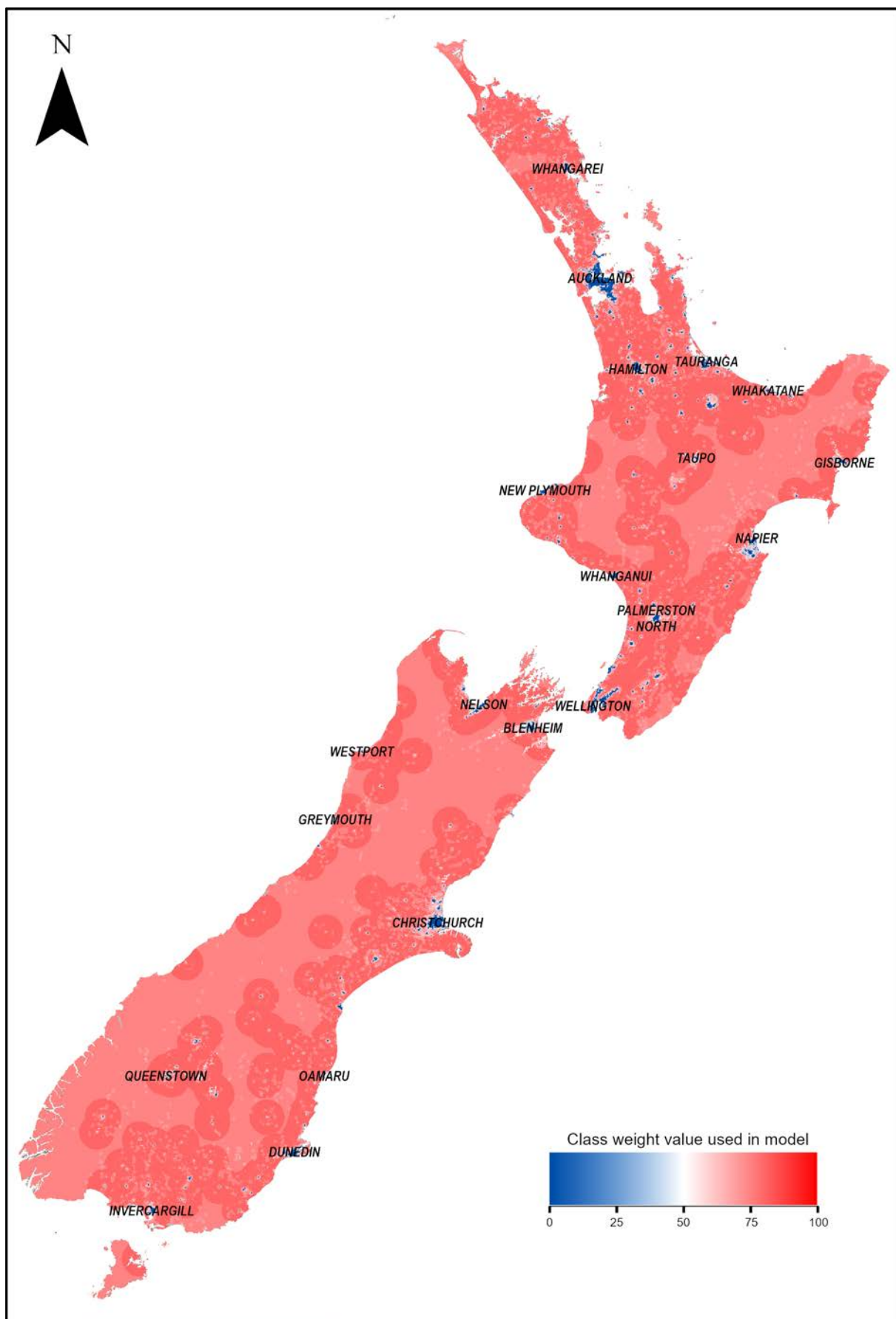


Figure 8.7 Level 2 cultural sensitivity predictive model component layer L2_SENSITIVITY_FM showing class weight values used. Red regions are interpreted as being less culturally sensitive than the blue areas (see Appendix 3).

9.0 AGGREGATE POTENTIAL MODELLING

Aggregate opportunity models for New Zealand have been created by combining 23 predictive maps to identify criteria suitable or not suitable for quarries. Level 1 mappable criteria layers are combined into five Level 2 predictive model component layers that represent the source lithology, land-use, future demand, supporting infrastructure and cultural sensitivity components, which are then combined into the Level 3 aggregate opportunity models for hard rock and gravel (Figure 9.1). The models represent areas where all parts of the aggregate opportunity concept are likely to occur and overlap, and therefore where there is the most opportunity for aggregate resources to be extracted.

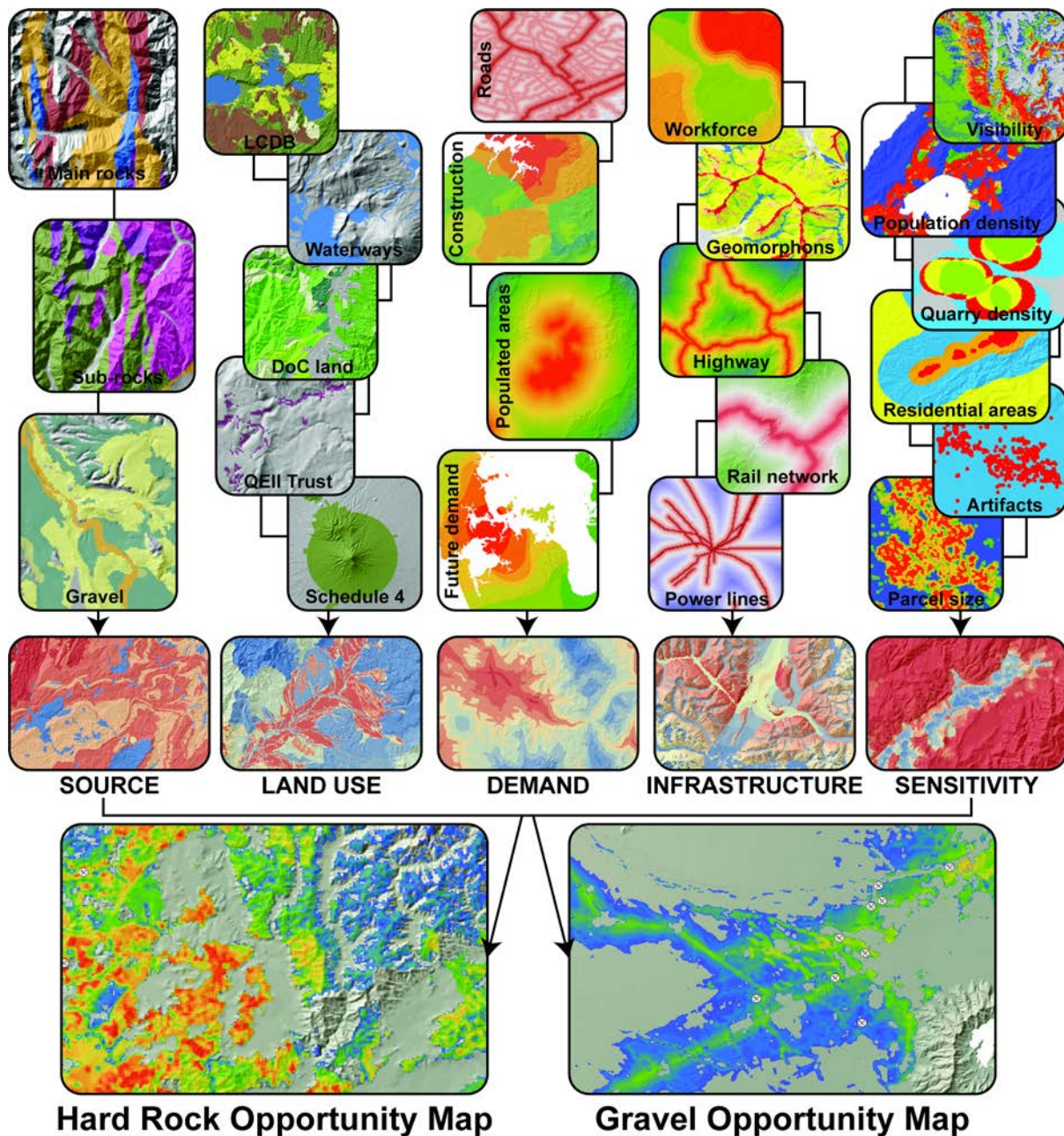


Figure 9.1 Summary diagram illustrating the mappable criteria layers that are combined into five predictive model component layers, before being combined into the hard rock and gravel aggregate opportunity models.

The final models are created using the fuzzy GAMMA operator with a GAMMA value of 0.8 to combine the Level 2 predictive model component layers of source rock, land use, future demand, supporting infrastructure and cultural sensitivity. The hard rock aggregate opportunity model is a culmination of 22 Level 1 layers and five Level 2 layers, and the gravel aggregate opportunity model has 20 Level 1 layers and five Level 2 layers (Table 9.1).

The modelling process has generated six Level 3 maps (Table 9.2) that can be used to assess the aggregate opportunity in New Zealand. Values are plotted between 0 and 1 on a black to red colour scale, where black to blue (low values) are unlikely to have aggregate opportunities; and light blue to red are those above neutral (a fuzzy membership value in the Level 2 maps of 0.5) and are likely to have an aggregate opportunity that should be investigated further. Level 3 modelling results are presented in Figure 9.2 for the hard rock aggregate opportunity concept and Figure 9.3 for the gravel aggregate opportunity concept.

Table 9.1 Layers listed by file names used in the aggregate opportunity modelling. Level 1 mappable criteria layers are combined into Level 2 predictive model component layers for both hard rock and gravel aggregate.

Level 1 – Hard Rock Mappable Criteria Layer	Level 2 – Hard Rock Predictive Model Component Layer	Level 1 – Gravel Mappable Criteria Layer	Level 2 – Gravel Predictive Model Component Layer
L1_SOURCE_MAINROCK	L2_SOURCE_HARDROCK	L1_SOURCE_GRAVEL	L2_SOURCE_GRAVEL
L1_SOURCE_SUBROCK			
L1_LANDUSE_DOC	L2_LANDUSE_HARDROCK	L1_LANDUSE_DOC	L2_LANDUSE_GRAVEL
L1_LANDUSE_LCDB		L1_LANDUSE_LCDB	
L1_LANDUSE_QEII		L1_LANDUSE_QEII	
L1_LANDUSE_S4		L1_LANDUSE_S4	
L1_LANDUSE_WATER		-	
L1_DEMAND_ROADS	L2_DEMAND	As for hard rock	As for hard rock
L1_DEMAND_POPULDEN			
L1_DEMAND_CONSTRUCTION			
L1_DEMAND_FUTURESQKM			
L1_INFRAS_GEOMORPH_HR	L2_INFRAS_HARDROCK	L1_INFRAS_GEOMORPH_GR	L2_INFRAS_GRAVEL
L1_INFRAS_HIGHWAY		L1_INFRAS_HIGHWAY	
L1_INFRAS_POWER		L1_INFRAS_POWER	
L1_INFRAS_RAILWAY		L1_INFRAS_RAILWAY	
L1_INFRAS_UNEMPLOYMENT		L1_INFRAS_UNEMPLOYMENT	
L1_SENS_CADASTRA	L2_SENSITIVITY	As for hard rock	As for hard rock
L1_SENS_CULTURAL			
L1_SENS_DIST2RES			
L1_SENS_POPULDEN			
L1_SENS_QUARRYDEN			
L1_SENS_VIEWSHED			

Table 9.2 Description of Level 3 aggregate opportunity models generated from the predictive model component layers, listed by file names.

Aggregate Opportunity Model	Description	Figure
L3_HARDROCK_AOM	A model of combined Level 2 predictive model component layers for the hard rock aggregate opportunity concept.	Figure 9.2
L3_HARDROCK_AOM_noES	A model of combined Level 2 predictive model component layers for the hard rock aggregate opportunity concept that excludes Level 2 component layers of land use and cultural sensitivity. This map can then be used to assess those factors from a source rock, demand and infrastructure model only.	Not plotted in this report
L3_HARDROCK_AT	A model of hard rock aggregate opportunity for sites above the anomalous threshold that is determined by operating quarry training sites.	Figure 9.6, Figure 9.7
L3_GRAVEL_AOM	A model of combined Level 2 predictive model component layers for the gravel aggregate opportunity concept.	Figure 9.3
L3_GRAVEL_AOM_noES	A model of combined Level 2 predictive model component layers for the gravel aggregate opportunity concept that excludes Level 2 layer components of land use and cultural sensitivity. This model can be used to assess those factors from source rock, demand and infrastructure considerations only.	Not plotted in this report
L3_GRAVEL_AT	A model of gravel aggregate opportunity for sites above the anomalous threshold that is determined by operating quarry training sites.	Figure 9.8, Figure 9.9

The Level 3 aggregate opportunity models have been assessed against 100 hard rock and 100 gravel training points. These training points represent existing operating quarries that are considered ideal examples of future quarries. The models in this study test very well, with most of the training points occurring in the highly ranked parts of the Level 3 models (Figures 9.4 and 9.5). These test results also allow a highly anomalous threshold to be determined (green lines in Figures 9.4 and 9.5). This is a value of the final model that should be used for assessing the aggregate opportunity and is derived from the value in the data that most of the training points are found to be above. To assess parts of the aggregate opportunity concept that has been considered within the modelling process already, maps can be easily removed from the final model. For example, the Level 2 cultural sensitivity and land-use layer components can be removed to analyse the potential in those areas (e.g. aggregate opportunity model with '_noES' in the suffix of the file name in Table 9.2).

The final models have been reclassified to only show areas above this threshold that best represent the regions of aggregate extraction opportunity in New Zealand (Figures 9.6–9.9). These maps show the areas of New Zealand that could be investigated further with more detailed desktop studies and ground-based exploration programmes to test their potential for a future quarry site. They could also be considered in land-planning programmes to assess the appropriate land use.

Appendix 2 of this report contains smaller-scale (1:500,000) maps of the aggregate opportunity for regions across New Zealand. They provide plots of the hard rock and gravel model results above the anomalous threshold on 42 maps. This report also includes a digital appendix (Appendix 3) of model layer data as GIS grids that include 23 Level 1 mappable criteria layers, eight Level 2 predictive model components layers and six Level 3 models.

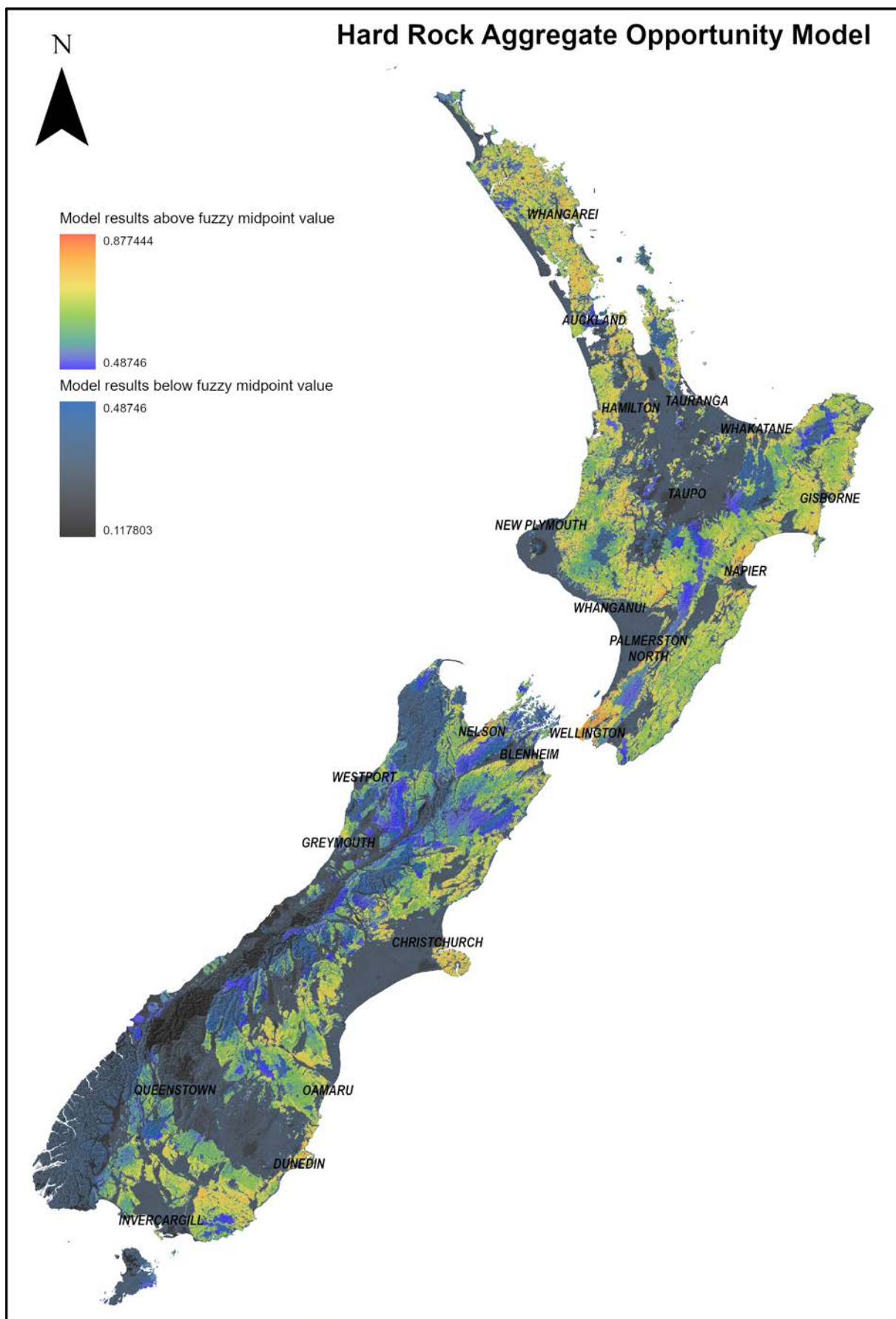


Figure 9.2 Results of the aggregate opportunity model for hard rock quarry locations. Map shows values above and below the fuzzy membership midpoint value of 0.5 (50%), where light blue to red values are more favourable for quarry operations than areas coloured dark blue to black.

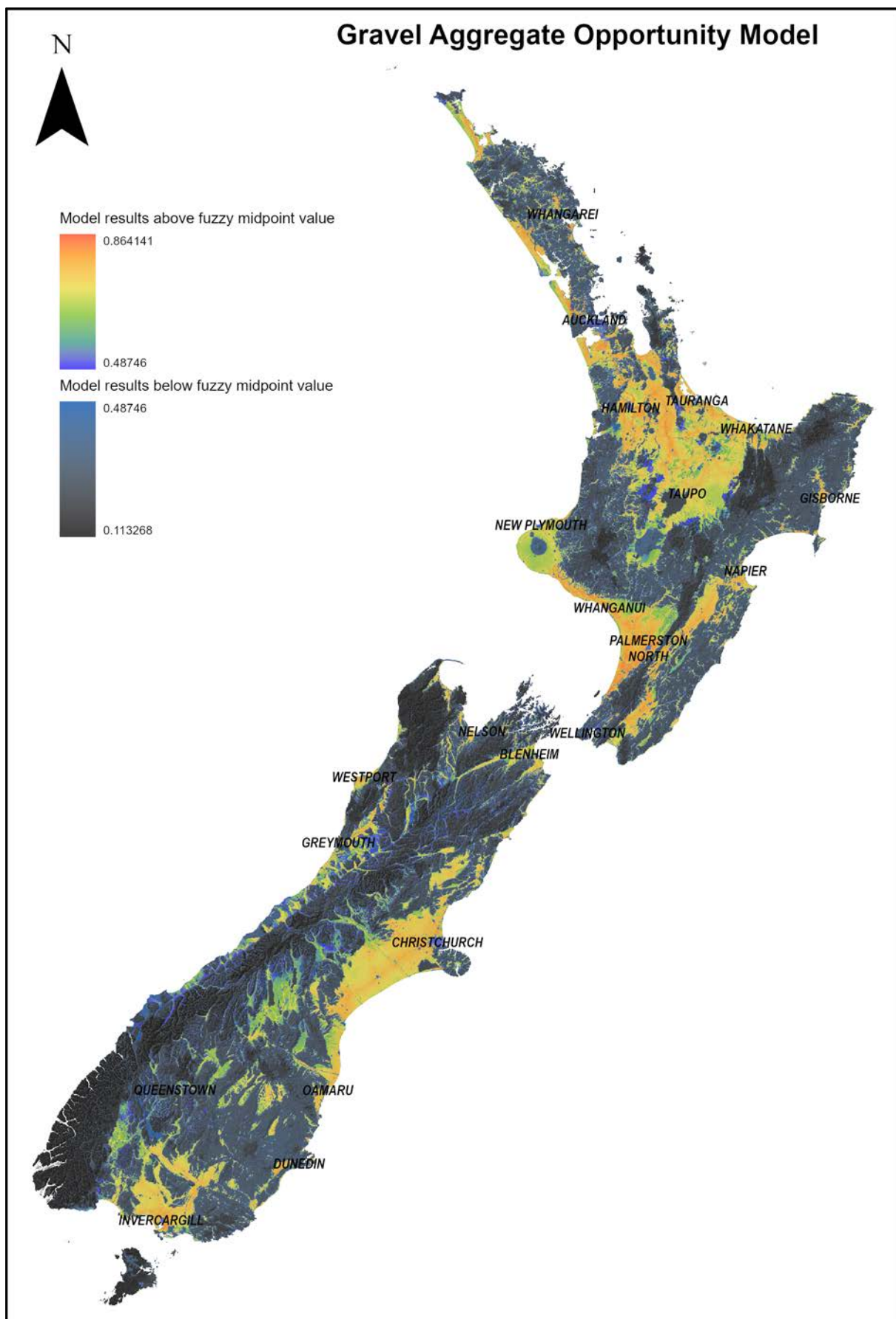


Figure 9.3 Results of the aggregate opportunity model for gravel quarry locations. Map shows values above and below the fuzzy membership midpoint value of 0.5 (50%), where light blue to red values are more favourable for quarry operations than areas coloured dark blue to black.

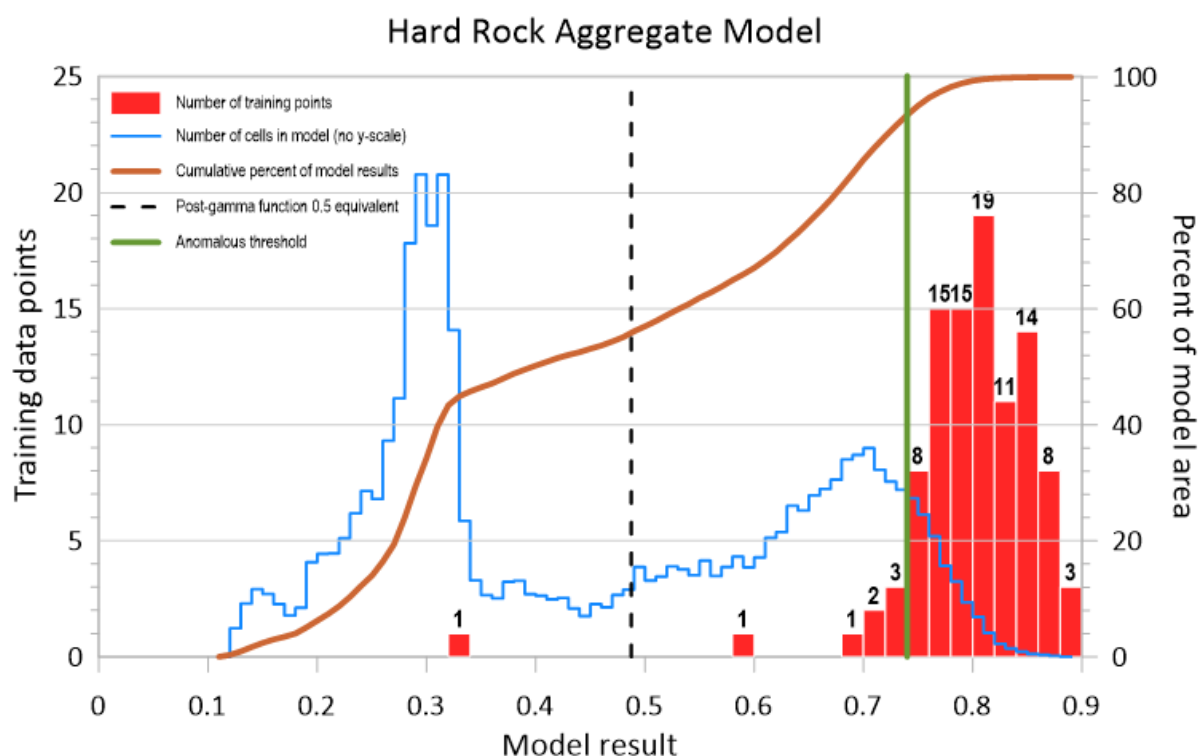


Figure 9.4 Chart of the hard rock model results compared to a selection of operating quarries used as training points to test the model. The red histogram illustrates the number of quarry training points for ranges of model results (fuzzy variable). The blue line is the number of cells in the model with the model result, and the brown line is the cumulative value of the cell areas as a percentage of the total model area. The black dashed line is the post-gamma function midpoint value, and the green line is the anomalous threshold where model results above this threshold are interpreted as significant quarry opportunities in New Zealand.

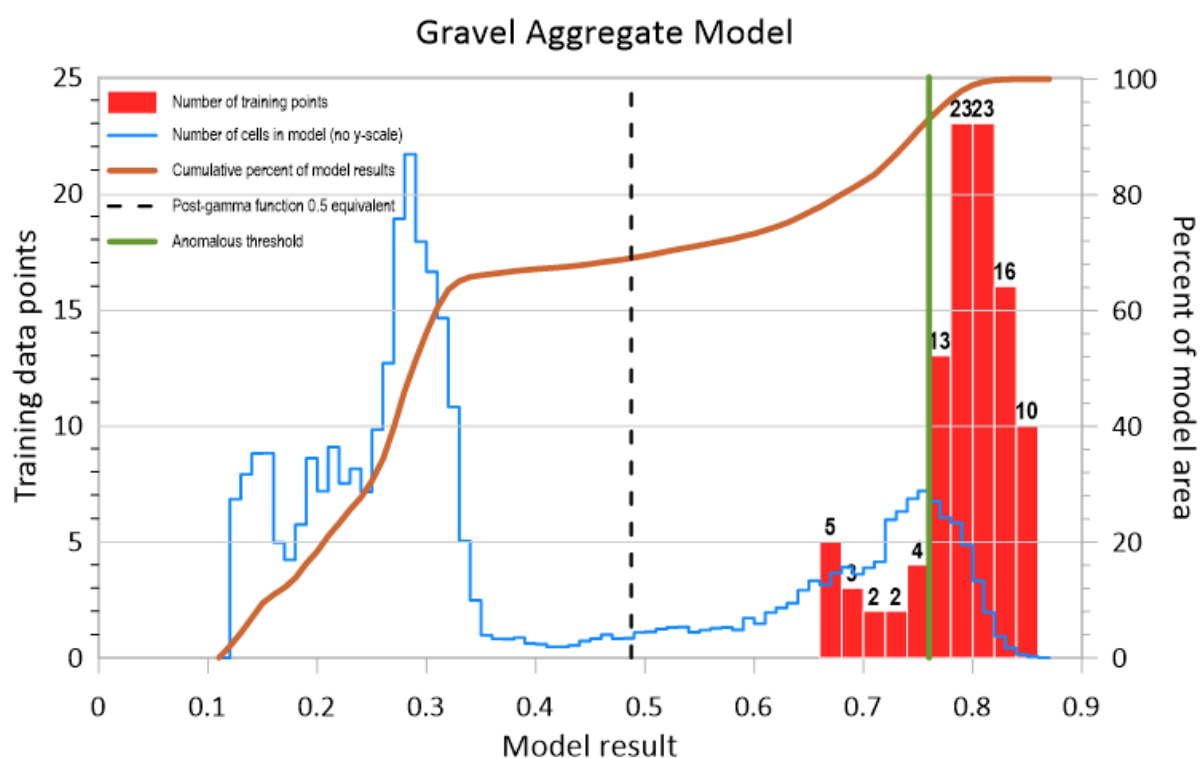


Figure 9.5 Chart of gravel model results compared to a selection of operating quarries used as training points to test the model. Data plotted in the chart are as described in Figure 9.4 above.

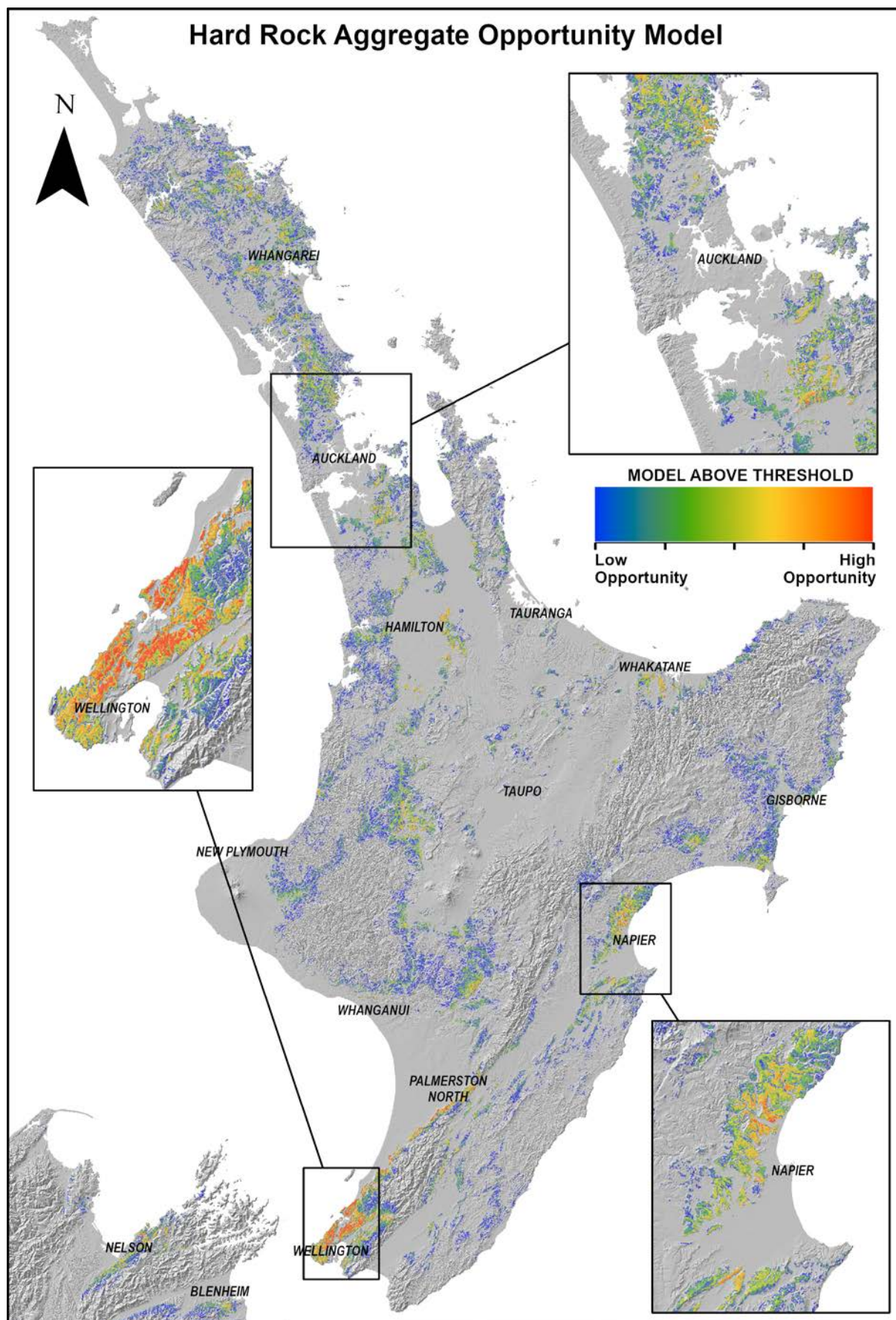


Figure 9.6 Map of the aggregate opportunity hard rock model results for the North Island. Colours represent areas above the anomalous threshold determined for the model, with blue representing comparatively low opportunity and red high opportunity. Inset maps illustrate more detailed results for Auckland, Napier and Wellington.

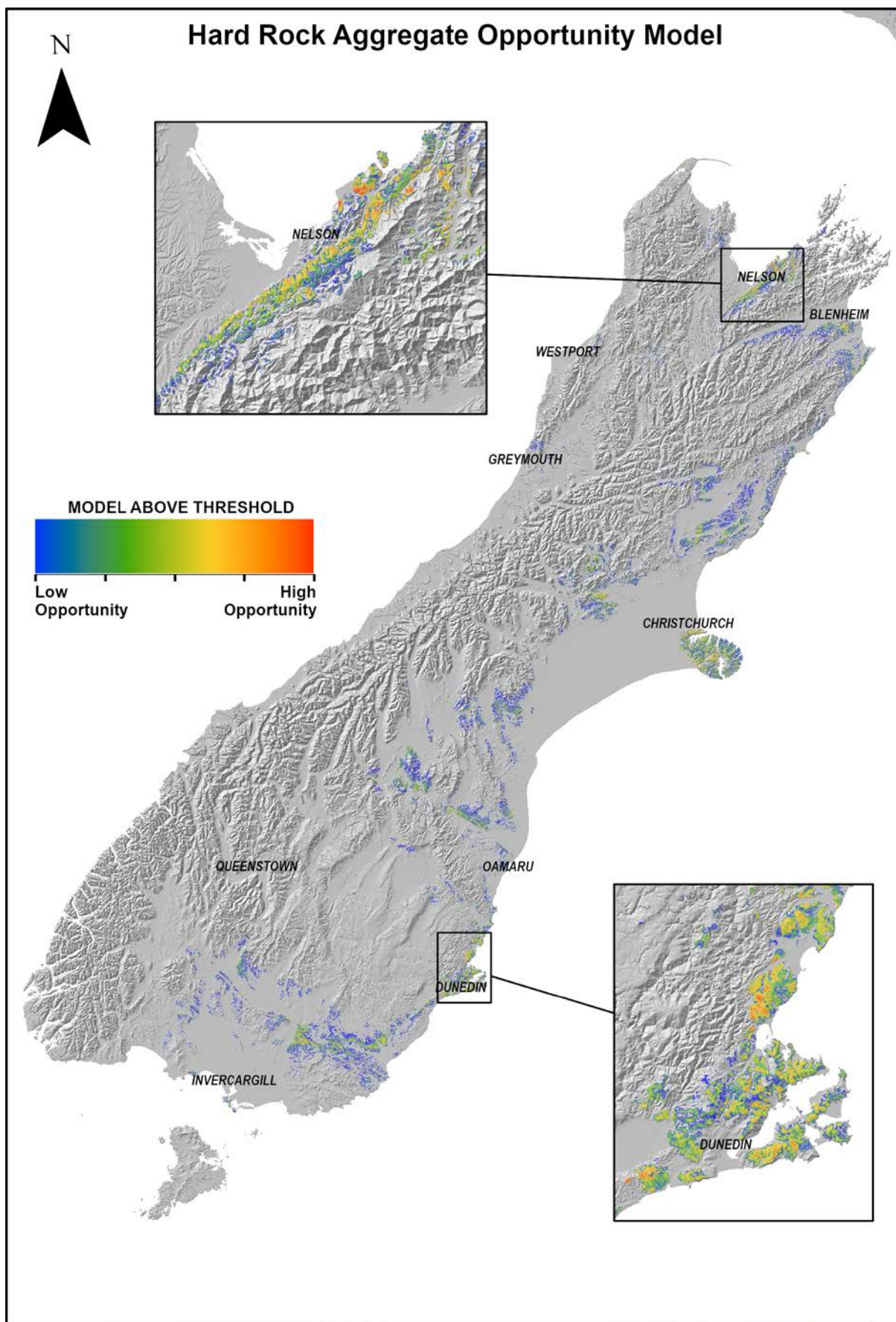


Figure 9.7 Map of the aggregate opportunity hard rock model results for the South Island. Colours represent areas above the anomalous threshold determined for the model, with blue representing comparatively low opportunity and red high opportunity. Inset maps illustrate more detailed results for Nelson and Dunedin.

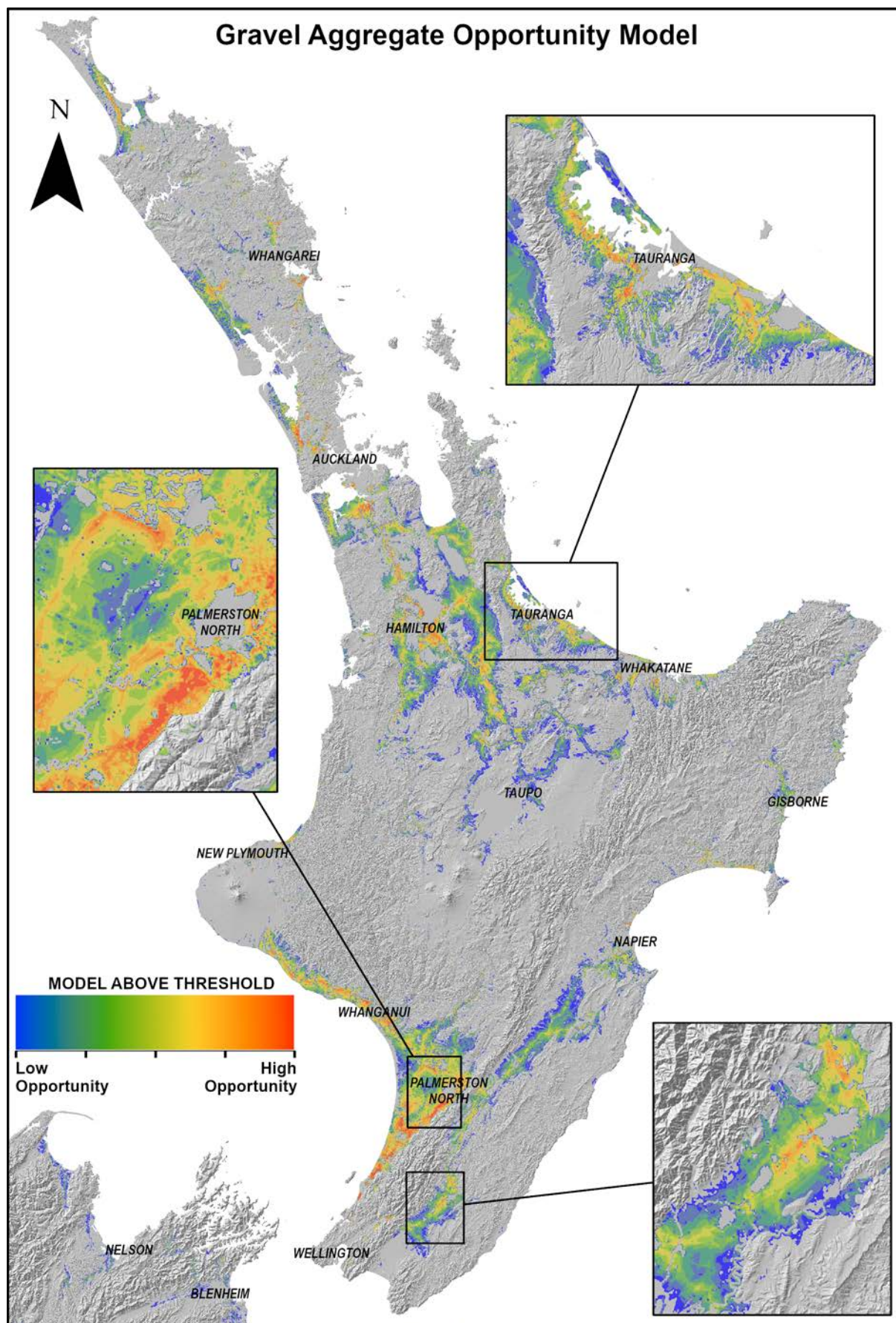


Figure 9.8 Map of the aggregate opportunity gravel model results for the North Island. Colours represent areas above the anomalous threshold determined for the model, with blue representing comparatively low opportunity and red high opportunity. Inset maps illustrate more detailed results for Tauranga, Palmerston North and Masterton.

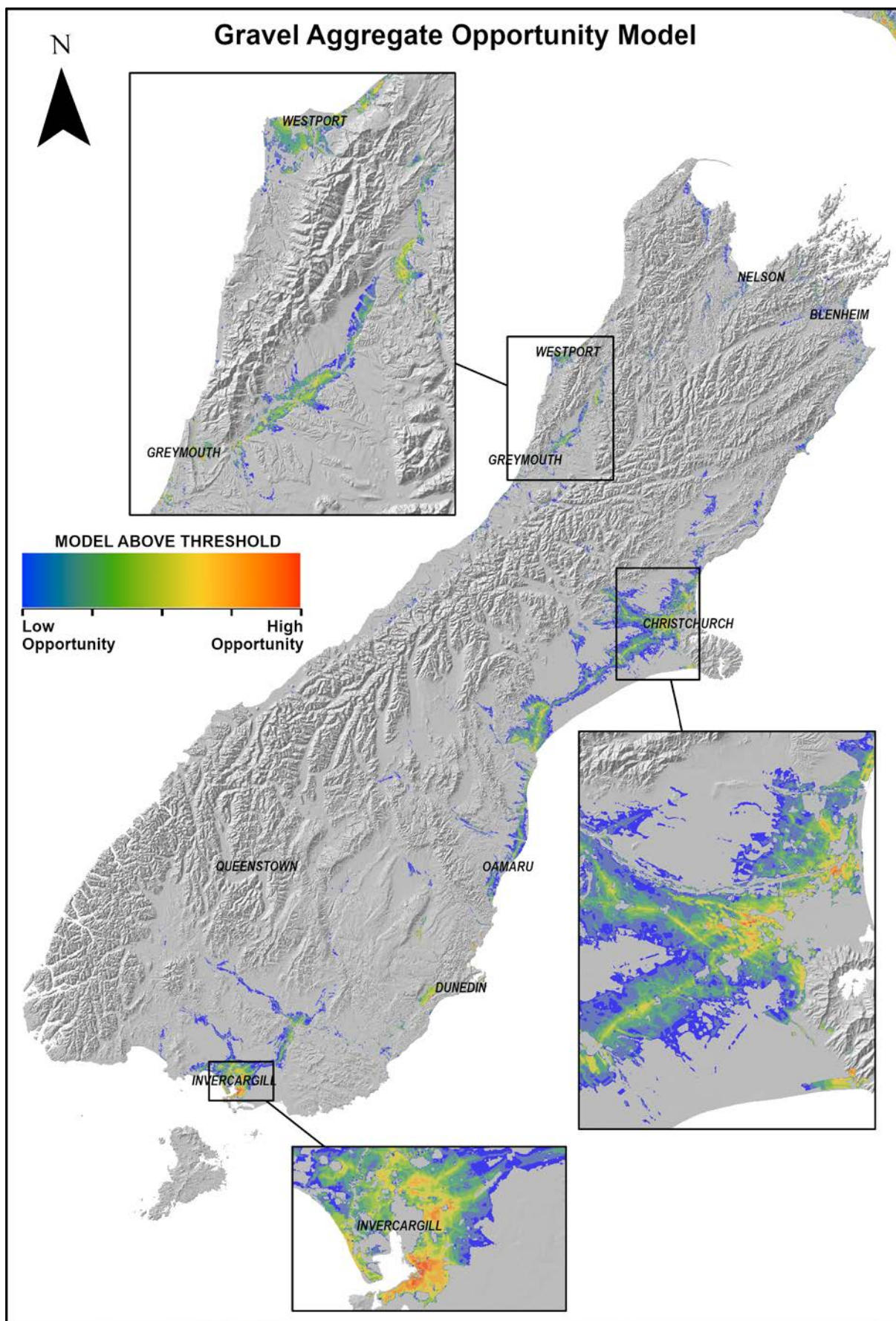


Figure 9.9 Map of the aggregate opportunity gravel model results for the South Island. Colours represent areas above the anomalous threshold determined for the model, with blue representing comparatively low opportunity and red high opportunity. Inset maps illustrate more detailed results for Westport, Greymouth, Christchurch and Invercargill.

10.0 RECOMMENDATIONS FOR FURTHER WORK

The results from this spatial modelling of aggregate opportunity can be analysed to understand in more depth their relationship to current land uses, conservation land classifications and which source rocks are more prevalent for future opportunity. The results could also be examined near areas of future large roading projects or infrastructure developments. These analyses can be easily undertaken using a GIS. An example is provided here where a simplified classification of the source rock lithology has been evaluated for the areas of hard rock and gravel aggregate opportunity (Figure 10.1). Although the variable model result values of the area in the model is not displayed, the map provides a better overview of the types and distribution of aggregate material in a region.

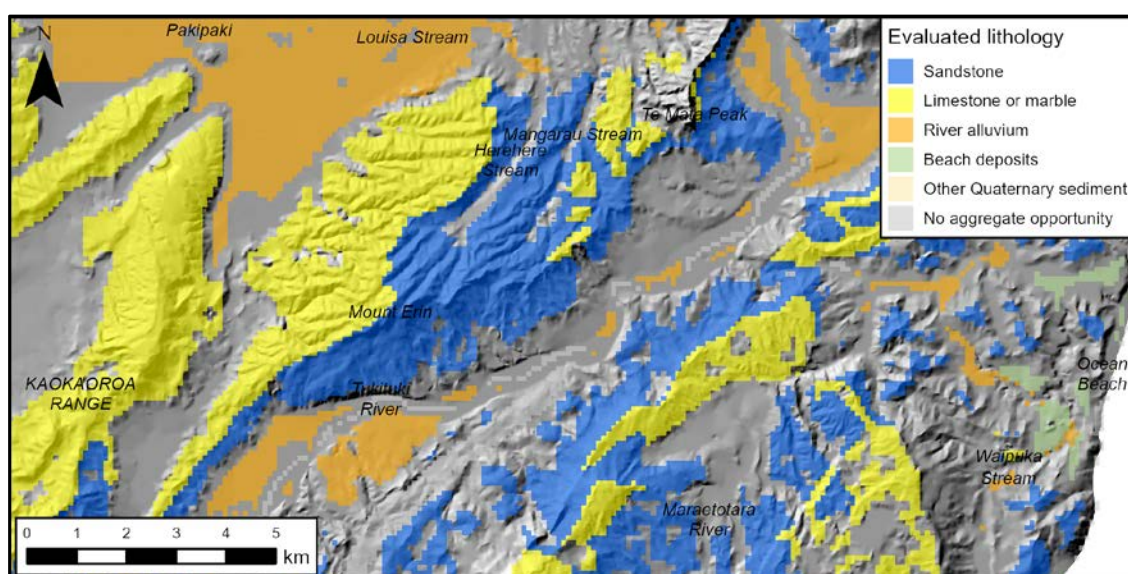


Figure 10.1 Map of area south of Havelock North showing simplified lithology types for only the areas of aggregate opportunity (evaluated lithology).

An analysis can also be made to investigate the current land use of sites determined to have aggregate opportunity. The total area of New Zealand is evaluated by the classes of land use from the LCDB database, and the areas above the anomalous threshold in the model are then also evaluated by the same classes (Figure 10.2). This shows that most of the areas determined by this model for aggregate opportunity are crop and grassland areas.

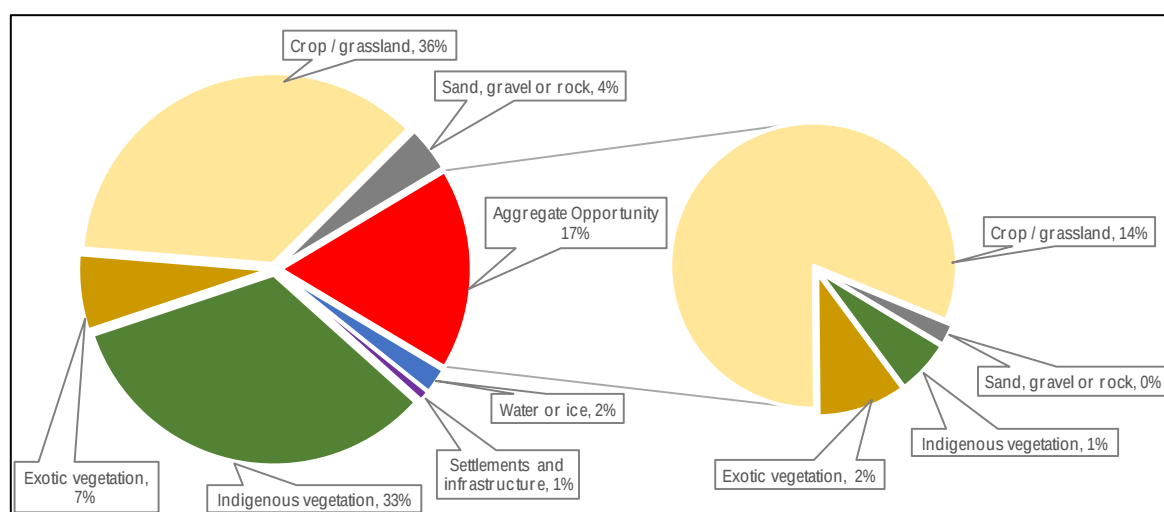


Figure 10.2 Charts illustrating the land-use classification from the LCDB data for all of the model area (left) and only the areas of hard rock and gravel aggregate opportunity (right).

The aggregate opportunity model can also be reviewed from a material availability perspective by regional council area. An example provided here shows the ratio of source rock lithologies for the areas above the anomalous threshold for each region of New Zealand (Figure 10.3). This shows which regions are enriched in a given source rock(s) and which regions may need to import particular source rock types from neighbouring regions. Other analyses based on this same data can be made where the cell count of anomalous areas of source rock types could also be levelled by population density to illustrate possible shortfalls in future aggregate production in a region.

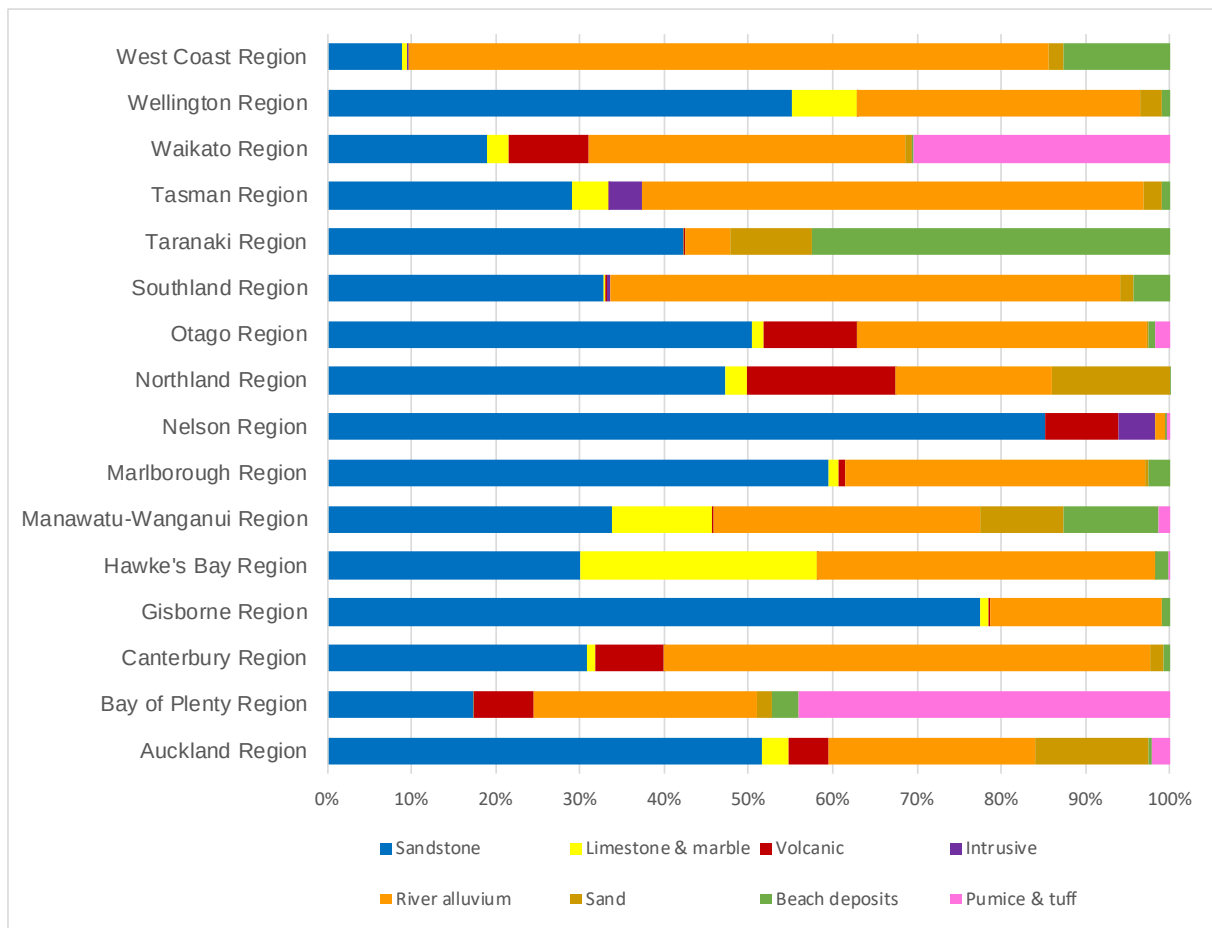


Figure 10.3 Chart showing the ratio of simplified classes of source rock lithology for the aggregate in each region of New Zealand.

The collection of additional data would improve the modelling for future iterations and analyses. Petrophysical information about aggregate source rocks is poorly known at a national scale in New Zealand. Material composition is broadly assumed from the geological maps used in this study, but these maps do not convey fine-scale variation in rock properties within individual geological units, small outcropping geology, or rock just below Quaternary cover that might be suitable. Development of a measured rock property database (e.g. density, impurity, weathering, fractures, etc.) would also be beneficial for characterising more detail within geological map units. The collection of additional land-use data for follow-up studies would also assist in understanding the opportunity values of future sites. These could include data from local and regional councils for parks and reserves that are currently not in an easily accessible national database. Future modelling should also consider land value to iwi groups, places of high scenic or tourism value, high-value agriculture zones and where future population expansion may encroach upon existing aggregate resources and quarries.

Examples of where additional information would improve the model are:

- In some places around Taranaki, cover rocks obscure shallow sources of hard rock volcanic material. The model does not represent the operating quarries in these areas due to the geological map used in the source predictive model component that classifies it as cover. Utilising more detailed geological maps that represented the sub-Quaternary geology and the classes of volcanic conglomerate would improve the aggregate opportunity in this area (Figure 10.4).
- In Wellington, there are large areas of regional and city council park land that is not included in the land-use component of the model due to a lack of a national-scale database of park land (Figure 10.5). A national database of these land areas for all city and regional council areas would improve the model.
- In Christchurch, parts of Banks Peninsula are modelled with high hard rock aggregate opportunity; however, the area is of high scenic value. A national database that specifies regions of high scenic value could easily be incorporated into future models.

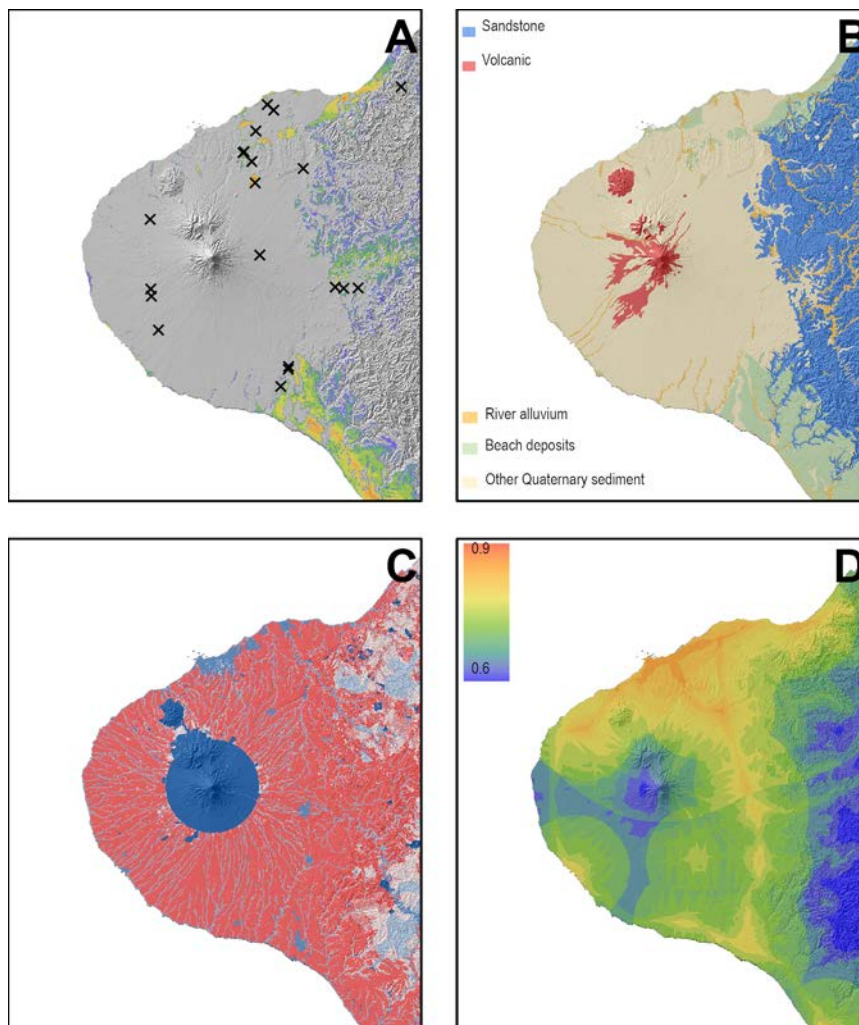


Figure 10.4 The Taranaki region, where the mapped Quaternary geology limits the aggregate opportunity in the model but where there are also operating quarries (A). The mapped geology in these areas (B) is non-river-derived Quaternary sediment (e.g. volcanic conglomerates). The Level 2 land use (C) and future demand maps (D, scale in fuzzy membership values) show that the region has aggregate opportunity.

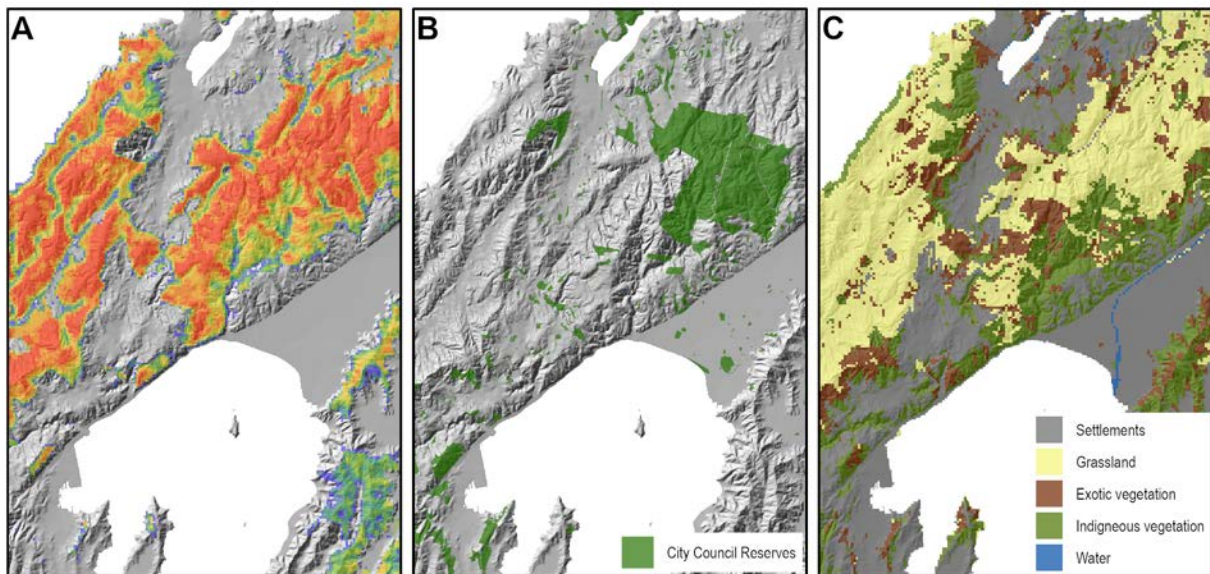


Figure 10.5 The Wellington region, where areas of the modelled aggregate opportunity are regional and city council park land. (A) Hard rock aggregate opportunity (scale as in Figure 9.6); (B) areas of parks and reserves; (C) land use from LCDDB showing that many park areas are grassland.

The model can also be used to assess new quarry sites or exploration areas based on the predictive model components. Table 10.1 provides two examples, where the Level 2 predictive model component values and the Level 3 final model values are extracted for a recently developed and a recently proposed quarry. The Willowbank Quarry in Wellington has excellent fuzzy membership values for all Level 2 maps (>0.8); however, the land-use value is low due to a wetland and drainage area near the site. This is mitigated at a financial cost during the operation of the quarry. Roydon Quarry near Christchurch also has good values for all parts of the Level 2 data, providing a high Level 3 aggregate opportunity result. Data such as these for other sites could be used for site evaluation or exploration planning (e.g. Appendix 4).

Table 10.1 Analysis of model data for Willowbank and Roydon quarry sites.

Quarry	Predictive Model Component	Fuzzy Membership Value
Willowbank Quarry	Level 3 Hard rock model	0.78
	Level 2 Source	0.94
	Leve 2 Land use	0.35
	Level 2 Demand	0.9
	Level 2 Infrastructure	0.85
	Level 2 Sensitivity	0.82
Roydon Quarry	Level 3 Gravel model	0.81
	Level 2 Source	0.83
	Leve 2 Land use	0.82
	Level 2 Demand	0.85
	Level 2 Infrastructure	0.78
	Level 2 Sensitivity	0.76

11.0 DISCUSSION AND SUMMARY

The development of infrastructure in New Zealand requires large quantities of hard rock and gravel aggregate material for roading and construction. These aggregates are ideally extracted locally to minimise the cost of transportation and emissions. Future opportunities for aggregate resource supply can be determined from databases of geological map and rock property information, but land-use, demand, infrastructure and cultural criteria also need to be considered to find the most suitable areas for future quarrying activities. In 2018, the domestic production of aggregate was 41 million tonnes (Mt) per year, and this amount is forecast to increase in the future; new supplies are therefore critical for the continued development of New Zealand's communities and infrastructure.

New Zealand is fortunate to have large areas of hard rock and gravel deposits throughout the country that can be utilised for aggregate supply. Much of this material is only weakly weathered and exposed at or near the surface, providing access to good-quality resources of aggregate. Aggregate in New Zealand can be largely grouped into two classes: **hard rock**, e.g. greywacke, sandstone, basalt and limestone; and **gravel**, e.g. unconsolidated deposits such as river gravels, sand and boulders. Aggregate is extracted based on its physical properties (strength, durability, cohesiveness, size), chemical properties (beneficial or lack of deleterious minerals) and typically on its homogeneity and volume at a site.

As well as these geological criteria, petrophysical properties and volume of resource, social and cultural aspects (proximity to urban areas, landscape values, areas of cultural significance), environmental (water, air and noise pollution) and resource economics (quality and distance to market) play a key role in the economic success of a quarry. Ideally, aggregate resources are extracted close to their end use; the cost of transporting aggregate doubles approximately every 30 km, so local sources are required to minimise the cost of new infrastructure projects.

Aggregates are well suited to spatial modelling techniques, as much of the data is easily available, in digital databases, and continuous across the entire study area. Data have been sourced from Land Information New Zealand (LINZ), the Department of Conservation (DoC), Manaaki Whenua Landcare Research, GNS Science, the Ministry for the Environment and Statistics New Zealand (Stats NZ). Data were identified that contribute to realising the aggregate opportunity; these are critical components for a suitable aggregate mining operation that can be spatially represented in a GIS with good coverage across New Zealand.

This project has adapted a mineral potential modelling approach to model future aggregate exploration and extraction opportunities in New Zealand. The **aggregate opportunity concept** developed uses a number of critical or highly important features that must be present for a quarry to succeed but also, importantly, contra-indicators that affect the viability of a quarry or restrictions to its development. Mappable criteria features are used in this modelling to represent all components of the aggregate opportunity concept. These are classified over relative and subjective ranges by considering advice from New Zealand industry experts and spatial statistics generated from 200 operating quarries selected as training points. The models and their component layers in this study are created at three levels; initially, mappable criteria layers from the source data, which are combined to create five intermediate predictive model component layers, before combining those into the final aggregate opportunity models. The study uses knowledge-driven fuzzy logic membership values and operators to combine the maps into the aggregate opportunity model. Fuzzy logic is a widely used and conceptually simple method for combining spatial data and maps.

This study has created predictive model component layers for **source rocks** for both hard rock and gravel types that are commonly quarried in New Zealand. Our knowledge of the lithology is broadly well known from existing geological maps, but these maps do not convey fine-scale variation in rock properties within individual geological units. However, at a national scale, these geological units can be qualitatively generalised in terms of their aggregate resource potential. This study has used the digital QMAP 1:250,000 scale geological map of New Zealand.

Land use is one of several non-geological predictive model component layers for determining sites that are suitable for quarrying activities. The modelling has included areas of restricted land where mining activities are prohibited or where access restrictions apply, such as Schedule 4 Crown-owned conservation land, DoC public conservation areas, QEII National Trust land, and waterways and waterbodies. The Land Cover Database (LCDB) that maps the different areas of vegetation, as well as other land uses, is particularly useful for identifying areas of significant high-value indigenous native vegetation.

Proximity to high-demand aggregate markets and roading projects is critical for understanding the **future demand** for aggregate. This predictive model component layer has used several mappable criteria layers to represent these markets, including the proximity to highly populated areas, the distance from roads classified by size and use, the predicted future aggregate production and forecast construction and building activity. Development of a quarry is ideally close to **supporting infrastructure**, and this has been assessed using mappable criteria, such as large roads and the railway network for transport of aggregate; proximity to electricity transmission, to supply enough energy for low-emission processing plants and mining equipment; and proximity to labour markets. An additional mappable criteria layer assessing suitable terrain for the style of extraction activity and deposit type has been included.

For all extractive activities, **cultural sensitivity** and social licence to operate is an important consideration. Ideally, quarries should be located close to their markets, but the sensitivity of residents to quarrying can place significant constraints on operators. This study has created mappable criteria layers based around population density developed from census data, cadastral parcel size (a proxy for populated areas) and mapped cultural artefacts to avoid places of importance to people and communities. Current and historic quarry density have been used to determine areas where historic acceptance of quarry activity may have occurred, and a visibility analysis has determined which parts of the landscape quarrying might be visible to the public.

Aggregate opportunity models for New Zealand have been created by combining 23 predictive model component layers. The models highlight areas where all the predictive model components of the aggregate opportunity concept overlap; where this occurs, there is the most opportunity for aggregate quarrying. The models can be used as part of an exploration programme for a new quarry to eliminate large areas of unsuitable land and focus on areas with the most potential for detailed ground-based exploration and rock quality testing. They can also be used to determine potential aggregate sources close to a city or large roading project so that they can be protected in the urban planning processes or used as a nearby source to avoid transporting material from other more distal sites.

The models have been assessed against hard rock and gravel training points (operating quarries that are considered ideal examples of future quarries). The models in this study test very well, with most of the training points occurring in the highly ranked parts of the final model. Some of the newest quarries, such as Willowbank in Wellington, Roydon in Christchurch and resources being developed in Opotiki, are all ranked highly in the model, indicating that it is functioning as a predictor of future aggregate opportunities.

With the demand for aggregate expected to continue increasing in future years, it is important to have local supplies identified and protected at the district planning level for future resource management. Understanding is also required on the economic effect of restricting access to resources due to regulatory changes or population expansion. The model presented here delineates areas that warrant more detailed study and could be used as a catalyst for further exploration. For future iterations of this modelling, engineering and rock property data, higher-resolution mapping of lithologic variation and data from councils and iwi on land use and value would be beneficial additions.

12.0 ACKNOWLEDGMENTS

Publication of this project would not have been possible without the support of the New Zealand Infrastructure Commission, Te Waihangā. The author would like to thank Mike Chilton (Aggretech Ltd), Tony Christie and Mark Rattenbury (GNS Science) for advice on the aggregate industry and elements of aggregate exploration utilised in this study. I would like to acknowledge Michelle Stokes (Kenex Ltd) who conceived the potential and need for a national aggregate model more than 15 years ago, even though digital data was not available to realise the modelling. Wayne Scott (AQA), Dave Jennings, David Heron and Rob Smillie (GNS Science) are thanked for their support of this research in the last few years. Regine Morgenstern, Brenda Rosser and Biljana Lukovic assisted with the geomorphon modelling. Brett Woods, Ross Copland and Rob Addison (Infrastructure Commission) and Nayana Islam (MBIE) provided helpful feedback, as well as advice on data and interpretation. The author also thanks members of the New Zealand aggregates industry who have shared their knowledge, allowing for improved maps and model analysis. Early versions of this project were supported by the Strategic Science Investment Fund to GNS Science. Murray Francis of Road Metals Ltd is thanked for permission to publish the photograph of Waimakariri Quarry. The author thanks Mark Rattenbury, Rose Turnbull and Chris Clowes for helpful reviews of this document and Kate Robb for formatting, layout and editing.

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APPENDICES

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APPENDIX 1 DATA SOURCES

Geographic Information System (GIS) data used in this modelling can be sourced easily from the internet and at very low or no cost. The table below lists the data names, custodians/owners, online source reference and access date of when the data was downloaded for this project.

Table A1.1 Digital data sources accessed for data used in this modelling.

Ref. No.	Data Name	Custodian	Source	Access Date
1	QMAP lithology	GNS Science	https://shop.gns.cri.nz/gnsgm1/	12/12/2020
2	River classification	Ministry for the Environment	https://data.mfe.govt.nz/layer/51845-river-environment-classification-new-zealand-2010-deprecated/	02/01/2019
3	QEII National Trust	QEII National Trust	https://qeinationaltrust.org.nz/publications-and-resources/gis-data/	04/03/2021
4	Schedule 4	New Zealand Petroleum and Minerals	Data provided by NZP&M upon request.	02/12/2019
5	Public conservation areas	Department of Conservation	https://koordinates.com/layer/754-doc-public-conservation-areas/	10/11/2019
6	Land Classification Database	Manaaki Whenua Landcare Research	https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/	8/03/2021
7	Rivers	LINZ	https://data.linz.govt.nz/layer/50327-nz-river-centrelines-topo-150k/	10/01/2021
8	Population (future)	Stats NZ	http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7587	01/04/2020
9	Territorial authority areas	Stats NZ	https://datafinder.stats.govt.nz/layer/104267-territorial-authority-2020-generalised/	01/04/2020
10	Roads	LINZ	https://data.linz.govt.nz/layer/50329-nz-road-centrelines-topo-150k/	10/01/2021
11	Current population	Stats NZ	https://www.stats.govt.nz/information-releases/statistical-area-1-dataset-for-2018-census-updated-march-2020	01/04/2020
12	Powerlines	LINZ	https://data.linz.govt.nz/layer/50311-nz-powerline-centrelines-topo-150k/	10/01/2021
13	Railway lines	LINZ	https://data.linz.govt.nz/layer/50319-nz-railway-centrelines-topo-150k/	10/01/2021
14	Unemployment	Stats NZ	https://www.stats.govt.nz/large-datasets/csv-files-for-download/	01/04/2020
15	Cadastral parcels	LINZ	https://data.linz.govt.nz/layer/51571-nz-parcels/	10/01/2021

Ref. No.	Data Name	Custodian	Source	Access Date
16	Residential areas	LINZ	https://data.linz.govt.nz/layer/50325-nz-residential-area-polygons-topo-150k/	10/01/2021
17	GERM database	GNS Science	https://data.gns.cri.nz/germ/	14/01/2021
18	Airports	LINZ	https://data.linz.govt.nz/layer/50237-nz-airport-polygons-topo-150k/	10/01/2021
19	Pā	LINZ	https://data.linz.govt.nz/layer/50308-nz-pa-points-topo-150k/	10/01/2021
20	Windmills	LINZ	https://data.linz.govt.nz/layer/50378-nz-windmill-points-topo-150k/	10/01/2021
21	Buildings	LINZ	https://data.linz.govt.nz/layer/50246-nz-building-polygons-topo-150k/	10/01/2021
22	Sports fields	LINZ	https://data.linz.govt.nz/layer/50355-nz-sportsfield-polygons-topo-150k/	10/01/2021
23	Showgrounds	LINZ	https://data.linz.govt.nz/layer/50344-nz-showground-polygons-topo-150k/	10/01/2021
24	Racetracks	LINZ	https://data.linz.govt.nz/layer/50316-nz-racetrack-polygons-topo-150k/	10/01/2021
25	Historic points	LINZ	https://data.linz.govt.nz/layer/50286-nz-historic-site-points-topo-150k/	10/01/2021
26	Golf courses	LINZ	https://data.linz.govt.nz/layer/50281-nz-golf-course-polygons-topo-150k/	10/01/2021
27	Cemetery polygons	LINZ	https://data.linz.govt.nz/layer/50255-nz-cemetery-polygons-topo-150k/	10/01/2021
28	Cemetery points	LINZ	https://data.linz.govt.nz/layer/50254-nz-cemetery-points-topo-150k/	10/01/2021
29	Vineyards	LINZ	https://data.linz.govt.nz/layer/50367-nz-vineyard-polygons-topo-150k/	10/01/2021
30	Elevation model	LINZ	https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/	08/01/2020
31	Mesh blocks	Stats NZ	https://datafinder.stats.govt.nz/layer/8347-meshblock-2013/	01/04/2020
32	Regional Council boundaries	Stats NZ	https://datafinder.stats.govt.nz/layer/25738-regional-council-2013/	01/04/2020
33	Urban and rural boundaries	Stats NZ	https://datafinder.stats.govt.nz/layer/98752-urban-rural-2019-generalised/	01/04/2020
34	Forecast construction and building activity	MBIE	https://www.mbie.govt.nz/assets/national-construction-pipeline-report-2020.pdf	31/03/2021

APPENDIX 2 REGIONAL MAPS OF AGGREGATE OPPORTUNITY

Maps of model results have been created at a 1:500,000 scale for 21 areas of New Zealand. For each region, there is a map of the hard rock and a map of the gravel aggregate opportunity model. Maps show the model results above the highly anomalous threshold. 42 maps are included in this appendix (2 maps for each of the 21 areas). The area covered by each of these maps is illustrated in Figure A2.1.

Table A2.1 Table of PDF maps for aggregate opportunity models for New Zealand regions.

Map No.	Region	Opportunity Model
R01	Northland	Hard rock
R02	Northland	Gravel
R03	Whangarei	Hard rock
R04	Whangarei	Gravel
R05	Auckland	Hard rock
R06	Auckland	Gravel
R07	Hamilton	Hard rock
R08	Hamilton	Gravel
R09	Bay of Plenty	Hard rock
R10	Bay of Plenty	Gravel
R11	Taranaki	Hard rock
R12	Taranaki	Gravel
R13	Taupo	Hard rock
R14	Taupo	Gravel
R15	Gisborne-Napier	Hard rock
R16	Gisborne-Napier	Gravel
R17	Manawatu	Hard rock
R18	Manawatu	Gravel
R19	Wellington	Hard rock
R20	Wellington	Gravel
R21	Marlborough-Nelson	Hard rock
R22	Marlborough-Nelson	Gravel
R23	North Canterbury	Hard rock
R24	North Canterbury	Gravel
R25	Canterbury	Hard rock
R26	Canterbury	Gravel
R27	South Canterbury	Hard rock
R28	South Canterbury	Gravel
R29	Tasman-Westport	Hard rock
R30	Tasman-Westport	Gravel
R31	Greymouth	Hard rock

Map No.	Region	Opportunity Model
R32	Greymouth	Gravel
R33	Westland	Hard rock
R34	Westland	Gravel
R35	South Westland	Hard rock
R36	South Westland	Gravel
R37	South Otago	Hard rock
R38	South Otago	Gravel
R39	Dunedin	Hard rock
R40	Dunedin	Gravel
R41	Southland	Hard rock
R42	Southland	Gravel

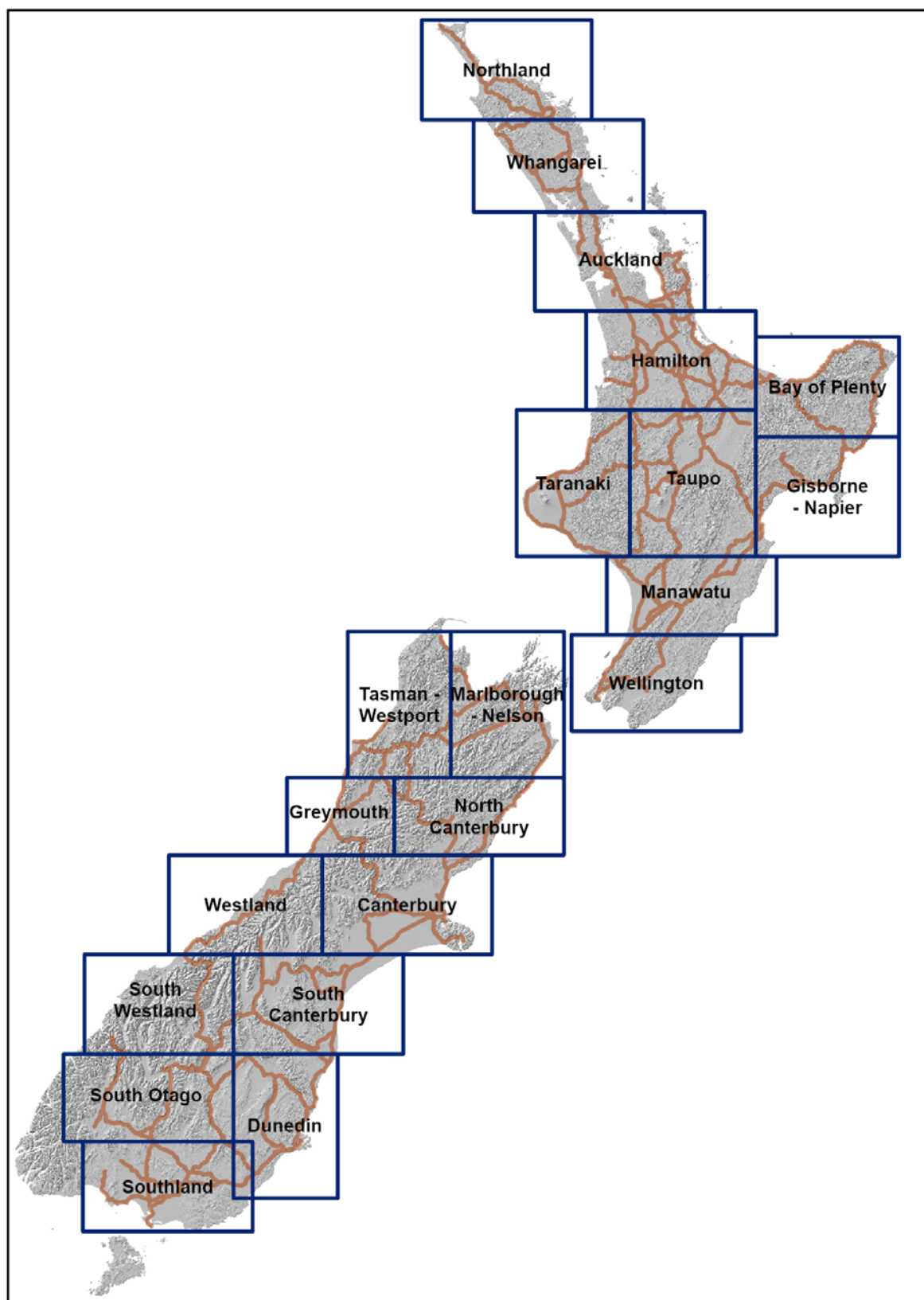


Figure A2.1 Location of regional-scale aggregate opportunity model result maps included as Appendix 2. Map areas overlap and in all cases are 1:500,000 scale when printed at A3 size.

APPENDIX 3 DIGITAL APPENDIX OF GIS DATA

A digital appendix is included with this report. It includes GIS data of the derivative data used to create the aggregate opportunity model in this study. Original source data is not provided in this dataset; see Appendix 1 for the source and owners of those data. All data are in ArcGIS grid format and within an ESRI Geodatabase and also GeoTIFF grids. All data are in the NZTM map projection. GIS file names are prefixed by the layer level (e.g. 'L1' for Level 1), then named for the aggregate opportunity concept component group (e.g. 'SOURCE' for source rocks), an abbreviated description of the layer, then a suffix of 'FM' for feature class weight or 'CR' for continuous reclassification (fuzzy membership values).

Table A3.1 Digital geographic information system (GIS) map files provided in the ESRI Geodatabase.

GIS File Name	Description	Source Data Reference*
L1_SOURCE_MAINROCK_FM	Level 1 layer of MAINROCK types for hard rock sources	1
L1_SOURCE_SUBROCK_FM	Level 1 layer of SUBROCK types for hard rock sources	1
L2_SOURCE_HARDROCK_FM	Level 2 layer of hard rock sources	N/A
L1_SOURCE_GRAVEL_FM	Level 1 layer of gravel sources	1, 2
L2_SOURCE_GRAVEL_FM	Level 2 layer of gravel sources	N/A
L1_LANDUSE_DOC_FM	Level 1 layer of Department of Conservation public conservation land	5
L1_LANDUSE_LCDB_FM	Level 1 layer of land classification database	6
L1_LANDUSE_QEII_FM	Level 1 layer of QEII National Trust land areas	3
L1_LANDUSE_S4_FM	Level 1 layer of Schedule 4 land areas	4
L1_LANDUSE_WATER_FM	Level 1 layer of waterways and waterbodies	7
L2_LANDUSE_GRAVEL_FM	Level 2 layer of land use suitability for gravel extraction	N/A
L2_LANDUSE_HARDROCK_FM	Level 2 layer of land use suitability for hard rock extraction	N/A
L1_DEMAND_ROADS_CR	Level 1 layer of distance from roads	10
L1_DEMAND_POPULDEN_CR	Level 1 layer of distance from highly populated areas	31
L1_DEMAND_CONSTRUCTION_FM	Level 1 layer of forecast construction and building activity	8, 33, 34
L1_DEMAND_FUTURESQKM_FM	Level 1 layer of estimated future production values	8, 9, 11, 32
L2_DEMAND_FM	Level 2 layer of the combined demand data	N/A
L1_INFRAS_GEOMORPH_GR_FM	Level 1 layer of geomorphon classes for gravel quarries	30
L1_INFRAS_GEOMORPH_HR_FM	Level 1 layer of geomorphon classes for hard rock quarries	30
L1_INFRAS_HIGHWAY_CR	Level 1 layer of distance from highways	10
L1_INFRAS_POWER_CR	Level 1 layer of distance from powerlines	12
L1_INFRAS_RAILWAY_CR	Level 1 layer of distance from railways	13
L1_INFRAS_UNEMPLOYMENT_FM	Level 1 layer of the unemployment percent	14
L2_INFRAS_HARDROCK_FM	Level 2 layer of the combined infrastructure data for hard rock extraction	N/A

GIS File Name	Description	Source Data Reference*
L2_INFRAS_GRAVEL_FM	Level 2 layer of the combined infrastructure data for gravel extraction	N/A
L1_SENS_CADASTRA_FM	Level 1 layer of cadastral parcel size	15
L1_SENS_CULTURAL_FM	Level 1 layer of cultural artefacts	18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29
L1_SENS_DIST2RES_FM	Level 1 layer of distance from residential areas	16
L1_SENS_POPULDEN_FM	Level 1 layer of population density	31
L1_SENS_QUARRYDEN_FM	Level 1 layer of historic quarry sites and density of operating quarry sites	17
L1_SENS_VIEWSHED_FM	Level 1 layer of visibility analysis	30
L2_SENSITIVITY_FM	Level 2 layer of the combined cultural sensitivity data	N/A
L3_HARDROCK_AOM	Aggregate opportunity model for hard rock	N/A
L3_HARDROCK_AOM_noES	As above, but with only source, demand and infrastructure	N/A
L3_HARDROCK_AT	Aggregate opportunity model above threshold area only	N/A
L3_GRAVEL_AOM	Aggregate opportunity model for gravel	N/A
L3_GRAVEL_AOM_noES	As above, but with only source, demand and infrastructure	N/A
L3_GRAVEL_AT	Aggregate opportunity model above threshold area only	N/A

* Source data reference number refers to column 1 in the table of Appendix 1.

The digital GIS data and other digital appendices can be downloaded using the links below:



<https://doi.org/10.21420/DQKB-ET09>

APPENDIX 4 OPERATING QUARRY ANALYSIS

To understand the local demand and supply, as well as the current operating quarries, this appendix provides supplementary data on model results for each quarry site, a distance calculation to list quarries near each other (in competition for local demand) and an estimate of demand at those quarry sites, as well as in regional and city council boundaries.

Model Results

The grid values for each of the Level 1, Level 2 and Level 3 maps have been assigned to the operating quarries used in this study. The grid value of data at each quarry site can be used to determine the aggregate opportunity value of a site, the source material, the current land use or other factors such as future demand or cultural sensitivity. Data are provided as a digital appendix in file 'OPERATING_QUARRY_ANALYSIS.CSV' and look-up values can be found from Appendix 5 or other tables within this report.

Proximity Analysis

To understand which quarries may be in competition for local demand, an analysis of operating quarries that are within a 50 km radius of each other has been completed. Although a road travel distance would be more realistic, the simplistic approach of a spatial radius provides a rough approximation, and further, more detailed analyses, could be undertaken. The table 'OPERATING_QUARRY_PROXIMITY.CSV' provides a list of quarries and the names of all the quarries of the same class (hard rock or gravel) within 50 km of their site.

Future Demand Analysis

To understand the future demand quantitatively instead of qualitatively, a **demand unit value** has been calculated for each cell in the model area. This demand unit value is derived from three anomalous classes from the L2_DEMAND map that are assigned unit values of 1, 2 and 3, with 3 being high demand areas such as major cities and the lower values being less demand areas such as smaller urban areas or populated rural areas (Figure A4.1). The sum of these demand units within a 50 km radius can be attributed to operating quarries to assess their potential regional demand. This value has been included in the proximity analysis table 'OPERATING_QUARRY_PROXIMITY.CSV' (see above). The demand units can also be summed by New Zealand region (Figure A4.2) or by other areas, such as territorial authority (Figure A4.3), and levelled by the area of those regions to assess the relative future aggregate demand.

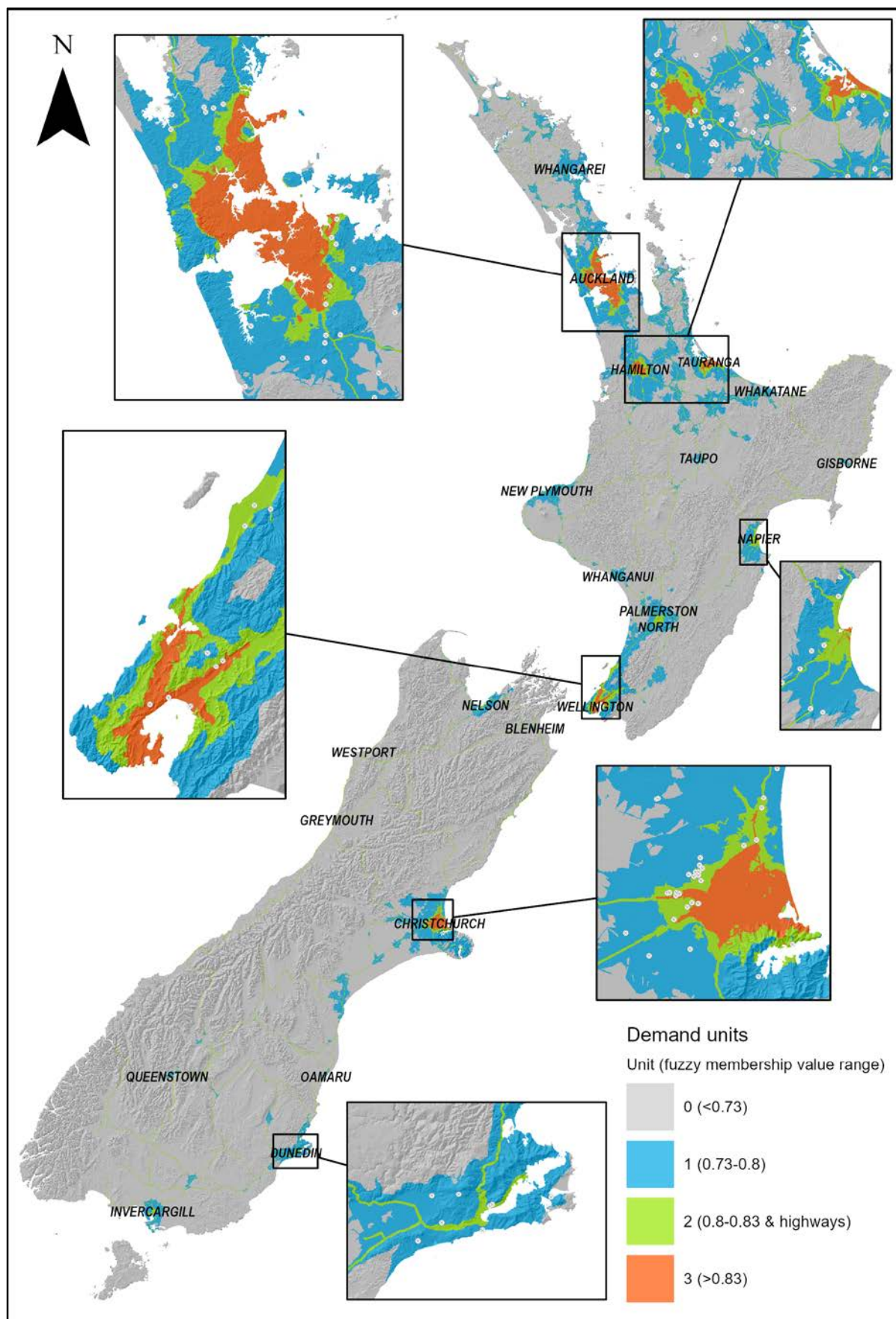


Figure A4.1 Map of demand units calculated from the L2_DEMAND predictive model component and highway locations. Demand units are regions of highest demand based on modelling of future aggregate demand in New Zealand. The higher values of demand unit represent higher aggregate demand requirements in the future.

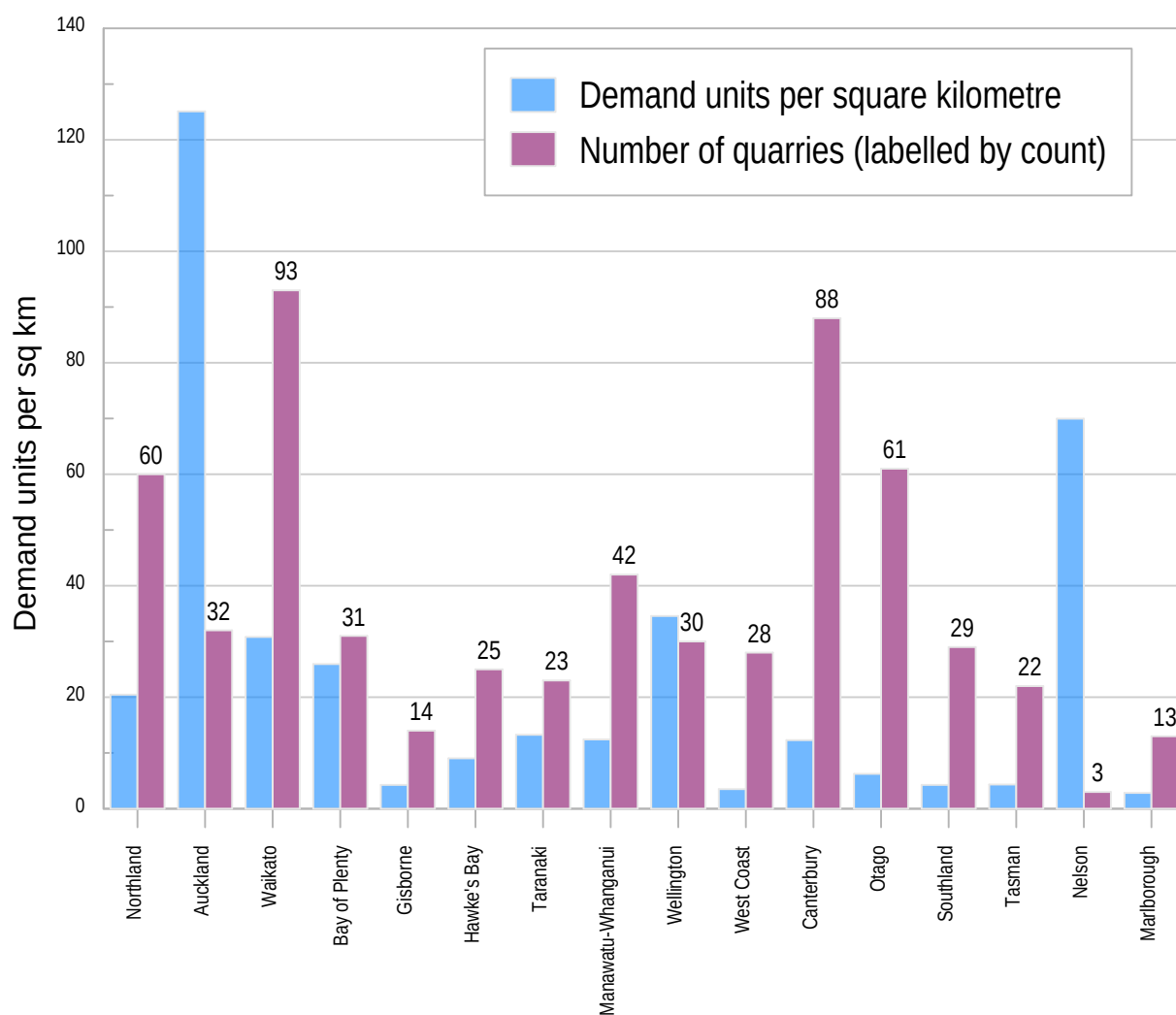


Figure A4.2 Demand unit value calculated for New Zealand regions and count of operating quarries. Demand units are based on the number of cells with moderate, high or very high demand values from the Level 2 demand predicative model component. Demand units are levelled by regional council land area.

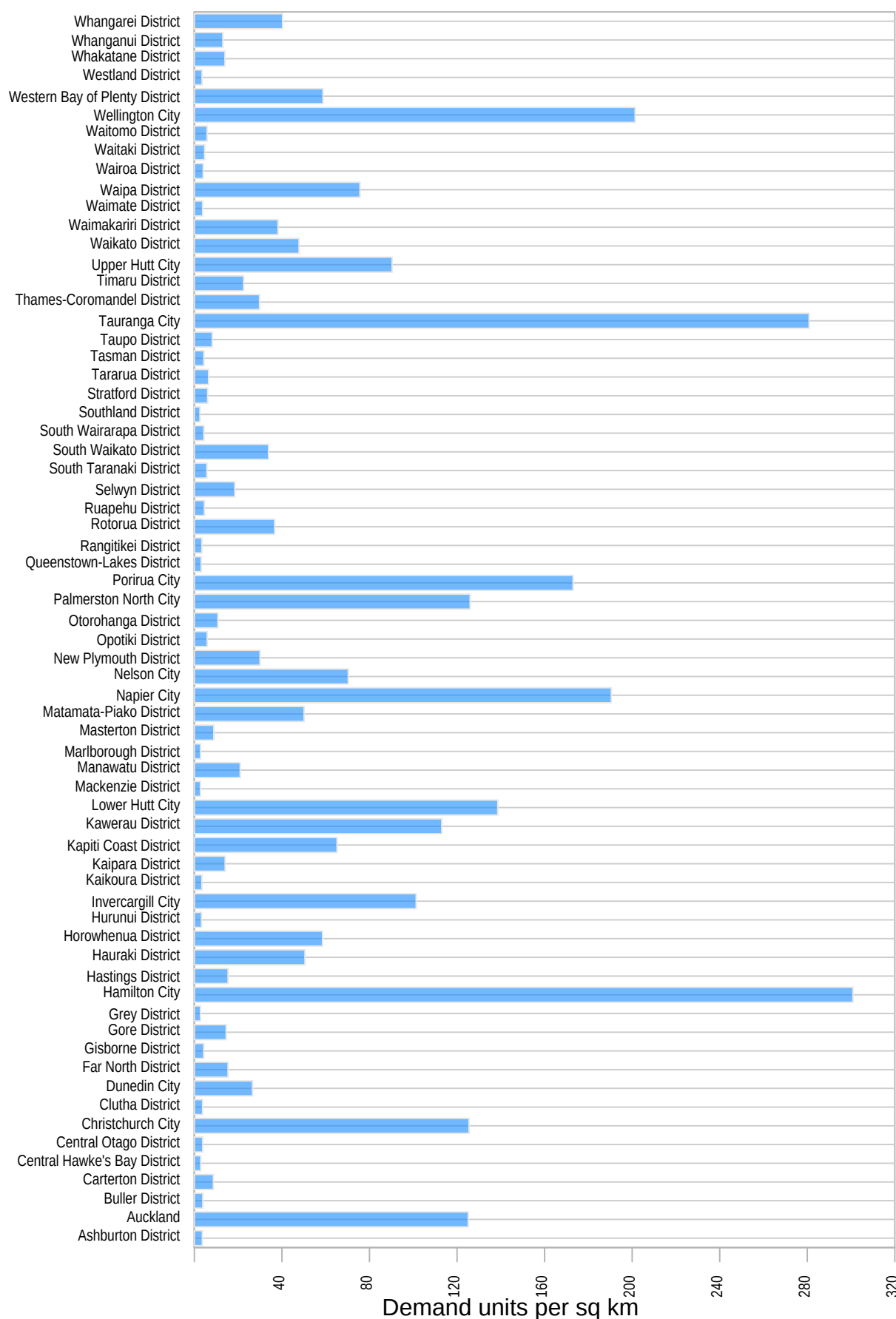


Figure A4.3 Demand unit value calculated for New Zealand territorial authorities. Demand units are based on the number of cells with moderate, high or very high demand values from the Level 2 demand predicative model component. Demand units are levelled by territorial authority land area.

APPENDIX 5 MODEL CLASS WEIGHT SUMMARY

The table below is a compilation of the map classes and associated class weights or fuzzy membership value ranges for each of the mappable criteria layers within the predictive model components. These can be used as look-up tables for digital GIS grid data in Appendix 3 or for reference when analysing map data.

Table A5.1 Class weights or fuzzy membership value ranges for mappable criteria layers used in this study.

Predictive Model Component	Mappable Criteria Layer	Description / Map Classes	Class Weight / Fuzzy Membership Value
LEVEL 2 MAPS	LEVEL 1 MAPS		
Source material Fuzzy membership values for this Level 2 component are the maximum (fuzzy OR) values from all Level 1 mappable criteria layers.	L1_SOURCE _MAINROCK	Other lithologies	1
		Other sediments (not Q)	52
		Marble	72
		Limestone	80
		Gneiss	62
		Mafic plutonic	73
		Granite	69
		Rhyolite	70
		Basalt	77
		Scoria	84
		Andesite and dacite	75
		CZ sandstone greywacke <TZ2	82
		MZ and PZ sandstone greywacke <TZ2	94
	L1_SOURCE _SUBROCK	Other lithologies	1
		Other sediments (not Q)	52
		Rhyolite	54
		Basalt	61
		Scoria	68
		Andesite and dacite	59
		CZ sandstone greywacke <TZ2	66
		MZ and PZ sandstone greywacke <TZ2	78
		Waioeka Sandstone (eK)	91
		Wairata Sandstone (IK)	92
		Whakatane Melange (eJ)	93
		Undifferentiated Lower Okiwa Group (massive sandstone) (IPI)	90
		Kaiwaka Formation (eQ)	86
		Okehu Group (eQ)	85

Predictive Model Component	Mappable Criteria Layer	Description / Map Classes	Class Weight / Fuzzy Membership Value
LEVEL 2 MAPS	LEVEL 1 MAPS		
	L1_SOURCE_GRAVEL	Other areas	1
		Other Quaternary rocks	40
		River alluvium from QMAP	71
		4 th Order in river alluvium	74
		5 th and 6 th Order in river alluvium	76
		7 th Order in river alluvium	81
		8 th Order in river alluvium	88
		Dune sand	83
		Ignimbrite, tuff and pumice	67
		Beach deposits	79
Land Use Fuzzy membership values for this Level 2 component are the minimum (fuzzy AND) values from all Level 1 mappable criteria layers.	L1_LANDUSE_WATER	More than 100 m from water feature	90
		Less than 100 m from water feature	65
	L1_LANDUSE_LCDB	Settlements and infrastructure	21
		Crop/grassland	82
		Exotic vegetation	71
		Indigenous vegetation	55
		Sand, gravel or rock	85
		Water or ice	14
	L1_LANDUSE_DOC	National Parks	10
		Scenic reserves, conservation parks, scientific reserves and sanctuary areas	15
		Wilderness, historic, nature, ecological, government, wildlife and fixed marginal areas	20
		Recreation, local purpose and amenity areas	25
		Stewardship areas	40
		Other land	90
	L1_LANDUSE_QEII	QE II National Trust land areas	6
		Other land	90
	L1_LANDUSE_S4	Schedule 4 land	5
		Other land	90

Predictive Model Component	Mappable Criteria Layer	Description / Map Classes	Class Weight / Fuzzy Membership Value
LEVEL 2 MAPS	LEVEL 1 MAPS		
Demand Fuzzy membership values of: 30, 32, 35, 38, 40, 42, 45, 48 assigned to eight classes below the break point of 0.54545; and fuzzy membership classes of: 55, 58, 60, 62, 65, 68, 70, 72, 75, 78, 80, 82, 85, 88, 90, 92, 95 assigned to 17 classes above the break point. Classes determined using natural breaks calculated in the GIS software.	L1_DEMAND_CONSTRUCTION	Class 1 (<\$0.4)	45
		Class 2 (\$0.4 – \$7.2)	55
		Class 3 (\$7.2 – \$29.2)	57
		Class 4 (\$29.2 – \$96)	60
		Class 5 (\$96 – \$261.3)	62
		Class 6 (\$261.3 – \$600)	65
		Class 7 (\$600 – \$1012.5)	68
		Class 8 (\$1012.5 – \$2700)	70
		Class 9 (\$2700 – \$4050)	75
		Class 10 (\$4050 – \$6750)	80
	L1_DEMAND_FUTURESQKM	>25000 t/sqkm	90
		5000–25,000	85
		2000–5000	80
		1000–2000	75
		500–1000	70
		250–500	65
		100–250	60
		50–100	50
		25–50	47
		<25 t/sqkm	45
	L1_DEMAND_ROADS	Fuzzification calculation from distance	0.31-0.90
	L1_DEMAND_POPUDEN	Fuzzification calculation from distance	0.26-0.90
Supporting Infrastructure Fuzzy membership values of: 30, 32, 35, 38, 40, 42, 45, 48 assigned to eight classes below the break point of 0.54545; and fuzzy membership classes of: 55, 58, 60, 62, 65, 68, 70, 72, 75, 78, 80, 82, 85, 88, 90, 92, 95 assigned to 17 classes above the break point. Classes determined using natural breaks calculated in the GIS software.	L1_INFRAS_UNEMPLOYMENT	>6.5	75
		5.8–6.5	72
		5.1–5.8	70
		4.4–5.1	68
		4.1–4.4	65
		3.7–4.1	62
		3.2–3.7	60
		2.7–3.2	50
		2.2–2.7	45
		1.4–2.2	40

Predictive Model Component	Mappable Criteria Layer	Description / Map Classes	Class Weight / Fuzzy Membership Value
LEVEL 2 MAPS	LEVEL 1 MAPS		
	L1_INFRAS _GEOMORPH_HR	Slope	80
		Ridge	75
		Spur	72
		Shoulder	70
		Other	30
	L1_INFRAS _GEOMORPH_GR	Flat	80
		Footslope	75
		Valley	70
		Hollow	60
		Other	30
	L1_INFRAS _HIGHWAY	Fuzzification calculation from distance	0.19-0.90
	L1_INFRAS _RAILWAY	Fuzzification calculation from distance	0.32-0.65
	L1_INFRAS_POWER	Fuzzification calculation from distance	0.27-0.75
Cultural Sensitivity Fuzzy membership values of: 30, 32, 35, 38, 40, 42, 45, 48 assigned to eight classes below the break point of 0.48746; and fuzzy membership classes of: 55, 58, 60, 62, 65, 68, 70, 72, 75, 78, 80, 82, 85, 88, 90, 92, 95 assigned to 17 classes above the break point. Classes determined using natural breaks calculated in the GIS software.	L1_SENS _VIEWSHED	Not visible or out of 10 km range	80
		<10	70
		10–20	65
		20–50	55
		50–100	45
		100–150	35
		>200	30
	L1_SENS _CULTURAL	Known cultural artefact	25
		Other areas	75
	L1_SENS _QUARRYDEN	No quarries in search distance (2000 m)	70
		1 quarry in search distance	75
		2 quarries in search distance	65
		3 or more quarries in search distance	40
		Historic quarrying activity	60

Predictive Model Component	Mappable Criteria Layer	Description / Map Classes	Class Weight / Fuzzy Membership Value
LEVEL 2 MAPS	LEVEL 1 MAPS		
	L1_SENS_DIST2RES	Distance 1 – too close (<500 m)	35
		Distance 2 – getting a bit close (500–2000 m)	65
		Distance 3 – best (2000–7000 m – 80%)	85
		Distance 4 – getting a bit far away (7–20 km)	70
		Distance 5 – too far away (>20 km)	60
	L1_SENS_POPULDEN	>200 people per km ²	20
		100–200 people per km ²	60
		50–100 people per km ²	75
		Less than 50 people per km ²	80
	L1_SENS_CADASTRA	Parcels <1000 m ³ and roads	25
		Parcels 1000–5000 m ³	40
		Parcels 5000–10,000 m ³	55
		Land >10,000 m ³	80

APPENDIX 6 MAP CLASS SUMMARY

The following charts illustrate the relationship between the currently operational quarries selected as training data and the classes of map data used in this study.

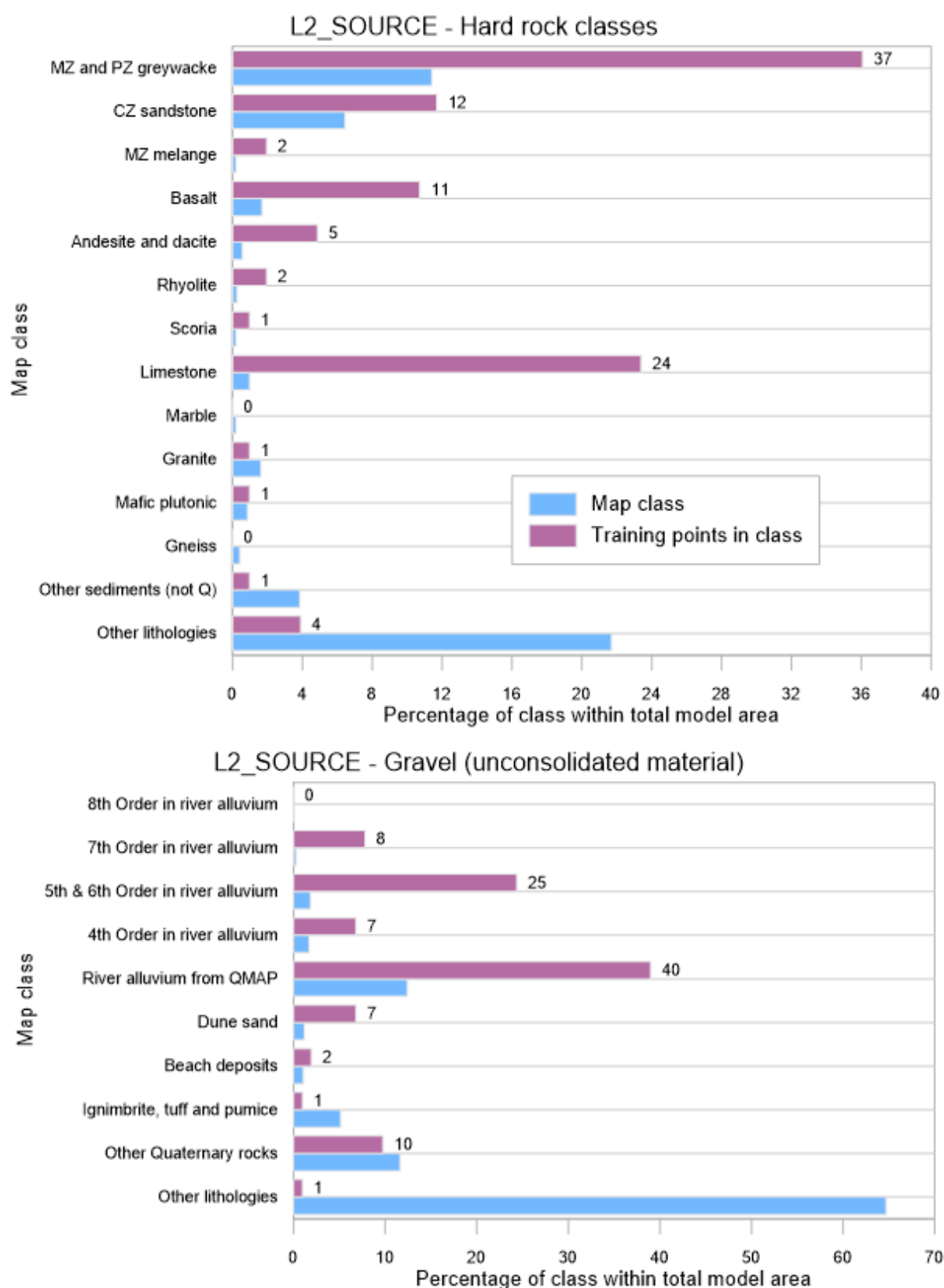


Figure A6.1 Level 2 source map classes shown as percentage of total model area and count of training data sites that fall into those classes.

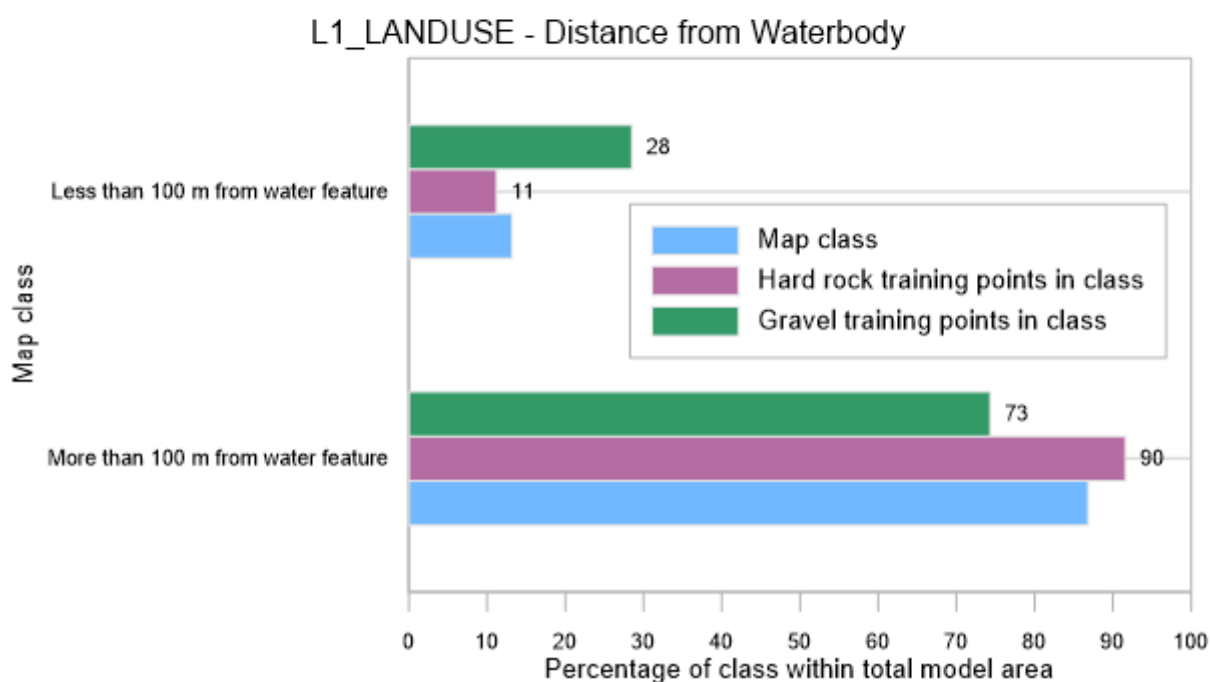
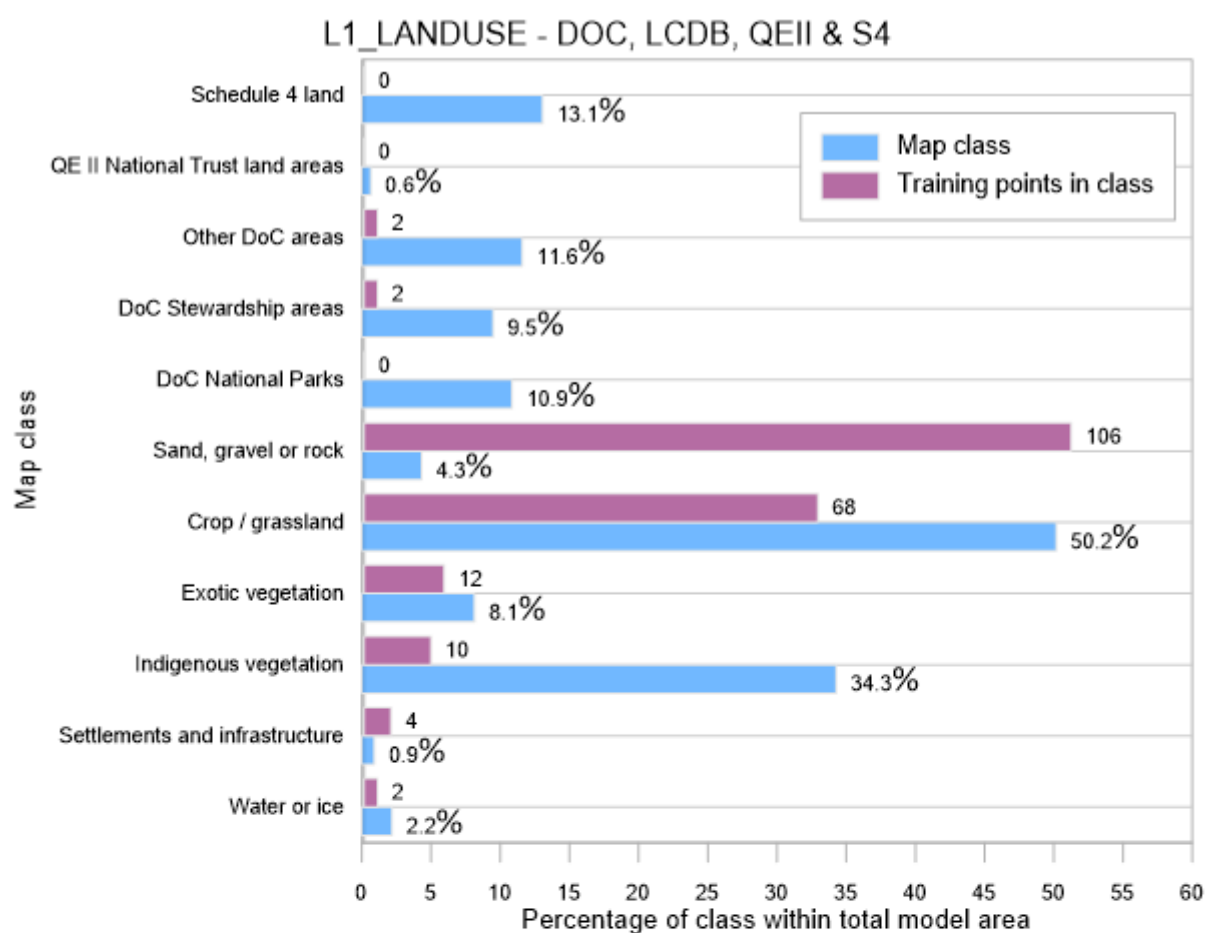


Figure A6.2 Level 1 land use map classes shown as percentage of total model area and count of training data sites that fall into those classes.

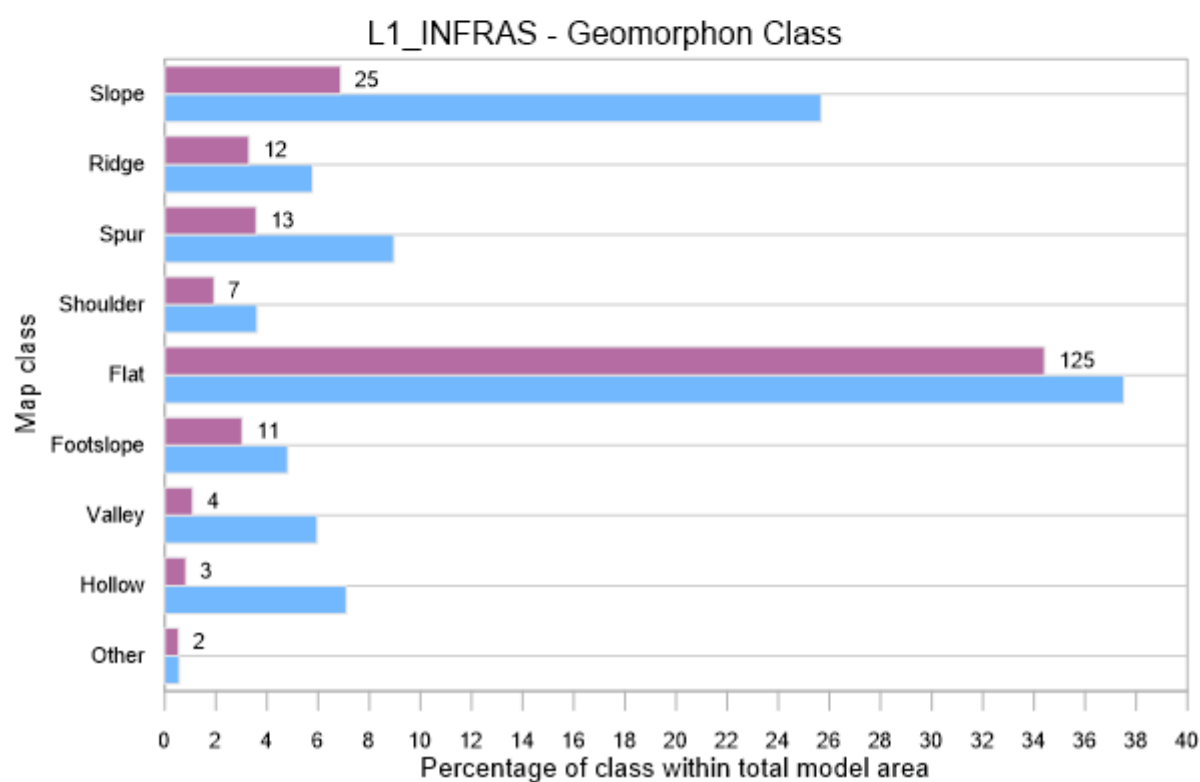
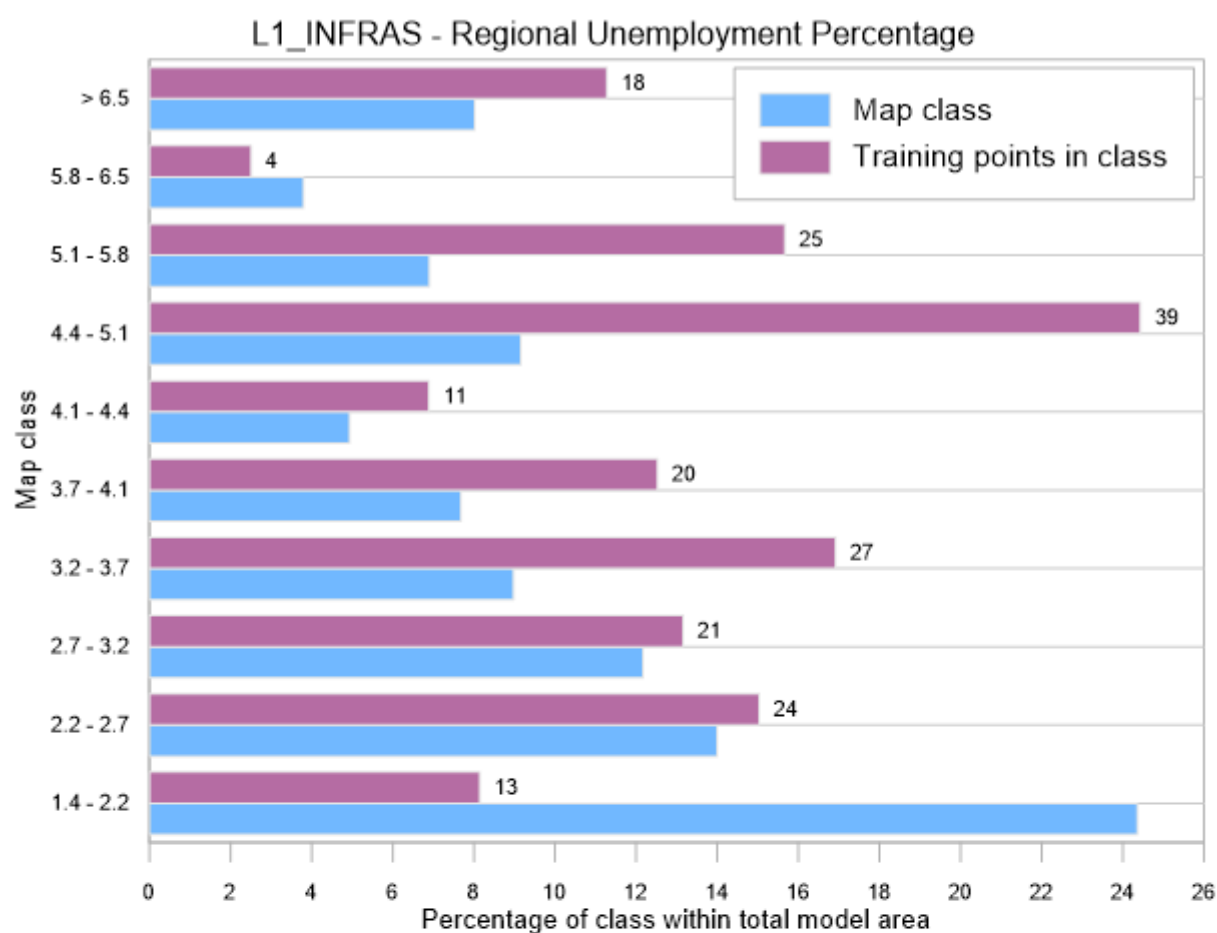


Figure A6.3 Level 1 supporting infrastructure classes for unemployment and geomorphon classes shown as percentage of total model area and count of training data sites that fall into those classes.

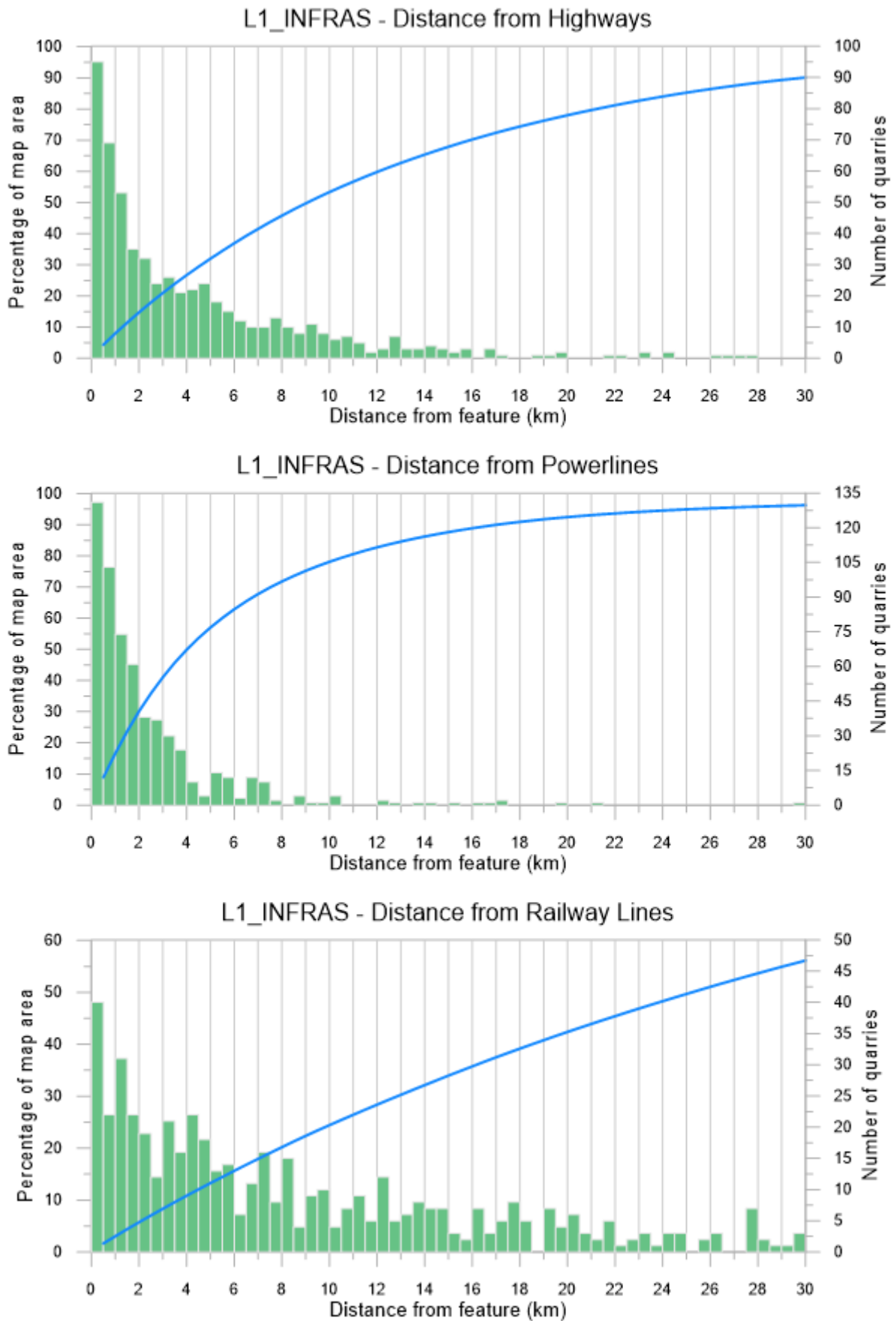


Figure A6.4 Level 1 supporting infrastructure classes for distance from highways (top), distance from powerlines (middle) and distance from railway lines (bottom) shown as cumulative percentage of total model area with increasing distance (line) and count of training data sites that fall into 500 m classes (bars).

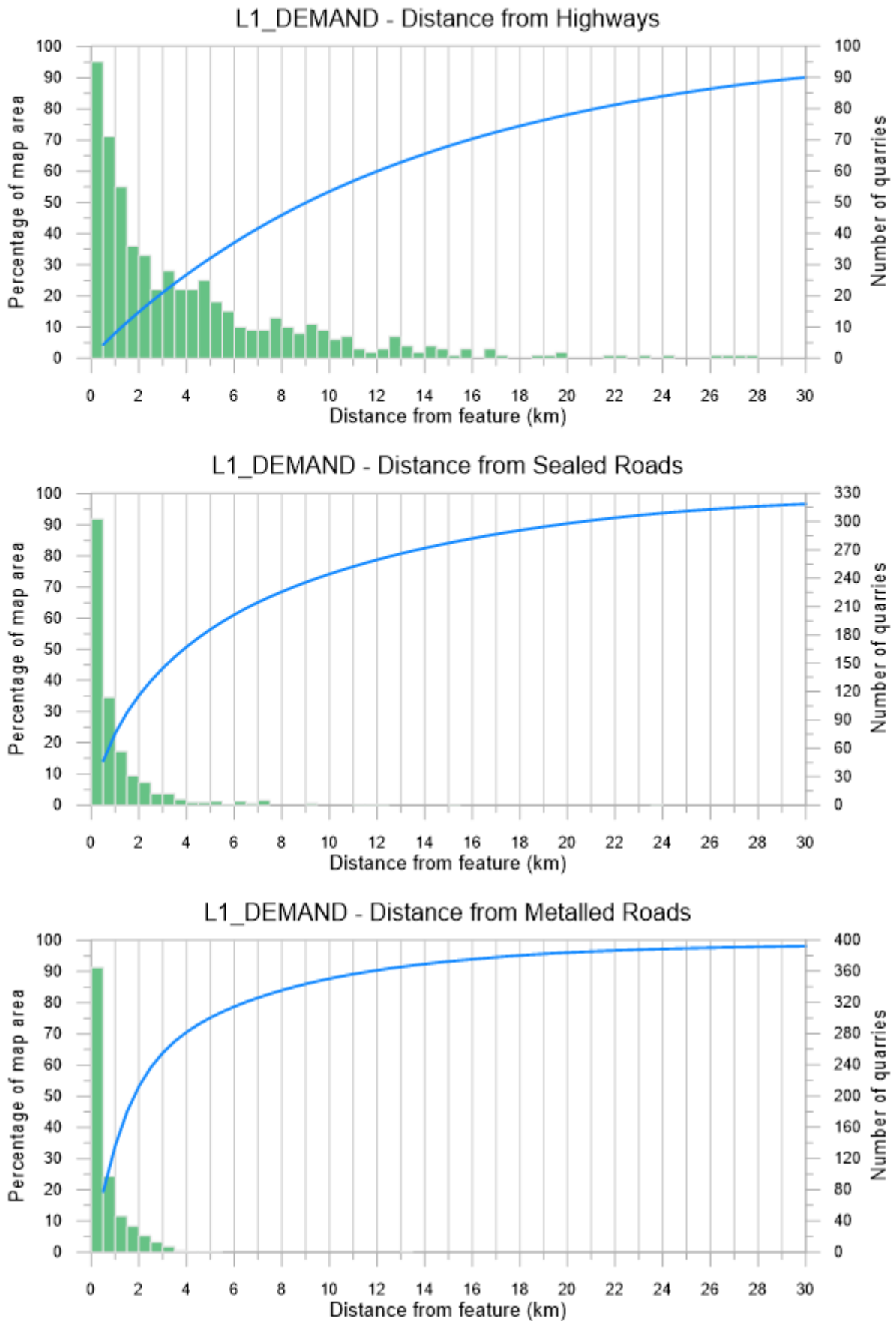


Figure A6.5 Level 1 demand classes for distance from highways (top), distance from sealed roads (middle) and distance metalled roads (bottom) shown as cumulative percentage of total model area with increasing distance (line) and count of training data sites that fall into 500 m classes (bars).

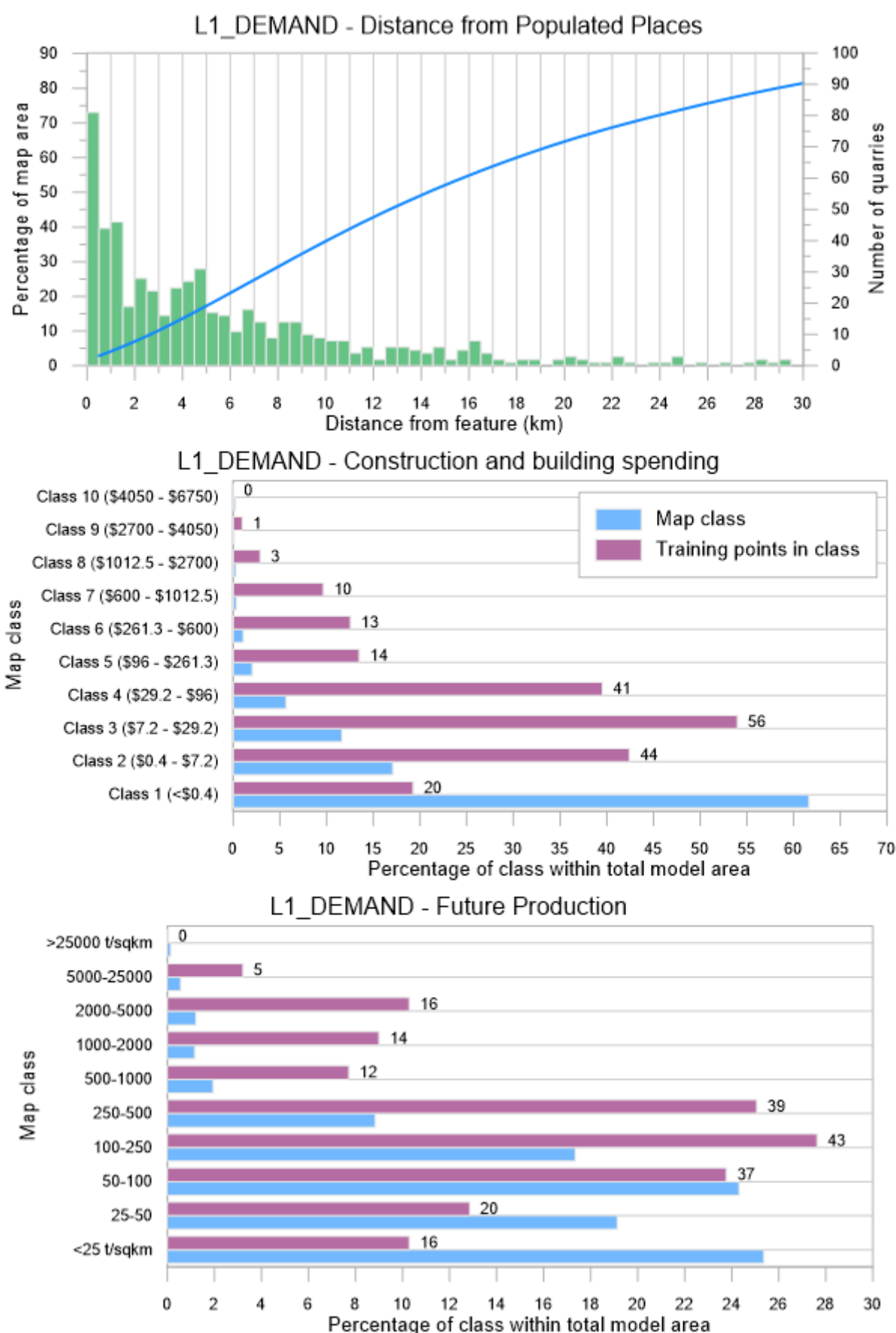


Figure A6.6 Level 1 demand data for distance from populated areas (top) shown as cumulative percentage of total model area with increasing distance (line) and count of training data sites that fall into 500 m classes (bars); and construction and building spending classes and estimated future production.

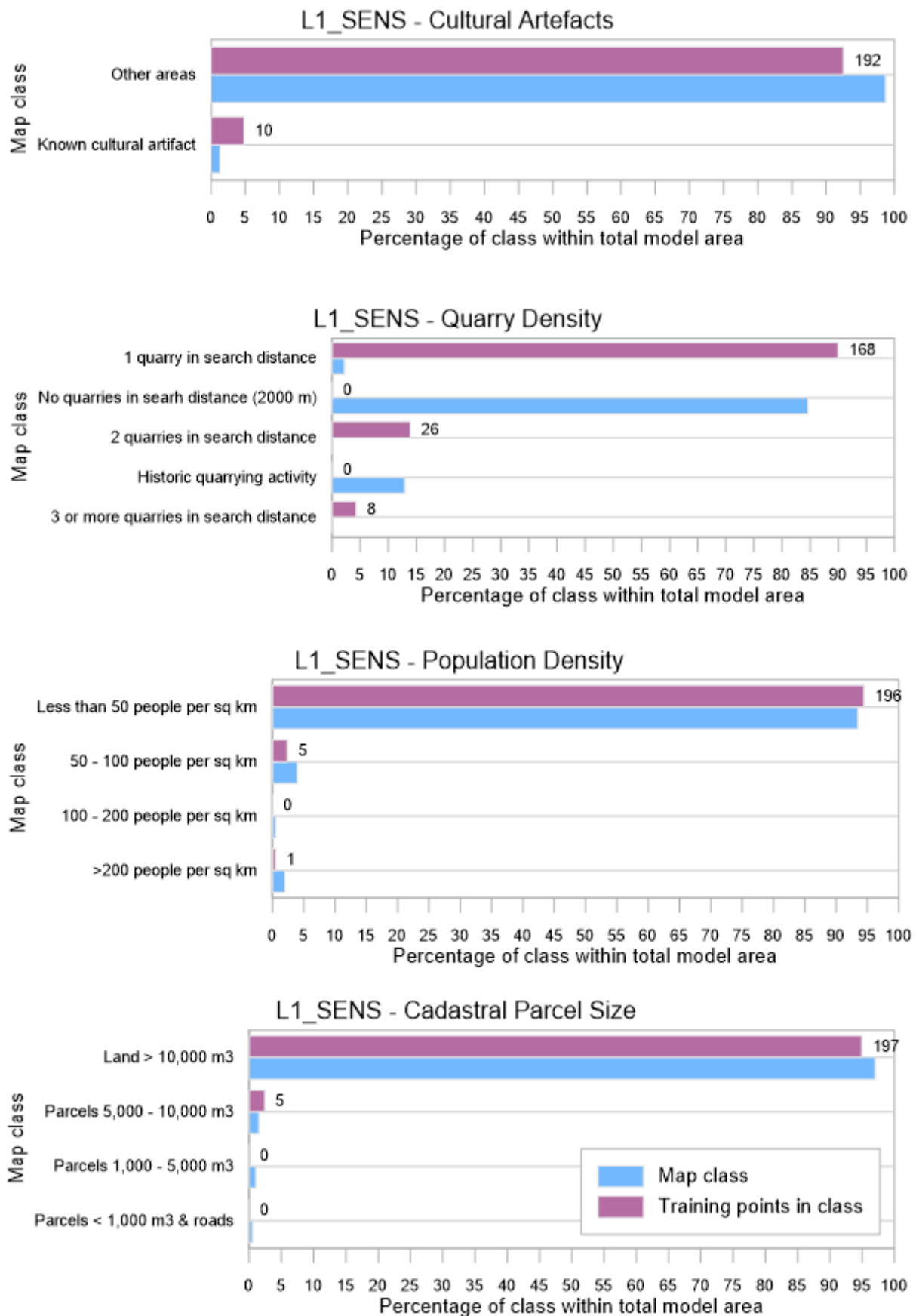


Figure A6.7 Level 1 cultural sensitivity classes for cultural artefacts, quarry density, population density and cadastral parcel size shown as percentage of total model area and count of training data sites that fall into those classes.

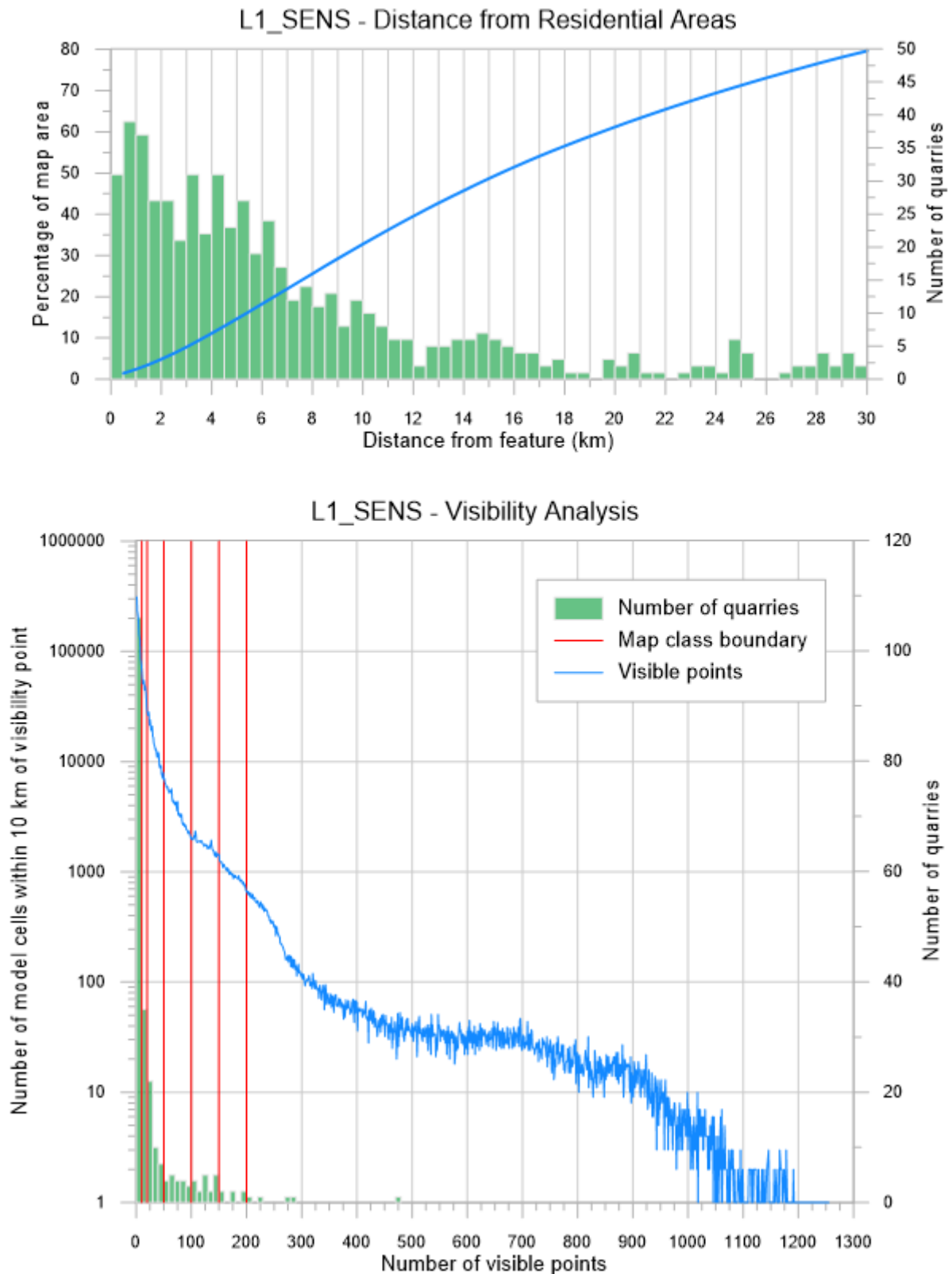


Figure A6.8 Level 1 cultural sensitivity data for distance from residential areas (top) shown as cumulative percentage of total model area with increasing distance (line) and count of training data sites that fall into 500 m classes (bars); and visibility analysis showing the number of model cells within the 10 km visibility distance analysis area for each value of visible point count (blue line), the map class range cut-off values (red lines) and the number of visible points for operating quarries in New Zealand (green bars).



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