

Aggregate Opportunity Modelling for the central and northwestern Otago area of New Zealand

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ABSTRACT

Efficient utilisation of aggregate resources is important for supporting infrastructure development and reducing operational and transport costs related to extraction of hard rock, gravel and sand aggregate materials. Aggregate opportunity has been mapped in the central to northwestern parts of Otago, encompassing much of the Queenstown Lakes and Central Otago districts. The presence of aggregate resource potential is a consideration for prioritising future land uses to support our growing economy. Delineated aggregate opportunity areas (places that have overlapping spatial data classes favourable for extractive activities) indicate where there is potential that an aggregate resource could be developed, provided that follow-up site-specific investigation confirms the geotechnical suitability of the material and that extractive activities would be compatible with factors such as community and iwi values and land-use zoning.

A spatial modelling approach using Geographic Information System (GIS) software forms the basis of aggregate opportunity modelling. The modelling involves three successive steps: classification of source data into mappable criteria layers, combination of criteria layers into predictive model components and generation of maps showing the spatial model results. A final component is creation of an overall aggregate opportunity model, emphasising areas with generally high potential for aggregate resources. In total, 19 mappable criteria layers were compiled from various source data and classified via aggregate-relevant parameters. Each map class was assigned a class weighting value that qualitatively ranks its importance as an aggregate indicator using expert knowledge from industry experts and spatial statistics. Fuzzy logic modelling was used to combine mappable criteria information and generate four categories of predictive model components (source material, land use, quarrying feasibility and cultural sensitivity). The four categories of predictive model components were combined into maps of spatial model results, which depict the aggregate opportunity, ranked from low to high, for three types of material (hard rock, gravel and sand). The spatial model results data were analysed and filtered to produce the overall aggregate opportunity model. These map-based GIS datasets of sand, gravel and hard rock aggregate opportunities can be used to manage aggregate resources, generate targets for exploration activities and provide insight into future resource development.

This approach acknowledges regulatory, economic and community-sensitivity considerations for aggregate prospectivity, while providing valuable insights into aggregate resource distribution and potential extraction sites. In the Otago project area, the hard rock opportunity is dominated by schist, which has some limitation for use as roading aggregate; hard sandstone ('greywacke') is generally a better aggregate material but, with its occurrence largely confined to the far northeast, its economic opportunity is notably more limited compared to schist. Other bedrock material types such as weak sandstone, conglomerate, limestone and volcanic rock (basalt) are largely confined to the eastern part of the project area, with limited localised distributions. Poorly consolidated river and stream deposits offer regionally extensive opportunities for gravel and sand resources in most of the valleys and basins of the central and northwestern Otago area, with particularly good opportunity east of Wānaka, around and north of Lake Dunstan, in the Manuherikia Valley and in the Maniototo Basin near Ranfurly. Sand is likely to be a companion material within many of the gravel opportunity sites, as well as within Neogene-age sand-dominated rock units. This project's findings facilitate informed decision-making for sustainable resource utilisation and infrastructure development in the central and northwestern Otago area.

KEYWORDS

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

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1.0 INTRODUCTION

The development of infrastructure requires large quantities of hard rock, gravel and sand aggregate material for roading, concrete and construction. New Zealand is fortunate to have large areas of accessible rock and gravel deposits throughout most of the country that can be utilised for aggregate. Much of this material is only slightly weathered at or near the surface. Aggregate in New Zealand can be largely grouped into three classes: (1) hard rock, including greywacke, sandstone, volcanic rocks and limestone; (2) gravel, particularly from river channels and alluvial terraces; and (3) sand from inactive and active dunes and river channels. This project uses a desktop approach to model opportunities for potential aggregate locations in the central and northwestern Otago area using geological, land use and other topographic and cultural considerations and builds on previous studies by Hill (2021).

Aggregate materials are ideally extracted near to their intended location of use to minimise the cost and emissions of transportation. Identifying where there are suitable resources and understanding the land use, transport distance factors and people's sensitivity to extractive activities are important considerations for planning future aggregate extraction locations in a process referred to as opportunity modelling (Hill 2021). Aggregate opportunity modelling is done by a desktop method using computer spatial analysis of map-based databases of geological, rock properties, land-use, infrastructure and cultural information to rank areas for future extraction potential. New Zealand's production of aggregate is approximately 45 million tonnes (Mt) per year (AQA c2022), with more than 75% occurring in the North Island (Christie et al. 2001). Production is forecast to increase, and new aggregate resources are necessary for continued development of New Zealand's infrastructure.

Aggregate suitability is determined by its physical properties (strength, durability, cohesiveness, size), chemical properties, few or no deleterious minerals and good homogeneity and volume of material at a quarry site. As well as these technical criteria, 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. The cost of aggregate doubles after ~30 km of transportation distance (NZIC 2021), so local sources are desirable for the cost-effectiveness of new infrastructure projects. Future aggregate prospectors and resource planners should carefully consider all of these parameters when seeking new quarry sites.

This project has mapped areas of **aggregate opportunity** using spatial modelling tools available in Geographic Information System (GIS) software. Aggregate opportunity areas are ranked higher where data indicate the likely existence of suitable aggregate material close to transportation routes and locations of use, with few adverse cultural, social and environmental factors. Also relevant to identifying aggregate potential are non-spatial considerations such as community values and legal frameworks, as well as ecological and human health factors. These non-spatial considerations are difficult to include in broad-scale aggregate opportunity models but can be approximated through proximity analysis (the closer they are to aggregate operations, the greater the sensitivity).

This modelling project uses the **aggregate opportunity concept** (Hill 2021), which identifies several important factors that must be present together for the occurrence of suitable aggregate, along with important considerations that tend to be unfavourable for quarry development (contra-indicators). Maps of geological material types, land use, quarry feasibility and sensitivity to extractive activities are used to represent all components of the aggregate opportunity concept. Map information is classified into subjective ranges and weighted relative to the aggregate opportunity concept by considering advice from industry experts and modelled ranges using spatial statistics.

There is complete coverage of the central and northwestern Otago areas by the GNS Science 1:250,000-scale geological map (Heron 2023), with accompanying illustrated descriptive books for the Wakatipu and Waitaki regional sectors of the geological map (Turnbull 2000; Forsyth 2001). This geological map series is commonly called 'QMAP' because it is a Quarter-Million-scale-mAP. The three basic components of the geological sequence are: (1) basement rock that is part of the Earth's crust, (2) layers of sedimentary or volcanic rock that sit on the basement ('cover strata') and (3) poorly consolidated sediments that form localised veneers over older rocks. In the project area, basement rock is mainly metamorphic schist that transitions towards the southwest and northeast into progressively lower-grade semi-schist and then unmetamorphosed 'greywacke' sandstone. In the far west, the basement is intrusive igneous rock. The cover strata are preserved mainly in the topographic basins and include relatively weak quartz-rich sandstones and mudstones, with localised areas of limestone, volcanic strata and greywacke conglomerate. The poorly consolidated sediments are mostly gravelly, with variable amounts of sand and mud, deposited by the action of rivers and streams and, in the northwest, by glacier action or through shoreline processes around lake margins. In hill terrain, the poorly consolidated sediments include landslide debris and scree/rock fall deposits.

Using the QMAP dataset, the geological sequence of the central and northwestern Otago area has been divided into 12 **aggregate type classes** (Figure 1.1). Basement rock is separated into schist (including semi-schist), 'greywacke' (Mesozoic sandstone) and three classes of intrusive igneous rock (diorite, gabbro, granite). Cover strata and poorly consolidated sediments are divided into older (Paleogene) and younger (Neogene) sandstone, limestone, basalt, gravel or sand, and sand. The basement rock resources are generally encountered in ridges and slope faces, while gravel or sand resources are generally found in the valleys, basins and near-to-basin margins. This project uses spatial modelling to highlight areas where there is good aggregate opportunity for each of those classes.

This report presents the aggregate opportunity for the central and northwestern Otago area, from Hyde in the east to the Main Divide of the Southern Alps in the west (Figure 1.1). The project area has approximately 130 operating or recently operated quarries that mostly extract poorly consolidated gravel or schist rock, with a lesser number of quarries targeting basalt, sandstone or sand. Most of the aggregate used for roading and concrete is sourced from gravel deposits. Quarried rock is used mainly for riprap (armour rock), drainage, retaining walls and building stones; schist is prone to chemical weathering due to high mica content and delamination of the schist layering, which weakens the rock and makes it less suitable for roading chip (Reyes et al. 2003).

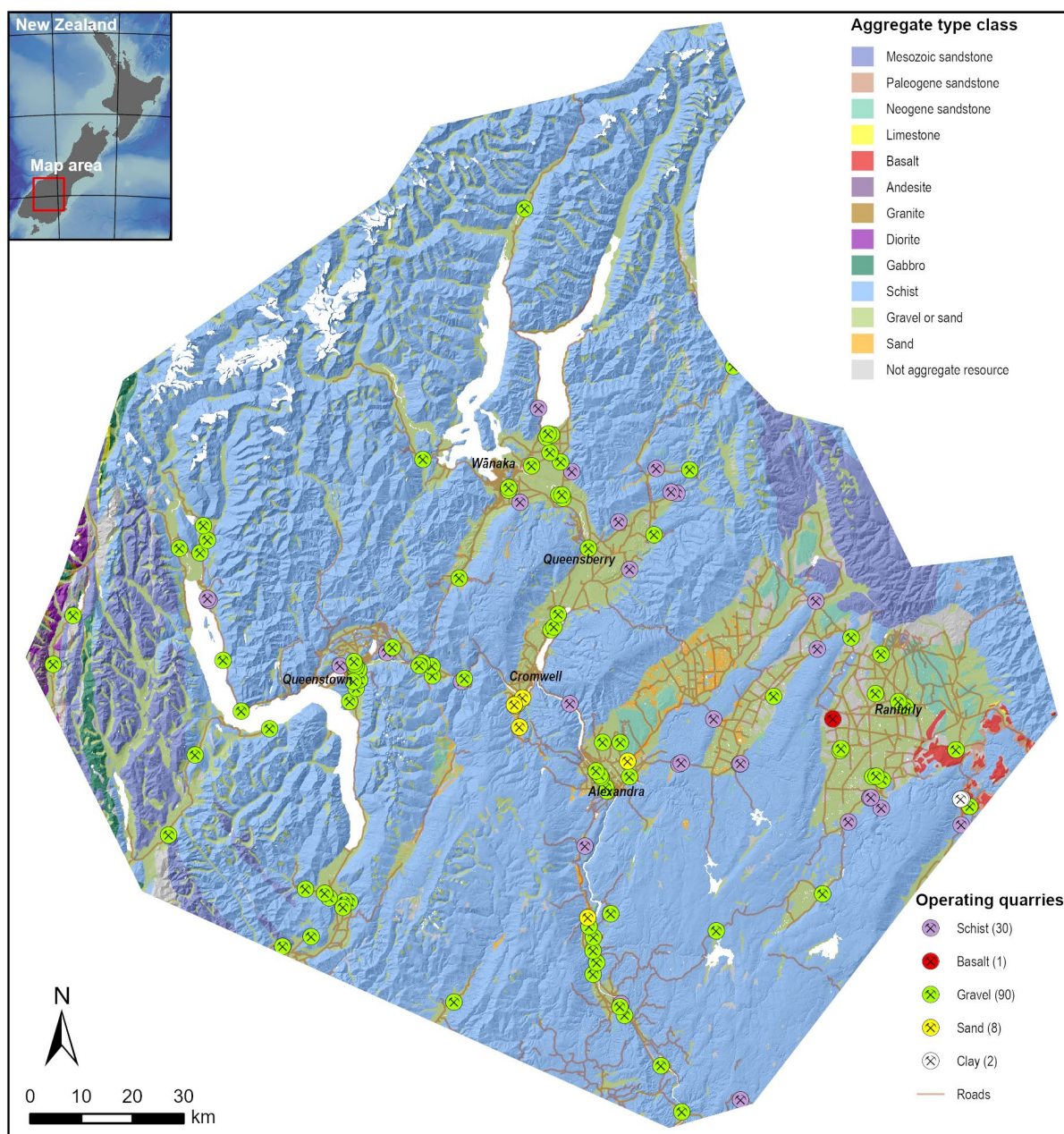


Figure 1.1 Map of aggregate type classes and the extent of the modelled area in the Queenstown Lakes and Central Otago districts. Aggregate type class is based on interpretation of the 1:250,000-scale geological map (Heron 2023), based on data fields: map unit name, description, main and sub-rock types, and age. Quarry locations from the Aggregate and Quarry Association New Zealand Quarry Database (AQA 2024).

2.0 DATA SOURCE, APPROACH AND SPATIAL ANALYSIS

The assessment of aggregate opportunities is well suited to spatial modelling techniques, as much of the information required is readily available in digital databases and continuous across the entire project area. Sources of the digital datasets include Toitū Te Whenua 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). The GIS is used to analyse the digital data and generate map classifications based on geology, land use, important infrastructure and cultural factors. Source data from various agencies (for example, geological data from GNS Science, protected land areas from DoC and population density from Stats NZ) were analysed and classified using dataset-appropriate GIS-based spatial techniques as summarised in Appendix 1 (see examples in Robinson et al. [2004], Blachowski [2014]; Blachowski and Buczyńska [2020] and Hill [2021]).

Classifications of these source data represent mappable criteria layers for the modelling (Figure 2.1). The Level 1 component of the modelling created 19 mappable criteria layers for the project area. The maps are 32 x 32 m cell size grids built with the GIS software, and the information fields in each dataset were used to arrive at a best representation of input data for the predictive components of the aggregate opportunity concept, while minimising co-dependence (e.g. duplicating more or less the same information across different datasets). Variably weighted groups of the mappable criteria layers were then combined to form four Level 2 predictive model component maps (Source material, Land use, Feasibility and Cultural sensitivity). These component maps were then weighted and combined using spatial modelling to form the Level 3 aggregate opportunity models (see Section 3).

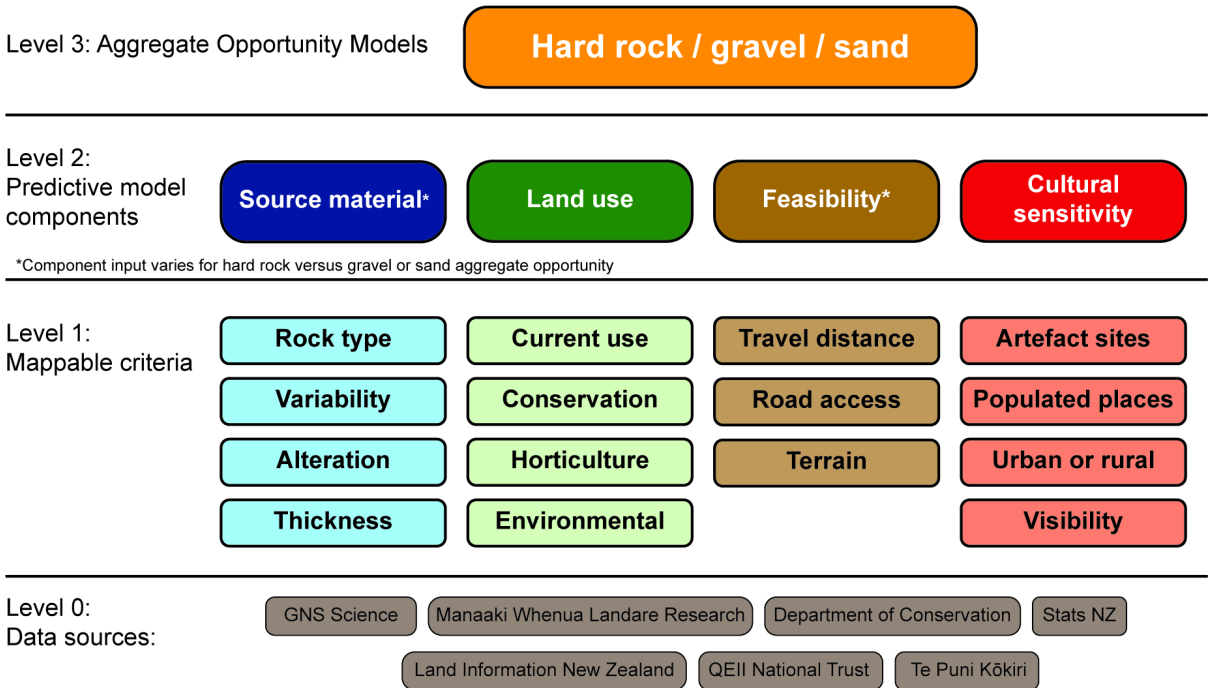


Figure 2.1 The aggregate opportunity concept involves classification and ranking of source data into mappable criteria layers that are variably weighted to support the predictive model components of Source material, Land use, Feasibility and Cultural sensitivity. The components are then weighted and combined into the Hard rock, Gravel and Sand aggregate opportunity models (modified after Hill [2021]).

For each of the mappable criteria layers, the map units (for example, different rock types, distance to public roads or distribution of population) are assigned a **class weight** between 0 and 100 (see Appendix 2). The class weight numerical values are assigned by expert opinion or derived from spatial statistics. They represent an assessment of the relative importance of a feature or map area classification to possible quarrying opportunities. For this project, a class weight of 50 indicates a neutral quarry opportunity (e.g. distance from a road that is neither ideal nor uneconomic). Progressively smaller values indicate increasingly unfavourable qualities (e.g. proximity to residential areas), while values beyond 50 indicate increasingly positive quarry opportunity. Most class weights range from 10 (for example, high-value conservation land) to 90 (for example, presence of a highly desirable rock type). Within the GIS, class weights are converted to **fuzzy membership values** for modelling by dividing them by 100 to give values between 0 and 1.

The class weighting approach has been guided by advice from New Zealand industry experts and local or regional council representatives. This guidance improves confidence that weights realistically represent the aggregate opportunity concept, especially for datasets where spatial statistical analyses were not applicable. GIS-based statistical approaches used spatial analyses of mapped parameters and weights-of-evidence analysis (see Hill [2021]) to test the correlation of mappable criteria layers with existing quarries.

The mappable criteria components are outlined in the subsections below, grouped under the headings of the Level 2 components and shown on a series of maps in Appendix 3. The Level 2 and 3 components are described and discussed in Section 3.

2.1 Source Material

The location and characteristics of source material is a fundamental component of the aggregate opportunity concept. There is generally good knowledge of geological material types and composition in the central and northwestern Otago area from existing 1:250,000-scale QMAP geological maps (Turnbull 2000; Forsyth 2001; and references therein). However, these maps are highly generalised and do not convey location-specific detail relevant to quarrying, such as proportions of interbedded sandstone and mudstone, or physical characteristics such as rock density, planes of weakness and fracturing, the degree of weathering or mineral composition of sands. This highlights that aggregate opportunity modelling is primarily aimed toward identifying potential target locations for aggregate, but there is still a need for site-specific investigation to determine the suitability for quarrying at any target location.

For example, if a hard rock resource is sought, the best material will generally be a strong rock with a consistent composition relatively free from significant jointing, fractures and weathering. The ideal gravel resources link to the intended use of the material. If the intent is to crush the gravel to a range of grain-size products, gravel with uniformly sized, hard, unweathered clasts free of reactive minerals, organic material and clay coatings may be best. Conversely, if seeking gravel that will pack down well, slightly weathered angular gravel with a range of grain sizes may be ideal. Sand can be the product of erosion of many different rock types. In New Zealand, sand typically contains quartz, feldspar and, locally, iron oxides and other heavy minerals. Sand resources can be sourced from weak sandstone, sand-rich materials from dunes or beaches or sandy matrix gravel deposits or these can be manufactured from crushing of coarser gravel-sized material. Like gravel deposits, sand should also be free of finer-grained material, should be inert and should not contain organic material or salts.

The various information fields in the QMAP dataset provided the geological input for the modelling. Over 250 unique classes of lithology (based on map name, description, lithology and age fields) are classified into 58 mappable criteria units (Appendix 3 – Map 1: Lithology) and given class weights based on their composition relative to an ideal source rock (Appendix 2). The QMAP geological map units are also reviewed in terms of subordinate rock material variability; rock units with less variability (monolithic) are more favourable than those with a lot of different material types. An assessment based on the unit description and lithology types of how variable the different materials are in each map unit, using a subjectively ranked scale from monolithic to highly variable (Appendix 2), is used to map that variability (Appendix 3 – Map 2: Subrock variability).

Other information in the QMAP dataset includes mapped locations of geological faults. Areas within or close to fault zones may be less favourable for quarry sites seeking hard rock because of closely spaced fracturing and/or alteration. Such sites may, on the other hand, be well suited if the target material is rock for crushing into gravel. Mappable criteria classes were created based on the proximity to major faults and distance from the fault (Appendix 3 – Map 3: Faults). A notable spatial correlation between mapped soil permeability classifications (LRIS 2010b) and gravel or sand resources helps distinguish between well-draining gravel or sand areas and areas of peat or finer-grained clay-dominated sediments (Appendix 3 – Map 4: Soil permeability).

2.2 Land Use

Land use is one of several non-geological information sources used in the modelling. Data from these sources include the locations and extents of various types of land-use classification that bear upon the possibility or suitability of particular land areas for quarrying. Five mappable criteria layers were created to quantify land-use parameters:

1. The LINZ cadastral database was used to identify areas of water conservation, environmental protection, parks, cultural sites (for example, hospitals, schools, cemeteries, historic reserves, etc.) and roads via a keyword search of the statutory actions data field (Appendix 3 – Map 5: Cadastral parcels).
2. DoC-managed public conservation land areas, with 21 types of conservation land differentiated using the Section data field. Class weights (Appendix 2) were assigned relative to conservation importance, ranging from 5 (National Parks, which are not suitable for quarrying activities) to 40 (stewardship areas where quarrying may be appropriate) (Appendix 3 – Map 6: Department of Conservation land).
3. The Land Cover Database (LCDB; LRIS Portal 2019) classifies New Zealand land area according to different types of vegetation and land uses, based on satellite survey data. There are 34 different types in the project area. This dataset is particularly useful for identifying areas of ecologically significant indigenous native vegetation, high-value cropland or areas more suitable for quarrying activities such as exposed rock or harvested forest. Each LCDB land-cover type was assigned an expert-assessed class weight based on the current land-use suitability for extractive activities (Appendix 2) (Appendix 3: Map 7: Land use classification database [LCDB]).
4. The Land Use Capability (LUC; LRIS Portal 2010a) database categorises land into eight classes based on its long-term productivity using physical qualities of the land, soil and environment. The National Policy Statement for Highly Productive Land (Ministry for the Environment and Ministry for Primary Industries 2022) promotes more restrictions being applied to LUC classes 1, 2 and 3 (land with no to moderate limitations for arable use). Lower weights (36–65) were assigned to these classes (Appendix 2), with weights between 70 and 96 assigned to other classes (Appendix 3: Map 8: Land use capability [LUC] class).

5. QEII National Trust land areas are located throughout New Zealand and, due to their protection status, are inappropriate for quarrying activity. These were assigned a very low class weight (6; Appendix 2) in the model (Appendix 3: Map 9: QEII National Trust covenant land).

2.3 Feasibility

Ideally, quarry developments should be close to supporting infrastructure, such as the road network, and end-users of the extracted material and should also be located within suitable terrain for the style of extraction activity and deposit type. This model component has used datasets to represent quarry feasibility that includes the distance from roads classified by size and use, as well as the driving distance along the roading network to potential aggregate end users. The assessment of suitable terrain for the style of extraction activity and deposit type is also included as part of the feasibility analysis.

The nature of the terrain is included as part of the feasibility component, as terrain affects the style of extraction at specific sites. In general, hard rock quarries favour steeper sites to access less-weathered material and to minimise the removal (stripping) of the overburden. Gravel and sand quarries are typically found in low-lying terrain, where materials have been deposited by river or dune systems. This project used an automated GIS method of analysing digital terrain models (geomorphon modelling; Jasiewicz and Stepinski 2013) to classify the project area into 10 terrain types (for example: ridge, slope or flat). Assignment of class weights was based on where the terrain is most suitable for quarrying. To reflect that different types of terrain are better suited to hard rock versus gravel/sand quarrying, two different class weight schemes were applied to the map units, one for hard rock and the other for gravel or sand quarrying, as shown in the predictive model component maps (Appendix 4, Maps 5 and 6; see Section 3.1) (Appendix 3 – Map 10: Geomorphon terrain class).

Transport cost is a key factor in the economics of aggregate production and supply. A GIS analytical method ('service area') was applied to classify the driving distance along sealed or two-lane metalled roads in relation to three population centre sizes: major, large and minor. A further analytical factor was applied to capture across-country distances away from those roads as a way of representing the cost involved in track or road development for off-road quarrying. Based on these considerations, class weights were determined from a small fuzzification function (Hill 2021) to produce the mappable criteria layer (Appendices 2 and 3). The weighting most favours proximity to larger populations where demand for aggregate can be expected to be greatest (Appendix 3 – Map 11: Driving distance).

Development of roads and tracks to access a new quarry site is an expensive investment. To incorporate this consideration, an across-country distance analysis of from three types of roads (highways, sealed roads and gravel roads) in the LINZ Topo 50 road data was used in the modelling (i.e. the approximate length of new road or track that would need to be developed). To create class weights, a small fuzzification function was used to calculate a fuzzy membership value dependent on the surface type and distance from the roads (Hill 2021) (Appendix 3 – Map 12: Road access).

2.4 Cultural Sensitivity

For all extractive activities, cultural sensitivity and social licence to operate are important considerations. Ideally, quarries should be located close to their markets, but the sensitivity of residents to quarrying can place significant constraints on operators. This project has created four mappable criteria layers that represent sensitivity considerations in relation to extractive activities:

1. Cultural sites and features such as archaeological sites, airstrips, cemeteries, hospitals, schools, historic sites, pā, marae, sport and recreation sites are identified and, together with an avoidance perimeter around those features, a low class weight is assigned to represent the general unsuitability of such sites for quarry development. Suitable perimeter distances have been determined from a spatial analysis of such sites and current operating quarries around New Zealand (Appendix 3 – Map 13: Cultural sites and features).
2. To show the extent of populated areas, a mappable criteria layer was produced through analysis of a LINZ dataset on large building locations, as well as a Stats NZ population density dataset (Appendix 1). A function was applied to delineate areas of lesser favourability for quarrying close to large buildings (>100 m²) and population centres. Class weights were applied based on expert knowledge, including experience from current operating quarries around New Zealand (Appendix 3 – Map 14: Populated building proximity).
3. Rural areas are generally more favourable for quarrying operations than built-up areas. To further inform the issue of quarrying close to where people live as addressed in (2) above, the LINZ Topo 50 dataset delineating densely populated residential areas and a Stats NZ dataset showing the locations and sizes of urban areas were combined to highlight the extent of towns and settlements in the project area. A class weighting of 25 was assigned to residential areas, and weights of between 55 and 65 to urban areas and rural settlements (Appendix 2) (Appendix 3 – Map 15: Residential, urban and rural land areas).
4. Community sensitivity to the visibility of quarries may have an influence on issues such as social licence, consenting and operational conditions for quarrying. A visibility analysis was undertaken to produce a mappable criteria layer that shows how much land surface can be seen from places where people may reside or travel. The LINZ Topo 50 datasets on sealed roads, residential areas and building outlines, together with the 8 m grid cell digital elevation model (DEM), were used for the analysis. The analysis assigns a point value of 1 to each building, to each hectare of a residential area, and once every 100 m along a sealed road. Then, for every grid cell of the DEM, a tally is made of all point values within a 5 km visible radius of the grid cell. The larger the tally, the less suitable the grid cell location would be for a quarry site, in relation to visual impacts (Appendix 3 – Map 16: Visibility of places, buildings and roads).

2.5 Data Gaps

Although there is a wealth of data that can be used to understand geology, land use, economics and community sensitivity in relation to extract activities, there is still a lot of information that is either not possible to map (non-spatial), not available or not evenly distributed over the project area (e.g. discontinuous data). These can be broadly classified into three groups: geotechnical, regulatory and cultural.

- Geotechnical data, including detailed datasets that convey fine-scale variation of lithology or rock properties (density, impurity, weathering, fractures, etc.). These are localised and site-specific, so cannot readily be used in regional-scale modelling.
- Regulatory data gaps include nationally consistent local and regional council zoning. Although data such as district plan zones, heritage areas and protected environments are mapped by all councils, the lack of standardisation in the terms and interpretations used, mapping techniques and data formats makes combining these data difficult and, in some cases, inappropriate.
- Cultural data gaps include less-tangible values of local communities and Māori custodians of land areas, as well as high scenic and tourism values.

These geotechnical, regulatory and cultural influences are important factors that should always be investigated early on as part of aggregate exploration or quarry development activity. They cannot be incorporated into this modelling project due to their non-spatial nature or limited availability but need to be carefully considered alongside the data-driven opportunity model results.

3.0 AGGREGATE OPPORTUNITY MODELLING

The aim of this project is to generate aggregate opportunity models for each of three aggregate resource classes: hard rock, gravel and sand. Although all three resource classes share the same criteria for land use and sensitivity, they differ in source material and feasibility; hence, there is a need for different models to incorporate these variations. The approach for collating input data for the modelling is set out in Section 2. The processing of the input data and production of model results are described in this section.

Underpinning the modelling is the knowledge-driven **fuzzy logic** spatial modelling technique (An et al. 1991; Bonham-Carter 1994; Zimmerman 2001). Fuzzy logic is a widely used and conceptually simple method for combining spatial data, using expert and statistically derived **fuzzy membership values** and **fuzzy operators** to combine input datasets. This approach has been applied in recent regional-scale aggregate modelling in New Zealand (see Hill [2021]), and the project described in this report represents a more detailed application of the approach. High-value results in the models represent areas where all parts of the aggregate opportunity concept are favourable and overlap, and therefore where there is the best opportunity for aggregate resources to be extracted.

3.1 The Modelling Sequence

The modelling involves a sequence of three steps (Figure 3.1):

- **Level 1:** Collation and processing of input data to produce gridded **mappable criteria** layers (see Section 2). For each mappable criteria dataset, the map units are assigned a class weight value in the range of 0–100, where higher values indicate greater aggregate opportunity (Appendix 3; Maps 1–16).
- **Level 2:** Four categories of **predictive model components** (Source material, Land use, Feasibility and Cultural sensitivity) are generated through various combinations of the mappable criteria layers (Appendix 4; Maps 1–7). An initial step converts the class weights to fuzzy membership values by dividing them by 100 to give values between 0 and 1. Then those maps are combined using the fuzzy GAMMA, AND and OR operators and the resulting values utilised in the Level 3 modelling.
- **Level 3:** Three spatial model result maps are created via combinations of the predictive model component maps using the fuzzy GAMMA function for each of the hard rock, gravel and sand predictive model component maps. The spatial model result maps have data values ranging from 0 to 1 that represent lowest to highest opportunity respectively (Figures 3.2–3.4; Appendix 5; Maps 1–3).

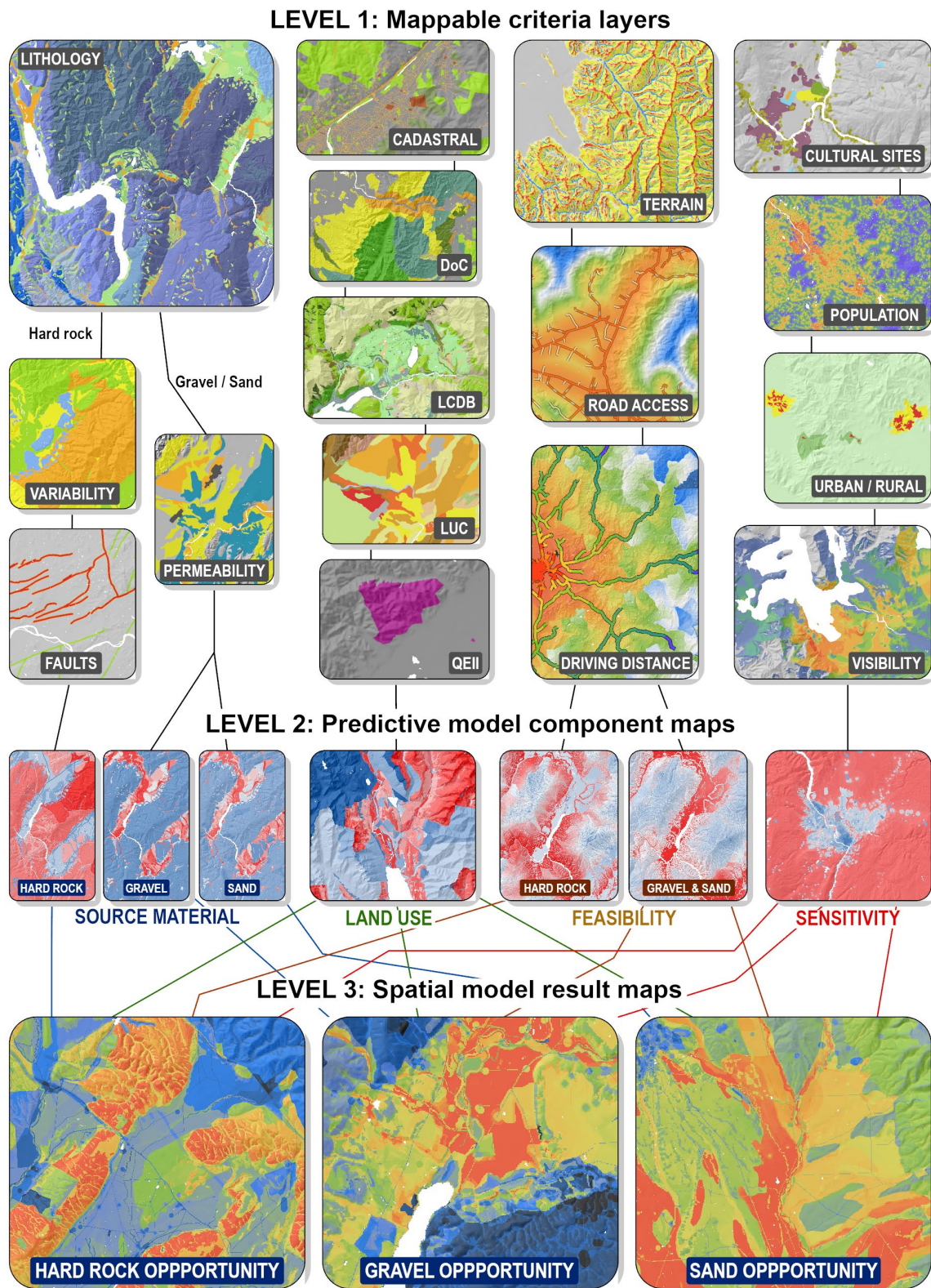


Figure 3.1 Overview of the spatial modelling process for aggregate opportunity modelling and examples of data maps generated for this project. Mappable criteria layers are combined to represent the predictive model components, which are then combined to create the spatial model result maps. Data combination varies for hard rock, gravel and sand models, where the source rocks and terrain maps vary for the different models. Level 1–3 maps for the whole project area are contained in Appendices 3, 4 and 5, respectively.

3.2 Modelling Results

The model results show the most suitable locations based on the mappable criteria overlap and therefore where there is the most opportunity for future aggregate extraction. Level 3 spatial model result maps for the hard rock, gravel and sand models are illustrated in Figures 3.2, 3.3 and 3.4, respectively. As a cross-check, historic and current quarry locations for each type of material are plotted on the maps, and this confirms that existing quarries largely coincide with areas of good opportunity.

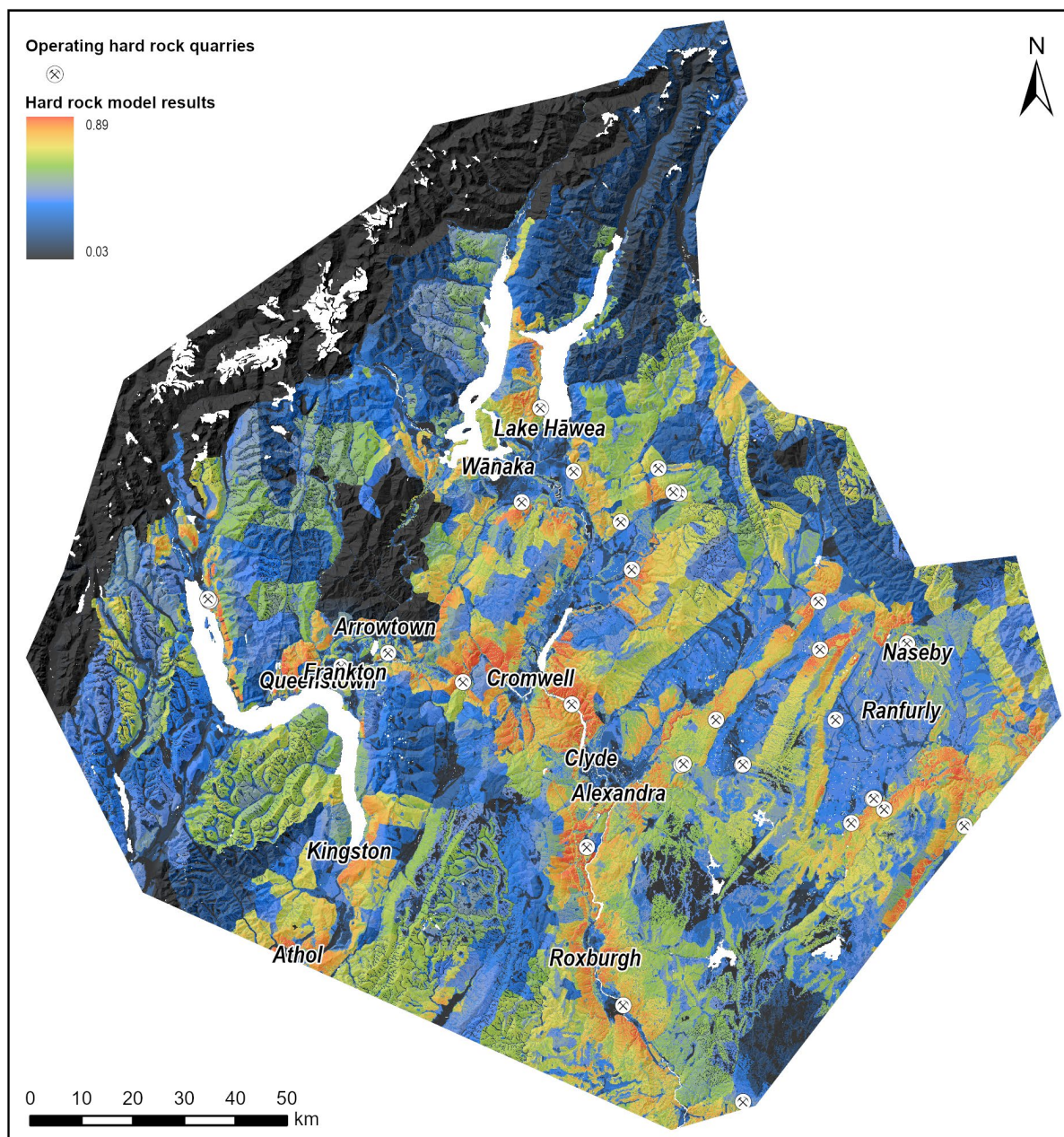


Figure 3.2 Level 3 map of spatial model results for hard rock material from the combined predictive component maps of source material, land use, feasibility and sensitivity. The map is scaled and coloured from fuzzy logic spatial model values that represent low (black) to high (red) results. A higher-resolution version of this map is provided in Appendix 5.

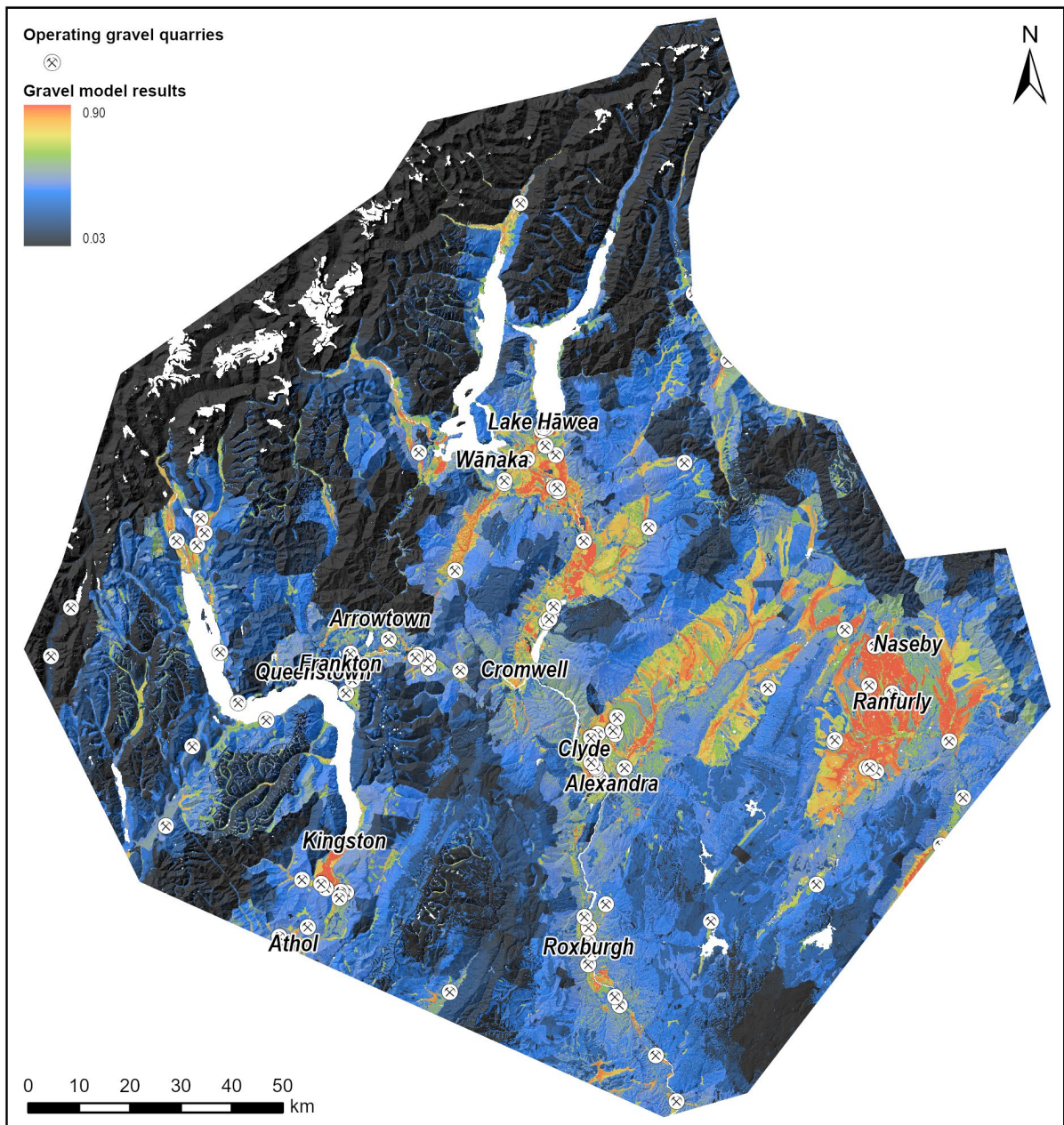


Figure 3.3 Level 3 map of spatial model results for gravel material from the combined predictive component maps of source material, land use, feasibility and sensitivity. The map is scaled and coloured from fuzzy logic spatial model values that represent low (black) to high (red) results. A higher-resolution version of this map is provided in Appendix 5.

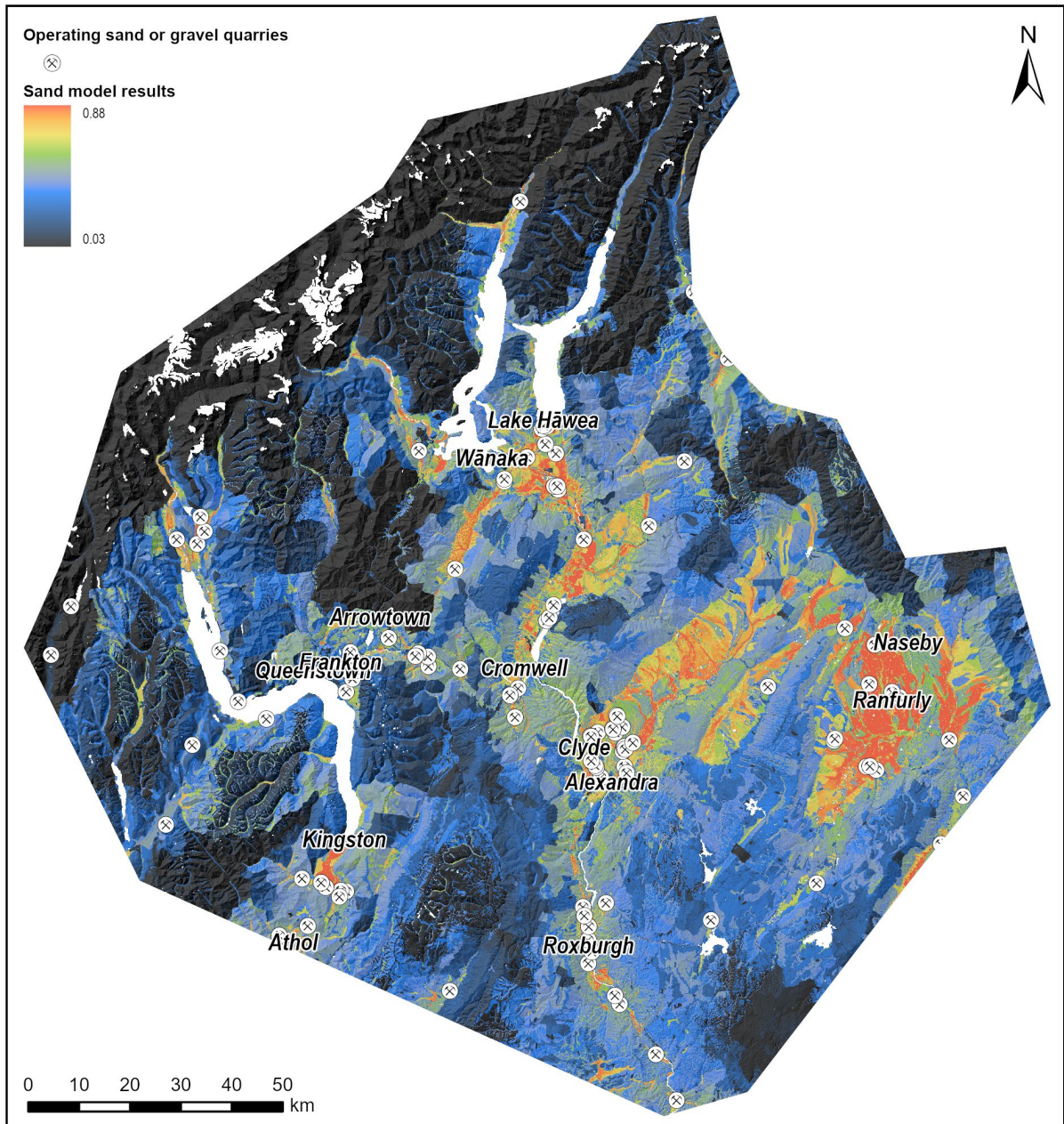


Figure 3.4 Level 3 map of spatial model results for sand material from the combined predictive component maps of source material, land use, feasibility and sensitivity. The map is scaled and coloured from fuzzy logic spatial model values that represent low (black) to high (red) results. A higher-resolution version of this map is provided in Appendix 5.

An overall **aggregate opportunity model** has been developed from the spatial model results maps after filtering out areas of relatively low values below a significance threshold (Figure 3.5; Appendix 8). This threshold was determined from a spatial and statistical analysis of the model results against a dataset of selected existing quarries (training points) that are considered to represent ideal examples of future quarries, together with an expert review of map patterns. The range of opportunity values that coincided with a significant number of training points was adopted as lying above the threshold, and grid cells with opportunity values below the lower limit of that range were excluded from the final aggregate opportunity model. Via this approach, the significance threshold is >0.65 for gravel and sand and >0.75 for other aggregate type classes (Appendix 7). Model areas above the threshold were further filtered into aggregate type classes of Mesozoic sandstone; schist; Paleogene- and Neogene-age sandstone; limestone, volcanic rocks of basalt, andesite and dacite; gravel; and sand

(see Figure 1.1). Maps of those classes represent where modelling indicates that there are better opportunities for aggregate resources. As many gravel deposits also include sand, the gravel spatial and opportunity models should be considered ‘gravel and sand’ opportunity sites. The sand opportunity model represents only those areas not already included in the gravel model where sand is more likely the dominant material type.

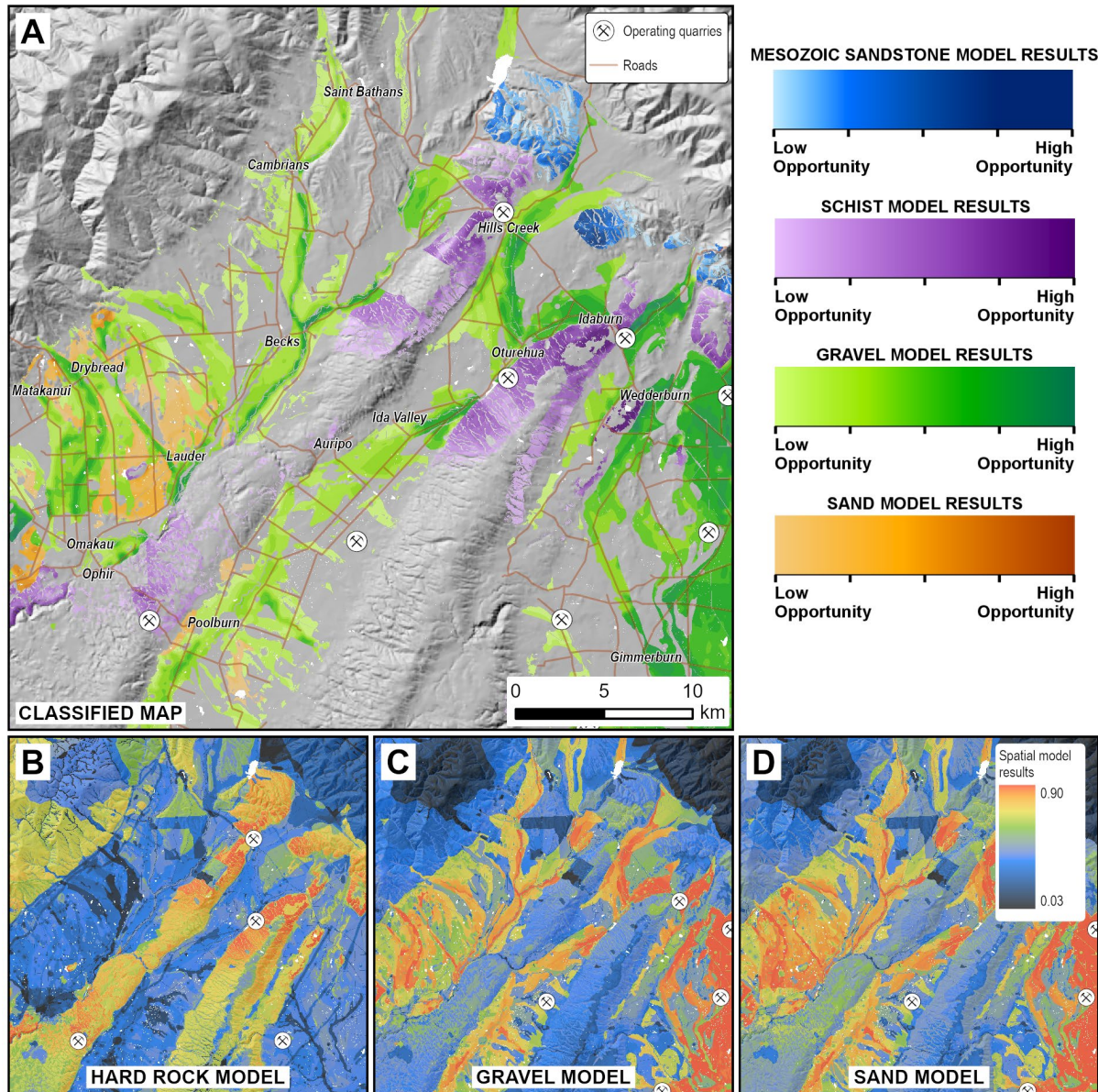


Figure 3.5 Example of an aggregate opportunity model (A) created from spatial model maps (B–D) for a northeastern part of the Central Otago area. The spatial model results map datasets were filtered using a significance threshold (see text) to exclude areas with opportunity values less than the threshold. The resulting aggregate opportunity model (A) was then classified and coloured according to aggregate type class (see Figure 1.1), with colour gradients illustrating lower to high aggregate opportunity.

Modelling results for aggregate opportunity around the whole project area, showing areas above the significance threshold and classified according to aggregate type class, are illustrated in Figure 3.6 and provided in high resolution in Appendix 6. Charts of model results relative to the project area and operating quarries are available in Appendix 7. Digital files for the overall aggregate opportunity model, in GIS (GeoTIFF) and Google Earth™ (KML) formats, are provided in Appendix 8.

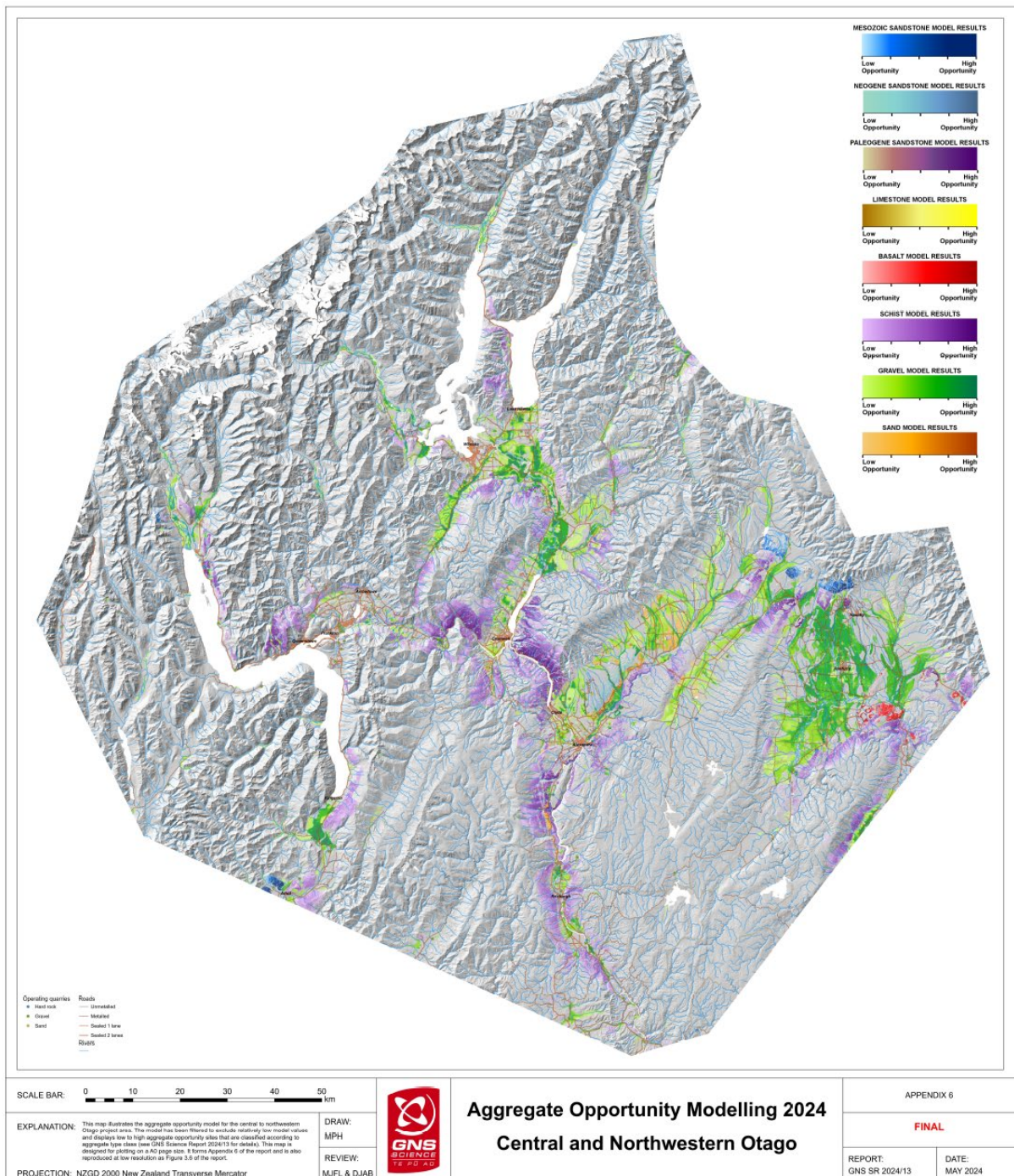


Figure 3.6 A representation of the aggregate opportunity model for the whole project area of central to northwestern Otago, filtered according to significance threshold and aggregate type class (see text and Figure 3.5 caption) and colour graded from low to high aggregate opportunity. A higher-resolution version of this map, scaled for presentation at A0 page size, is provided in Appendix 6.

Areas of hard rock type classes modelled with high aggregate opportunity, as identified in this report, comprise only 4.1% of the project area, with most of this in schist rock (3.8%). The best hard rock aggregate opportunities for Mesozoic sandstone ('greywacke') are in small areas north of Wedderburn and southeast of St Bathans, totalling only 0.1% of the project area. Although low to moderate opportunity for schist aggregate occurs throughout much of the project area, high opportunity is mainly concentrated near major roads because most parts of the road network are unsealed.

The Neogene-age sandstone unit has good aggregate opportunity in the middle Manuherikia Valley and northern part of the Maniototo Basin between Waipiata and Naseby. It mainly comprises weathered sandy greywacke conglomerate (Maniototo Conglomerate) that, although reasonably compacted, will mostly break up on excavation, so is more of a gravel/sand than rock resource. The Paleogene-age sandstone unit mainly consists of weak quartz sandstone (Hogburn Formation) outcropping in localised areas east of Ranfurly. Limestone with good aggregate opportunity is confined to a very localised outcrop area near Naseby. Volcanic rock (basalt of the Dunedin Volcanic Group) opportunity is good in localised areas about the Ranfurly to Hyde area, where it is mostly weathered rubbly material, but with some zones where hard bluestone is present (DJA Barrell 2024, pers. comm.). The rock character and depth of weathering will be important considerations if prospecting for volcanic rock quarry sites.

Areas of gravel modelled with the best aggregate opportunity comprise 5.6% of the project area, and many of these gravel sites will also include sand as a companion material type. However, the mica content of the gravels needs to be considered if the material is schist-derived. Gravel occurs in many of the valleys around the central and northwestern Otago area, with the best opportunity mapped east of Wānaka, around and north of Lake Dunstan, in the Manuherikia and Ida valleys and in the Maniototo Basin near Ranfurly. Differing content can be expected depending on position in the landscape. Floodplains and terraces of medium to large rivers will likely have relatively clean, sandy, coarse gravel, while alluvial fans in the basins and along valley margins are likely to be characterised by more silty and angular gravel. In the vicinities of lakes Wakatipu, Wānaka and Hawea, gravelly glacial till will be highly variable in character, which would need to be quantified if prospecting for aggregate. The validation of higher-opportunity places in relation to existing extraction operations (Appendix 7) supports this modelling approach, and the mapped results suggest that there are good gravel opportunities in the central and northwestern Otago area.

Sand suitable for quarrying in the central and northwestern Otago area is limited, with opportunity comprising only 0.2% of the project area. Sand sites are modelled within the Neogene-age sand units of the Bannockburn and Dunstan formations and conglomerate units in the Hawkdun Group, as well as within glacial and river/stream deposits. Mica content will be an important consideration if the sand is schist-derived. Sand is also likely to be a companion material within many of the gravel opportunity sites.

4.0 SUMMARY AND CONCLUSIONS

The development of infrastructure in the central to northwestern Otago areas 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, but, unfortunately, the demand for aggregate for urban areas often conflicts with the urban population's sensitivity to quarrying, which places limitations on operators and developers.

An assessment of aggregate resources can be determined from geological databases (e.g. geological maps, rock property data), but land-use, infrastructure and cultural criteria should also be considered to find the most suitable areas for extraction and supply. New Zealand's domestic production of aggregate is 45 Mt per year, and this amount is forecast to increase in the future. Identifying new aggregate sources is therefore important for the continued development of our communities and infrastructure.

This project uses an **aggregate opportunity concept** that identifies several important or highly desirable features that must be present for a quarry to succeed but also those factors that detrimentally affect the viability of a quarry or impose restrictions on its development. While the location of the rock material is an important component of the modelling process, this research has also utilised datasets that represent quarry feasibility, such as the distance to road infrastructure, driving distance along the road network to end-users of the aggregate and terrain suitability analysis and also cultural-sensitivity indicators. The sensitivity of people to quarrying can impose significant constraints on operators. This project has produced maps that represent population density and cultural features, as well as residential, urban and rural land classes. An analysis has also estimated the line-of-sight visual impact of quarries on communities so that this consideration can be built into the modelling.

Modelling is undertaken in three steps:

1. The input data were classified into **mappable criteria** layers to represent all components of the aggregate opportunity concept. Each map is re-classified to quantify the suitability of a new aggregate quarry at any given location. The suitability range (0–100) is defined based on spatial statistics and advice from industry and local government experts.
2. **Predictive component maps**, representing the four parts of the aggregate opportunity concept (source material, land use, quarry feasibility and cultural sensitivity), are created by combining the mappable criteria.
3. **Spatial model results maps** are produced, which are combined predictive component maps for hard rock types (e.g. sandstone, schist, limestone and basalt), gravel (as well as gravel-associated sand) and sand sites for which there is likely to be **aggregate opportunity**.

The modelling maps emphasise the most suitable locations after combination of the input feature layers, and therefore where there is greater opportunity for aggregate quarrying.

The central and northwestern Otago area is fortunate to have large areas of hard rock and gravel deposits that can potentially be utilised for aggregate supply. Much of this material is exposed at or near the surface, providing access to good-quality resources. Hard rock aggregate is dominated by schist of varying grade throughout the area, with minor amounts of sandstone, limestone and basalt. Gravel and sand are extractable from river and stream deposits and sand-rich rock units. Schist rock or gravels sourced from some schist rock types have limited value for roading chip or other high-wear applications due to high mica content.

High aggregate opportunity for Mesozoic sandstone ('greywacke') is in small areas north of Wedderburn and southeast of St Bathans. Although moderate opportunity for schist aggregate occurs through much of the project area, high opportunity for this rock is concentrated near the major sealed roads. Neogene- and Paleogene-age sandstone units have good aggregate opportunity in the Manuherikia Valley, Maniototo Basin (between Waipiata and Naseby) and localised areas east of Ranfurly, although these mainly comprise of weathered sandy greywacke conglomerates that are weak and should be considered more as a gravel/sandy resource than hard rock. Opportunity for limestone is confined to a very localised outcrop; however, basalt has opportunity the Ranfurly to Hyde area, where there may be some zones of hard 'bluestone' present. Gravel aggregate opportunity occurs in many of the valleys around the central and northwestern Otago area, with the best opportunity mapped east of Wānaka, around and north of Lake Dunstan, in the Manuherikia and Ida valleys and in the Maniototo Basin. Differing content can be expected, depending on position in the landscape, and the mica content of the gravels needs to be considered if the material is schist-derived. Sand suitable for quarrying is limited, and opportunity is mapped within the Neogene-age sand units of the Bannockburn and Dunstan formations and conglomerate units in the Hawkdun Group, as well as within glacial and river/stream deposits, where sand is also likely to be a companion material within many of the gravel opportunity sites. As with gravel deposits, mica content will be an important consideration for sand resources.

Although there is a wealth of data that can be used to understand geology, land use, economics and community sensitivity to extractive activities relating to aggregate opportunity, there is still a lot of information that is not possible to map, not available or not evenly distributed over the project area. New data that could improve the aggregate opportunity modelling in the central and northwestern Otago area include fine-scale geological maps and rock property distribution data (density, impurity, weathering, fractures, etc.) and consistently mapped local and regional council zoning. Mapping the less-quantifiable values of local communities and Māori custodians of land areas, as well as scenic and tourism values, will always be a challenge; however, these are important factors that should always be investigated early on as part of any aggregate exploration or quarry development. This project's findings facilitate informed decision-making for sustainable resource utilisation and infrastructure development in the central and northwestern Otago area.

This project for the central and northwestern Otago area is part of a series of regional-scale aggregate opportunity models. Other studies for the Wellington region and Bay of Plenty and northern and southern Auckland areas (Hill and Chilton [2024a, 2024b, 2024c, 2024d], respectively) follow very similar modelling processes as those utilised in this project to understand the aggregate opportunity in these regions.

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APPENDICES

The appendix files for this report are provided as a downloadable dataset from the GNS Science Dataset Catalogue using the link below:

<https://doi.org/10.21420/6ASK-WG49>

APPENDIX 1: Summary table of source data and spatial modelling techniques.

APPENDIX 2: Tables of mappable criteria grid and class weight values (GRID : CWV).

APPENDIX 3: Mappable criteria layers (Level 1 maps) – 16 x A3-scale maps.

APPENDIX 4: Predictive component maps (Level 2 maps) – 7 x A3-scale maps.

APPENDIX 5: Spatial model results maps (Level 3 maps) – 3 x A3-scale maps.

APPENDIX 6: Aggregate opportunity modelling results map – 1 x A0-scale map.

APPENDIX 7: Charts of model results relative to the project area and operating quarries.

APPENDIX 8: Digital spatial data of model results.

The results from this project are provided as digital data, which include the spatial model results (Level 3 maps) and aggregate opportunity model results (areas above the significance threshold) that can be used in GIS mapping software such as ArcGIS or QGIS, as well as in Google Earth™.

Table A.1 List of Appendix 8 digital geographic information system (GIS) map files, provided in the GeoTIFF grid format or as files that can be loaded and visualised using Google Earth (KML format).

GIS File Name	Description	Format
AOM24_OTAGO_L3_HARDROCK	Spatial model results for hard rock	GeoTIFF
AOM24_OTAGO_L3_GRAVEL	Spatial model results for gravel	GeoTIFF
AOM24_OTAGO_L3_SAND	Spatial model results for sand	GeoTIFF
AOM24_OTAGO_MZSANDSTONE	Aggregate opportunity model for Mesozoic sandstone	GeoTIFF
AOM24_OTAGO_PGSANDSTONE	Aggregate opportunity model for Paleogene sandstone	GeoTIFF
AOM24_OTAGO_NGSANDSTONE	Aggregate opportunity model for Neogene sandstone	GeoTIFF
AOM24_OTAGO_LIMESTONE	Aggregate opportunity model for limestone	GeoTIFF
AOM24_OTAGO_SCHIST	Aggregate opportunity model for schist	GeoTIFF
AOM24_OTAGO_BASALT	Aggregate opportunity model for basalt	GeoTIFF
AOM24_OTAGO_GRAVEL	Aggregate opportunity model for gravel	GeoTIFF
AOM24_OTAGO_SAND	Aggregate opportunity model for sand	GeoTIFF
AOM24_OTAGO_MZSANDSTONE	Aggregate opportunity model for Mesozoic sandstone	KML
AOM24_OTAGO_PGSANDSTONE	Aggregate opportunity model for Paleogene sandstone	KML
AOM24_OTAGO_NGSANDSTONE	Aggregate opportunity model for Neogene sandstone	KML
AOM24_OTAGO_LIMESTONE	Aggregate opportunity model for limestone	KML
AOM24_OTAGO_SCHIST	Aggregate opportunity model for schist	KML
AOM24_OTAGO_BASALT	Aggregate opportunity model for basalt	KML
AOM24_OTAGO_GRAVEL	Aggregate opportunity model for gravel	KML
AOM24_OTAGO_SAND	Aggregate opportunity model for sand	KML



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