# Resource assessment using GIS modelling of orogenic gold mineralisation and wind energy potential in Wellington, New Zealand.

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## Abstract

Prospectivity modelling of orogenic gold mineralisation and ideal locations for wind farm development has been completed over southwest Wellington in New Zealand. This modelling used a combination of the GIS based weights of evidence and fuzzy logic techniques. These models were undertaken to illustrate the power of GIS modelling in regional resource evaluation and how they can be used to quickly identify areas of land which should be considered for wind farm development or those where new gold deposits might exist. The mineral deposit modelling was constrained by the minerals systems concept which defines those parts of a mineralisation system that are critical to the ore-forming process. The Wellington gold model identified possible sources of metals in the region, structures that could be used for fluid migration, mineral trap zones ideally suited to host a mineral deposit, and outflow zones that may indicate a subsurface deposit. Similarly, the Wellington wind farm model identified ideal sites to develop a wind farm using elements critical for successful turbine placement such as wind speed, terrain, sources of air turbulence, access and land use. The models were validated against known areas of historical gold mining such as at Terawhiti and the turbine locations of Meridian Energy’s new West Wind development. The modelling clearly shows that the resource potential in southwest Wellington is greater for wind energy especially after consideration of potential archaeological and environmental restrictions which may rule out key areas of possible orogenic gold mineralisation identified by the model. The spatial modelling techniques used here can be applied elsewhere in New Zealand to evaluate resource potential, whether for wind, gold, or any other land based resource, and can help planners and land owners manage future developments and their assets more effectively.

***Keywords:*** orogenic gold, gold exploration, wind energy, wind farm, GIS, prospectivity modelling.

## Introduction

Spatial modelling in a geographic information system (GIS) is a powerful tool for analysing digital data. We have used GIS databases of information over the southwest region of Wellington to predict the most likely locations of orogenic gold deposits and the best locations to place turbines for wind energy generation. This project was undertaken to assess the most suitable and economic use for this land area and to illustrate how predictive modelling could be used in other locations to help with land management. It is critical that all the factors involved in the resources being modelled are understood and replicated spatially for the model to be effective. Cutting-edge environmental and terrain modelling, as well as a wealth of historic geological research, has been classified using criteria from mineral and energy systems concepts for orogenic gold deposits and wind turbine sites. By combining these data with weights of evidence and fuzzy logic modelling techniques targets can be generated for each resource in the study area. The results from our spatial modelling allows explorers to undertake fast assessment of regional prospectivity and gives them the opportunity to prioritise spending, undertake economic modelling, and focus on regions which are most likely to yield successful results. These types of GIS studies can also be used by government or regional councils to undertake land management studies which identify the best use of land in their region.

## Wellington goldfields

The southwest region of Wellington encompassing the Terawhiti, Makara and Karori mineral fields (Fig. 1) has undergone mining for gold since the 1850's. This included an initial phase of alluvial mining followed by mining of quartz reefs in the 1880's and again in the 1900's with some renewed exploration in the 1980's (Brodie, 1986). Many of the small adits mined into the hillsides were not economic due to the small amount of gold and the discontinuous nature of the mineralised veins. There is currently no exploration for gold in this area and there are now only a few small historic adits visible in the hillsides with nearby remnants of historic tramways and battery equipment from 100 years ago. The Wellington region has forty-nine gold mineral occurrences recorded in the geological literature (Brodie, 1986; McIntyre, 1995; Begg and Johnston, 2000; GNS Science GERM database). Only a few gold occurrences were of economic success and became mining operations. These successes were mostly located west of the Terawhiti Fault on Terawhiti Hill (Fig. 1).

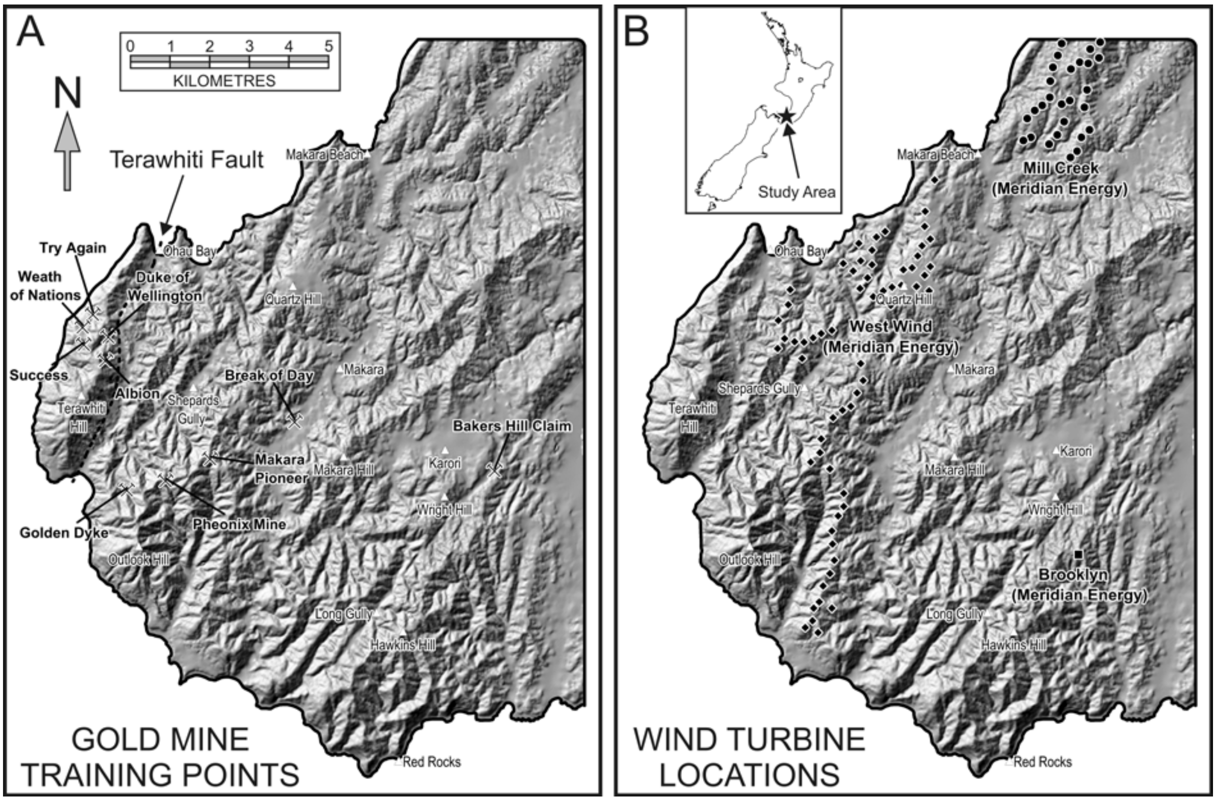

**Figure 1.** Map showing the southwest Wellington study area with historic mining operations used as training points (a) and current wind turbine placements of the existing West Wind and proposed Mill Creek wind farms (b).

An orogenic deposit model is proposed by many workers for the concentrations of gold in the Wellington region (e.g. McIntyre, 1995; Christie, 2002). The metamorphism and deformation of the basement sedimentary terrane to greenschist facies produced fluid which transported and concentrated gold from within the sedimentary pile into structural traps (Fig. 2). Wellington is very similar to other New Zealand Mesozoic orogenic gold terranes such as Marlborough and Otago. These schistose rocks are one of the key lithogical targets for gold exploration in New Zealand and host deposits such as Macraes Flat in Otago. For areas east of the Terawhiti Fault, recent explorers have suggested that the mineralisation style may be different or a less developed equivalent to that in the higher grade schists west of the

Terawhiti Fault (Utting, 1982; Taylor, 1984; McOnie, 1985; Bates, 1987). We would expect our modelling to show these areas as less prospective for orogenic gold.

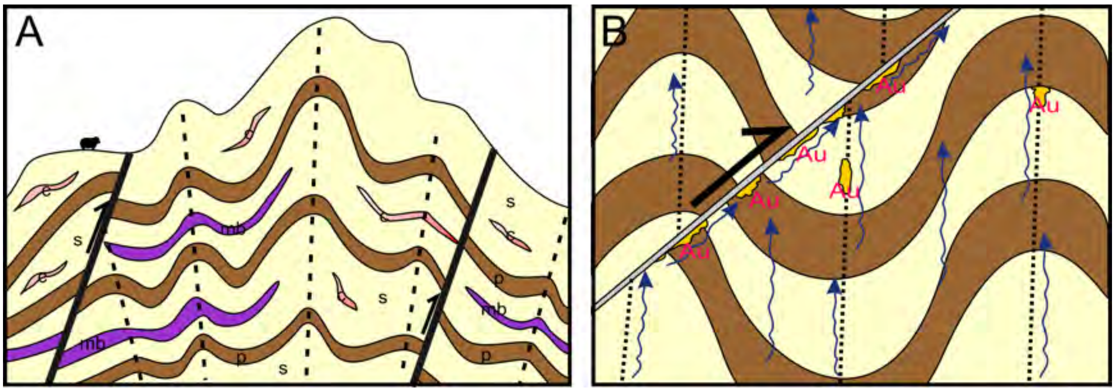

**Figure 2.** Cartoon of orogenic gold mineralisation model for the Wellington region. A: Regional deformation of psammitic (s), pelitic (p), metabasalt (mb), and chert (c) sediments. B: Fluid (represented by arrows) moving up cleavage planes, fold axial surfaces, and fault planes depositing gold (Au) in structural traps.

In this study the minerals systems concept has been used to define those parts of the mineralisation system which are critical to the ore-forming process (Wyborn et al., 1994). The critical parameters of ore deposit formation are identified from existing literature about the mineral system (Christie, 2002; Groves et al., 2003; Pitcairn et al., 2006; Mortensen et al., 2010) and mapped spatially using GIS analysis to predict mineral potential in the study region (e.g. Partington et al., 2002; Partington and Sale, 2004). This modelling has mapped possible sources of metals in the region, structures that could be used for fluid migration, structures ideally suited to host a mineral deposit and outflow zones which indicate a subsurface deposit.

The source and energy for gold in our model is mapped by the location of greenschist facies sedimentary rocks (textural zone 2a or greater) deformed during the Mesozoic. Hematite rich cherts and metabasalts may have played a role as potential source rocks; however, due to their small volume and poorly mapped extents they have not been used in this study. Ore fluids are thought to be released from minerals in dehydration reactions during metamorphism driven by short lived thermal events in the crust (Mortensen et al., 2010). In Wellington these fluids have travelled along structural pathways (Fig. 2b) such as fold hinges and fault planes (McOnie, 1985) before precipitating quartz-carbonate veins during late-stage ($D_3$) brittle fracturing (McIntyre, 1995). Chemical traps from fluid interaction with graphitic pelite units in the host rocks may have assisted with gold precipitation in some faults. Areas with mapped quartz veins and quartz reefs have been used as a proxy in this model for where fluid flow and vein precipitation has occurred. We have assumed that current active faults ($D_4$ deformation) were not developed in the Mesozoic and therefore not used as fluid pathways. Using the GNS Science Active Faults Database to identify these $D_4$ structures, only older Mesozoic faults were extracted from geological map data (McIntyre, 1995; Begg and Johnston, 2000) and combined with mapped Mesozoic folds in the study area to represent pathways for fluid flow. Traps were further identified in the area using anomalous rock chip gold geochemistry digitised from exploration reports (e.g. Taylor, 1984; GNS Science PETLAB database). Outflow zones where mapped using anomalous pathfinder element geochemistry (Ag, As, Cu, Ni, Mo, Pb, W, and Zn) in rock chip samples and anomalous gold and pathfinder element geochemistry in stream sediment and soil samples.

# Wellington Wind Energy

As electricity consumption continues to grow worldwide and with rising concerns for environmental issues caused by global warming there is an increasing demand for renewable sources of energy. Worldwide, wind energy has become a strong player in the clean energy mix and the Wellington region is well known for its wind energy resource and our study aims to illustrate how suitable sites for wind turbines can be determined using spatial modelling. This is not the first time GIS modelling techniques have been applied to the problem of wind farm siting (e.g. Baban and Parry, 2001; Hansen, 2005). In this study we build on previous work by developing advanced techniques for assessing the suitability of terrain features which are combined with high resolution mesoscale wind speed maps and other spatially relevant data to develop a prospecting system for wind energy. In our model, wind speed and terrain maps are combined with other social, infrastructure and environmental factors that affect the development of a wind farm.

Our modelling uses a three-phase wind prospecting approach to map predictive variables used to determine the ideal sites for wind turbines. These three phases include assessment of the wind speed to determine available energy at a site, analysis of terrain criteria for turbine siting, and measures of site suitability to account for social and economic factors. Wind speed is the most important criteria for the suitability of a site for a wind farm. We use wind speed and direction data from mesoscale modelling that is developed from three-dimensional models that simulate airflow over complex terrain and use high-quality historical meteorological observations to characterise the long-term wind distribution of a particular area. For our model wind speed data is analysed and classified into ranges suitable for the different classes of modern turbines and regional economic constraints of the study area.

While wind speed is the most important criteria, the terrain that surrounds a turbine site is also critical for successful placement. Characteristics of the immediate and surrounding terrain of a turbine site can have an effect on construction costs and also on turbulence and the inflow angle of wind which can cause unwanted wear and tear on the turbine components and reduced operating life. Terrain modelling techniques have been developed using digital elevation data to create predictive maps of slope, aspect to the main wind direction, complexity of surrounding terrain, ridgelines, and upwind terrain effects. Slope at the turbine site is an important factor that affects the cost of wind turbine construction and when coupled with wind speed and direction, can create turbulence and high inflow angles that have a negative effect on wind turbine operation and energy capture (Fig. 3a). Complex surrounding terrain can also create undesirable wind inflow angles and turbulence (Fig. 3b) and is assessed in our modelling by searching the areas surrounding each cell for slope variability. Elevated terrain features upwind of turbine positions can cause turbulence that persists for several kilometres downwind therefore detailed analysis of elevated terrain features has been conducted considering the dominant wind direction to determine the exposure of each cell in the model (Fig. 3c). The slope at the turbine location should ideally be facing the main wind direction; therefore analysis of terrain aspect was carried out to determine the direction that each grid cell is facing (Fig. 3d). Hydrological modelling tools have also been used to isolate local topographic highs such as ridgelines. It is common to place wind turbines in elevated areas such as ridgelines due to higher wind speed at elevation and the speed up effects these features have on the local wind regime if oriented correctly. Sharp, steep ridgelines may create unwanted turbulence; however, these areas are weighted down in the model by the terrain complexity and elevated surrounding terrain predictive maps.

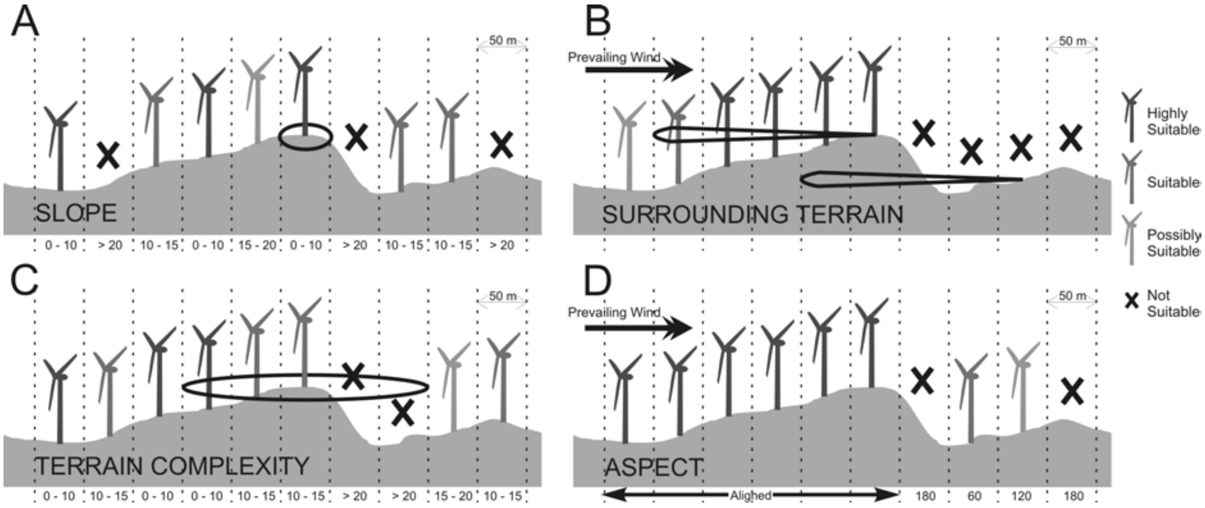

**Figure 3.** Terrain modelling techniques developed for classifications of slope (a), surrounding terrain (b), terrain complexity (c), and aspect (d).

Terrain analysis and wind speed data can be used to determine the technically feasible locations for wind turbine operation; however, when looking for suitable wind farm sites other non-technical parameters related to infrastructure, social, cultural, and the environment need to be considered. Our modelling study includes predictive maps that locate sites close to existing transmission lines and roads to minimise construction costs; we analyse the land use and map areas away from built-up and populated areas; we map areas based on their conservation status and distance from waterways to avoid and minimise impact on sensitive environmental locations; and we also consider elevation as higher altitudes not only create difficult construction conditions but reduced air density causes lower energy production. For a site in the study area to be suitable for wind turbine placement each of the three phases of the wind prospecting system (wind speed, terrain, and site suitability) need to be present.

## Spatial data modelling of orogenic gold and wind energy potential

Spatial data modelling requires a digital GIS database from which predictive evidence for a particular resource can be developed based on a process based model and ideally training data sets based on successful economic resource areas, which in this case are historic gold mines or wind turbine locations. The Wellington area contains forty-five mapped hard rock gold mineral occurrences making it an ideal region for a weights of evidence spatial model using the known gold occurrences as training points. In contrast, due to the complexity of the data developed for the wind energy modelling and the wealth of expert knowledge used in its development, fuzzy logic modelling was more appropriate for this resource type. The spatial data modelling therefore utilises two different spatial modelling techniques, with each type specifically chosen based on the data and expert knowledge available.

The weights of evidence spatial data modelling technique (Bonham-Carter, 1994) was used in the Wellington orogenic gold study to evaluate the wealth of geological data. This technique requires an understanding of the deposit mineral system, uses digital databases of geological information that include lithological mapping, structural interpretations, geochemistry, and importantly includes known economic deposits as training data to weight the model inputs. The main geological features from the orogenic gold mineral system model have been used to develop predictive maps from the available digital data using spatial modelling techniques such as buffering, intersections, interpolation, density algorithms, or from expert assigned attributes of genetic significance. The weights of evidence modelling technique combines these weighted predicative maps to create a prospectivity map showing areas favourable for orogenic gold deposits in Wellington.

As a first step in the spatial correlation calculation, a 20 by 20 metre grid was generated over the study area (Fig. 1) which represents the minimum scale that the data should be viewed at. The modelling used a unit cell size of 0.2 $km^2$ which is intended to represent the approximate size of the mineral system. Ten mineral deposit locations for hard rock gold mineralisation were extracted from the mineral occurrence databases (Begg and Johnston, 2000) as a training data set. These occurrences were chosen to have a suitable distribution throughout the study area. The training data and unit cell give a prior probability of 0.01108; i.e. there is a 0.01108 chance of finding an orogenic gold deposit in any 0.2 $km^2$ block before any knowledge about the mineral system is applied. The Golden Crown gold prospect in the Terawhiti area of Wellington, one of the most successful mines in the region, was excluded from this training data so the location could be used as an independent test of the modelling results. Thirty-six predictive themes were developed from the available digital data for the Wellington orogenic gold model. From these, seven were chosen as having the best regional coverage, a significant spatial association with the mineralisation model, and where possible not to duplicate predictive map patterns to reduce the effects of conditional dependence (Table 1). The resulting grid was classified into areas of relative prospectivity and used to target regions in Wellington for follow-up investigation.

**Table 1.** Predictive maps used in the weights of evidence Wellington orogenic gold model.

| Min. Sys. | Layer | Description | C | StudC |
|---|---|---|---|---|
| Source, energy & fluids | TZ2 | Textural Zone > 2a rocks (greenschists) | 3.59 | 5.39 |
| | Vein & Quartzites | Mapped veins and quartzites buffered to 300 m. | 3.65 | 3.36 |
| Pathways | Faults & Folds | Mesozoic faults and folds buffered to 100 m. | 3.02 | 3.80 |
| Traps | Rock Au | Rock chip samples Au > 0.5 ppm buffered to 250 m. | 7.60 | 0.76 |
| Outflow | Rock PFE's | Anomalous rock pathfinder elements (PFE) As, Cu, Ni, Mo, & Zn buffered to 400 m. | 2.30 | 2.09 |
| | Stream & Soil Au | Catchments with stream sediment samples Au > 60 ppb & soil samples (200 m buffer) with Au > 25 ppb. | 2.44 | 3.04 |
| | Stream PFE's | Catchments with stream sediment samples anomalous in Ag, As, Cu, Pb & Zn. | 6.71 | 0.67 |

Spatial correlations between the training data and individual predictive maps were calculated using weights of evidence spatial modelling techniques in the MI-SDM spatial data modeller extension developed for MapInfo GIS software (Higham, 2006). The modelling technique is a Bayesian statistical approach which allows the analysis and combination of data to predict the occurrence of deposits. It is based on the presence or absence of a characteristic or pattern and the occurrence of a deposit. The spatial correlation of mapped data in the model can be calculated by using the relationship of the area covered by the predictive feature being tested and the number of training data points that fall onto it. This produces a W+ result based on training points falling on the predictive feature and a W- result based on training points falling where the feature is absent. A W+ value greater than zero indicates a positive correlation with the mapped data, whereas a W- less than zero indicates a negative association with the non-mapped area. The contrast, which is the difference between W+ and W-, gets higher with an increase in the correlation between the predictive features and the training data (i.e., a map that correlates well with the selected training data for orogenic gold will have a high contrast value). The spatial association of each predictive theme is based on the contrast (C) and the level of uncertainty (StudC). The uncertainty is calculated from the standard deviations of W and C (Ws and Cs), from which the studentised value of the contrast (StudC) can then be calculated (the ratio of the standard deviation of the contrast (Cs) to the contrast (C)). StudC gives an informal test of the hypothesis that C=0 and as long as the ratio is relatively large, implying the contrast is large compared with the standard deviation, then the contrast is more likely to be real. This ratio is best used as a relative indicator of spatial correlation, rather than an absolute sense. In this study a strong correlation is inferred from C values > 3.0 and StudC values > 1.5. The final weighted geological predictor themes were combined and a gridded response was generated representing the intersection of all the input themes in a single integer grid.

The Wellington wind energy model used the fuzzy logic spatial modelling technique (Bonham-Carter, 1994) to evaluate the wind energy potential of the study area. Fuzzy logic is a popular and easily understood method for combining datasets using expert opinion to derive weights that rank the relative importance of each variable. Each dataset used is classified using expert knowledge and then each class is weighted using a fuzzy membership function that expresses the degree of importance of the variable as a predictor of the feature under consideration. Maps may be combined by a variety of fuzzy operators (e.g. fuzzy AND or fuzzy Gamma) according to a scheme that may be represented with an inference network. These functions were all carried out on predictive maps developed in a GIS using the Spatial Data Modeller extension (Sawatzky et al, 2004) developed for ESRI’s ArcGIS software. By combining the input predictive maps using the fuzzy operators the output from the model is a map showing wind farm suitability.

This wind energy modelling study reviewed all available digital data-sets of atmospheric, topographic, environmental, geological, and cadastral information over the Wellington region. Of these, the modelling used eleven predictive maps that were created using buffering, classifying, and spatial algorithms developed specifically for this study. The expert knowledge and parameters for generating this data and classifying the results into multi-class and binary maps came from existing wind turbine siting requirements. Once the eleven predictive maps were generated covering the wind speed, terrain, and site suitability components of the wind prospecting system the map areas were assigned fuzzy membership functions (i.e. model weightings) and combined using fuzzy operators. The wind speed and terrain predictive maps were combined using the fuzzy Gamma operator and the site suitability predictive maps were combined using the fuzzy AND operator (Fig. 4). The fuzzy AND operator ensured that any sites not suitable based on one or more predictive maps would not be a suitable site in the combined site suitability map. This is in contrast to the fuzzy Gamma operator which allows for a poor predictive area in one map to still be prospective if there are other maps with good predictive features in the same location. The technically suitable site map (wind and terrain) and the site suitability map were combined using a fuzzy Gamma operation to generate the wind energy prospectivity model.

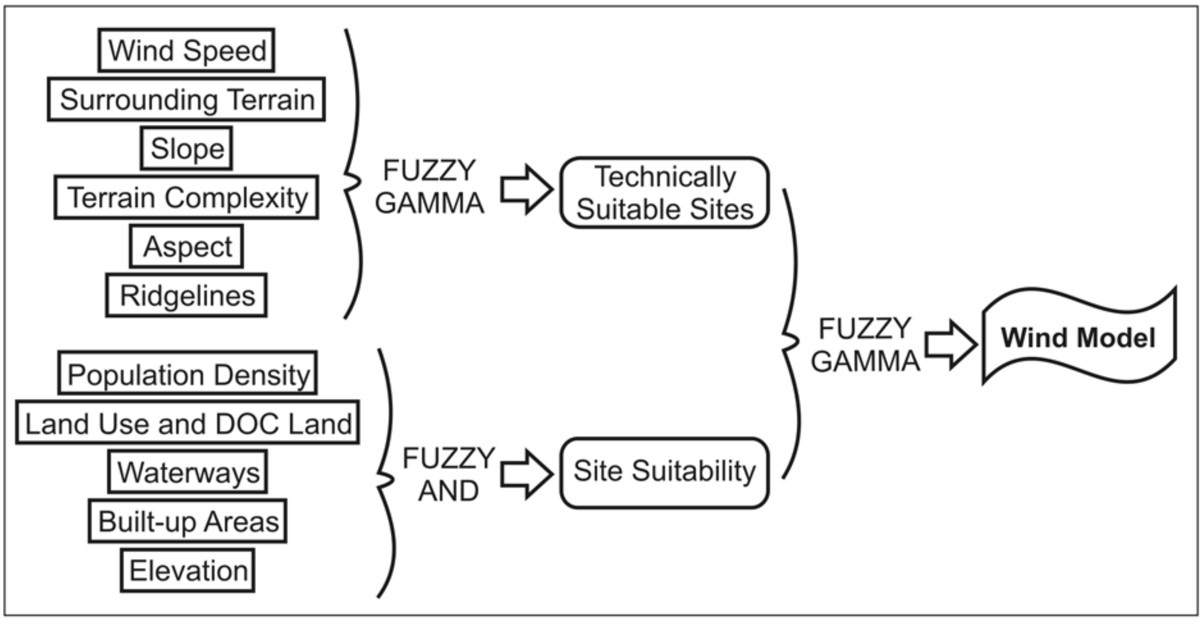

**Figure 4.** Fuzzy logic decision tree for Wellington wind energy modelling.

## Modelling results and land management

Spatial modelling of orogenic gold and wind energy potential using weights of evidence and fuzzy logic techniques has highlighted exploration targets for both resources (Fig. 5). The orogenic gold prospectivity study has generated several targets in the Wellington region with the highest prospectivity target over the Terawhiti Hill region west of the Terawhiti Fault. This model has highlighted the importance of greenschist facies sedimentary source rocks as well as Mesozoic faults and folds which act as pathways and traps for the mineralisation. The model successfully identified all known occurrences of gold in the study area (Fig. 5a). Importantly, the Golden Crown mine near Terawhiti Hill excluded from the training data, was modelled as highly prospective supporting the validity of this model as a predictor for orogenic gold mineralisation. The wind energy prospectivity model has highlighted several ridgelines and open hilltop regions suitable for turbine placement in the Outlook Hill, Makara and Ohariu Valley areas. The modelling results map the existing turbine sites from Meridian Energy’s new West Wind development very well (Fig. 5b) supporting the validity of this model as a predictor of turbine placement for wind energy. This modelling clearly shows the importance of terrain as well as wind speed for predicting turbine locations.

The prospective area for orogenic gold at Terawhiti is 0.9 km$^2$ and is small compared with targets from similar modelling studies in Otago (e.g. Partington and Sale, 2004) in which locations such as Macraes Flat have targets fifty times this size. The small size of the prospective area, along with no other significant targets to the east of the Terawhiti Fault, makes gold exploration a low priority. The Terawhiti Hill target is also over several archaeological heritage sites; over an area that hosts several rare native coastal plants and seabird nesting sites; and is also visible from a coastline considered to hold considerable scenic value in Wellington (Fig. 5b). These environmental considerations significantly reduce the suitability of the region as a gold exploration target. Our wind energy model shows that the study area could support a large number of wind turbines when compared with similar modelling studies in the lower North Island (e.g. Peters and Walter, 2009). Importantly, highly prospective turbine targets exist away from the environmentally sensitive areas of Terawhiti Hill. Our targets are over farm land away from metropolitan areas where noise and visual pollution is minimised, are in proximity to major transmission lines, and near tracks and roadways for easy access.

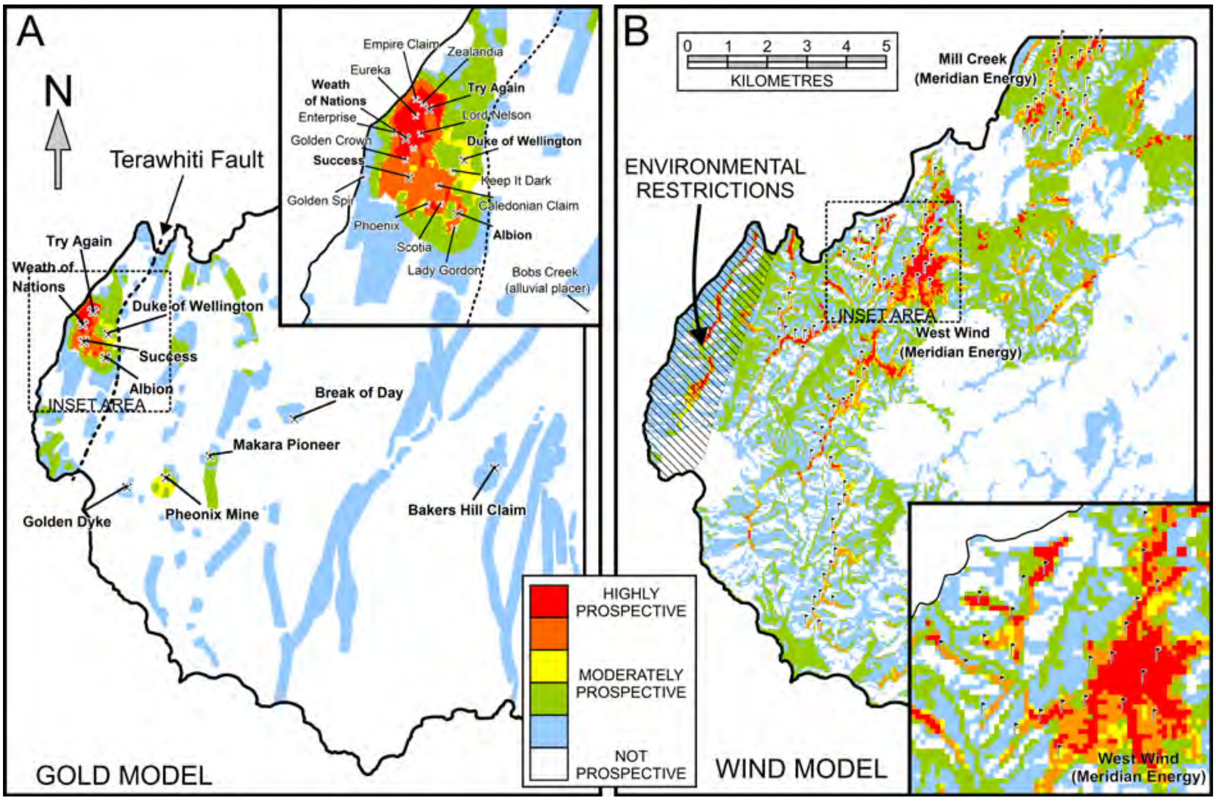

**Figure 5.** Maps showing the modelling results for (a) the Wellington orogenic gold weights of evidence model with historic mineral occurrences shown as crosses; and (b) the Wellington wind energy model with current wind turbine placements shown as small flag symbols.

## Conclusions

Our modelling using weights of evidence and fuzzy logic techniques has clearly shown the resource most suitable in southwest Wellington is wind energy after consideration of the prospective areas for each model. Archaeological and environmental restrictions and the small target area ruled out prospective regions identified by the modelling for orogenic gold mineralisation. The large area of prospective targets for wind energy located throughout the Makara and Ohariu Valley areas indicates a significant resource for wind energy exists in Wellington. The models successfully identified existing gold mineral occurrences and wind turbine sites validating the techniques in this study as suitable predictors of potential gold and wind energy resources. Spatial modelling techniques used in this study could be applied in other locations to evaluate resource potential, whether it is for wind, gold, or any other land based resource, and can help resource planners and explorers manage future developments and their assets more effectively.

## Acknowledgements

B. Walter, S. Faulkner, M. Green (Aurecon New Zealand Limited) are thanked for their assistance in developing the terrain modelling techniques and allowing us to use their Wellington mesoscale wind speed data. Geologists at Kenex are thanked for developing the digital databases underpinning the spatial models in this study. E.

Puccioni (Kenex Ltd, Wellington) is thanked for developing computer software for the advanced terrain modelling. GNS Science PETLAB, GERM and Active Fault databases were used in this study.

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