

WISE

Waikato Integrated Scenario

Explorer

Technical specifications

Version 1.6

Prepared by:

Rutledge DT¹, Cameron M², Briggs C⁷, Elliott S³, Fenton T⁶, Hurkens J⁴, McDonald G⁵, McBride G³, Phyn D⁷, Poot J², Price R¹, Schmidt J⁸, van Delden H⁴, Tait A⁸, Urich P¹⁰, Vanhout R⁴, Woods R⁹.

¹Landcare Research, Hamilton

²National Institute of Demographic and Economic Analysis, University of Waikato, Hamilton

³National Institute for Water and Atmospheric Research, Hamilton

⁴Research Institute for Knowledge Systems, Maastricht, The Netherlands

⁵Market Economics Ltd, Takapuna

⁶ Alchemists Ltd, Invercargill

⁷Waikato Regional Council, Hamilton

⁸National Institute for Water and Atmospheric Research, Wellington

⁹National Institute for Water and Atmospheric Research, Christchurch

¹⁰CLIMsystems Ltd, Hamilton

For:

Waikato Regional Council

Private Bag 3038

Waikato Mail Centre

HAMILTON 3240

February 2022

Document #: 21547006

Peer review by
Dr Beat Huser

Date January 2022

Approved for release by:
Lisette Balsom

Date January 2022

Disclaimer

This technical report has been prepared for the use of Waikato Regional Council as a reference document and as such does not constitute Council's policy.

Council requests that if excerpts or inferences are drawn from this document for further use by individuals or organisations, due care should be taken to ensure that the appropriate context has been preserved, and is accurately reflected and referenced in any subsequent spoken or written communication.

While Waikato Regional Council has exercised all reasonable skill and care in controlling the contents of this report, Council accepts no liability in contract, tort or otherwise, for any loss, damage, injury or expense (whether direct, indirect or consequential) arising out of the provision of this information or its use by you or any other party.

Acknowledgement

The New Zealand Foundation for Research, Science & Technology (FRST) funded the 'Creating Futures' project under contract ENVW0601 to Waikato Regional Council Landcare Research funded early ISDSS development as part of the Sustainable Futures Waikato Capability Fund project. The authors thank Dr Beat Huser for reviewing the document. Waikato Regional Council provided additional funding and administrative support for the project, as well as ongoing updating and maintenance of the WISE model since completion of the Government research contract ENVW0601.

Table of contents

Acknowledgement	i
WISE overview	1
Project and client	1
Objective	1
Future Development	4
1 Introduction: Creating futures project	5
1.1 Overview	5
1.2 Spatial decision support system development	6
1.3 Use and application of WISE	7
2 WISE specifications	9
2.1 Overall system design	9
3 Model descriptions – reader’s guide	13
4 GEONAMICA® framework – RIKS	14
4.1 Model blocks	15
4.2 Simulation engine	15
4.3 Incorporating user input	17
5 Climate change scenarios – CLIMsystems	19
5.1 Metadata	19
5.2 Summary	19
5.3 Description	20
5.4 Equations	22
5.5 Links	22
6 Hydrology – NIWA	23
6.1 Metadata	23
6.2 Summary	23
6.3 Description	23
6.4 Equations	25
6.5 Links	27
7 Waikato region Economic Futures Model (EFM) - Market Economics	28
7.1 Metadata	28
7.2 Summary	28
7.3 Description	29
7.4 Equations	32
7.5 Links	37
8 Water quality – NIWA	38
8.1 Metadata	38
8.2 Summary	38
8.3 Description	38
8.4 Equations	40
8.5 Links	42
9 Zoning tool – Waikato Regional Council	43
9.1 Metadata	43
9.2 Summary	43
9.3 Model description	44
9.4 Equations	50

9.5	Links to other models	50
10	Multi-Region Demographic model – University of Waikato	53
10.1	Metadata	53
10.2	Summary	53
10.3	Description	54
10.4	Equations	55
10.5	Links	57
11	Residential Demands model – RIKS	58
11.1	Metadata	58
11.2	Summary	58
11.3	Description	58
11.4	Equations	58
11.5	Calculation of initial densities	59
11.6	Links	61
12	Land use change – RIKS	62
12.1	Metadata	62
12.2	Summary	62
12.3	Description	62
12.4	Equations	76
12.5	Links	86
13	User-defined spatial indicators	87
13.1	Metadata	87
13.2	Summary	87
13.3	Description	87
13.4	Equations	88
13.5	Links	97
14	Terrestrial biodiversity – Landcare Research	98
14.1	Metadata	98
14.2	Summary	98
14.3	Description	98
14.4	Equations	100
14.5	Links	100
15	Future development	102
	References	107
Appendix A	The Waikato region EFM Concordance Notations	113
Appendix B	Process for Translating Land Use by Industry (<i>lu wo luc_i</i>) to Land Use by Aggregated Industry (<i>luc wo luc_{lucatt}</i>) in the Waikato region EFM	117
Appendix C	Technical Process for Generating Spatial Data Layers Used in the Land Use Change Model	118
Appendix D	The Land Suitability Tool	121

Figures

Figure 1	Four stages of ISDSS development in Objective 2 of the Creating Futures Project.	6
Figure 2	WISE Version 1.6 system design.	10
Figure 3	Example of relationships between variables in different model blocks.	15
Figure 4	Logic diagram showing differences between variables and parameters.	16
Figure 5	Non-lagged (left image) and lagged (right image) relationships between model variables.	16
Figure 6	The global mean temperature change of the four selected RCP scenarios. The graph shows that up to 2030, global mean temperature is projected to increase by about 1.0° C, irrespective of the RCP scenario and subsequently the future temperature change projections diverge by 2070 and even more by 2100, depending on the RCP scenario.	21
Figure 7	Implementation of inter-annual climatic variability in WISE.	22
Figure 8	The inputs, outputs, and storages of the annual hydrology model.	24
Figure 9	The annual filling and emptying of soil moisture in response to climate seasonality.	24
Figure 10	The Waikato region EFM system structure.	29
Figure 11	Key spatial elements of the SPARROW model system.	39
Figure 12	Districts within the Waikato region as of September 2016.	44
Figure 13	Process followed to delineate and evaluate zoning scores.	45
Figure 14	Screenshot of the zoning matrix for Waipa District Council.	48
Figure 15	Examples of categorical zoning grid layers for Dairy Farming (left) and Residential – Low Density (right) land uses as at 2030.	52
Figure 16	All cells in the neighbourhood are in exactly one concentric circle. The index of the circle depends on the distance of the circle's cells to the centre of the neighbourhood (circle 1).	64
Figure 17	For the calculation of the neighbourhood effect, a circular neighbourhood consisting of 196 cells is applied (left). For each land use function, the transition rule is a weighted sum of distance functions calculated relative to all other land use functions and features (right).	65
Figure 18	Example of the neighbourhood function for Influence of Residential – Low Density on Residential – Low Density in WISE.	66
Figure 19	Land-use map for 2013, the start year for simulations in WISE Version 1.6.	68
Figure 20	Example of suitability map for Other Cropping land use.	76
Figure 21	Effect of proximity to the network as a combined function of distance and the distance decay parameter. (a) $a_{s,f} = 1$ (positive distance decay factor) means that a cell is more suitable for land use f if that cell is closer to the node or link of interest; (b) $a_{s,f} = -1$ (negative distance decay factor) means that a cell is more suitable for land use f if that cell is farther from the node or link of interest.	77
Figure 22	Areas belonging to search radii of 0, 1, 1.42, 2, 2.24, 2.83, and 3, respectively.	88
Figure 23	Distribution of threatened environments in the Waikato region at the start of the WISE simulation period.	101
Figure 24	Process diagram for development of 2018 Land Use layer.	118
Figure 25	Land Use Change Model – Factors and base maps	125
Figure 26	Land Use Change Model - Interpretation	126

Tables

Table 1	Six possible relationships between model variables. T stands for a transitory variable and A for an accumulating variable	17
Table 2	Climate change scenarios and global temperature, 2063 data is applied in WISE for AR5 data	20
Table 3	Overview of Representative Concentration Pathways (RCPs)	21
Table 4	Links between the Climate Change Scenarios and other models	22
Table 5	Links between the Hydrology model, the Climate Change model and Land Use Change models.	27
Table 6	Structure of the Water Quality – Land Use Change model link table	40
Table 7	Links between the Water Quality model and other models	42
Table 8	Data sources used to compile zoning information in WISE	46
Table 9	Activity status as defined under Section 77B of the RMA	47
Table 10	Default activity status for city and district councils included in the WISE model. For those areas occurring within the hydrologically modelled area but not within Waikato region administrative boundaries, a default zoning status was assigned	49
Table 11	Links between Zoning and other models	50
Table 12	Order of precedence of categories within WISE	51
Table 13	Categories and default values for activity types in the zoning model	52
Table 14	Links between WOW and other models	57
Table 15	Starting population proportions and densities for the residential classes derived for WISE V1.6 Reference scenario	61
Table 16	Links between the Residential Demands component and other models	61
Table 17	Distances and distance-numbers in the cell neighbourhood	63
Table 18	Types of land-use classes within the Land Use Change model	64
Table 19	Summary statistics for varying grid cell resolutions for the Waikato region. Total cell count = the total number of cells in the full extent, i.e. # rows x # columns. Active cell count = total cells bounded by the Waikato region coastline and interregional boundaries, i.e. all cells containing land or freshwater within Waikato region boundaries	67
Table 20	Land-use classes for the Land Use Change model in WISE 1.4	69
Table 21	Accessibility model block inputs, parameters and outputs	80
Table 22	Neighbourhood influence inputs, parameters, and outputs	81
Table 23	Suitability outputs	81
Table 24	Zoning algorithm for determining precedence among zones	83
Table 25	Zoning inputs, parameters, and outputs	83
Table 26	Algorithm for allocating land use based on calculated transition potentials	84
Table 27	Land use model inputs, parameters, and outputs	85
Table 28	Links between the Land Use Change model and other models	86
Table 29	Parameters used in the spatial indicators component	89
Table 30	Cluster indicator parameters	91
Table 31	Neighbourhood indicator parameters	92
Table 32	Distance indicator parameters	93
Table 33	Distance to map indicator parameters	94

Table 34	Mask/mapping indicator parameters	95
Table 35	Habitat fragmentation indicator parameters	96
Table 36	Land use change indicator parameters	97
Table 37	Links between user-defined spatial indicators and other models within WISE	97
Table 38	Spatial data layers used in the biodiversity model to analyse ecosystem representativeness	99
Table 39	LENZ environments threat categories, and defining criteria	99
Table 40	Links between terrestrial biodiversity and other models within WISE	100
Table 41	Suggested improvements and enhancements for WISE grouped by category (and in a relative order of priority within each category).	104
Table 42	Land-use Classification Input Data Layers	119
Table 43	Zoning Input Data Layers	119
Table 44	Data Layers used in WISE 1.4-1.6 Suitability Tool	121
Table 45	Grid Layers used in WISE 1.4-1.6 suitability tool for each land use type	122

WISE overview

Project and client

Creating Futures was a 4-year project (2006-2010) funded by the New Zealand Foundation for Research, Science and Technology. The project brought together an interdisciplinary team consisting of a regional council and social, environmental and economic researchers. The project aimed to develop new methods and tools to support integrated, long-term planning by:

- 1) developing processes to evaluate, deliberate, and choose regional futures through scenario analysis and multi-criteria deliberation frameworks, and
- 2) developing an integrated spatial decision support system (ISDSS), dubbed the Waikato Integrated Scenario Explorer or WISE, to support the evaluation and deliberation processes.

Together those tools were designed to help councils identify links and explore trade-offs between economic, environmental and social/cultural outcomes and the cumulative effects of many decisions over space and time.

This report outlines the technical specifications for WISE Version 1.6. WISE is an integrated framework designed to help examine weakly structured or unstructured problems characterised by many actors, many possibilities, and high uncertainty. WISE (version 1.0) was originally developed under objective 2 of the Creating Futures project to support and facilitate a range of integrated, long-term policy development and planning processes undertaken by Waikato Regional Council, in particular the development of regional policy and planning under the Resource Management Act, long-term council community planning under the Local Government Act and other non-statutory spatial planning initiatives

WISE is intended to help Waikato Regional Council explore possible long-term regional futures considering in a holistic manner by integrating the following topics (listed alphabetically):

- Climate Change
- **Demographics¹**
- **Economics¹**
- Hydrology
- **Land Use Change¹**
- Terrestrial Biodiversity
- Water Quality.

Objective

- Develop WISE to support evaluation and deliberation of different policy and planning strategies and scenarios in the context of long-term integrated planning as required by the Local Government Act and the Resource Management Act. In addition, WISE could help explore the consequences of alternative strategies and options under non-statutory planning processes such as, Future Proof, Waikato Plan, Economic Development Strategy.

¹ Population, economics and land use change, including the interactions between them, are the three key sub-modules in WISE.

WISE specifications

- Overview
 - WISE permits simulations of regional development from the period 2018–2068 at an annual time step.
 - WISE specifications consist of an overall systems design that includes integrated components operating at four spatial scales:
 - NZ & the World
 - Waikato region
 - Districts
 - Local (e.g., 100 m × 100 m grid cells for the Land Use Change model).
 - Users can change various model parameters or input assumptions to explore the consequences of different strategies or actions.
 - WISE is implemented in the Geonamica[®] framework. Geonamica[®] is an object-oriented application framework developed by the Research Institute for Knowledge Systems. Geonamica[®] is a programming framework specially tailored for developing ISDSSs that feature integrated dynamic models as core elements and has an extendible toolbox containing ready-to-use software building blocks required for the development of models, analysis tools and user interfaces.
- Scale: New Zealand to Global
 - Climate Change Scenarios –corresponding to three greenhouse gas emission scenarios (low – mid – high) from the Intergovernmental Panel on Climate Change (IPCC, Global 5th Assessment report (AR5) (IPCC 2013). The climate change scenario projections are based on the average of output from 40 Global Climate Models (GCM), statistically downscaled to 0.05° lat/long (approximately 5km) spatial resolution for the WISE study area (Waikato region). Scenarios (Low, +0.90°C global mean warming at 2100; Medium, 1.65°C global mean warming by 2100; High +4.09°C global mean warming by 2100) for use at sub-national scales in New Zealand. It includes three climate variables: average annual temperature (°C), average annual rainfall (mm), average annual potential evapotranspiration (mm). The user may select from one of four possible options:
 - No climate change
 - Historic interannual variation only
 - Climate change trend only (low, medium, or high)
 - Climate change and historic interannual variation.
 - External Economic Drivers – consist of 4 key economic factors that may strongly influence New Zealand and/or the Waikato region:
 - International exports (\$NZ₂₀₁₈m)
 - Interregional exports (\$NZ₂₀₁₈m)
 - Gross Fixed Capital Formation (\$NZ₂₀₁₈m).
- Regional Scale
 - Waikato Region Waikato region Economic Futures Model (EFM). The Waikato region EFM estimates future economic activity in approximately 50 industries (constant \$NZ₂₀₁₈) in the region based on regional household demand and the external economic drivers discussed above. Economic activities generate demand for land, which is an input to the Land Use Change model. The Land Use Change model determines the actual land supplied to the Waikato region EFM, which then adjusts final economic activity to reflect

that supply. In addition to modelling economic activity, the Waikato region EFM also models the employment and several environmental factors including energy use and energy-related CO₂ emissions, and solid waste generated.²

- Hydrology – consists of a simple hydrological simulation model developed specifically for WISE. The model simulates total annual surface runoff (mm/year) and summer flow yields (litres/second/km²) based on inputs of rainfall, potential evapotranspiration and land use.
- Water Quality – an adaptation of the U.S Geological Survey SPARROW model to New Zealand (Elliott et al. 2005). SPARROW estimates pollution loads of nitrogen and phosphorus (tonners/year) for each individual reach as defined within subcatchments of the Waikato River network.
- District Scale
 - Zoning – consists of a tool that allows users to input individual zoning rules and regulations. Zoning indicates where different land uses may or may not occur. Rules or regulations can apply to different areas and also be in force for different periods of time. A user can specify the precedence among the different rules and regulations and also specify the likelihood for a particular land use to occur based on its RMA activity status. For example, permitted activities would have a probability of 1, while prohibited activities would have a probability of 0.
 - Demographics – consists of a demographic model developed by the University of Waikato that projects population over time, expressed as single-year male and female age cohorts (number of persons). The model runs the entire country, with the results for the 11 districts of the Waikato region extracted for inclusion in WISE (with some adjustment for the parts of each district that lie outside of the region).
- Local Scale
 - Land Use Change – a dynamic, spatially explicit cellular automata model that models land-use change across a 100 m × 100 m grid of the Waikato region for 26 classes of land use. For each grid cell at each time step, the model calculates the potential for a cell to transition to every land use based on four factors:
 - Accessibility – assesses the attractiveness of a location for different land uses based on the proximity to desirable or undesirable features (e.g., distance from a dairy farm to a dairy factory) using a distance-decay algorithm. Users can add new features for consideration and adjust the weightings used in the algorithm to test different assumptions about accessibility. Zonal accessibility is included statically and indicates global accessibility to activities (typically population and jobs) per district.
 - Local influence – assesses the attractiveness of a location (grid cell) for a land use based on the composition of land use in the surrounding neighbourhood. For each pair of land uses, the user specifies a function defining the strength (high, low, none) and direction (positive/negative) interaction out to a maximum distance of 8 grid cells (800 m) from the cell of interest. The model sums up the weights of all the cells in the surrounding neighbourhood to produce a composite score for each cell of interest. Also each land use has a transition value at distance 0, i.e. the cell itself, which determines how easy or difficult it is to change from that land use.

² Regional water accounts measuring water use and availability is currently developed. Water data will then be linked to economic activity and land use to assess how efficient water is currently being used and to explore future constraints and development options. The energy use/emissions and waste data require updating.

- Suitability – scored from 0 (unsuitable) to suitable (1) based on different combinations of factors. Users can use the suitability maps provided or develop their own suitability layers.
- Zoning – see above under district scale for a discussion of the zoning.

Land-use change is driven by external demands for land (hectares) from the demographic model (residential uses) and the Waikato region EFM (economic uses). The model attempts to meet the external demands by assigning cells with the highest transition potentials to the appropriate land use until the demand is met.

- Terrestrial Biodiversity – tracks changes in regional threatened environment status for Land Environments of New Zealand (LENZ) Level II land environments (100 environment classes nationally) represented at 100 m × 100 m resolution. The threatened environment classification combines information on land cover with information on legally protected areas and land environments to provide information on terrestrial biodiversity status across a range of scales.
- Indicators
 - WISE produces a range of indicators that a user can examine.
 - Indicators include:
 - Numeric indicators such as population or economic activity.
 - Set spatial indicators such as water quality or land use maps.
 - User-defined spatial indicators based on pre-defined algorithms which can be set up to assess a specific need (i.e. relative spatial access to facilities).
 - Users can opt to save indicator information as a time-series either in Excel spreadsheets (numeric) or maps/images (spatial).

Future Development

- Feedback on WISE was collected during the development of WISE and subsequently.
- Based on the feedback, a list of suggested improvements and enhancements was compiled and prioritised based on interactions between the project team and Waikato Regional Council.
- Further improvements have been made in subsequent versions:
 - WISE version 1.1: addition of Zoning Tool; enhancements to the graphical user interface
 - WISE version 1.2: improved performance of Zoning Tool; changed the link between the hydrological, economic and land use models to give more consistent results.
 - WISE version 1.3: updated district boundaries; improved calibration of the land use model; addition of Monte Carlo tool; enhancements to the scenario manager.
 - WISE version 1.4: modelling resolution increased to 100m x 100m, updated initial land use layer, updated zoning layers from TA's and zoning setting reviewed, population data updated to 2013 census data, land use suitability tool introduced, and specific suitability layers added, economic and climate data updated based on current data and projections.
 - WISE version 1.5: added user-defined indicators, added contingency table tool, added functionality to upgrade previous geopoint files, upgrades to software to work with newer versions of Excel and Windows, updated climate maps.
 - WISE version 1.6: added population scenario functionality and a set of population scenarios (2018-2068), updated economic and land use models to base year 2018, updated calibration of economic and land use models.

- Waikato Regional Council has provided funding for ongoing update and further development of WISE as part of its Long-Term Plan (LTP 2021-2031), and is currently exploring various possibilities for updating and improving WISE.
- WISE as a tool for integrated spatial planning: As part of the RMA reform, the Government signalled a requirement for the development of long-term regional spatial strategies to help coordinate and integrate planning and decision-making.³

1 Introduction: Creating futures project

1.1 Overview

Creating Futures (formerly Choosing Regional Futures) was a 4-year project funded by the Foundation for Research, Science and Technology (FRST) that began 01 July 2006 and finished 30 September 2010. Creating Futures aimed at developing, testing and implementing new methods and tools to help inform communities of the long-term effects of current development patterns and trends and to inform choices and planning for desired futures.

The project brought together an interdisciplinary team of stakeholders (Waikato Regional Council, the lead agency) and social, environmental and economic researchers within New Zealand (AgResearch, Landcare Research, Market Economics, NIWA, Scion, University of Waikato) and internationally (Research Institute for Knowledge Systems – Netherlands and Université de Versailles Saint Quentin-en-Yvelines – France).

The Creating Futures project had two objectives:

1. Develop processes to enable evaluation, deliberation and choice of alternative futures for social, environmental, economic and cultural changes through the use of scenario analysis linked to multi-criteria evaluation frameworks
2. Develop an integrated spatial decision support system (ISDSS) that integrates key aspects of the economy, environment, and society/culture. The ISDSS allows users to explore plausible futures of regional development in a quantitative and spatially explicit manner, evaluate and compare different policy and planning strategy options, and help monitor and report on progress towards achieving long-term sustainable community goals and outcomes.

The tools developed through the project were designed to help identify links and explore trade-offs among economic, environmental and social/cultural outcomes, including cumulative effects over space and time. The aim was that the information, knowledge and tools from the project could be widely used and applied for policy development, planning, and resource management, initially by regional and local/city councils and eventually by other organisations.

The research project was designed to ensure close interaction between researchers and end-users such that the resulting ISDSS could be integrated into strategic planning and policy making and resource management by Waikato Regional Council and interested city and district councils. The question of exactly how the ISDSS will be used by councils remains an active area of investigation. By linking researchers and end-users from the beginning, the project provided a direct pathway for uptake of the information, tools and knowledge gained by councils and allowed them to gradually build their capacity and capability for using tools like the ISDSS as well as the associated deliberation methods to inform integrated, long-term planning.

This report provides the specifications for Version 1.4 of the ISDSS produced by the Creating Futures project. The ISDSS was dubbed the Waikato Integrated Scenario Explorer or WISE. This report follows on from a draft specifications report prepared earlier (Rutledge et al. 2007a) and

³ <https://environment.govt.nz/what-government-is-doing/key-initiatives/resource-management-system-reform/overview/>

also incorporates additional feedback received during end-user workshops (Huser et al. 2008; van Delden et al. 2010) and case studies (Wedderburn et al. 2009). These specifications represent the fourth and final stage of ISDSS development, i.e. validation and optimisation, within the Creating Futures project (Figure 1).

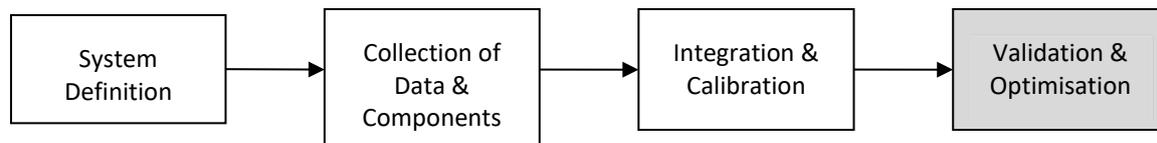


Figure 1 Four stages of ISDSS development in Objective 2 of the Creating Futures Project.

This report provides the current specifications for WISE including the overall system design and detailed information for each model including metadata, a summary, a detailed description, equations, and links to/from other models.

1.2 Spatial decision support system development

Objective 2 of Creating Futures sought to develop an ISDSS that allows users to explore “what-if” questions related to complex issues of sustainable development that require integrated planning and decision-making, e.g., for regional development and the community outcomes process required by the Local Government Act (Oxley et al. 2002; Engelen et al. 2003; Rutledge et al. 2007b; Rutledge et al. 2008).

Advantages of such an approach include

- 1) Integration of cultural, economic, environmental, and societal issues
- 2) Identification of links and feedbacks among issues
- 3) Limitations are explicitly identified, i.e. only so much land, soil, labour supply, investment capital, etc.
- 4) Demonstration of the importance of location in determining environmental effects
- 5) Aggregation or disaggregation of information/data/indicators across scales from national to local.

Potential limitations for developing an ISDSS include

- 1) Lack of spatially explicit data at the appropriate resolution
- 2) Poor knowledge of single processes or links among processes
- 3) Technical complexity involved in developing such systems
- 4) Difficulty of calibrating and/or validating such models.

WISE development consisted of a 4-stage process: 1) system definition, 2) collection and development of data and components, 3) integration and calibration, and 4) optimisation (Figure 1).

System definition (Stage 1) consisted of identifying the issues and questions that WISE should address and the corresponding models, data, and links among them that would help address those issues and questions. The research team identified key research questions, reviewed regional community outcomes, and compiled lists of available and desired knowledge, data, and models. Based on that information, the team prepared a scoping report and technical specifications document (Rutledge et al. 2007a) that outlined the overall system design and provided draft specifications for suggested models. The proposed design attempted to balance prioritisation and feasibility of addressing key questions/issues/outcomes against customary project constraints (time, budget, staff) as well as availability of required information. The report was provided to Waikato Regional Council for review and comment.

Collection and development of data and components (Stage 2) consisted of 1) gathering existing data and models and adapting them for inclusion into WISE, 2) generating new data or models that were required for particular models, and 3) identifying links among models in WISE including determining the exact specifications of those links

Integration and calibration (Stage 3) involved integrating all data and models into WISE, calibrating individual models, and adjusting model equations and parameters accordingly. Integration and calibration occurred using a staged, iterative process as follows:

1. Integration of the Land Use Change Model and WDREEM
2. Integration of demographic model outputs into #1
3. Integration of the Climate Change Scenarios, Hydrology, and Water Quality Models into #2
4. Integration of the Terrestrial Biodiversity model into #3
5. Integration of the Zoning Tool into #4.

The process was not exactly linear as depicted but instead iterative as various adjustments were made at each stage of integration. In addition to regular interaction with Waikato Regional Council staff, two workshops with a wide range of end-users were held in November 2008 and November 2009 to obtain broader feedback (Huser et al. 2009; van Delden et al. 2010). The workshops generated a substantial list of comments and suggestions for improving and enhancing WISE, some of which were incorporated into WISE Version 1.1. Most fell outside the original scope of the Creating Futures project but remain the subject of on-going future development (see section 14).

Validation and optimisation (Stage 4) were the final phase of WISE development. This phase involved validating the outputs from individual models incorporated into WISE against the results from the original stand-alone models (Elliott 2009; Schmidt 2009; Tait 2009; Cameron 2010; McDonald 2010; Price 2010). That process identified inconsistencies between outputs of the stand-alone WISE version of several models, specifically Hydrology (Schmidt 2009), Water Quality (Elliott 2009), the Waikato region EFM (McDonald 2018), and the demographic model (Cameron and Cochrane 2021). In each case the reasons for the discrepancies were isolated (e.g., errors in the WISE code, incorrect equation or algorithm), and the WISE version of the model was corrected until the outputs matched. In addition, several minor software improvements were undertaken to improve overall WISE performance and aspects of the WISE graphical user interface (GUI) were changed based on end-user feedback.

1.3 Use and application of WISE

Since the conclusion of the FRST funded research contract, the Waikato Regional Council has become the custodian of WISE. It has continued to promote the use and development of WISE in the Waikato.

Waikato Regional Council has continued a program of development and update to keep the WISE model up-to-date and targeted to user needs. This version represents a significant improvement with more recent start date, updated population and economic parameters, and additional functionality in model.

The WISE model has been used for a range of projects since its initial development. Case study examples of its use are being developed over time and made available on the website.⁴ The most recent application has used the power of WISE to project land use into the future across the Waikato region and ally these results at a census area unit level to project future population, households, works force and employment.⁵ Other applications include assessing urban sprawl

⁴ <http://www.creatingfutures.org.nz/case-studies/>

⁵ <http://www.waikatoregion.govt.nz/tr201603/>

impacts under different zoning in Future Proof area, and identifying implications of promoting 'Carbon Farming' on future rural land use.

Other 'spin-off' benefits have also occurred from the WISE project for the wider spatial planning community. A follow-on spatial planning research project (Sustainable Pathways 2 [SP2]⁶) has created Integrated Scenario Explorer (ISE) models for Auckland and Wellington regions. A technical user group for these ISE models has been operating to share knowledge between users of WISE and SP2 outputs. A related Envirolink Tools project has also been undertaken through Massey University and WRC to create a directory for decision support systems (DSS) like WISE/ISE.⁷ This directory brings together in one place the metadata for a wide range of DSS's and case study examples of their use.

Discussions and scoping proposals have also been undertaken for the possible development of an 'Upper North Island' version of WISE/ISE. These discussions are being driven through the Upper North Island Strategic Alliance (UNISA).

⁶ http://www.massey.ac.nz/massey/learning/departments/centres-research/eernz/sustainability-pathways-2/sustainability-pathways-2_home.cfm

⁷ <http://tools.envirolink.govt.nz/>

2 WISE specifications

2.1 Overall system design

2.1.1 Overview

The overall system design for WISE Version 1.6 (Figure 2) consists of an integrated set of models that operate across four spatial scales: NZ & the World, the Waikato region, cities and districts (e.g., Hamilton, Waipa, Matamata-Piako), and local for the land use change (100 m × 100 m grid cells) and terrestrial biodiversity models (100 m × 100 m grid cells). Each model consists of more detailed sub-models, each of which varies in detail, data, and internal structure.

WISE operates on an annual time step, with simulations beginning in 2018 and ending in 2068.

Arrows represent links or flows among the different models. The direction of the arrow shows the direction of flow. For example, the demographic model generates information on population at the district level. Population is pooled among all districts to create a supply of labour to drive regional level demand for goods and services in the Waikato region EFM.

Below are short summaries for each of the models within WISE. The sections that follow provide more detail on each model and its components.

2.1.2 New Zealand to global scale

The New Zealand to Global scale includes Climate Scenarios and Economic Drivers. These contain information on conditions operating exogenously or outside the Waikato region that influence or “drive” events within the region. These drivers, as they are called, operate at broader national or global scales and are generally beyond the influence of decision-makers within the Waikato region. Climate Scenarios include 3 pre-defined scenarios derived from IPCC 5th Assessment Report (AR5) (IPCC 2013) and downscaled to New Zealand and adapted to the Waikato region. In WISE the three scenarios span the range of possible climatic trends to 2063: low (IPCC AR5 RCP2.6 scenario), medium (RCP4.5), and high (RCP8.5). The Climate Change scenarios include temperature (°C), rainfall (mm), and potential evapotranspiration (mm). The Climate Change Scenarios also include the ability to include historic inter-annual variability to reflect shorter-term climatic cycles such as El Nino/La Nina.

Economic drivers contain required information for the Economic Futures Model (EFM, discussed further below). There are four key external drivers:

1. International exports (i.e. demand outside New Zealand)
2. Inter-regional exports (i.e. demand within New Zealand from other regions)
3. Gross fixed capital formation (e.g., new buildings, equipment, plant and machinery etc.)
4. Changes in inventory (e.g., changes in goods not yet sold).

All values for 1–4 above are expressed in constant \$NZ₂₀₁₈m.

Users can explore different future scenarios based on different assumptions about future climate change and economic trends.

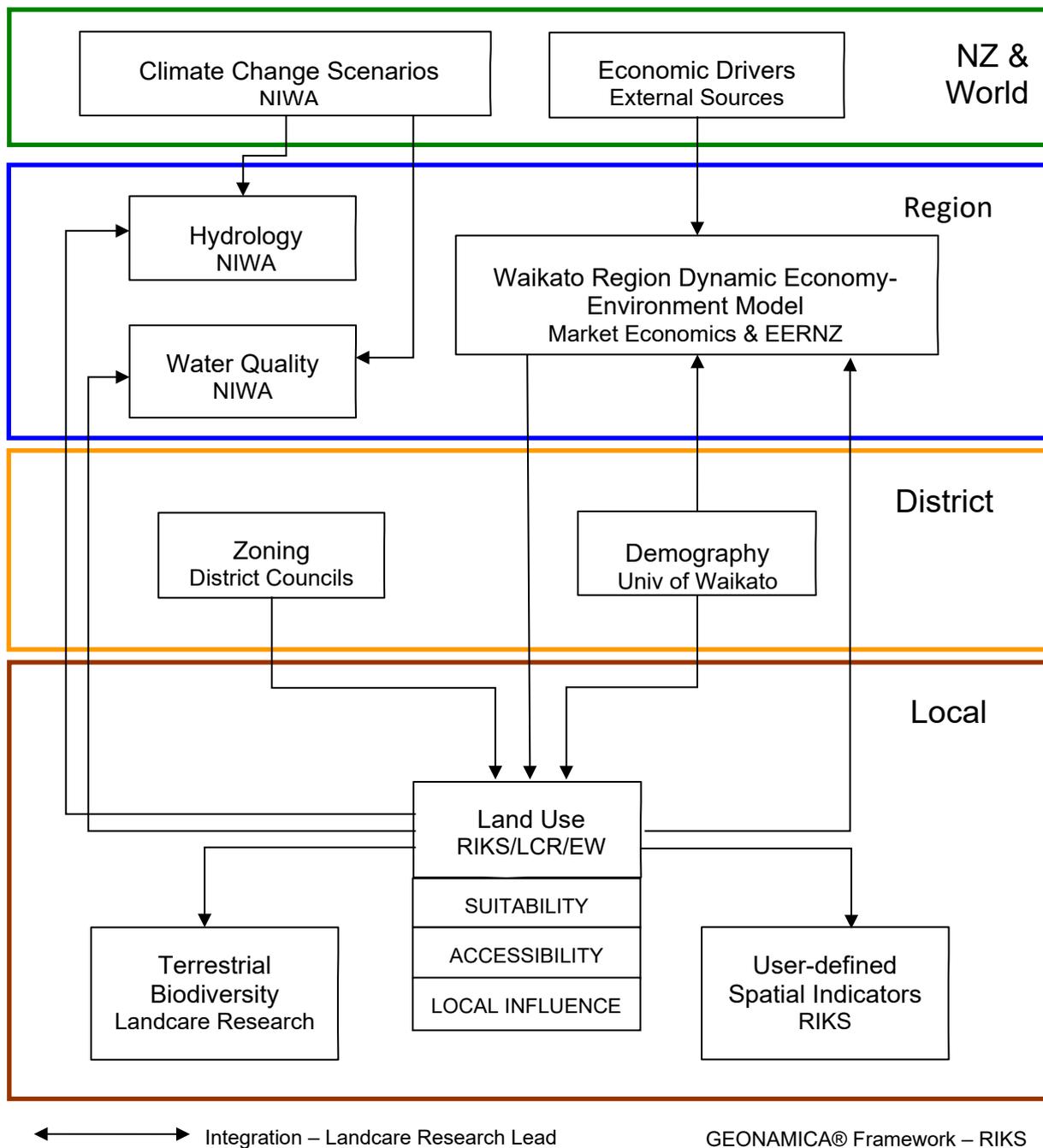


Figure 2 WISE Version 1.6 system design.

2.1.3 Regional scale

The regional scale contains three models: The Waikato region Economic Futures Model (EFM), Hydrology, and Water Quality. The Waikato region EFM is a dynamic systems model of the regional economy and environment-economy interactions. The Waikato region EFM consists of three sub-modules:

1. Demand-side
2. Supply-side
3. Reporting.

The Waikato region EFM models trends in approximately 50 industries of the regional economy and provides information on economic activity, environmental use, and labour markets. The demand-side module estimates demand by industry, which is the sum of the four external economic drivers described above and regional household consumption (demand). Associated with each economic industry is a demand for land, which depends on an eco-efficiency index (e.g. hectares required /\$ economic output). The Waikato region EFM presents demand for land to the Land Use Change model (see below), which determines the final amount of land supplied to each land use. The supply-side module adjusts, if necessary, final economic activity depending on the amount of land allocated to each economic industry by the Land Use Change model. The reporting module provides information and indicators related to the economy (e.g., final demand in constant \$NZ₂₀₁₈m), environment, (e.g., resource use or residual outputs in appropriate units), or labour markets (e.g., employment, labour force productivity).

The Hydrology model estimates annual surface water runoff and the expected water yield in the driest summer month for a 500 m × 500 m grid across the region. These are calculated from spatially varying climate, soil and vegetation hydrological responses.

Water Quality consists of a version of the SPARROW model developed by the U.S. Geological Survey that has been adapted to New Zealand conditions. SPARROW estimates total annual loads of nitrogen and phosphorus (tonnes/year) for sub-catchments within the region as a function of climate, land use, soils, and point-source pollution sources.

2.1.4 District scale

The District scale contains two models: Zoning Tool and Demographics. The Zoning Tool determines where different land uses may or may not occur. The Zoning Tool allows a user to input various zones, plan, rules, designations, overlays etc. as desired to simulate the effects of different zoning policies on future land-use development. For each zone, rule, etc., the user may specify a probability of change ranging from 0 (land use prohibited) to 1 (land use permitted). Each zoning rule may operate over the entire simulation (2006–2050) or for specified periods of time only, e.g., a targeted economic growth zone in effect from 2015 to 2025.

The demographic model runs at the national level, but produces outputs for each district or part district (after some adjustment) in the Waikato region.⁸ The model includes information on fertility, mortality, internal migration between districts, and international migration.

⁸ As of September 2010. Effective 01 December 2010 the portion of Franklin District in the Waikato Region became part of the Waikato District as a result of the creation of the consolidation of the Auckland Region and several district councils, including parts of Franklin, into the new Auckland Council.

2.1.5 Local scale

The Local Scale consists of two models: Land Use Change and Terrestrial Biodiversity. In WISE land use is represented as a grid of 100 × 100 m cells, while the Terrestrial Biodiversity represents the status of land environments as a grid of 100 × 100 m grid cells.

The Land Use Change model dynamically models land-use change over time based on demand for residential land uses generated by the WOW model and demand for economic land uses generated by the Waikato region EFM. Each year the model evaluates the potential for land use at each 100 × 100 m grid cell to transition to every other land use. For each grid cell the model ranks the transition potential of all the land uses based on a combined score from four factors:

1. Accessibility – distance from the grid cell in question to key relevant features, for example the distance from residential areas to the central business district
2. Local influence – composition of land use in the neighbourhood (8 cell radius or 800 m) around each cell as well as the current land use
3. Suitability – estimated suitability of land for different uses scaled from 0 (not suitable) to 10 (highest suitability) based on various factor considered relevant to a particular land use
4. Zoning – the potential for future development to occur at a grid cell based on knowledge of regional and district plans and other statutory requirements, ranging from 0 (prohibited) to 1(permitted) or, in a few cases, >1 (actively stimulated).

The Land Use Change model operates as follows. First, it determines the vector of transition potentials for each grid cell for each land use. Second, it allocates land use to the cell with the highest regional potential for a demanded land use (residential or industry). Third, it continues to allocate land use iteratively until it meets the external demands for residential and economic land uses, if possible.

The Terrestrial Biodiversity model tracks annual changes the status of Threatened Environments (Figure 23). Threatened Environments are an indicator of ecosystem representativeness based on a combination of biodiversity condition (land cover), protection (New Zealand Protected Areas Network), and Land Environments of New Zealand (LENZ). The model accepts land use from the Land Use Change model as input, translates land use into land cover (native or non-native), and then determines the amount of native cover remaining by LENZ land environment and amount protected to calculate each land environments threat status.

The user-defined spatial indicator component allows the user to add spatial indicators on demand by selecting one from a set of available algorithms, when required providing additional input data and configuring indicator parameters. Examples of such indicators are expansion of urban areas, distance from residential locations to the nearest recreation site, urban development in areas prone to flooding—requiring a map indicating areas prone to flooding—and job potential, which is the ratio between the number of jobs and inhabitants in the vicinity of a residential location.

3 Model descriptions – reader’s guide

To make it easier to locate information, each section describing a model follows a common format. This includes five primary subsections providing the following information:

- *Metadata*: table of pertinent metadata including
 - Name
 - Contact person
 - Scale
 - Input Data
 - Internal Data
 - Output Data.
- *Summary*: an overall summary of the model including a brief description of the inputs and outputs
- *Description*: a more detailed description of the concepts, ideas, and assumptions underpinning the model
- *Equations*: the full set of equations describing each model
- *Links*: table of inputs and outputs to/from other models within WISE. Specifically:
 - *Inputs*: data passed *from* other components within WISE including external drivers, policy options, user-definable data layers, or data from another model
 - *Outputs*: data passed *to* other models within WISE
 - *Comments*: descriptions of any methods required to transform data passed to or from one model to another or other important information of note.

The section describing GEONAMICA[®] deviates from this structure, as GEONAMICA[®] is a software framework for building integrated models and not a model itself.

4 GEONAMICA® framework – RIKS

WISE was developed as an application within the GEONAMICA software framework. GEONAMICA is an object-oriented application framework (Fayad et al. 1999) developed by RIKS to build decision support systems based on spatial modelling and (geo) simulation. It has been developed over the past 20 years and has been used to generate integrated spatial decision support systems, such as

1. UNHARMED (Van Delden *et al*, 2015, Van Delden *et al*, 2016a) – a decision support system for disaster risk reduction, applied to Greater Melbourne, Greater Adelaide and Tasmania, Australia.
2. RECARE IAM (Van Delden *et al*, 2016b) – a Europe-wide integrated assessment model for the impact of policy and land management options on soils and ecosystem services.
3. DESURVEY IAM (Van Delden *et al.*, 2009) – an integrated modelling framework for rural development with applications to semi-arid regions in Europe and Africa.
4. LUMOCAP PSS (Van Delden *et al.*, 2010) – a policy support system for evaluating the impacts of agricultural policies on the European land use and landscape.
5. WADBOS (Engelen et al. 2003a) – an application to explore the state and management of the Wadden Sea north of the Netherlands
6. ENVIRONMENT EXPLORER (Engelen et al. 2003b) – an integrated spatial decision support system in which social, economic and ecological processes are simulated to explore policy alternatives in relation to the quality of the environment in which Dutch citizens live, work and recreate.
7. MEDACTION PSS (Van Delden et al. 2007) – an integrated policy support application to assess the main issues underlying the causes and effects of land degradation and develop integrated planning policy options and mitigation strategies to combat desertification in the Northern Mediterranean region
8. XPLORAH (Van Delden 2008) – an integrated application to explore policy development, land use planning and resource management in Puerto Rico
9. MOLAND (Barredo et al. 2003) – a generalised dynamic system for modelling urbanised European regions.

Besides these, RIKS has used GEONAMICA to develop METRONAMICA, a template ISDSS that includes a local dynamic land-use interaction model (used in WISE), a spatial indicator component (used in WISE), a regional interaction model, a transport model, an econometric declarative modelling component and/or a demographic model – depending on the exact version (Van Delden and Hurkens, 2011). It can be used to set up a specific ISDSS without the need for additional software development by filling the system with data, calibrating the model and training the users.

An ISDSS such as WISE has three major components:

1. *Database* – to store information used by the system, including raster or vector map data, time series data and cross-sectional data
2. *Model base* – to manage the models within the system including specifying and scheduling interactions among them
3. *User interface* – to enable a user of the system to interact the models and data.

GEONAMICA® offers set components for storing map data, time series and cross-sectional data. It provides a modelling framework based on the Discrete Event System Specification (DEVS) formalism (Zeigler et al. 2000) that includes a model controller for managing the models including ensuring that the models interact properly and scheduling models to perform actions at specified times. To create a user interface, GEONAMICA® includes a skeleton structure and a

software class library of user interface components, such as map display and editing tools, list and table views and two-dimensional graph editing components.

The strength of GEONAMICA[®] lies in its modelling framework, which provides a generic structure for that facilitates the integration of a variety of different models and enabling the resulting integrated, complex, dynamic models to be executed easily and efficiently. The environment enables users to run simulations interactively, by allowing them to interact with the system and observe the results of their actions directly in a comprehensive manner and save the results for further analysis or presentation purposes.

4.1 Model blocks

The GEONAMICA[®] modelling framework builds on the DEVS formalism such that models are composed of model blocks, which are encapsulated parts of a model that can communicate with each other and with the system through a standardised interface. A model block contributes to the entire model – in its simplest representation as a collection of variables and equations or algorithms – through the variables it contains, and the procedures associated with it to compute the value of these variables.

Model blocks communicate with each other through input and output ports. An input port allows a model block to gain read-only access to a variable of another model block, such that it can be used for computation. An output port allows read-only access to one of the variables of a model block. By linking all input ports of a model block to output ports of other model blocks, we create a coupled component.

The collection of interlinked components forms the system that represents our entire model. For each particular system, the model is specified in an Extensible Markup Language (XML) file. The listed model blocks are activated and coupled at run-time, thereby allowing a change of the model without the explicit need for additional programming and allowing different versions of a model to be maintained in parallel. Data hiding is applied to model variables within a model block that should only be accessed through dedicated ports.

4.2 Simulation engine

The simulation engine tells each model block when to compute the value of its variables for a specific point in time. The model block responds by telling the simulation engine when it should calculate again. To keep the model output comprehensible for the user, the simulation engine always keeps all model blocks up to date with the global simulation time.

A problem arises when trying to calculate more than one variable in a model block. Consider, for example, a model with two model blocks (Figure 3). Model block A has the variables X and Y and model block B has the variable Z. The value of the variables is calculated as:

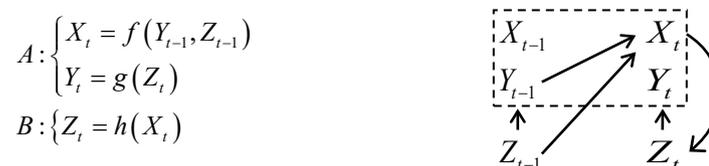


Figure 3 Example of relationships between variables in different model blocks.

These relations are depicted schematically on the right-hand side of Figure 3. The arrows indicate that a variable (head) is dependent on the value of another variable (tail). We can easily see that X should be calculated before Y and Z, and Z should be calculated before Y. However, if X and Y are in the same model block, they should be calculated simultaneously, because calculation procedures are associated with model blocks, not with individual variables. We must therefore make a distinction between variables that are dependent on a lagged value

(accumulating variables) and variables that are only dependent on current values (transitory variables). So, X is an accumulating variable and Y and Z are transitory variables. The complete determination of the type of a variable is depicted below in Figure 4.

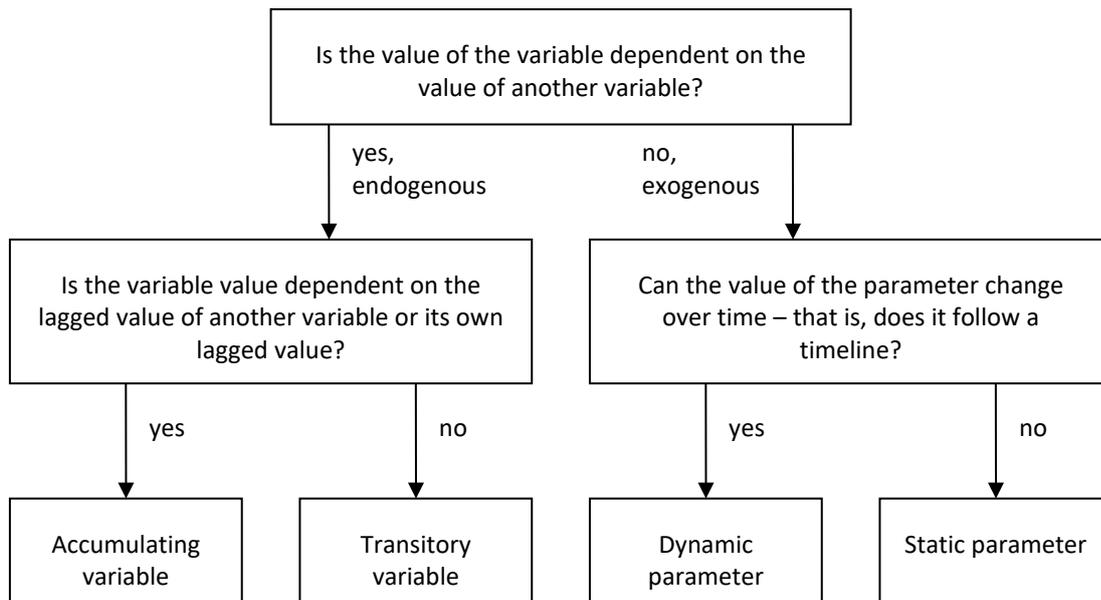


Figure 4 Logic diagram showing differences between variables and parameters.

To model the example in Figure 3, we split the computation of a model block into two parts: one in which all accumulating variables are calculated and one in which all transitory variables are calculated. First, all accumulating variables are calculated for all model blocks. Next all transitory variables are calculated. This separation does not resolve all precedence relations. In the example above (Figure 3), we see that the transitory variables of model block A should still be calculated before those of model block B.

Because accumulating variables depend on lagged values, we need to specify an initial value at the start of a simulation. The initial value replaces the calculation procedure for accumulating variables at the beginning of a simulation. Once the simulation begins, the model calculates the transitory variables, which are then used to calculate and update the accumulating variables.

Once we know the dependencies between variables, the remaining precedence relations can be derived automatically. On the left in Figure 5, we see a non-lagged relation and on the right we see a lagged relation. Depending on the variable type, X and Y will have six different possibilities (Table 1).



Figure 5 Non-lagged (left image) and lagged (right image) relationships between model variables.

Table 1 Six possible relationships between model variables. T stands for a transitory variable and A for an accumulating variable

Relation	X_{t-1}	X_t	Y_t	Meaning	Brief
$Y_t = f(X_t)$	-	T	T	X must be calculated before Y is calculated.	$X < Y$
$Y_t = f(X_t, Y_{t-1})$	-	T	A	This is impossible, since all accumulating variables must be calculated before all transitory variables.	-
$Y_t = f(X_t)$	-	A	T	OK; all accumulating variables are calculated before all transitory variables.	OK
$Y_t = f(X_t, Y_{t-1})$	-	A	A	X must be calculated before Y is calculated.	$X < Y$
$Y_t = f(X_{t-1}, Y_{t-1})$	T	-	A	OK; all accumulating variables are calculated before all transitory variables.	OK
$Y_t = f(X_{t-1}, Y_{t-1})$	A	-	A	Y must be calculated before X is calculated.	$Y < X$

The relations between variables can be derived from the connections between input and output ports. Hence, the order in which the variables of the model should be calculated can be derived once we know the model coupling. To upscale this order to model blocks, we add equality relations (in terms of precedence) between all accumulating and all transitory variables of the same model block. Note that, since the precedence relations between variables are relevant to either the accumulating or transitory computation phase, depending on the type of variables involved, the order in which model block calculate can differ in the two phases.

While the GEONAMICA[®] framework builds on the DEVS formalism, it does not comply with it fully. In the DEVS formalism, the distinction is made between rate and state variables. First, the change of all state variables is calculated and stored in rate variables. Next, the state variables are updated with the rate variables. This method allows model blocks to calculate completely independently at the cost of having to store the change of each variable explicitly, even when a variable could be updated directly. The GEONAMICA[®] model framework takes advantage of such redundancies to reduce the strain on resources. This comes at the cost of generality. Any specific model that can be implemented using the DEVS formalism can be also implemented using the GEONAMICA[®] modelling framework.

4.3 Incorporating user input

The simulation engine keeps all model blocks up to date with the current simulation time to present a comprehensible output to the user. During the course of a simulation, we iteratively take time steps to advance the state of the system. At the start of a time step, we update parameter values changed by the user and recalculate the transitory variables dependent on these parameters. Next, we can advance the simulation clock and calculate the accumulating variables of each model block in the order derived from the precedence relations between variables. Finally, the transitory variables of each model block are updated in their respective order and the new output is presented to the user. The next simulation step is performed when the user instructs the system to do so or automatically if desired.

If we strictly follow the process outlined, a user could interact with the system only after a single time step is completed and before the next one starts. Allowing a user to alter parameter values in the middle of a simulation step could result in undetermined system behaviour, especially if they alter parameter that should remain constant, i.e. a parameter in a biophysical model that has been empirically determined. We therefore need a mechanism that allows the user to interact with the system during the course of a simulation step, but guarantees that parameter values remain constant during this period. This mechanism has been incorporated in the interface ports of model blocks.

Interface ports provide access to the parameter values of a model block that can be altered by the user between simulation steps. The changes made in the user interface are cached in the

interface port to which the user interface is linked. At the beginning of a simulation step, the user interface ports are instructed to relay their cached changes to the actual parameter values. This way, we require no further synchronisation between user interface and model processes, as far as the updating of parameter values is concerned, thereby greatly reducing the overhead caused by such synchronisation issues.

5 Climate change scenarios – CLIMsystems

5.1 Metadata

1.	Model Component	CLIMATE CHANGE SCENARIOS
2.	Organisation	CLIMsystems
3.	Contact	Peter Urich/Yinpeng Li
4.	Spatial Resolution	0.05° lat/long (~ 5km) (as grid)
5.	Temporal Resolution	Annual
6.	Input Data	None
7.	Internal Data	1995 Temperature (°C, as grid) 2063 Temperature – IPCC Low Scenario (°C, as grid) 2063 Temperature – IPCC Medium Scenario (°C, as grid) 2063 Temperature – IPCC High Scenario (°C, as grid)
8.		1995 Rainfall (mm, as grid) 2063 Rainfall – IPCC Low Scenario (mm, as grid) 2063 Rainfall – IPCC Medium Scenario (mm, as grid) 2063 Rainfall – IPCC High Scenario (mm, as grid)
9.		1995 Potential Evapotranspiration (mm, as grid) 2063 Potential Evapotranspiration – IPCC Low Scenario (mm, as grid) 2063 Potential Evapotranspiration – IPCC Medium Scenario (mm, as grid) 2063 Potential Evapotranspiration – IPCC High Scenario (mm, as grid)
10.		Annual Anomalies 1972–2013 – Temperature (°C, as series of grids) Annual Anomalies 1972–2013 – Rainfall (mm, as series of grids) Annual Anomalies 1972–2013 – Potential Evapotranspiration (mm, as series of grids)
11.	Output Data	Temperature (°C, as grid) Rainfall (mm, as grid) Potential Evapotranspiration (mm, as grid)

5.2 Summary

Climate change scenarios project trends to 2063 for annual rainfall (mm), annual average temperature (°C) and annual potential evapotranspiration (PET, mm). The three scenarios correspond to three greenhouse gas emissions scenarios produced as part of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC 2013).

Table 2 Climate change scenarios and global temperature, 2063 data is applied in WISE for AR5 data

Scenario	AR5	2063	2100
Low	RCP2.6	+0.94	+0.90
Mid	RCP4.5	+1.46	+1.65
High	RCP8.5	+2.27	+4.09

The climate change scenario projections are based on the average of output from 40 Global Climate Models (GCMs) compiled for the IPCC AR5. GCM output has been statistically downscaled to 0.05° lat/long (approximately 5 km) spatial resolution for the WISE study area.

A user may also specify no climate change trend. In addition, a user may decide whether or not to include historic inter-annual variability, resulting in four possible climate scenarios. Historic inter-annual variability adds year-to-year variation to the long-run climate trends based on observed values related to shorter term climatic cycles such as El Niño/La Niña.

The climate change scenarios were not updated for V1.6 as the IPCC AR6 report and scenarios had not been completed when this model was updated.

5.3 Description

We implemented a technique called pattern scaling to produce climate patterns for global coverage (0.5°*0.5°) (see Appendix 1 for a full description of this method). Pattern scaling has a higher degree of confidence for temperature-related impacts, while less confidence for precipitation-related impacts of climate change can be expected. This is because attributes of climate variability and anthropogenic change are often unresolved due to large variability in precipitation patterns. As a result, systems affected by multiple variables including extreme climatic variables (for instance, agricultural cropping systems, livestock production systems and natural ecosystems), usually face higher uncertainty with respect to climate change related impacts.

Ensembles (or parallel scenarios) of up to 40 Global Climate Models (GCMs) were used to generate the future scenarios, by providing the range of ensemble member values per variable. The spatial scenarios and statistics produced are presented using median values of the ensemble. 40 GCMs included in IPCC AR5 (CMIP5) were employed for the ensemble. Details of the GCMs used for producing the future scenarios of specific variables are provided in the CLIMsystems report (Urich and Li 2015).

The following steps were undertaken to produce the results contained in this Assessment (and further details of the steps are provided in report supplied by CLIMsystems, Urich and Li 2015):

1. Temperature and precipitation patterns were normalised, using the global mean temperature change of the corresponding period and GCM; and
2. Spatial and statistical analyses were undertaken based on the ensemble results, for: (a) the Baseline period (1976-2013, from observed climate data from NIWA), and (b) one future time period: 2063, for the different variables.

To generate the future climate scenarios, the Representative Concentration Pathways (RCPs) from IPCC Fifth Assessment Report (IPCC, 2013) were used. The RCPs are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its Fifth Assessment Report (AR5). The four RCPs, RCP2.6, RCP4.5, RCP6.0, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 (of 2.6, 4.5, 6.0, and 8.5 W/m², respectively) (Table 3).

Table 3 Overview of Representative Concentration Pathways (RCPs)

	Description	CO2 Equivalent	SRES Equivalent	Publication – IA Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m ² in 2100.	1370	A1FI	Raiahi <i>et al.</i> 2007 – MESSAGE
RCP6.0	Stabilization without overshoot pathway to 6 W/m ² at 2100	850	B2	Fujino <i>et al.</i> ; Hijioka <i>et al.</i> 2008 – AIM
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m ² 2100	650	B1	Clark <i>et al.</i> 2006; Smith and Wigley 2006; Wise <i>et al.</i> 2009 – GCAM
RCP2.6	Peak in radiative forcing at about 3 W/m ² before 2100 and decline	490	None	van Vuuren <i>et al.</i> , 2007; van Vuuren <i>et al.</i> 2006 - IMAGE

Figure 6 shows the global mean temperature change projected for four RCP scenarios, between 1995 and 2100. Global mean temperature changes projected ranges from 0.73°C (RCP2.6) to 0.96°C (RCP8.5) by 2030, and by 2100, between 0.9°C under RCP2.6 and 4.09°C under RCP8.5 (Table 3).

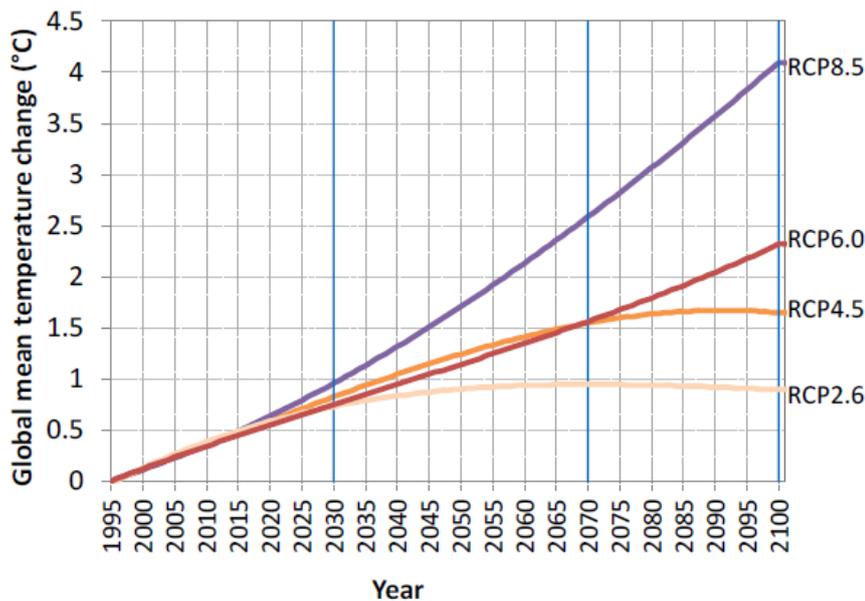


Figure 6 The global mean temperature change of the four selected RCP scenarios. The graph shows that up to 2030, global mean temperature is projected to increase by about 1.0° C, irrespective of the RCP scenario and subsequently the future temperature change projections diverge by 2070 and even more by 2100, depending on the RCP scenario.

WISE also includes annual grids of temperature, rainfall and PET anomalies, which are annual differences from the long-term mean for the period 1972–2013 (40 years). If a user chooses,

the inter-annual variability (anomalies) can be superimposed on the climate change trends to simulate natural year-to-year variations in weather patterns that are driven by events such as El Niño/La Niña. This 40-year data sequence is repeated to provide climate change estimations up to 2063.

Climate change scenarios include values for the start year (1995) and end year (2063) for each cell of the 0.05° grid. Values for intervening years for each grid cell are linearly interpolated based on the slope between the climate scenario start year (1995) and end year (2063).

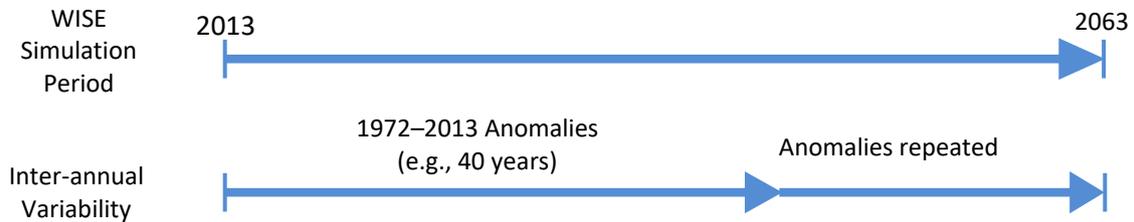


Figure 7 Implementation of inter-annual climatic variability in WISE.

5.4 Equations

Climate change scenarios include values for the start year (1995) and end year (2063) for each cell of the 0.05° grid. Values for intervening years for each grid cell are linearly interpolated based on the slope between the climate scenario start year (1995) and end year (2063), such as for temperature:

$$Temp_{t,x,y} = \left(\frac{Temp_{2050,x,y} - Temp_{1990,x,y}}{60} \right) \times Temp_{1990,x,y}$$

where

$Temp_{t,x,y}$ = Temperature in current year t at grid cell x,y in °C

$Temp_{2050,x,y}$ = Temperature in 2063 at grid cell x,y in °C

$Temp_{1990,x,y}$ = Temperature in 1995 at grid cell x,y in °C

Note that the Climate Scenario start year (1995) is *not* the same as the start year of the WISE simulation (2013). Values for the climate layers at 2013 are interpolated as described above.

There are no model equations associated with inter-annual variability. Each year is supplied as its own grid.

5.5 Links

The Climate Change Scenarios link to the Hydrology and Water Quality models as indicated in Table 4.

Table 4 Links between the Climate Change Scenarios and other models

Type	Model Component	Data Passed	Comments
Inputs	none		
Outputs	Hydrology	Rainfall PET	
	Water Quality	Rainfall	Weighted average of the 4 nearest 0.05° grid cells applied to each sub-catchment

6 Hydrology – NIWA

6.1 Metadata

1. Model Component	Hydrology
2. Organisation	NIWA
3. Contact	Daniel Collins and Ross Woods
4. Spatial Resolution	500 m (as grid)
5. Temporal Resolution	Annual
6. Input Data Required	Annual rainfall (mm/y, as grid) Annual potential evapotranspiration (mm/y, as grid) Land use (as grid)
7. Internal Parameters	Seasonality of rainfall (dimensionless, 0–1, as grid) Seasonality of potential evapotranspiration (dimensionless, 0–1, as grid) Mean number of rain days per year (days, as grid) Profile readily available water capacity in soil (mm, as grid) Flow seasonality (no dimensions, 0–1, as grid) Land use categories (as grid) Canopy capacity (mm, as a parameter look-up table from Land Use categories)
8. Output Data	Annual runoff for the year (mm/year, as grid) Minimum monthly summer flow yield per unit area (litres s ⁻¹ km ⁻² , as grid)

6.2 Summary

The Hydrology model is a simple hydrological simulation model developed specifically for WISE. It includes the impacts of spatially varying climate, soil and vegetation on hydrological response. The outputs of the model are the annual surface water runoff for each year and the expected water yield in the single driest summer month.

6.3 Description

The Hydrology model assumes that climate varies smoothly during each year, and that within this smooth seasonal variation, rain falls in random pulses. The random pulses of rain are stored on the plant canopy if there is sufficient capacity, and then evaporated. Excess rain overflows the canopy and reaches the ground, where it is assumed to gradually fill the soil moisture store. Once the soil moisture store fills (in winter), any additional rain produces runoff. Recharge of groundwater by deep seepage of excess soil water is assumed to be negligible. Water is evaporated from this soil water store at the potential evapotranspiration rate until the store is empty. The basic structure of the model for a grid cell is shown in Figure 8, and the seasonal filling and emptying of soil moisture are shown in Figure 9.

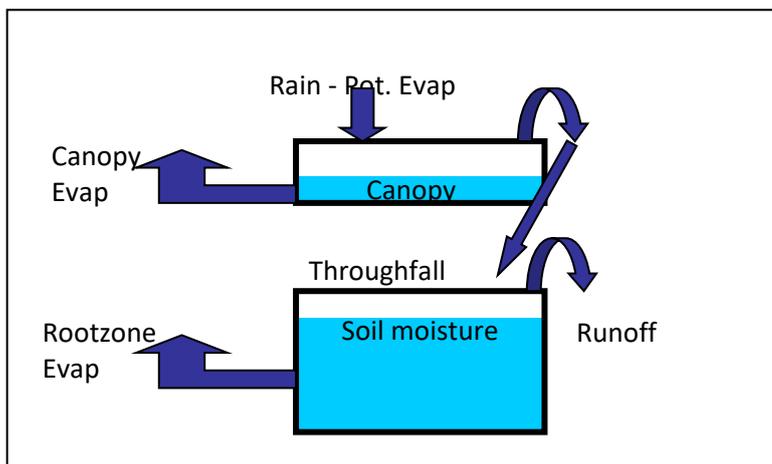


Figure 8 The inputs, outputs, and storages of the annual hydrology model.

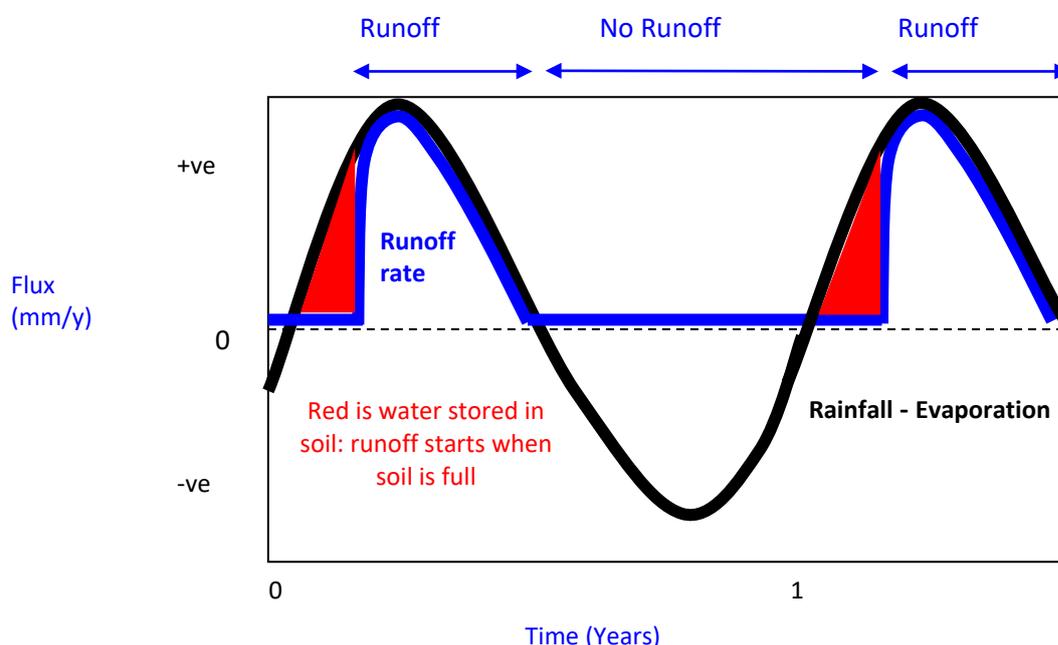


Figure 9 The annual filling and emptying of soil moisture in response to climate seasonality.

If there are changes in the modelled climate or vegetation, then the model outputs will respond to this. Changes in climate affect the rainfall and potential evapotranspiration (PET), whereas changes in vegetation affect mainly the interception capacity of the plant canopy.

Calculations are made separately for a 500 m × 500 m grid using a simplified set of analytical solutions, based on Woods (2003, 2007). The summer flows are calculated as a predicted proportion of the flow for the year, based on empirical analysis of data from the Waikato region. Sample applications of this model for New Zealand, Australia and globally have been presented at a recent international conference (Woods 2008).

Canopy capacity is determined by current land use from the Land Use Change model through a look-up table. Soil water holding capacity comes from the Fundamental Soils Layer, which is found in the New Zealand Land Resource Inventory (Wilde et al. 2000); these values only apply to the upper 0.9m of the soil profile. The water holding capacity value is adjusted to account for increased rooting depth of tall vegetation (Schenk & Jackson 2002 J. Ecology).

6.4 Equations

Climate component

The model is based on dimensionless variables (as indices) describing the various components of the water balance. As the first step, a non-dimensional climate dryness index R is calculated, which describes mean annual potential evaporation as a fraction of mean annual rainfall. Small values of R ($R < 1$) mean that annual rainfall exceeds annual potential evaporation, i.e. a wet climate, whereas $R > 1$ indicates a dry climate. In the Waikato, R ranges from about 0.3 (very wet) to 0.7 (moderately wet) on an annual basis:

$$R = \frac{E_p}{P}$$

where

P = Annual rainfall (mm/y)

E_p = Annual potential evaporation (mm/y)

The mean rate of rainfall and potential evaporation are assumed to vary seasonally as sine functions, with the amplitude and timing of the maxima and minima determined by the rainfall and potential evaporation seasonality parameters ϕ_p and ϕ_E (Woods 2003). Hence, a climate seasonality index, S , can be defined, where small values indicate that the ratio between potential evaporation and rainfall does not change much during the year:

$$S = |\delta_p - \delta_E R|$$

where

ϕ_p and ϕ_E = dimensionless seasonal amplitude of rainfall and potential evaporation

Specifically, the seasonal variations in rainfall and potential evaporation rates are modelled as sine curves whose amplitudes are $P\phi_p$ and $E_p\phi_E$, respectively. In winter, the rainfall and potential evaporation rates are $P\cos(\phi_p)$, and $E_p\cos(\phi_E)$, respectively, while in summer they are $P\sin(\phi_p)$, and $E_p\sin(\phi_E)$. In the Waikato, rainfall has a weak to mild winter maximum, implying ϕ_p values ranging from 0.1 to 0.3, and potential evaporation has a strong to moderate summer maximum, with ϕ_E values ranging from -0.9 to -0.7 .⁹ Typical values of S are about 0.4 – 0.5 in the Waikato region.

Canopy component

The intermittency of the rainfall distribution is described by the input variable N , the number of raindays per annum. The mean rainstorm event depth (mm) over that time can be derived as P/N . A dimensionless canopy storage capacity, W_c , can be calculated, indicating what proportion of an average rain event can be stored in canopy:

$$W_c = \frac{W_{cm}}{P/N}$$

⁹ If ϕ_p is positive, the largest seasonal rainfall is at the end of July; if ϕ_p is negative, the largest seasonal rainfall is at the end of January; a positive value of ϕ_E indicates the potential evaporation has a seasonal maximum at the end of July (Northern Hemisphere), while a negative ϕ_E gives a January maximum (Southern Hemisphere).

where

w_{cm} = Canopy capacity (mm)

N = Number of raindays per annum

From the above the mean annual dimensionless canopy throughfall Z_c , can be calculated as a fraction of the annual rainfall (Woods 2003):

$$Z_c = \frac{1 - R^{-1}}{e^{w_c(1-R^{-1})} - R^{-1}}$$

Soil component

The root zone dryness index, R_r is calculated as the ratio of precipitation at the soil surface (= throughfall) to potential evaporation at the soil surface (= potential evaporation – canopy evaporation) (see Woods (2003) for derivation):

$$R_r = \frac{R - (1 - Z_c)}{Z_c}$$

In similar fashion, the seasonality index for the net root zone input, S_r , is derived from the climate seasonality index (S) as the dimensionless amplitude of net root zone input relative to mean throughfall. A large value of S_r indicates a marked seasonal imbalance between supply and demand for root zone water:

$$S_r = \frac{S}{Z_c}$$

A dimensionless index for profile readily-available water, W_r , can be calculated, indicating how much annual rain can be stored in soil zone:

$$W_r = \frac{w_{rm}}{TP}$$

where

w_{rm} = $w_{rm0} \max[1, (w_{cm} / w_{cm_ref})^2]$ this provides an adjusted water holding capacity, with allowance for deeper rooting depth of plants taller than pasture

w_{rm_ref} = canopy capacity of pasture (1 mm)

w_{rm0} = Profile readily available water (mm, provided as soil attribute, see Wilde et al. 2000)

T = 1 year

The seasonality index for the net input into the root zone can now be adjusted for the actual soil water storage capacity leading to the adjusted root zone input seasonality index S_{rs} (Woods 2003):

$$S_{rs} = \max\left(S_r - \pi \frac{W_r}{Z_c}, 0\right)$$

Runoff component

With the above definitions, the mean annual runoff as fraction of throughfall, Z_{rs} , can be derived as follows (Woods 2003):

$$Z_{rs} = \max[\max(0, 1 - R_r), S_{rs} h_s]$$

where

$$h_s = \begin{cases} 0 & x_s > 1 \\ \frac{x_s \sin^{-1}(x_s) + \sqrt{1-x_s^2}}{\pi} - \frac{x_s}{2} & -1 \leq x_s \leq 1 \\ 1 & x_s < -1 \end{cases}$$

and

$$x_s = \frac{R_r - 1}{S_{rs}}$$

From the above, the mean annual runoff Q_{ann} [mm/y] is derived by scaling mean annual rainfall P with the dimensionless canopy throughfall Z_c and Z_{rs} :

$$Q_{ann} = PZ_cZ_{rs}$$

Mean summer runoff, Q_{summ} [mm], is derived by multiplying flow seasonality q_{seas} (an input) with mean annual runoff:

$$Q_{summ} = Q_{ann}q_{seas}$$

where

q_{seas} = Seasonality of flow (0–1, dimensionless)

Flow seasonality q_{seas} is an indicator for how much the annual runoff is concentrated in summer: for the extreme case of $q_{seas} = 1$ all the annual flow occurs in summer (no flow in winter), for $q_{seas} = 0$ all the annual flow occurs in winter, for $q_{seas} = 0.5$ half of the annual flow occurs in summer. For the Waikato region, higher summer runoff occurs in the headwaters of the central volcanic plateau, whereas the lower Waikato has a more equal flow distribution over the year.

Mean summer specific yield, Y_{summ} [$L s^{-1} km^{-2}$], is calculated from mean summer runoff, by unit conversion:

$$Y_{summ} = \frac{10^6}{365.25 \times 24 \times 3600} Q_{summ}$$

6.5 Links

The Hydrology model links to the Climate Change Scenario and the Land Use Change models as indicated in Table 5.

Table 5 Links between the Hydrology model, the Climate Change model and Land Use Change models.

Type	Model Component	Data Passed	Comments
Inputs	Climate Change Scenarios	Rainfall	Weighted average of the 4 nearest grid cells
		PET	Weighted average of the 4 nearest grid cells
	Land Use Change	Land Use	Land use determines the canopy capacity w_{cm} (mm) via a look-up table
Outputs	None		

7 Waikato region Economic Futures Model (EFM) - Market Economics

7.1 Metadata

1. Name	Waikato region Economic Futures Model (EFM)
2. Organisation	Market Economics
3. Contact	Garry McDonald
4. Spatial Resolution	Region
5. Temporal Resolution	Annual
6. Input Data	Population (# persons by age, sex) International Exports (\$ ₂₀₁₈ m NZD, time series) Inter-regional Exports (\$ ₂₀₁₈ m NZD, time series) Gross Fixed Capital Formation (\$ ₂₀₁₈ m NZD, time series) Change in Inventory (\$ ₂₀₁₈ m NZD, time series) Land-Use Productivity Index (unit less) Multi-factor Productivity Rates (% , time series)
7. Internal Data	Leontief Input-Output Matrix Coefficients Ghosh Supply Input-Output Matrix Coefficients Age-Cohort Consumption Coefficients
8. Output Data	Final Output for approximately 50 Economic Industries (\$ ₂₀₁₈ m NZD) Gross Regional Product (\$ ₂₀₁₈ m NZD) Land Demanded by Economic Industry (hectares) Multi-factor productivity (%) Employment (# of jobs) Unemployment (%) Resource Inputs (units vary) Residual Outputs (units vary) Energy Demands (Gigajoules)

7.2 Summary

The section describes the structure of the Waikato region Economic Futures Model (EFM), followed by a detailed mathematical description of the Waikato region EFM's modules. Appendix A is an index relating: (1) industry notations to their associated approximately 50 industry definitions; (2) the land-use category notations to their full descriptions; (3) the socio-economic reporting variable notations to their full names; (4) the employment reporting variable notations to their full names; and (5) the environmental reporting variable notations to their full names. Appendix B describes the method used to translate outputs provided by the Waikato region EFM at the Australia-New Zealand Standard Industrial Code (ANZSIC) level to the land-use classes used within the Land Use Change model.

The Waikato region EFM is based primarily on an analysis of economic activities within the Waikato region, with all economic activities categorised into one of industry types (refer to Appendix A). The economic system is also conceptualised as open, in the sense that account is taken of international and inter-regional imports and exports. Finally, the Waikato region EFM runs over a period of 50 years, beginning with a base year of 2018 and ending in 2068.

Figure 10 depicts the causal structure of the Waikato region EFM model. This is followed below by a detailed commentary on the model structure. As a starting point, it can be noted that the Waikato region EFM is composed of two economic modules, one relating to 'economic demand' the other to 'economic supply'. The demand and supply modules are not, however, directly

connected. The Demand-Side module provides estimates of land demand by economic industry that then feed into the Land Use Change model. Subsequently, the outputs of the Land Use Change model act as an input to the Supply-Side module.

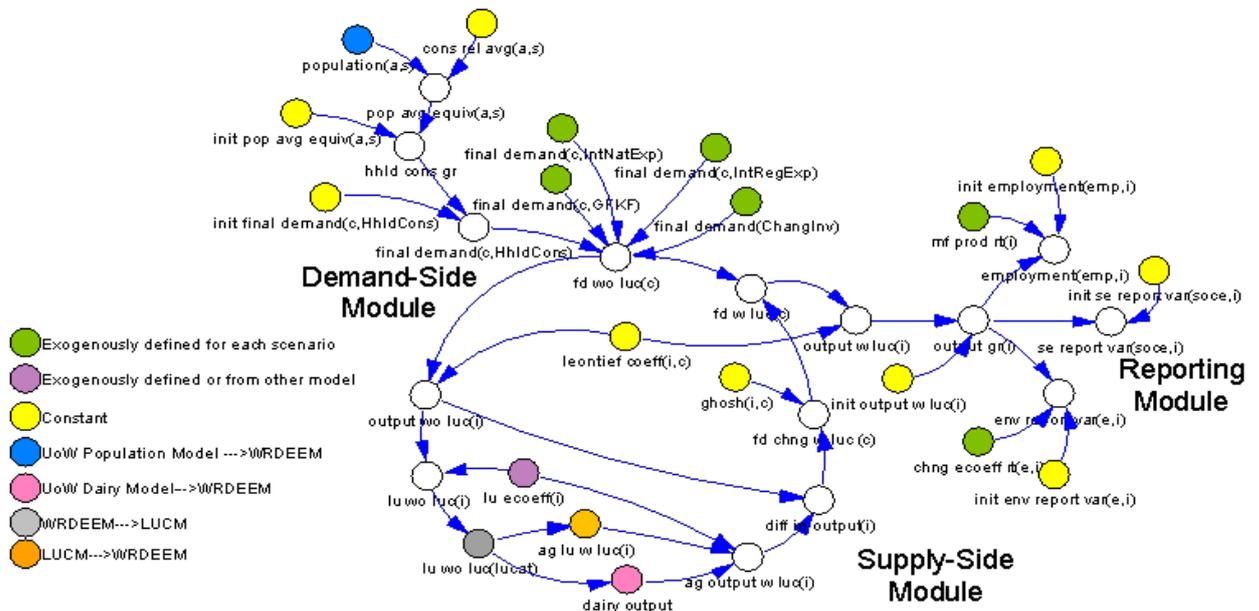


Figure 10 The Waikato region EFM system structure.

7.3 Description

The purpose of the two Waikato region EFM economic modules is to estimate future economic outputs for each of the economic industries within the Waikato region. Once estimates of economic output are obtained, they are translated into socio-economic and environmental reporting variables.

7.3.1 Demand-side module

The Waikato region EFM’s estimates of economic output by industry are primarily determined through the application of the Demand-Side module. First, the module estimates future outputs of each industry based on projections of future final demands for each industry’s goods and services driven by within-regional household demand and exports to other regions in New Zealand and internationally. Second, the module translates demand-based output estimates to estimates of land demanded (hectares) by each industry. This translation is necessary to interface with the Land Use Change model. These two processes are discussed further below.

7.3.2 Demand-side estimates of output by industry

To derive demand-based estimates of output by each industry, the model first derives estimates of the total annual value of final demands for Waikato Region’s commodities for each year of the study ($fd\ wo\ luc_c$). It then calculates the annual total economic output (intermediate and final goods) required to be produced by each industry within the region ($output\ wo\ luc_i$) to satisfy that level of final demands. Importantly, the model considers not only the *direct* impacts of changes in future final demand, but also the *indirect* supply-chain (or backward linkages) associated with these changes. Growth in a service industry final demand may, for example, result in growth in manufacturing and primary industry output because of supply-chain purchases. The application of economic interdependencies (also termed ‘Leontief inverse coefficients’) is essential for evaluating these indirect or supply-chain effects. The economic interdependencies used in the model ($leontief\ coeff_{i,c}$) are derived exogenously through application of input-output mathematics prescribed in the model.

The estimates of future total final demand by commodity comprise five categories: household consumption ($final\ demand_{c,HhldCons}$), international exports ($final\ demand_{c,IntNatExp}$), inter-regional exports ($final\ demand_{c,IntRegExp}$), gross fixed capital formation ($final\ demand_{c,GFKF}$), and changes in inventory ($final\ demand_{c,ChngInv}$). The process for deriving future estimates for each category is as follows:

- (a) *Household Consumption*: The Waikato region EFM derives estimates of future household consumption primarily through estimates of future population. Except as qualified below by the population ageing effect, it is assumed that each person within the Waikato Region consumes a constant mix of goods and services. Thus, any population growth for the region will result in a proportional increase in the amount of goods and services consumed. The model utilises Waikato region population projections by single-year age-sex cohort as provided from the demographic model (see Section 10 below).

To account for the implications of changing demographic structure on household consumption, the Waikato region EFM multiplies each cohort projection for a particular year by a cohort-specific consumption scalar ($cons\ rel\ avg_{a,s}$). These scalars define the ratio of spending by an average person across all cohorts, to the spending of an average person within the subject cohort. The summed values across all cohorts for a given year are then normalized to \$₂₀₁₈m NZD (the base year for the Waikato region EFM is 2018). The resulting value for a particular year provides an estimate of the growth in total household consumption ($hhld\ cons\ gr$) from the base year ($init\ final\ demand_{c,HhldCons}$).

- (b) *International Exports*: Estimates of future international exports are exogenous inputs to the model and may be changed by the user to suit the scenario being investigated. The Waikato region EFM includes baseline projects for future international exports that were generated by applying the national long-run average growth rates for export commodities by industry to the Waikato region's 2018 international export estimates obtained from Market Economics Ltd's multi-regional input-output table for the Waikato region (Market Economics Ltd, 2018). The long-run growth rates by export commodity were determined according to econometric analysis. Selection of the time series techniques applied depended on the underlying dynamic behaviour of the industry output being analysed. Where historical observations fluctuate around a long-run mean, stationary time series methods were applied (e.g., the AMRA process) (Barron & Targett 1985). Where historical observations indicate a consistent upwards or downwards movement, non-stationary time series methods are used (e.g., Holt's method) (Barron & Targett 1985). The data utilised in this time series analysis were derived from Statistics New Zealand's Overseas Trade Exports – Trade, Merchandise: Monthly Estimates of all Harmonised System Items 1989–18.
- (c) *Inter-regional Exports*: Inter-regional exports (i.e. exports to other regions within New Zealand) are exogenous inputs to the model and can be changed by the user to suit the scenario being investigated. The Waikato region EFM includes a baseline series of the Waikato region's inter-regional exports. These baseline inter-regional trade values were derived from the Waikato region estimates produced from Market Economics multi-regional input-output table (MRIO) for New Zealand (Smith *et al.*, 2015). A linear program is used to estimate known imports/exports by sector in each region as constraints and a distance decay function to select between regions, i.e. the model selects those suppliers with surplus outcome that are closest to the region which desires it.
- (d) *Gross Fixed Capital Formation (GFKF)*: Estimates of future sales of commodities to gross fixed capital formation are exogenous inputs to the model and can be changed by the user to suit the scenario being investigated. Baseline estimates are directly provided in the Waikato region EFM. Future growth rates were determined, as with international exports, through statistical time series (econometric) analysis. The data utilised in the time series analysis of GFKF are derived from Statistics New Zealand's National Accounts Gross Fixed Capital Formation by Industry.

(e) *Changes in Inventory*: Changes in inventory are also an exogenous input to the model and can also be changed by the user to suit the scenario being investigated. Baseline estimates provided are provided directly in the Waikato region EFM. Note: for many industries changes in inventory are very small compared with international exports, inter-regional exports, and GFCF.

7.3.3 Demand-side estimates of industry land use

The amount of land required by each industry within the Waikato Region ($lu\ wo\ luc_i$) is calculated directly from the estimates of industry output ($output\ wo\ luc_i$). For each year, the annual estimate of output for a particular industry is multiplied by the industry-specific land-use productivity rate ($lu\ ecoeff_i$), which defines the average number of hectares required per million dollars of output for that industry. In WISE, land-use productivity rates are set as constant values according to data calculated for the base year.

7.3.4 Interface with the land use change model

Estimates of land demanded by economic industry constitute the link between the Waikato region EFM and the Land Use Change model. However, before the estimates of land demanded from the Waikato region EFM can be input into the Land Use Change model, the outputs from the Waikato region EFM's -industry classification system must be translated into the land-use categories used in the Land Use Change model ($lu\ wo\ luc_{lucat}$). Appendix B contains the procedure for undertaking this translation.¹⁰

Once provided with estimates of the land demanded (hectares), the Land Use Change model determines the extent to which the demand can be satisfied by the available supply of land. It is possible that the demand for land, especially agricultural land, will not be met by the supply of suitable land within the Waikato region. The purpose of the Supply-Side module is therefore to adjust the initial demand-based estimates of economic output by industry to account for the potential constraints in the supply of land for different industries. The Land Use Change model provides the actual amount of land supplied by industry (hectares), which is translated to output supplied ($\$_{2018m}\ NZD$) by the inverse of the land-use productivity rate ($1/ lu\ ecoff_i$). The output supplied is fed back into the Waikato region EFM's Supply-Side module.

7.3.5 Supply-side module

Once provided with estimates of the annual supply-constrained output, the Waikato region EFM's Supply-Side module calculates the indirect flow on (or forward linkages) impacts of constraints on land use, for example, a reduction in the land used for Dairy Cattle Farming will result not only in a direct reduction in Dairy Cattle Farming output but also, through indirect forward linkages, in a reduction in Dairy Processing output. These effects are captured through the use of input-output mathematics (i.e. the $ghosh_{i,c}$), which enables calculation of the supply-constrained adjustments required to the original estimates of total final demand by commodity ($fd\ chng\ w\ luc_c$). Once these adjustments are made, new estimates of final demand for the Waikato Region are provided ($fd\ w\ luc_c$) that take account of potential constraints in the availability of land for Dairy Cattle Farming. To complete the Supply-Side module, the new estimates of total final demand by commodity are then translated into final estimates of industry output ($output\ w\ luc_i$) through application of input-output mathematics ($leontief\ coeff_{i,c}$).

7.3.6 Reporting module

This module translates the estimates of industry output ($output\ w\ luc_i$) into various indicators for reporting. The Waikato region EFM produces the following series of indicators:

¹⁰ Note that $\sum_i lu\ wo\ luc_i$ is greater than $\sum_{lucat} lu\ wo\ luc_{lucat}$ as some of the industry categories (namely, Fishing, Road Transport and Water and Rail Transport) are not allocated to a land-use category. The land required for these activities is either not relevant to the Land Use Change model or will be determined by other models.

- (1) *Socio-economic*: Each indicator (*se report var_{soce,i}*) is calculated by taking estimates of the value of the indicator for industry *i* in the 2018 base year, and multiplying by a scalar that defines the total change in industry *i* output from the base year (*output gr_i*). All values are \$₂₀₁₈m NZD.
- Added value
 - International imports
 - Final demand
 - Output
 - Household consumption
- (2) *Employment/Occupation*: Employment/occupation (Modified Employment Counts or MECs) for each industry *i* (*employment_{emp,i}*) are calculated in a similar method to the socio-economic indicators described in (1), with employment/occupations for industry *i* for the 2018 base year multiplied by a change in output scalar for the industry (*output gr_i*). A further multiplication is then required to take account for the rate of change in labour force productivity. Default productivity values have been incorporated into the model.
- (3) *Environmental*: Seven environmental indicators are calculated for each industry. Their calculation begins by multiplying a particular industry's base environmental indicator for 2018 (*env report var_{e,i}*) by the growth in that industry's output from the 2018 base year (*output gr_i*). Account is also taken of improvements in eco-efficiency/reductions in residuals over time. The rates of change in eco-efficiency (*chn_g ecoeff rt_{e,i}*) are set exogenously, and a user can change the values to suit the scenario being explored.
- Energy Use – Diesel (gigajoules of oil equivalent)
 - Energy Use – Electricity (gigajoules of oil equivalent)
 - Energy Use – Geothermal (gigajoules of oil equivalent)
 - Energy Use – Petrol (gigajoules of oil equivalent)
 - Energy Use – Total (gigajoules of oil equivalent)
 - Energy-related CO2 emissions (tonnes)

7.4 Equations

7.4.1 Elements and arrays within the Waikato region EFM

A complete list of arrays and their elements is presented below. Because the Waikato region EFM utilises input–output mathematics, it assumes that each industry produces only one homogenous commodity (i.e. Ind01 produces only Com01). A concordance matching the industry (*i*) notations to the Waikato region EFM industry codes and full names is provided in Appendix A. Also provided in this Appendix are the concordances matching the environmental and socio-economic reporting variable notations (*e*, *emp*, *soce*) to the associated full names and a concordance matching the land use categories (*lucat*) notations to the full land-use category names.

Age	A	0–4 yrs, 5–9 yrs 10–14 yrs, 15–19 yrs, 20–24 yrs, 25–29 yrs, 30–34 yrs, 35–39 yrs, 40–44 yrs, 45– yrs, 50–54 yrs, 55–59 yrs, 60–64 yrs, 65–69 yrs, 70–74 yrs, 75–79 yrs, 80–85 yrs, 85-90 yrs, 90-95 yrs, 95 yrs and over
-----	---	---

Commodity	<i>C</i>	Com01, Com02, Com03, Com04, Com05, Com06, Com07, Com08, Com09, Com10, Com11, Com12, Com13, Com14, Com15, Com16, Com17, Com18, Com19, Com20, Com21, Com22, Com23, Com24, Com25, Com26, Com27, Com28, Com29, Com30, Com31, Com32, Com33, Com34, Com35, Com36, Com137, Com38, Com39, Com40, Com41, Com42, Com43, Com44, Com45, Com46, Com47, Com48
Environment Reporting Variable	<i>e</i>	ERV01, ERV02, ERV03, ERV04, ERV05, ERV06, ERV07, ERV08, ERV09, ERV10, ERV11, ERV12, ERV13, ERV14, ERV15, ERV16, ERV17, ERV18, ERV19, ERV20, ERV21, ERV22, ERV23, ERV24, ERV25, ERV26, ERV27, ERV28, ERV29, ERV30, ERV31, ERV32, ERV33, ERV34, ERV35, ERV36, ERV37, ERV38, ERV39, ERV40, ERV41, ERV42, ERV43, ERV44, ERV45, ERV46, ERV47, ERV48, ERV49, ERV50, ERV51, ERV52, ERV53, ERV54, ERV55, ERV56, ERV57, ERV58, ERV59
Employment Reporting Variable	<i>emp</i>	Emp01, Emp02, Emp03, Emp04, Emp05, Emp06, Emp07, Emp08, Emp09, Emp10, Emp11, Emp12, , Emp13, Emp14, Emp15, Emp16, Emp17, Emp18, Emp19, Emp20, Emp21, Emp22, Emp23, Emp24, Emp25, Emp26, Emp27, Emp28, Emp29, Emp30, Emp31, Emp32, Emp33, Emp34, Emp35, Emp36, Emp37, Emp38, Emp39, Emp40, Emp41, Emp42, Emp43, Emp44, Emp45, Emp46, Emp47, Emp48
Final Demand	<i>F</i>	HhldCons, GFKF, IntRegExp, IntNatExp, ChngInv
Industry	<i>I</i>	Ind01, Ind02, Ind03, Ind04, Ind05, Ind06, Ind07, Ind08, Ind09, Ind10, Ind11, Ind12, Ind13, Ind14, Ind15, Ind16, Ind17, Ind18, Ind19, Ind20, Ind21, Ind22, Ind23, Ind24, Ind25, Ind26, Ind27, Ind28, Ind29, Ind30, Ind31, Ind32, Ind33, Ind34, Ind35, Ind36, Ind37, Ind38, Ind39, Ind40, Ind41, Ind42, Ind43, Ind44, Ind45, Ind46, Ind47, Ind48
Land Use Category	<i>luc</i>	LUCat01, LUCat02, LUCat03, LUCat04, LUCat06, LUCat06, LUCat07, LUCat08, LUCat09, LUCat10, LUCat11
Sex	<i>s</i>	male, female
Socio-Economic Reporting Variable	<i>soce</i>	SocEcon01, SocEcon02, SocEcon03

7.4.2 Demand-side module

The demand-side estimates of annual output for a given industry i are calculated as:

$$output\ wo\ luc_i = \sum_c (leont\ coeff_{i,c} \times fd\ wo\ luc_c). \text{ As measured in } \$_{2018m},$$

where

$leont\ coeff_{i,c}$ =the Leontief inverse matrix coefficient for commodity c , industry i .

$fd\ wo\ luc_c = \sum_{f=1}^n (final\ demand_{c,f})$. The estimate of total annual final demand ($\$_{2018m}$) for commodity c without taking account of potential constraints in the supply of land.

$final\ demand_{c, HhldCons} = init\ final\ demand_{c, HhldCons} \times hhld\ cons\ gr$. The annual value of commodity c sales to household consumption ($\$_{2018m}$).

$final\ demand_{c, GFKF}$ = an exogenous estimate of the annual sales of commodity c to gross fixed capital formation ($\$_{2018m}$).

$final\ demand_{c, IntNatExp}$ = an exogenous estimate of the annual sales of commodity c to international exports ($\$_{2018m}$).

$final\ demand_{c, IntRegExp}$ = an exogenous estimate of the annual sales of commodity c to interregional exports ($\$_{2018m}$).

$final\ demand_{c, ChngInv}$ =an exogenous estimate of the annual sales of commodity c to change in inventory stocks ($\$_{2018m}$).

$pop\ avg\ equiv_{a,s}$ = $population_{a,s} \times cons\ rel\ avg_{a,s}$. A quantification of the spending propensity of a particular age-sex cohort as measured in 2003 average person equivalents.

$init\ pop\ avg\ equiv_{a,s}$ = $pop\ avg\ equiv_{a,s}$ for the 2018 base year. As measured in 2003 average person equivalents.

$population_{a,s}$ = Population projections by age, sex cohort, as measured in number of people. To be obtained from the University of Waikato's Population Model.

$cons\ rel\ avg_{a,s}$ = Age, sex cohort-specific consumption scalar defining the level of private and public household consumption relative to an average person (dimensionless).

$hhld\ cons\ gr = \left(\frac{\sum_{a,s} pop\ avg\ equiv_{a,s}}{\sum_{a,s} init\ pop\ avg\ equiv_{a,s}} \right)$ A growth scalar in household consumption from the 2018 base year (dimensionless).

$init\ final\ demand_{c, HhldCons}$ =annual household consumption of commodity c for the 2018 base year ($\$_{2018m}$).

7.4.3 Supply-side module

Taking into account the flow-on economic (forward) impacts of constraints in the supply of land for agricultural purposes, final estimates of output by industry (\$_{2018m}) may be determined according to the equation:

$$output\ w\ luc_i = \sum_c (leont\ coeff_{i,c} \times fd\ w\ luc_c),$$

where

$fd\ w\ luc_c$ = $fd\ wo\ luc_c + fd\ chng\ w\ luc_c$. The final estimate of total final demand for commodity c as measured in \$_{2018m}.

$fd\ chng\ w\ luc_c$ = $\sum_i (ghosh_{i,c} \times diff\ in\ output_i)$. The change required (\$_{2018m}) to the demand-side estimate of total final demand for commodity c to account for constraints in the supply of agricultural land.

$diff\ in\ output_i$ = $output\ w\ luc_i - output\ wo\ luc_i$. The difference in land-use estimates for each industry between that derived under the Land Use Change model and that derived from the Demand-Side Module. For non-agricultural industries (i.e. Ind05 and Ind07-Ind48), $diff\ in\ output_i$ is set to zero as account is only taken of potential constraints in agricultural land.

$ghosh_{i,c}$ = The estimated change in annual total final demand for commodity c (\$_{2018m}) required to account for a one unit change in the output of industry i . These values are determined exogenous to the model and are based on 'forward multipliers' for the agricultural industries.

7.4.4 Reporting module

For each industry category i the Waikato region EFM reports 4 socio-economic indicators, an employment/ occupation indicator, and 6 environmental indicators. The method for deriving these indicators is as follows:

$se\ report\ var_{soce,i}$ = $init\ se\ report\ var_{soce,i} \times output\ gr_i$. The socio-economic reporting variable for industry i (\$_{2018m}).

$employment_{emp,i}$ = $init\ employment_{emp,i} \times output\ gr_i \times (1 - mf\ prod\ rt_i)^{(t)-2004}$
The total employment/occupation numbers in industry i . The unit of measurement varies according to the reporting variable with employment measured in either full-time-equivalent employees (FTEs), employment counts (ECs) or modified employment counts (MECs) and occupations measured in the number of people employed.

$env\ report\ var_{e,i}$ = $init\ env\ report\ var_{e,i} \times output\ gr_i \times (1 - chng\ ecoeff\ rt_i)^{(t)-2004}$
The magnitude of the environmental reporting variable e for industry i , as measured by GJ of oil equivalents (in the case of delivered energy use), tonnes (in the case of energy-related CO₂ emissions and solid waste production) and kg (in the case of N₂O and CH₄ emissions).

where

$init\ se\ report\ var_{soce,i}$ = $se\ report\ var_{soce,i}$ for the 2018 base year as measured in \$_{2018m}.

<i>init employment_{emp,i}</i>	= <i>employment_{emp,i}</i> for the 2018 base year as measured in FTEs, ECs, MECs or persons.
<i>init env report var_{e,i}</i>	= <i>env report var_{e,i}</i> for the 2018 base year as measured in GJ of oil equivalents (in the case of energy) or in tonnes (in the case of energy-related CO ₂ emissions and solid waste production) and kg (in the case of N ₂ O and CH ₄ emissions).
<i>output gr_i</i>	= <i>output w luc_i / init output w luc_i</i> . A scalar defining the level of output of industry <i>i</i> relative to the 2018 base year.
<i>init output w luc_i</i>	= The value of output (\$ _{2018m}) for industry <i>i</i> in the 2018 base year.
<i>mf prod rt_i</i>	= The annual rate of increase in output per employee industry <i>i</i> . In the sample model these productivities have been set with base values.
<i>chngecoeff rt_{e,i}</i>	= The annual rate of increase in eco-efficiency for energy use/emission <i>e</i> and industry <i>i</i> .

Aggregated socio-economic and environmental indicators can also be determined:

<i>tot se report var_{soce}</i>	= $\left(\sum_i value\ added_{soce,i}\right) + hhld\ value\ added_{soce}$. The total estimate of a socio-economic reporting variable (value added, interregional imports or international imports) for the Waikato Region economy (\$ _{2018m}).
<i>tot employment_{emp}</i>	= $\sum_i employment_{emp,i}$. Total employment/occupation numbers in the Waikato Region economy as measured in ECs, MECs or persons.
<i>tot env report var_e</i>	= $\left(\sum_i env\ report\ val_{e,i}\right) + hhld\ env\ report\ value_e$. The total energy use/residuals for environmental indicator <i>e</i> . Measured in GJ of oil equivalents (in the case of delivered energy use), tonnes (in the case of energy-related CO ₂ emissions and solid waste production) and kg (in the case of N ₂ O and CH ₄ emissions).

where

<i>hhld se report var_{soce}</i>	= <i>init hhld se report var_{soce}</i> x <i>hhld cons gr</i> . The value added contribution of households (\$ _{2018m}).
<i>hhld env report var_e</i>	= <i>init hhld env report value_e</i> x <i>hhld cons gr</i> . The total household energy use/energy related emissions for environmental indicator <i>e</i> . Measured in GJ of oil equivalents (in the case of delivered energy use), tonnes (in the case of energy-related CO ₂ emissions and solid waste production) and kg (in the case of N ₂ O and CH ₄ emissions).
<i>init hhld se report var_{soce}</i>	= <i>hhld se report var_{soce}</i> for the 2018 base year (\$ _{2018m}).
<i>init hhld env report var_e</i>	= <i>hhld env report var_e</i> for the 2018 base year.

7.5 Links

The Waikato region EFM links with the Demography model and the Land Use Change model (Table 5).

Table 5 Links between the Waikato region EFM and other models

Type	Model Component	Data Passed	Comments
Inputs	Land Use Change	Supply of land	Amount of land (ha) supplied to the supply-side module to calculate final economic activity (<i>ag lu w luc_i</i>)
	Demography	Population	Population data is passed to calculate labour force participation (%)
Outputs	Land Use Change	Demand for land	Amount of land demanded; calculated by multiplying the economic activity (\$ ₂₀₁₈ m) x the land productivity index

Demand-side

Demand-side estimates of the land required by Waikato region industries are calculated as:

$$lu\ wo\ luc_i = output\ wo\ luc_i \times ind\ ecoeff_i.$$

The land demanded (ha) by industry *i*.

where

$$lu\ ecoeff_i = \text{the land productivity of industry } i \text{ as measured by the average area of land required per unit of output (ha per } \$_{2018}\text{m). The land productivity estimates for other industries have, at this stage, been set as constant values defined according to the base year.}$$

The demand estimates of land required by each industry according to the -industry classification (i.e. *lu wo luc_i*) are aggregated into the 12-industry classification used in the Land Use Change model (*lu wo luc_{lucat}*) according to the mapping set out in Appendix B.

Supply side

As discussed earlier, any constraints on agricultural land as determined by the Land Use Change model are returned to the Supply-Side Module according to:

$$diff\ in\ output_i = output\ w\ luc_i - output\ wo\ luc_i.$$

The difference in land use estimates for each industry between that derived under the Land Use Change model and that derived from the Demand-Side Module. For non-agricultural industries (i.e. Ind05 and Ind07-Ind48), *diff in output_i* is set to zero as account is only taken of potential constraints in agricultural land.

Final demand is then re-calculated to account for flow-on economic (forward) impacts of land constraints as discussed above. Note that the difference can be positive or negative.

8 Water quality – NIWA

8.1 Metadata

1.	Name	SPARROW - <u>S</u>patially <u>R</u>eferenced <u>R</u>egression <u>o</u>n <u>W</u>atershed <u>A</u>tttributes
2.	Organisation	NIWA (with U.S. Geological Survey)
3.	Contact	Sandy Elliott
4.	Spatial Resolution	Stream reach and sub-catchment (typically 0.5 km and 0.5 km ² , respectively)
5.	Temporal Resolution	Annual
6.	Input Data	Rainfall (mm) (as grid) Land Use (as grid)
7.	Internal Data	Stream/lake/impoundment network (as shapefile) Slope (as grid) Soil Drainage Class (as grid) Distribution of Point Sources (as shapefile) Delivery Type – Drainage Delivery Type – Rain Land Use Source Coefficient – Nitrogen Land Use Source Coefficient – Phosphorus Land Use Drainage Exponent – Nitrogen Land Use Drainage Exponent – Phosphorus Land Use Rain Exponent – Nitrogen Land Use Rain Exponent – Phosphorus Point Source Load – Nitrogen Point source Load – Phosphorus Reservoir Decay – Nitrogen Reservoir Decay – Phosphorus Stream Attenuation – Low Flow – Nitrogen Stream Attenuation – Low Flow – Phosphorus Stream Attenuation – High Flow – Nitrogen Stream Attenuation – High Flow – Phosphorus
8.	Output Data	Mean Annual Load of Total Nitrogen by Stream reach (mean kg N/year over a 5-year period) Mean Annual Load of Total Phosphorus by Stream reach (mean kg P/year over a 5-year period)

8.2 Summary

SPARROW estimates mean annual loads over a 5-year period of nutrients from present and future distributions of point sources, climate, soil types, land slope, drainage characteristics, and land uses. It does not explicitly consider long-term lags attributable to groundwater storage and release. The New Zealand implementation of the SPARROW model has been developed in collaboration with the US Geological Survey and calibrated on Waikato regional data (Alexander et al. 2002) and on data from the nationwide National Rivers Water Quality Monitoring Network (Elliott et al. 2005) at a finer resolution.

8.3 Description

The SPARROW model accounts for “routing, accumulation, and decay”, and infers contaminant losses. Its spatial surface has been implemented on NIWA’s River Environment Classification database (Snelder et al. 2004), at 30-m grid resolution, on which stream/lake/reservoir locations were added. The resulting national model has nearly 600 000 stream reaches.

Data for concentrations of Total Nitrogen and Total Phosphorus collected from the 77 sites in NIWA’s National River Water Quality Monitoring Network were combined with river flow

information from those sites to estimate total annual loads. The model was calibrated against these data, i.e., by adjusting its coefficients to optimise the match with the calculated loads. In doing so, it used information on: (a) point sources of nutrients (from Regional Council data, consultancy reports, and informed estimations), (b) land use (combining data from AgriBase (AsureQuality) and the Land Cover Database 2 (Ministry for the Environment (2004)), and (c) mean stream flow using rainfall and evapotranspiration modelling.

The model's structure allows calibration not only of the contribution of point sources and land uses, but also land-to-water delivery variables (e.g., rain, drainage efficiency) and in-stream attenuation ("decay"). An implementation for the Waikato region has been reported (Alexander et al. 2002), and also for the whole nation (Elliott et al. 2005). For implementation in WISE, model parameters were re-calibrated for the Waikato region, taking into account stream reaches from the Waikato region as a whole and not just the Waikato River basin. Also, the WISE implementation relies on these pre-calibrated parameters; SPARROW coefficients within WISE are therefore static and are not dynamically recalculated/recalibrated during a model run.

SPARROW has two very desirable properties that give enhanced credence to its results. First, it is "data hungry": it demands and uses large quantities of environmental data of many types. Second, while statistical in nature (model coefficients are largely unconstrained and are optimised by the model fitting procedure during calibration), its coefficients are *physically interpretable*. For example, it produces settling rates for reservoirs and these can be checked for physical plausibility against other, local and independent settling studies.

Finally, SPARROW's output can calculate nutrient loads at any point on the landscape, and it can also calculate the fraction of the load delivered to any downstream point, highlighting the relative importance of all upstream sources. The key spatial elements of SPARROW are shown below (Figure 11).

Note that in calculating total N and P, the environmentally more harmful proportions of the load are disguised (dissolved reactive phosphorus, nitrate and ammonia) nevertheless the model gives a high-level spatial picture of nutrient losses.

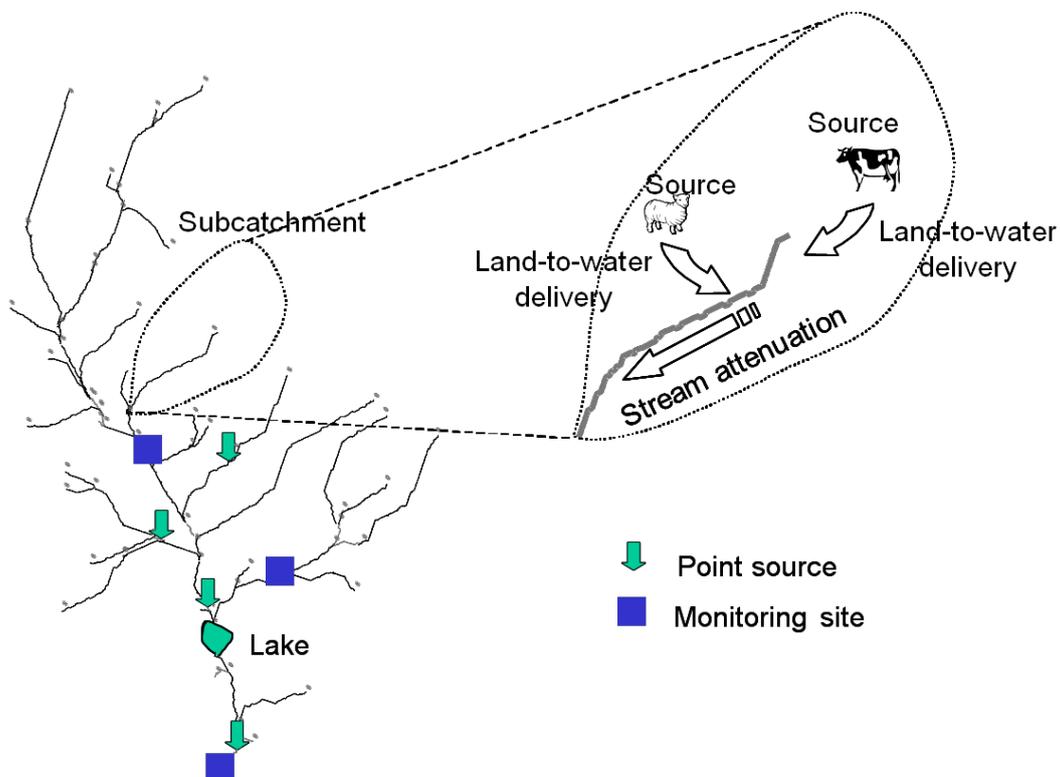


Figure 11 Key spatial elements of the SPARROW model system.

8.4 Equations

8.4.1 Sources

The stream reach network is a dendritic system of reaches and nodes (Figure 11). Each reach has a single subcatchment associated with it. A reach may also have a lake associated with it. Data on a reach (e.g., length, flow) and its associated catchment characteristics (e.g., areas of different land-uses) are stored in a record in a table.¹¹ Sources within subcatchments that contribute nutrient loads to a reach include land uses and point sources. Contributions of an individual source (land use or point source) are calculated as follows:

$$S_{ij} = c_i A_{ij}$$

where

S_{ij} = amount of source from land use class i generated in subcatchment j (kg/year)

c_i = the source coefficient for land-use class i (kg ha⁻¹ yr⁻¹)

A_{ij} = the total area of land use class i in subcatchment j (ha).

For point sources, A is the amount of nutrients emitted (kg/year) and $c_i = 1$.

Because the subcatchments are a shapefile (vector) spatial layer whereas land use is a grid (raster) spatial data layer, a link table is used to calculate the total area of each land-use class in each subcatchment. The link table contains information about how much of each grid cell (x,y, hectares) occurs in each subcatchment j (Table 6).

Table 6 Structure of the Water Quality – Land Use Change model link table

Grid Cell		Subcatchment ID	Area (hectares)
X Coordinate	Y Coordinate		

8.4.2 Source modification factors

The contribution from each source is modified by two factors, rainfall and drainage, using the following formula:

$$S'_{ij} = S_{ij} \prod_k \exp[-\alpha_{ik} (d_{jk} - \bar{d}_k)]$$

where

S'_{ij} = nutrient discharge from source after modification (kg/year)

α_{ik} = modification exponent for land use class i for modification type k (m⁻¹ yr for rainfall, dimensionless for drainage class)

d_{jk} = value of the delivery variable for modification type k in subcatchment j (m yr⁻¹ for rainfall, dimensionless for drainage class)

\bar{d}_k = mean value of the delivery variable for modification type k across the entire modelled region (m yr⁻¹ for rainfall, dimensionless for drainage class).

¹¹ In principle, this could be extended so that more than one 'subcatchment' can be associated with a particular reach.

8.4.3 Attenuation in stream reaches

Nutrient loads can decrease as a result of attenuation through a reach. This is calculated as follows:

$$F_{sj} = \exp(-k_{sj}L_j)$$

where

F_{sj} = fraction of the stream s load carried through subcatchment j (%)

k_{sj} = the stream (s) attenuation coefficient in subcatchment j (km^{-1})

L_j = the length of the reach in subcatchment j excluding any portion that lies within a lake (km).

For the WISE nitrogen model,

$$k_{sj} = aQ_j^{-b}$$

where

a = proportionality constant ($\text{km}^{-1}(\text{m}^3 \text{s}^{-1})^b$)

Q_j = the mean annual flow of the reach in subcatchment j ($\text{m}^3 \text{s}^{-1}$)

b = flow exponent (dimensionless).

For the WISE phosphorus model, a stepwise function was used.

$$k_{sj} = \begin{cases} k_1 & : Q_j \leq Q_1 \\ k_2 & : Q_j > Q_2 \end{cases}$$

Loads entering a reach from an upstream node have this attenuation applied. Loads entering from the catchment associated with the reach (the incremental catchment) have attenuation over only half of the reach.

8.4.4 Attenuation in lakes (reservoir decay)

In stream reaches with lake outlets, attenuation is applied to account for settling of nutrient loads within the lake. Lake attenuation is calculated as follows:

$$F_l = \frac{R_l}{k_l + R_l}$$

where

F_l = fraction of the load carried through lake l in reach j (dimensionless)

R_l = lake overflow rate (m yr^{-1})

k_l = effective settling velocity for lake l (m yr^{-1}).

Also:

$$R_l = \frac{q_l}{A_l}$$

where q_l is the flow rate out of the lake and A_l is the plan area of the lake.

For reaches without lake outlets, the fraction carried is 1 (i.e. no loss).

For any reach, the lake fraction carried and the stream fraction carried are multiplied together to give the total fraction carried.

8.4.5 Routing method

Nutrient loads in stream reaches are accumulated along the dendritic network, i.e. from upstream to downstream. Mathematically, stream reaches are sorted according to a calculation order that ensures nutrient loads in upstream reaches are calculated first. The algorithm then loops through the list of reaches. For each reach it:

1. calculates the unmodified source from each land use i or point source in local subcatchment j
2. modifies the source from each land use i in local subcatchment j
3. sums all sources in local subcatchment j
4. adds the modified, attenuated load from the upstream subcatchment $j - 1$
5. attenuates the total source due to stream and/or lake (if applicable) in subcatchment j .

Mathematically those steps are:

$$S_{ij} = c_i A_{ij}$$

$$S'_{ij} = S_{ij} \prod_k \exp[-\alpha_{ik} (d_{jk} - \bar{d}_k)]$$

$$S'_j = \sum_i S'_{ij}$$

$$S''_j = S'_j + \sum_{\substack{\text{upstream} \\ \text{reaches } j-1}} S''_{j-1}$$

$$S''_j = (F_{sj} \times F_{lj}) \times S'_j$$

where S''_j is the attenuated load at the downstream end of reach j .

There is also provision to divert a fraction of the load from a reach based on the location of flow diversions in the catchment. In that case, in Step 4 above, only a fraction of the load from the upstream node is carried into the reach of interest. The diversion fractions are provided as a fraction of the reach.

8.5 Links

The Water Quality model links with the Climate Change Scenarios and the Land Use Change model (Table 7).

Table 7 Links between the Water Quality model and other models

Type	Model Component	Data Passed	Comments
Inputs	Climate Change Scenarios	Rainfall	Weighted average of the 4 nearest 0.05° grid cell to each subcatchment
	Land Use Change	Land Use	Land use determines the source coefficient (c_i) via a look-up table Land use determines the value of the rain exponent and drain exponent for N loading (α_{ik})
Outputs	None		

9 Zoning tool – Waikato Regional Council

9.1 Metadata

1.	Name of Model	Zoning
2.	Organisation	Waikato Regional Council
3.	Contact	Craig Briggs / Tony Fenton
4.	Spatial Resolution	100m (as grid layer)
5.	Temporal Resolution	Annual
6.	Input Data	2013 Land Use (as grid) Protected Areas Network (as grid) District Reserves and Covenants (as grid) Waikato Regional Council Flood and Erosion Control Land (as grid) District Council Designations (as grid) District Council Overlays (as grid) District Council Zones (as grid) District Extent (as grid)
7.	Internal Data	Zoning Status (categorical) Zoning Parameters (numeric)
8.	Output Data	Zoning (categorical, as grid) Zoning (numerical, as grid)

9.2 Summary

Zoning delineates areas with differing degrees for potential future land use development. It is an input into the Land Use Change model (Section 11). The Zoning Tool inspects sets of zoning maps compiled from various sources such as regional and district plans (**Error! Reference source not found.**¹²). Each zone in a map is called a category and has an explicit or inferred zoning status¹² that applies to at least one land use. Based on an order of precedence among categories specified by the user, the zoning tool annually determines the zoning status of the highest-ranking category for a land use in each grid cell. The zoning status is then translated to a user-specified numerical zoning score, from which a 100 × 100-m resolution grid layer is generated for supply to the Land Use Change model.

Zoning scores are not constrained but typically range from 0 (prohibited) to 1 (permitted). Zoning scores <1 impede future development by lowering the overall score for a land use at a particular location. Conversely, users can also specify zoning scores >1 to simulate the encouragement of future development, e.g., economic development zones.

¹² As defined by Section 77B of the Resource Management Act.



Figure 12 Districts within the Waikato region as of September 2016.

9.3 Model description

Under the Resource Management Act, regional and district councils identify activities that could cause adverse effects to the environment and develop rules to manage, mitigate, or in some cases, completely avoid those effects. The rules are codified in regional and district

plans. In addition, other relevant zoning information can be found in other data sources such as non-statutory planning strategies or national datasets, e.g., protected areas in the conservation estate. The process involves translating the various rules and other statutory requirements into a comprehensible set of information for processing and use by WISE (13).

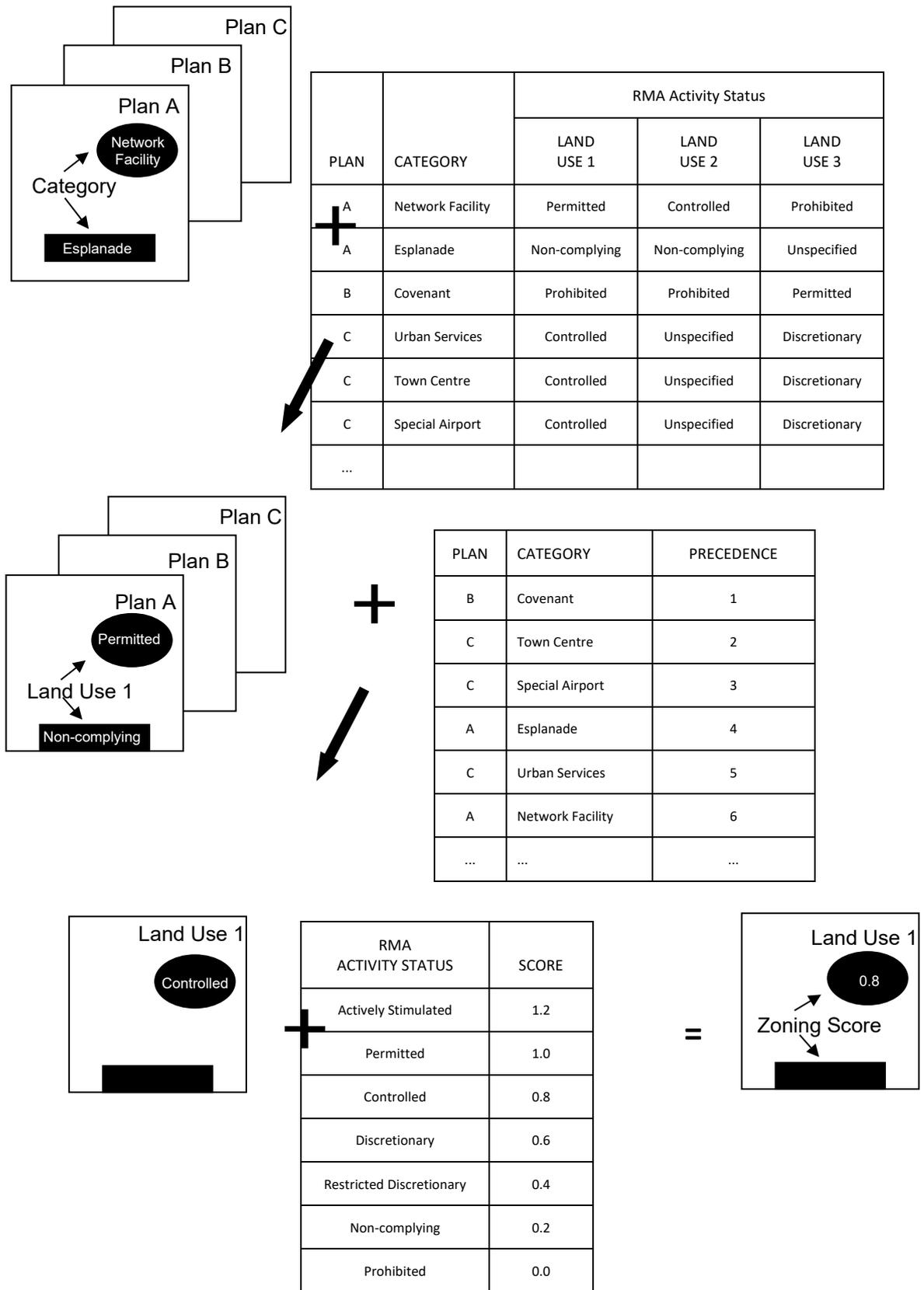


Figure 13 Process followed to delineate and evaluate zoning scores.

First, a series of maps are generated that correspond to different plans or strategies (simply “plans” hereafter). The plan maps contain one or more categories showing various elements in the plan. Frequent examples from district and city plans include zones (in a more restricted sense than used here), designations, and overlays. Others include flood hazard areas, protected areas such as conservation estate of covenants, air noise boundaries, etc. For WISE 1.6, several national, regional, and local information sources were used to compile zoning information (Table 8).

Table 8 Data sources used to compile zoning information in WISE

Data Source	Extent	Reference
Land Cover Database Version 5	National	LRIS (2019)
District Valuation Roll	Region	Waikato Regional Council
CRS Property and District Reserve data	Region	Waikato Regional Council
Territorial Authority (TA) District Plans ¹³	District	District Councils
TA Default Rules ¹⁴	District	District Plans

Second, an assessment was undertaken to determine the appropriate activity status for each land use within a zone. Under section 77B of the Resource Management Act activities fall into one of six activity statuses, which vary in their implications for interpretation and application of rules used to develop the zoning layers (Table 9).

Rules vary among districts in accordance with plan for a district. To develop zoning layers for WISE, an independent review (Environmental Management Services Limited 2019) was undertaken of each district plan for the 11 districts within the Waikato region. The purpose of the review was to determine the most likely activity status for each land use within each TA based on an interpretation of the rules, zones, overlays, policy areas or designations contained within each district plan. As the RMA regulates *activities* and not *land use* per se, each land use could have a range of associated activities with varying activity types. In determining the overall activity status for a particular land use, a permissive approach was taken such that the least restrictive activity type was applied to each combination of zoning and land use. However, the resolution of the land-use model (100 × 100-m grid cells) often meant that the most permissive activity type was not assigned for those land uses having a very small spatial extent (such as home occupations).

The review produced a set of 11 land use-zoning matrices (as Excel spreadsheets), one for each city/district council, which identified the RMA activity status for each combination of zoning and land use (**Error! Reference source not found.14**). Waikato Regional Council modified a small number of activity statuses after the review was finished. All changes and the reason for the change were recorded in the zoning spreadsheet (Fenton & Briggs 2016). The matrices provided the basis to develop sets of zoning status rules that were applied as outlined in Table 8 above for generating zoning grid layers.

When considering the city/district plans collectively it became clear that each plan has a distinct format and approach to its policies and the underlying rule structure. Notwithstanding this, the basis for rule structures is generally either activity-based or effects-based, and the approach to determining activity type either restrictive or permissive (Table 9). In the matrix, plans with an

¹³ As of September 2010 the Waikato region encompassed 12 districts in whole or in part. The new Auckland Region formally took effect on 01 November 2010, at which point the portion of the former Franklin district in the Waikato region became part of the Waikato district.

¹⁴ Where no higher ranked category occurred in the precedence order a default activity status was assigned to a cell. This includes parts of districts outside the Waikato regional administrative boundary but within the boundary of the area included in the Hydrology model analysis.

activity-based approach were easier to assess as the types of land use activities described in the matrix could more easily be associated with the activities outlined in the plan.

Table 9 Activity status as defined under Section 77B of the RMA

Activity Status	Definition
Permitted	If an activity is described in this Act, regulations, or a plan or proposed plan as a permitted activity, a resource consent is not required for the activity if it complies with the standards, terms, or conditions, if any, specified in the plan or proposed plan.
Controlled	<p>If an activity is described in this Act, regulations, or a plan or proposed plan as a controlled activity,—</p> <ul style="list-style-type: none"> <li data-bbox="539 528 1383 723">(a) a resource consent is required for the activity; and unless it has insufficient information to determine whether or not the activity is a controlled activity; and the consent authority must grant the resource consent, unless it has insufficient information to determine whether or not the activity is a controlled activity; and <li data-bbox="539 730 1383 792">(b) the consent authority must specify in the plan or proposed plan matters over which it has reserved control; and <li data-bbox="539 799 1383 898">(c) the consent authority’s power to impose conditions on the resource consent is restricted to the matters that have been specified under paragraph (b); and <li data-bbox="539 904 1383 972">(d) the activity must comply with the standards, terms, or conditions, if any, specified in the plan or proposed plan.
Restricted Discretionary	<p>If an activity is described in this Act, regulations, or a plan or proposed plan as a restricted discretionary activity,—</p> <ul style="list-style-type: none"> <li data-bbox="539 1061 1383 1097">(a) a resource consent is required for the activity; and <li data-bbox="539 1104 1383 1167">(b) the consent authority must specify in the plan or proposed plan matters to which it has restricted its discretion; and <li data-bbox="539 1173 1383 1272">(c) the consent authority’s powers to decline a resource consent and to impose conditions are restricted to matters that have been specified under paragraph (b); and <li data-bbox="539 1279 1383 1346">(d) the activity must comply with the standards, terms, or conditions, if any, specified in the plan or proposed plan.
Discretionary	<p>If an activity is described in this Act, regulations, or a plan or proposed plan as a discretionary activity,—</p> <ul style="list-style-type: none"> <li data-bbox="539 1435 1383 1471">(a) a resource consent is required for the activity; and <li data-bbox="539 1478 1383 1541">(b) the consent authority may grant the resource consent with or without conditions or decline the resource consent; and <li data-bbox="539 1547 1383 1621">(c) the activity must comply with the standards, terms, or conditions, if any, specified in the plan or proposed plan.
Non-Complying	<p>If an activity is described in this Act, regulations, or a plan or proposed plan as a non-complying activity,—</p> <ul style="list-style-type: none"> <li data-bbox="539 1718 1383 1753">(a) a resource consent is required for the activity; and <li data-bbox="539 1760 1383 1823">(b) the consent authority may grant the resource consent with or without conditions or decline the resource consent.
Prohibited	If an activity is described in this Act, regulations, or a plan as a prohibited activity, no application may be made for that activity and a resource consent must not be granted for it.

A	B	C	D	E	J	K	L	M	N
Land Use/Zoning Matrix - Waipa District Operative District Plan (2016)									
					2500sqm to 6ha	500-1000 sqm up to 2500 sqm	<400 sqm		
		24 Land Use Classes			Residential - Lifestyle Blocks (Fn)	Residential - Low Density (Fn)	Residential - Medium to High Density (Fn)	Commercial (Fn)	Community Services (Fn)
	Zone, Designation or Overlay Types	Zone Areas or Designation Purposes	Zone/Overlay/Designation description	Status					
	Rural	Rural	The Rural Zone is primarily a pastoral rural working environment that is reliant on the rural land and soil resource of the District, and is largely typified by an open rural landscape. Dairy Farming is the main rural land use in the District, followed by beef, and sheep farming. Horticulture is also a prominent contributor to the District. Although there are fewer properties involved in the equine industry, it is also a very significant part of the District's rural landscape. The Residential Zone of the District is where most people in Waipā live. It is principally located in the two main towns of Cambridge and Te Awamutu with a small existing area located at Karāpiro. Over the lifetime of this Plan most of the new residential growth will be directed to Cambridge and Te Awamutu and by 2050 it is anticipated that these two towns will have nearly doubled in size. Development within the Zone is anticipated to be consistent with the Strategic Policy Framework including the Waikato River Vision and Strategy.	Operative	NC	NC	NC	NC	D
		Residential	The Residential Zone of the District is where most people in Waipā live. It is principally located in the two main towns of Cambridge and Te Awamutu with a small existing area located at Karāpiro. Over the lifetime of this Plan most of the new residential growth will be directed to Cambridge and Te Awamutu and by 2050 it is anticipated that these two towns will have nearly doubled in size. Development within the Zone is anticipated to be consistent with the Strategic Policy Framework including the Waikato River Vision and Strategy.	Operative	NC	D	D	NC	D
	Residential	Te Awamutu South Residential Area	The Te Awamutu South Residential Area is a new growth area. There are particular design outcomes sought for the area with specific standards applying.	Operative	NC	D	D	NC	D
		Picquet Hill Residential Area	The Picquet Hill Residential Area in Te Awamutu is a new growth area. There are particular design outcomes sought for the area with specific standards applying.	Operative	NC	D	D	NC	D
		St Kilda Residential Area	There are specific provisions that apply to the St Kilda Residential Area. The area has particular design outcomes that were developed through a structure planning process and are integral to the overall development of the area.	Operative	NC	D	D	NC	D
		Cambridge Residential Character Area	There are specific provisions that apply to the Cambridge Park Residential Area. The area has particular design outcomes that were developed through a structure planning process and are integral to the overall development of the area.	Operative	NC	D	D	NC	D
	Large Lot Residential	The name Large Lot Residential reflects the predominantly residential nature of the zone, which has a lower density and a more rural feel than in the Residential Zone. The areas covered in the previous Waipa District Plan by the Rural Residential Policy Area have been incorporated into this zone along with the smaller villages and some proposed new areas. People living in this zone are generally seeking to live in a semi-rural environment, while remaining within commuting distance to urban centres.	Operative	D	NC	NC	NC	D	
	Significant Mineral Extraction	The Significant Mineral Extraction Zone provides for regionally significant mineral extraction activities within the District, by zoning land for this purpose and providing specific policies and methods that are tailored to the scale, intensity and character of these operations.	Operative	NC	NC	NC	NC	D	
	Reserve	There is a significant amount of land in the District that has been classified (into various categories) as a reserve under the Reserves Act, as well as fee simple and endowment land administered by Council that are used as reserves. These reserves are managed within this zone.	Operative	NC	NC	NC	NC	NC	
	Commercial	The Commercial Zone is located in Te Awamutu and Cambridge and also in Pirongia, Kihikihi and Ōhaupo. The central business districts of Cambridge and Te Awamutu provide the primary retail, office and commercial service areas in the District.	Operative	NC	NC	NC	P	P	
	Industrial	The Industrial Zone is mainly located within the two towns of Te Awamutu and Cambridge. In Cambridge it is located at Hautapu, Carters Flat and Matos Segedin Drive. In Te Awamutu it is located at Paterangi Road and off Bond Road. These areas have developed over time with a range of manufacturing and process industries. While most industries within these areas serve local needs there are also other industries that serve wider needs. In addition to these existing zones, further land has been identified for industrial development at Hautapu and Bond Road Te Awamutu. These areas are zoned, but are not serviced. Land has also been identified at Raynes Road (19.5ha) where it will complement the growth of business located within the Airport Business Zone.	Operative	NC	NC	NC	NC	NC	

Figure 14 Screenshot of the zoning matrix for Waipa District Council.

Waikato Regional Council also had to assign default activity status (categorical and numerical) to areas occurring outside the regional administrative boundary but partly within the hydrologically modelled area (Table 10).

Effects-based plans were more difficult to assess, as some assumptions were required about each potential land use and the types of effect it might have. In this case, the resulting matrices tended to have many Permitted activity statuses for permissive plans and many Discretionary or Non-Complying activity statuses for restrictive plans. In some cases, the details of a consent application for a specific land use proposal may alter the result.

The effect of subdivision rules was also considered in relation to the residential land uses. Subdivision rules, in the main, focus on physical aspects of the land being subdivided, although a few plans differentiated subdivision status to some extent based on land use. Net lot area was a strong driver for subdivision rules and results in impacting the activity status of the residential land uses in the matrix, and, in 75% of the plans, also results in some instances of activities becoming considerably more restricted.

Other controls that apply to land-use change or development have not been reflected in the matrices or in corresponding spatial data. These include activities on the surface of water and other tools such as bylaws. Some aspects of structure plans for some TA's have been included particularly to allow for use of future growth cells and to provide for staging of land availability for residential and industrial growth. Restrictions in district plans on indigenous vegetation clearance and the objectives of new Regional Policy Statement have been broadly represented by increasing restriction on more mature indigenous vegetation. Other rules and regional council controls with relevance to wetland clearance and the Taupo Variation are also applied to a limited extent.

Based on a review of the regional plan, the 11 district plans, and several other statutory plans and designation (e.g., protected areas), a total of 280 unique overlays, designations, etc., (generally referred to as zones here) applied across the region at varying locations. Not every zone applied to every land use. Collectively approximately 2500–3000 rules were assigned to these zones across the Waikato region in some way. Not every rule has been included. Many were not considered legislatively or spatially significant; others were too complex to assess or map. In some instances, the rules were known but spatial data were lacking.

Table 10 Default activity status for city and district councils included in the WISE model. For those areas occurring within the hydrologically modelled area but not within Waikato region administrative boundaries, a default zoning status was assigned

District	Rule Structure Basis	Nature of Rules	Default Activity Status
Hamilton City	Activity	Restrictive	Non-complying (0.2)
Waikato	Effects	Permissive	Permitted (1.0)
Waipa	Activity	Permissive (predominantly)	Permitted (1.0)
Matamata-Piako	Activity	Restrictive	Non-complying (0.2)
South Waikato	Activity	Restrictive	Non-complying (0.2)
Taupo (in part)	Effects	Permissive	Permitted (1.0)
Thames-Coromandel	Activity	Prescriptive	Non-complying (0.2)
Hauraki	Activity	Restrictive	Non-complying (0.2)
Rotorua (in part)	Activity	Restrictive	Non-complying (0.2)
Otorohanga	Effects	Permissive	Permitted (1.0)
Waitomo (in part)	Effects	Permissive	Permitted (1.0)
Marine Region	Not assessed	Not assessed	Prohibited (0)

Further investigation might conclude some zones have greater significance on land-use change than initially thought. If all data were available and all rules were thoroughly assessed and mapped, there could potentially be 300–400 zones to consider, or as many as twice the number currently implemented.

A full copy of the planning review (BECA Ltd. 2019), the zoning update process undertaken in 2019 (Fenton et. al. 2021) and the original zoning methodology (EW Documents 1589639 and 1391838) are available from Waikato Regional Council.

Third the underlying spatial zoning data is imported from GIS into the zoning tool of WISE as a series of “categories” under plans. Categories are then compared to one another based on a precedence order specified by the user (Table 12). A “zoning status” (the same thing as “activity status” but named differently in the WISE model) is then assigned to those categories of relevance to each land use function. The resulting zoning maps, one for each land use function, indicate the zoning status of a grid cell for a particular land use or set of land uses.

Finally categorical zoning statuses are transformed into numerical values for use in the Land Use Change model (Table 10). The minimum value is 0 (Prohibited). Increasing values indicate more permissive zoning, with a value of 1 indicating a “permitted” activity status. Values over 1 are also possible, which indicates areas where particular land uses are actively stimulated.

Currently a simple method of assigning zoning has been applied to the existing extent of indigenous vegetation (restricted discretionary region-wide) and wetland (discretionary region-wide) as at 2006. This could be made more complex but would involve consideration of at least a dozen additional rules. Currently zoning statuses assigned to these two categories only apply to rural land uses. Urban land uses usually have even more restrictive zoning applied to them in areas where indigenous vegetation and wetlands typically occur, although there are a few exceptions.

Below are examples of the resulting categorical zoning maps for the land uses “Dairy Farming” and “Residential – Low Density” as at 2030 (Figure 15).

9.4 Equations

Zoning does not involve equations per se, other than the translation of categorical activity status into a numeric zoning score. See Section 11.4.4. for more information.

9.5 Links to other models

Zoning links with the Land Use Change model (Table 11).

Table 11 Links between Zoning and other models

Type	Model	Data Passed	Method
Inputs	None		
Outputs	Land Use Change	Zoning Score	Grid layer of numeric values used as a factor in the calculation of transition potentials for each land use function at each time step

Table 12 Order of precedence of categories within WISE

Order	Rule, Designation, Overlay, etc.	Interpretation	Categorical Activity Type	Numerical Activity Type
1	Existing land use as at 2013	Where a land use already occurs at 2013, assume “permitted” activity type	Permitted	1
2	PAN-NZ	All land-use functions assumed “prohibited” as location is legally protected	Prohibited	0
3	District Reserves & Covenants	All land-use functions Except Community Services on District Reserves	Prohibited Permitted	0 1
4	WRC Land	All land-use functions Except Dairy Farming Sheep, Beef & Deer Farming	Prohibited Permitted Permitted	0 1 1
5	TA Designations	All land-use functions Except Community Services on Public Facilities or Proposed Public Facilities	Prohibited Permitted	0 1
6	Internationally or Nationally Significant Natural Areas Overlay	All rural land-use functions	Discretionary	0.4
7	Existing “Tall Forest” Indigenous Vegetation Land Use as at 2013	All land-use functions	Prohibited	0
	Existing “Broadleaf” Indigenous Vegetation Land Use as at 2013	All land-use functions	Prohibited	0
	Existing “Scrub” Indigenous Vegetation Land Use as at 2013	All land-use functions	Non-Complying	0.2
8	Existing Wetland Land Use as at 2013	All land-use functions	Discretionary	0.4
9	TA Overlays or Policy Areas	Zoning status determined by Land Use-Zoning Matrix (see Section 9.3.1 below)	Varies	Varies

10	TA Zones	Zoning status determined by Land Use-Zoning Matrix (see Section 9.3.1 below)	Varies	Varies
11	TA Default	Zoning status determined by default rules (see Table 13 below)	Varies	Varies

Table 13 Categories and default values for activity types in the zoning model

Category	Value
Actively stimulated	1.2
Permitted	1
Controlled	0.8
Discretionary	0.6
Restricted discretionary	0.4
Non-complying	0.2
Prohibited	0

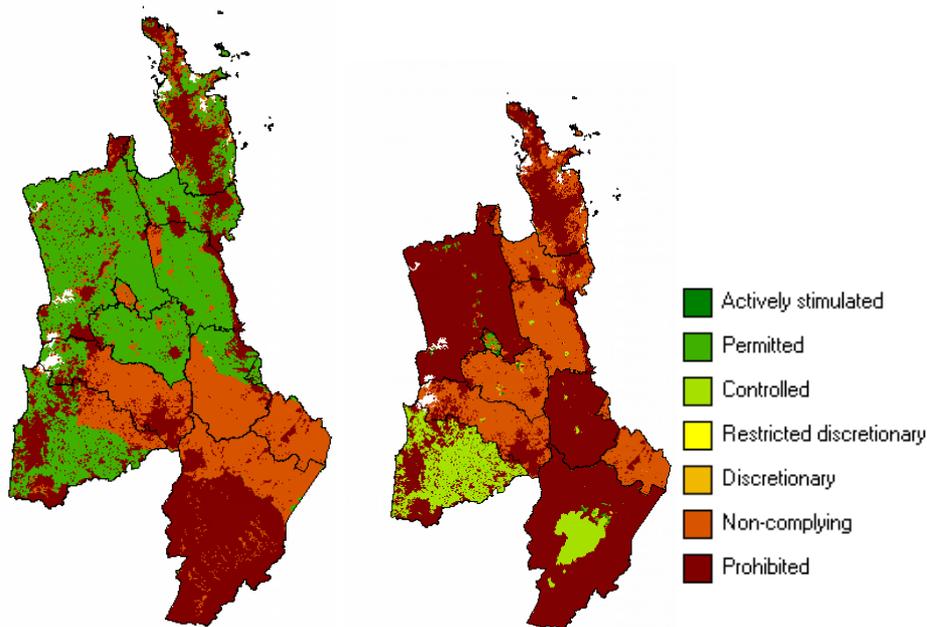


Figure 15 Examples of categorical zoning grid layers for Dairy Farming (left) and Residential – Low Density (right) land uses as at 2030.

10 Multi-Region Demographic model – University of Waikato

10.1 Metadata

1) Name	Multi-Region Demographic Model
2) Organisation	University of Waikato
3) Contact	Michael Cameron
4) Spatial Resolution	District
5) Temporal Resolution	Annual
6) Input Data	Total Fertility Rate (by district, time series) Life Expectancy at birth (by district, time series) International Migration (immigration and emigration, persons per district, time series)
7) Internal Data	2013 Population × 1-year age/gender cohort (persons per district) Fertility rate × 1-year female age cohort, and birth gender ratio (per district) Survivorship rate × 1-year age/ gender cohort (per district) Internal migration × 1-year age/gender cohort (per district) Emigration × 1-year age/ gender cohort (per district) Immigration × 1-year age/ gender cohort (per district)
8) Output Data	Population × 1-year age/gender cohort (persons per district)

10.2 Summary

The demographic model generates possible future populations, referred to as population projections, starting from a given base population and assumptions about the demographic processes of fertility, mortality and migration (both internal migration between districts in New Zealand, and between New Zealand and overseas). The methodology used is broadly that of the standard cohort-component model that is also widely used by other agencies, including Statistics New Zealand and RIKS.

The general approach used for population projections in WISE is described in Cameron and Cochrane (2021). The current population (base population) is first defined, and then assumptions are made about demographic changes to this population, using the cohort component model. This is a stock-flow model that is based on the following fundamental “accounting identity” of population growth:

$$P_{i,t+1} = P_{i,t} + B_{i,t} - D_{i,t} + I_{i,t} - O_{i,t}$$

where

$P_{i,t+1}$ = usually resident population in district i at the *end* of year t

$P_{i,t}$ = usually resident population in area i at the *beginning* of year t

$B_{i,t}$ = births to mothers residing in area i *during* year t

$D_{i,t}$ = deaths of residents of area i *during* year t

$I_{i,t}$ = inward migration from other regions and from overseas into region i *during* year t

$O_{i,t}$ = outward migration of residents from area i to other regions or to overseas *during* year t .

Starting with a given base year population, the population one year later is then calculated with the equation above. This defines the base population of the following year. This procedure is repeated for each year through to the end of the projection period. This is done for both genders. Separate assumptions are used for each of the demographic “drivers”. Births are derived by multiplying age specific fertility rates by the numbers of women of childbearing age (13-49). Deaths are derived by multiplying age- and gender-specific survivorship rates by the numbers of people of each age and gender. Internal migration flows in total for each district are derived from a gravity model. They are allocated by age and gender by multiplying the total flow by age- and gender-specific migration rates. International migration (emigration and immigration) are derived from a time series econometric model, and then similarly allocated by age and gender by multiplying the total flow by age- and gender-specific migration rates.

The combination of demographic change assumptions, when applied to the current population, allows the calculation of possible future populations. Such calculations are referred to as population *projections* rather than population *forecasts*, because they depend on sets of assumptions and no explicit assessment is made of the relatively likelihood of the assumptions being correct in the future. Varying the assumptions across projections simply permits a sensitivity analysis that provides a relatively broad range of possible outcomes.

The key innovation that differentiates the demographic model from the cohort component models in use by Statistics New Zealand and others is the inclusion of a gravity model to explicitly drive internal migration flows.

10.3 Description

The demographic model runs independently of WISE, using Vensim simulation software (Ventana Systems 2008). The model produces population projections by single-year-of-age, that are contained in a Microsoft Excel spreadsheet that WISE accesses to obtain the data necessary for a simulation.

As noted above, the model requires age- and gender-specific data inputs, as follows:

- (i) Base population data by single-year-of-age and gender, for all territorial local authorities (TLAs, e.g., districts and cities), for the beginning of the first year of the projection period (currently 30 June 2018);
- (ii) Fertility rates by single-year-of age for all females aged 13-49, for each TLA, for all years of the projection period (currently 2018–2068);
- (iii) Survivorship rates by single-year-of-age and gender, for each TLA, for all years of the projection period (currently 2018–2068);
- (iv) Internal migration migration by single-year-of-age and gender, for each TLA, for all years of the projection period (2018–2068);
- (v) Emigration by single-year-of-age and gender, for each TLA, for all years of the projection period (2018–2068); and
- (vi) Immigration by single-year-of-age and gender, for each TLA, for all years of the projection period (2018–2068).

These data inputs have been derived by the University of Waikato from Statistics New Zealand data.

10.4 Equations

10.4.1 General formulae

The demographic model uses three sets of equations to generate population projections. The general formulae for deriving the population at each year-of-age and each gender are as follows:

$$P_{agl}^{t+1} = \begin{cases} a = 0 : P_{0gl}^{t+1} = \frac{1}{2}(B_{gl}^t + N_{-1gl}^t) \times S_{-1gl}^t + \frac{1}{2}(B_{gl}^t + N_{-1gl}^t) \\ 1 \leq a \leq 99 : P_{agl}^{t+1} = (P_{(a-1)gl}^t + \frac{1}{2}N_{(a-1)gl}^t) \times S_{(a-1)gl}^t + \frac{1}{2}N_{(a-1)gl}^t \\ a = 100 : P_{100gl}^{t+1} = (P_{99gl}^t + \frac{1}{2}N_{99gl}^t) \times S_{99gl}^t + \frac{1}{2}N_{99gl}^t + \\ (P_{100gl}^t + \frac{1}{2}N_{100gl}^t) \times S_{100gl}^t + \frac{1}{2}N_{100gl}^t \end{cases}$$

where

- P_{agl}^{t+1} = population of age a and gender g in location l at time $t+1$ (with t measured in years);
- $P_{(a-1)gl}^t$ = population of age $a-1$ and gender g in location l at time t ;
- B_{gl}^t = number of births of gender g in location l between time t and time $t+1$;
- $N_{(a-1)gl}^t$ = net migration of people of age a and gender g to/from location l between time t and time $t+1$; a positive number represents more people moving into l than moving out, while a negative number represents more people moving out of l than in;
- $S_{(a-1)gl}^t$ = survivorship rate for people of gender g in location l and age $a-1$ at time t , who survive to age a at time $t+1$;
- a = age subscripts ranging from -1 to 100 with -1 representing births during the previous twelve months; 0 representing those of age 0 ; $1 \dots$ representing those of age $1 \dots$; 100 representing those aged 100 or over;
- g = gender subscripts, with 1 representing male and 2 representing female;
- l = subscripts ranging from 1 to 66 , with each number representing one of the TLAs in New Zealand (of which only the Waikato TLAs are included in WISE).¹⁵

The main additional assumption implicit in this formula is that migration, births, and deaths are all evenly spaced throughout the year. This allows half of the migrants and half of the births to be subject to the full year's survivorship rate. It should also be emphasised that the age group represented by $a=100$ is actually all people of gender g in location l aged 100 or over. To convert whole-TLA populations to part-TLA populations in WISE (for those TLAs that are not wholly contained within the Waikato Region), the proportion of the TLA population in the Waikato Region is assumed constant (and equal to the proportion in the base population, currently 30 June 2018).

¹⁵ Chatham Islands Territory is not included in the demographic model.

10.4.2 Births

Births are calculated using the following formula:

$$B_{gl}^t = \begin{cases} g = 1 : B_{gl}^t = G_l^t \times \sum_{a=13}^{49} (F_{al}^t \times (P_{a2l}^t + \frac{1}{2} N_{a2l}^t)) & (\text{males}) \\ g = 2 : B_{gl}^t = (1 - G_l^t) \times \sum_{a=13}^{49} (F_{al}^t \times (P_{a2l}^t + \frac{1}{2} N_{a2l}^t)) & (\text{females}) \end{cases}$$

where G_l^t is the fraction of births between time t and time $t+1$ that are male (the masculinity ratio of births) in location (TLA) l ; and F_{al}^t is the fertility rate for women of age a in location (TLA) l between time t and time $t+1$, and other terms remain as defined above.

These formulae contain two additional implicit assumptions. First, gender bias in births between male and female children is assumed to be constant both across time and among TLAs at 105.5 male children for every 100 female children or $G = 0.513$. This is consistent with the experience of New Zealand over the past several decades. Second, only women between the ages of 13 and 49 are assumed to have children, as women outside that age range have very few children.

10.4.3 Net migration

Net migration for each year-of-age and each gender is calculated using the following formula:

$$N_{agl}^t = (M_l^t \times H_{agl}) - L_{agl}^t + (I_l^t \times J_{agl}) - (E_l^t \times K_{agl})$$

where

M_l^t = internal in-migration of people from all other TLAs in New Zealand to location l between time t and time $t+1$;

H_{agl} = fraction of internal in-migrants to location l of age a and gender g ;

L_{agl}^t = internal out-migration of people of age a and gender g from location l to other TLAs in New Zealand between time t and time $t+1$;

I_l^t = immigration of people from overseas to location l between time t and time $t+1$;

J_{agl} = fraction of immigrants to location l of age a and gender g ;

E_l^t = emigration of people to overseas from location l between time t and time $t+1$; and

K_{agl} = fraction of emigrants from location l of age a and gender g .

Internal out-migration, L_{agl}^t , is calculated using the following formula:

$$L_{agl}^t = \sum_{j=1}^{66} (M_{lj}^t \times H_{agj})$$

$$L_{agl}^t = \sum_{j=1}^{66} (M_{lj}^t \times H_{agj})$$

where

M_{lj}^t = internal in-migration of people from location l to location j between time t and time $t+1$ (and $M_{lj}^t = 0$ for all $l=j$); and

H_{agj} = fraction of internal in-migrants to location j of age a and gender g .

10.4.4 External factors

The parameters used in the demographic model cannot be altered. However, alternative scenarios (high, medium, low; and medium without COVID) can be selected.

10.5 Links

The demographic model links with the Land Use Change model and the Waikato region EFM as indicated in Table 14.

Table 14 Links between WOW and other models

Type	Model	Data Passed	Comments
Inputs	None		
Outputs	Land Use Change	Population	Population determines the demand for land (ha) for each of the three residential land-use classes as explained below
	The Waikato region EFM	Population	Population is used to calculate labour force participation rates

Population from the demographic model determines demand for land for the three residential land use categories (Lifestyle Blocks, Low Density, Medium-High Density) in the Land Use Change model. Population is converted into demand for residential land as follows:

$$L_{cl} = \frac{P_l \times r_{cl}}{d_{cl}}$$

where

L_{cl} = demand for residential land of class c in district l (hectares)

P_l = total population in district l (persons)

r_{cl} = fraction of population preferring residential land use class c (unitless) in district l , as specified by the user

d_{cl} = average density of residential land use class c in district l (persons/hectare).

Note that r_{cl} and d_{cl} are specified by the user and can change over the course of a simulation (i.e. they are specified as time lines). By definition the three ratios r_{cl} (one for each residential land use class) should sum to a value that is less than or equal to one in all districts, i.e.

$$\sum_{c=1}^3 r_{cl} \leq 1$$

11 Residential Demands model – RIKS

11.1 Metadata

1)	Name	Residential Demands Model
2)	Organisation	Research Institute for Knowledge Systems (RIKS)
3)	Contact	Hedwig van Delden
4)	Spatial Resolution	District
5)	Temporal Resolution	Annual
6)	Input Data	Population
7)	Internal Data	Per district: proportion of people living in each residential land use class and outside residential areas, population density of each residential land use class
8)	Output Data	Demands (ha) per residential land use class

11.2 Summary

The Residential Demands component converts population per district into land demands for various land use classes. It also calculates the proportion of people living outside residential classes.

11.3 Description

Based on the population per region and the proportion of people living in various residential classes as well as outside residential areas, this component calculates the number of people living in each of the three residential land use categories (Lifestyle Blocks - LB, Low Density Residential - LDR, Medium-High Density Residential - MHDR) and outside residential areas. The number of people living in each residential class is next converted into a demand for land of the accompanying residential land use type using the density specific for each residential land use class.

Initial values for the proportion of people living in residential classes and outside residential areas as well as initial values for densities of each residential land use class are calculated using a triangulation of statistical data on population and dwellings, land use data and plot data from the property valuation database. Values obtained through this approach are then compared to perceived plausibility ranges and if required adapted to fall within these boundaries.

Changes to residential densities and population proportions over time can be entered by the user based on assumptions regarding densification, sub-division, household size and area required per dwelling including the outdoor space (garden, driveway, etc).

11.4 Equations

Listed below are the inputs, intermediate variables and outputs used in generating the residential demands module. This is followed by an equation which distributes total population over the different residential land uses and calculates the land demand for each residential class by applying a district specific density per residential land use type to the various residential populations within each district.

Inputs

$${}^tTP_i = \text{Total population at time } t \text{ in region } i \text{ [people].}$$

Intermediate variables

${}^tD_{f,i}$ = Average population density of residential land use function f in region i at time t
[people/cell].

${}^tp_{f,i}$ = Share of total population living in residential land use function f in region i at time t .

Outputs

${}^tLUD_{f,i}$ = Land use demand for residential land use function f at time t [cells].

Equation

Total population is distributed over the different residential land uses and then converted from people to cells by dividing the total population per residential land use type by the population density of that land use type.

$${}^tLUD_{f,i} = \frac{{}^tTP_i \cdot {}^tp_{f,i}}{{}^tD_{f,i}}$$

Note that $p_{f,i}$ and $D_{f,i}$ are specified by the user and can change over the course of a simulation (i.e. they are specified as time lines). By definition the four ratios $p_{f,i}$ (one for each residential land use class per district and one for people living outside residential classes per district) should sum to a value that is equal to one in all districts.

$$\sum_{f=1}^4 p_{f,i} = 1$$

11.5 Calculation of initial densities

(Alchemists Ltd)

For the initial calculation of the densities of each residential class, the proportion of people living in the three residential classes and the proportion of people living outside residential areas, the following data sources are used:

- Initial land use layer (2018, polygon)
- LINZ Address Points layer (extracted 2019)
- Census population (2018, values per district)
- Number of people per dwelling from census (2018, household size per district)

In summary the estimation of residential densities and proportions was based on the premise that each address point within a residential land use class would contain the average household size for its respective residential land use class based on the census population data for each district. Applying this assumption to each property valuation parcel classed as residential land use, in the 2018 land use map, then allow for calculation of residential densities and proportions.

The detailed steps and assumptions involved in these estimations are:

- The 2018 land use layer in polygon format (which was used to create land use grid in WISE) is linked to the LINZ address points layer using 'Join attribute by location' to provide a data set with address point, District name, Land Use code and Polygon area
- The Address points that had non-residential land use codes were then excluded from the data set to provide only address points within land parcels classified as one of the

three residential land use classes. This assumes that the proportion of residential dwellings in commercial and manufacturing land uses would be relatively low.

- Using this approach and factoring in the percentage of unoccupied dwellings (using the 2013 census data as 2018 data was unavailable) then estimates matched the number of people living in private dwellings within about 5%.
- These district population estimates in each residential land use class were then divided by the area of that land use in the district based on the grid in the WISE land use maps to provide starting residential densities. These population estimates also provided the starting proportions of population by residential land use class.
- Some small final adjustments were made to the density figures to ensure the sums of densities and areas matched the starting district population in the population model.

The final starting estimates for residential densities and proportions are outlined in Table 15. The residential densities and proportions can be adjusted in future years to reflect expected outcomes of district plan policies and rules or changes in household behaviour/expectations. In the model these can be set at different levels in 2025, 2035, and 2055. These numbers were adjusted for some of the districts, particularly Future Proof councils, based on discussions with policy and planning staff at each of the councils to determine what changes were most likely based on their expert input.

Table 15 Starting population proportions and densities for the residential classes derived for WISE V1.6 Reference scenario

	Thames-Coromandel District	Hauraki District	Waikato District	Matamata-Piako District	Hamilton City	Waipa District
DENSITIES						
Residential - lifestyle blocks	0.95	1.25	1.86	1.67	2.47	1.98
Residential - low density	13.77	19.82	26.95	23.46	33.53	24.91
Residential - medium-high density	28.36	53.2	51.64	47.54	86.69	45.23
	Thames-Coromandel District	Hauraki District	Waikato District	Matamata-Piako District	Hamilton City	Waipa District
POPULATION PROPORTIONS						
Residential - lifestyle blocks	0.0676	0.1524	0.3682	0.1283	0.0138	0.2260
Residential - low density	0.7988	0.6321	0.4194	0.6047	0.8464	0.5992
Residential - medium-high density	0.0766	0.0309	0.0178	0.0282	0.1254	0.0658
Outside residential areas	0.0569	0.1844	0.1945	0.2386	0.0144	0.1091
	Otorohanga District	South Waikato District	Waitomo District	Taupo District	Rotorua District	
DENSITIES						
Residential - lifestyle blocks	1.3	1.7	1.22	0.77	1.01	
Residential - low density	20.19	23.21	20.53	19.36	16.85	
Residential - medium-high density	60	60	60	50.15	60	
	Otorohanga District	South Waikato District	Waitomo District	Taupo District	Rotorua District	
POPULATION PROPORTIONS						
Residential - lifestyle blocks	0.2068	0.0961	0.1452	0.0825	0.2656	
Residential - low density	0.4018	0.7569	0.5400	0.8238	0.0926	
Residential - medium-high density	0.0057	0.0120	0.0063	0.0614	0.0000	
Outside residential areas	0.3856	0.1350	0.3085	0.0323	0.6418	

11.6 Links

The Residential Demands component links with Mutli-Region Demographic model and the Land Use Change model as indicated in Table 16.

Table 16 Links between the Residential Demands component and other models

Type	Model	Data Passed	Comments
Inputs	Population	Population	Population determines the demand for land (ha) for each of the three residential land-use classes
Outputs	Land Use Change	Demand for each residential land use type	Total area for each residential land use class in hectares per district per year.

12 Land use change – RIKS

12.1 Metadata

1)	Name	Cellular Automata Dynamic Land Use Change
2)	Organisation	RIKS
3)	Contact	Hedwig van Delden
4)	Spatial Resolution	100m x 100m grid
5)	Temporal Resolution	Annual
6)	Input Data	Land Use (as grid) Land Use Suitability (as grid) Zoning (as grid) Accessibility Network (as shapefiles) Industry Land Use Demand (hectares, the Waikato region EFM) Residential Land Use Demand (hectares, WOW)
7)	Internal Data	Local Influence Matrix Accessibility Parameters
8)	Output Data	Land Use (as grid) Transition Potential (as grid)

12.2 Summary

The Land Use Change model dynamically simulates land-use change by evaluating 1) demand for different land uses as a function of drivers of economic activities and demographic trends, and 2) a suite of four factors: accessibility, neighbourhood influence, suitability, and zoning. At each time step, the Waikato region EFM (Section 7) and Mutli-Region Demographic model (Section 10) present a demand for land in hectares to the Land Use Change model. The model then allocates land-use change based on analysis of the four factors until demands have been met or there is no more available land to allocate.

12.3 Description

12.3.1 Generic constrained cellular automata model

Cellular automata (CA) get their name from the fact that they consist of *cells* – like the cells on a checkerboard – and that cell states may evolve according to a simple transition rule, the *automaton*. A conventional cellular automaton consists of:

- a *Euclidean space* divided into an array of identical cells. For geographical applications a 2 or 3-dimensional array is most practical
- a cell *neighbourhood*. For flow and diffusion processes the 4 (*Von Neumann neighbourhood*) or 8 (*Moore neighbourhood*) adjacent cells are sufficient, but for most socio-economic processes larger neighbourhoods are required
- a set of discrete *cell states*
- a set of *transition rules*, which determine the state of a cell as a function of the states of cell itself and in relation to the state of cells in a specified neighbourhood around the cell of interest
- *discrete time steps*, with all cell states updated simultaneously.

Until recently, CA models raised only limited interest in the geographical community despite the fact that Tobler (1979) referred to them as “*geographical models*”. Originally, they were developed to provide a computationally efficient technique for investigating the general nature

of dynamic systems. Recent applications, however, have been directed at representing geographical systems more realistically, both in terms of the processes modelled and the geographical detail. These advances have been accompanied by an increase in the complexity of the models and in the effort to build more realistic models (Couclelis 1997). A concise overview of the application of CA models in land-use modelling and spatial planning can be found in Engelen et al. (1999).

RIKS have developed a generic constrained cellular automata model and applied it to urban (White & Engelen, 1993, 1994, 1997; White et al. 1997) and regional (Engelen et al. 1993, 1995, 1996, 1997, 2000, 2002a) cases.

In this section, we will consistently use the following notation:

- LU The set of all land uses. An element of this set – a land use – will be referred to by the letter f .
- t Time index of a variable. All dynamic variables have a time index that is written in superscript to the left of the variable, for example, tZ .
- c A cell on the a grid (map) with coordinates x (row) and y (column). Sets or variables that are defined for each cell on the map are preceded by a set of brackets within which the specific cell is indicated – for example, $f(c)$ is the land use function occupying cell c .

Other notation will be introduced when appropriate.

12.3.2 The cell space

The cell space consists of a 2-dimensional rectangular grid of square cells each representing an area ranging from 50 × 50 m to 1000 × 1000 m in resolution. Grid extent and shape varies according to the requirements of the application, but is typically less than 1000 × 1000 cells. WISE 1.6 uses a 100 × 100-m grid cell size. Grid extent may be larger (i.e. more rows and/or columns), but at the cost of longer run times. The same applies to the resolution of the model: it is technically possible to increase the resolution of the CA model, but this would geometrically increase the number of cells in the neighbourhood of interest for a specified distance, thus considerably increasing execution time. Moreover, before increasing the resolution of the CA model, it is essential to analyse whether this would lead to any better results. It would be inefficient to decrease the size of the cells beyond the typical physical entities, the blocks or plots of land, that are the subject of the location decisions of the spatial agents determining the use of the land. Very often also, the data will not be available or will become unreliable at high resolutions so that the processes modelled are laden with uncertainty. Thus, a higher spatial resolution might give a false impression of more detail and information, but could result in less realistic and/or less accurate spatial dynamics.

12.3.3 The cell neighbourhood

The cell neighbourhood is defined as the circular region around the cell out to a radius of eight cells. The neighbourhood thus contains 196 cells (Figure 16) arranged in 30 discrete distance zones forming concentric circles. We indicate the collection of cells that form the neighbourhood of a cell c by $D(c)$. The distance between cells a and b , $d(a,b)$, is given by $\sqrt{X^2 + Y^2}$, where X and Y represent the horizontal and vertical distance between the cells, respectively (Table 17).

Table 17 Distances and distance-numbers in the cell neighbourhood

Concentric circle	1	2	3	4	5	6	7	8	9	10
Distance (in cells)	0	1	1.41	2	2.24	2.83	3	3.16	3.61	4
Concentric circle	11	12	13	14	15	16	17	18	19	20
Distance (in cells)	4.12	4.24	4.47	5	5.10	5.39	5.66	5.83	6	6.08
Concentric circle	21	22	23	24	25	26	27	28	29	30
Distance (in cells)	6.32	6.40	6.71	7	7.07	7.21	7.28	7.62	7.81	8

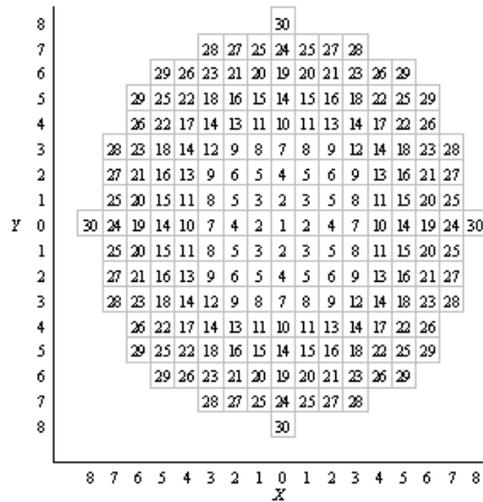


Figure 16 All cells in the neighbourhood are in exactly one concentric circle. The index of the circle depends on the distance of the circle’s cells to the centre of the neighbourhood (circle 1).

The neighbourhood radius varies depending upon grid resolution. For WISE the land use model operates on a 100 × 100-m grid, so that the neighbourhood radius is 800 m. This distance delimits an area that is similar to what residents and entrepreneurs commonly perceive to be their neighbourhood. It should thus be sufficient to allow the CA transition rules to capture local-scale spatial processes. The neighbourhood moves as the cell of interest (cell 1 in Figure 16) changes.

12.3.4 Cell states

Cell states represent the dominant land use in each cell. A distinction is made among dynamic elements, called *land-use functions* and *land-use vacant states*, and static elements, called *land-use features* (Table 18). Land-use features will not change as the result of micro-scale dynamics. They do not change location, but influence the dynamics of the land-use functions and land-use vacant states and thus affect the general allocation process. Increasing the number of states in the CA will increase – in theory at least – the number of possible state transitions of each cell, and defining transition rules will become more complicated. Again, it requires special attention on behalf of the model developer to keep this complexity within limits. It is useful to distinguish between land uses if and only if these land uses behave differently in space. If, however, their spatial dynamic is very similar, then land uses can just as well be combined into a single land-use function.

Table 18 Types of land-use classes within the Land Use Change model

Land Use Type	Dynamics at			Type of Microdynamics	Examples
	Regional Level	Local Level			
Function	Yes	Yes		Active	Residential – Low Density Community Services Forestry Manufacturing
Vacant	No	Yes		Passive	Indigenous vegetation Wetlands

Feature	No	No	Static	Marine
			Does not change during the simulation	Urban Parks

Neighbourhood effects

A fundamental idea underpinning a CA model is that the state of a cell at any time depends on the states of the cells within its neighbourhood. Thus, a neighbourhood effect must be calculated for each of the land use function states to which the cell could be converted. In our models, the neighbourhood effect represents the attraction (positive) and repulsion (negative) effects of the various land uses and land covers within the neighbourhood (Figure 17).

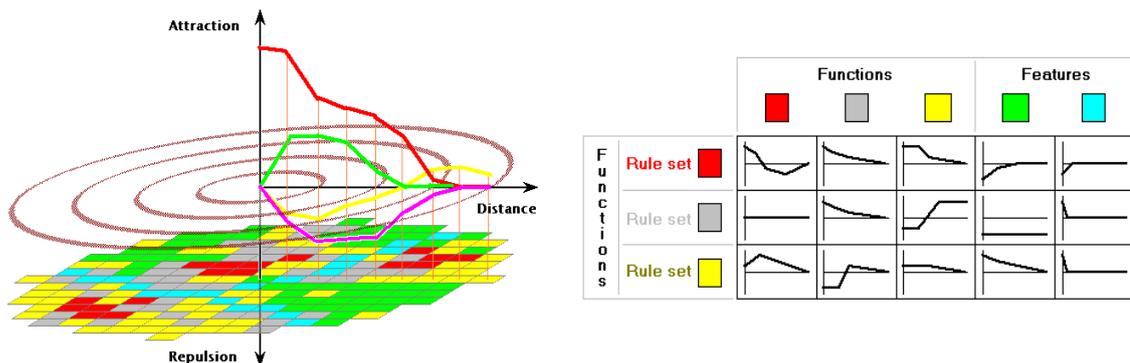


Figure 17 For the calculation of the neighbourhood effect, a circular neighbourhood consisting of 196 cells is applied (left). For each land use function, the transition rule is a weighted sum of distance functions calculated relative to all other land use functions and features (right).

In general, cells that are more distant in the neighbourhood will have a smaller effect. Thus, each cell in a neighbourhood will receive a weight according to its state and its distance from the central cell.

An example of an influence function for the influence of one land use on another land use is shown in Figure 18. At every distance in the CA neighbourhood the neighbourhood influence function could be specified. This has the advantage of enabling the definition of very complex functions. However, its disadvantage is the large number of parameters that could be defined, which could significantly complicate the calibration process. To overcome largely this difficulty, the influence functions are transformed to splines defined by only several points. For these splines, the following properties should hold:

- The inertia value is always given on the vertical axis, that is, at distance 0. Thus, the first point is (**a** on Figure 18)
- The second point must be located at distance 1 (**b** on Figure 18)
- The last point of the spline should have value 0, such that for all distances larger than *d*, the function value is 0 (**c** on Figure 18)
- There can also be points between the second and the last point (**d** and **e** on Figure 18), although increasing the number of points increases complexity again.

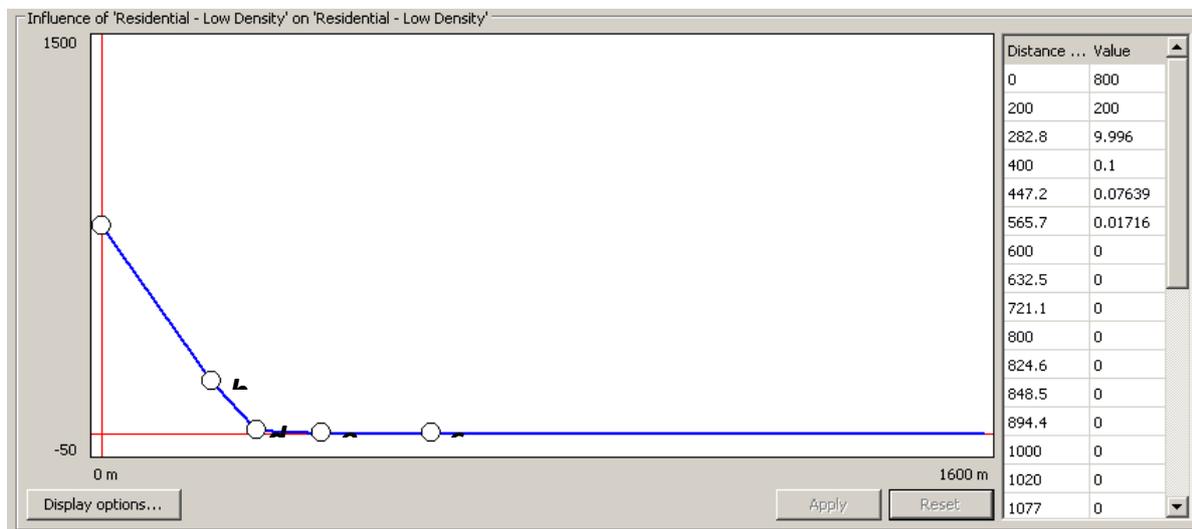


Figure 18 Example of the neighbourhood function for Influence of Residential – Low Density on Residential – Low Density in WISE.

12.3.5 Transition rules

The goal of the CA model is to simulate the dynamic behaviour of land-use change by allocating one cell state (land use) to each cell on the map. The allocation is performed on the basis of an algorithm that evaluates a vector of values – one value for each possible cell state (land use), known as transition potentials. In WISE, transition potentials are determined on the basis of four factors:

- Accessibility
- Neighbourhood influence
- Suitability
- Zoning

For land-use functions, the CA model allocates cells to a land use and attempts to meet the external demand from the Waikato region EFM (industrial uses) and WOW (residential uses). In this case the transition potentials are a function of all four factors.

For land-use vacant states, the CA model allocates cells to a vacant land use if, and only if, there is available suitable land that is not demanded by land-use functions. Most often the total area of land-use vacant states decreases over time as demand for land-use functions increases. In the default case, the transition potential is only a function of suitability, although a user could choose to include other factors in the calculation of the transition potential.

For land-use features, no changes occur, although features can influence other land uses via neighbourhood influence or accessibility.

12.3.6 Land Use Change model spatial data layers

The following sections describe the spatial data layers used in the Land Use Change model: land use, suitability and accessibility. Zoning, which also influences land-use change, was previously described in Section 8.

12.3.6.1 Land use

The choice of land-use classes and the type of micro-scale dynamics was critical to the overall functioning of WISE. The number of land-use classes affects the speed of the simulation, as does the grid cell resolution. More land-use classes (the maximum is currently 32 classes) would cause WISE to run more slowly. Finer resolution would also result in slower model simulations.

Table 19 shows both the total and active (i.e. cells containing either land, freshwater or marine within Waikato regional boundaries) number of grid cells for the Waikato region at various spatial resolutions.

Table 19 Summary statistics for varying grid cell resolutions for the Waikato region. Total cell count = the total number of cells in the full extent, i.e. # rows x # columns. Active cell count = total cells bounded by the Waikato region coastline and interregional boundaries, i.e. all cells containing land or freshwater within Waikato region boundaries

Cell Size (m)	# of Rows	# of Cols	Total Cell Count	Active Cell Count
25	12 832	6 636	85 153 152	39 280 154
100	3 208	1 659	5 322 072	2 455 148
250	1 283	664	851 912	392 802
500	642	332	213 144	98 188

The choice between number of land-use classes and spatial resolution depends on the intended use of WISE. If intended *primarily for in-house use to evaluate policy strategies or resource management issues*, for example, WISE could have a relatively high number of classes and/or finer spatial resolution, as overall execution time would not be a critical consideration. If intended to support community consultation processes where overall speed of execution was critical to effective engagement, WISE would generally have fewer land use classes and/or a coarser resolution.

Following consultation among Waikato Regional Council staff and project team members, a 200 × 200-m spatial resolution and 25 classes (Table 20) were chosen to represent land use within WISE 1.3. During the review process for WISE 1.4 update it was now considered advantageous to increase the spatial resolution to 100 x 100-m. This would allow for better representation of urban land use change which was seen as a key area of interest for the application of WISE. During the development of V1.6 one additional land use class was included (Vacant Urban land). No other additional land use classes were considered necessary for the V1.6 update. The reviewed setup represented a compromise that provided an improved level of spatial detail while still keeping run time manageable for some interactive uses with stakeholders.

Table 16 lists the 26 land-use classes for WISE. Of those classes, 4 are vacant states, 14 are functions, and seven are features. *Land Outside the Study Area* and *Marine Outside the Study Area* are also listed and shown in the land-use map to provide spatial context. Of the 14 land-use functions, 3 are residential land uses with demand determined by the WOW model, while the remaining 11 land-use functions are non-residential (e.g., commercial, dairy farming) land uses with demand determined by the Waikato region EFM.

The choice of land-use type is not fixed. Land uses can be re-assigned to a new type. For example, aquaculture is currently a feature that reflects both its highly limited nature currently in the Waikato region and lack of supporting models in WISE 1.4. If aquaculture becomes more pervasive and subject to market conditions similar to other primary production uses (dairying, forestry), modelling it dynamically as a land-use function may make more sense. Similarly, carbon credit markets could generate enough demand for regeneration of native forest to consider treating indigenous vegetation as a function rather than a vacant state. That would also require adjustments in the Waikato region EFM to account for those new markets.

Appendix C lists the input data layers used to develop the land-use classification and briefly outlines the process used to generate the 2013 land-use layer using these classes. Waikato Regional Council holds the databases and associated algorithms used to generate the land-use layer. Note that not all input data layers may be publicly available.

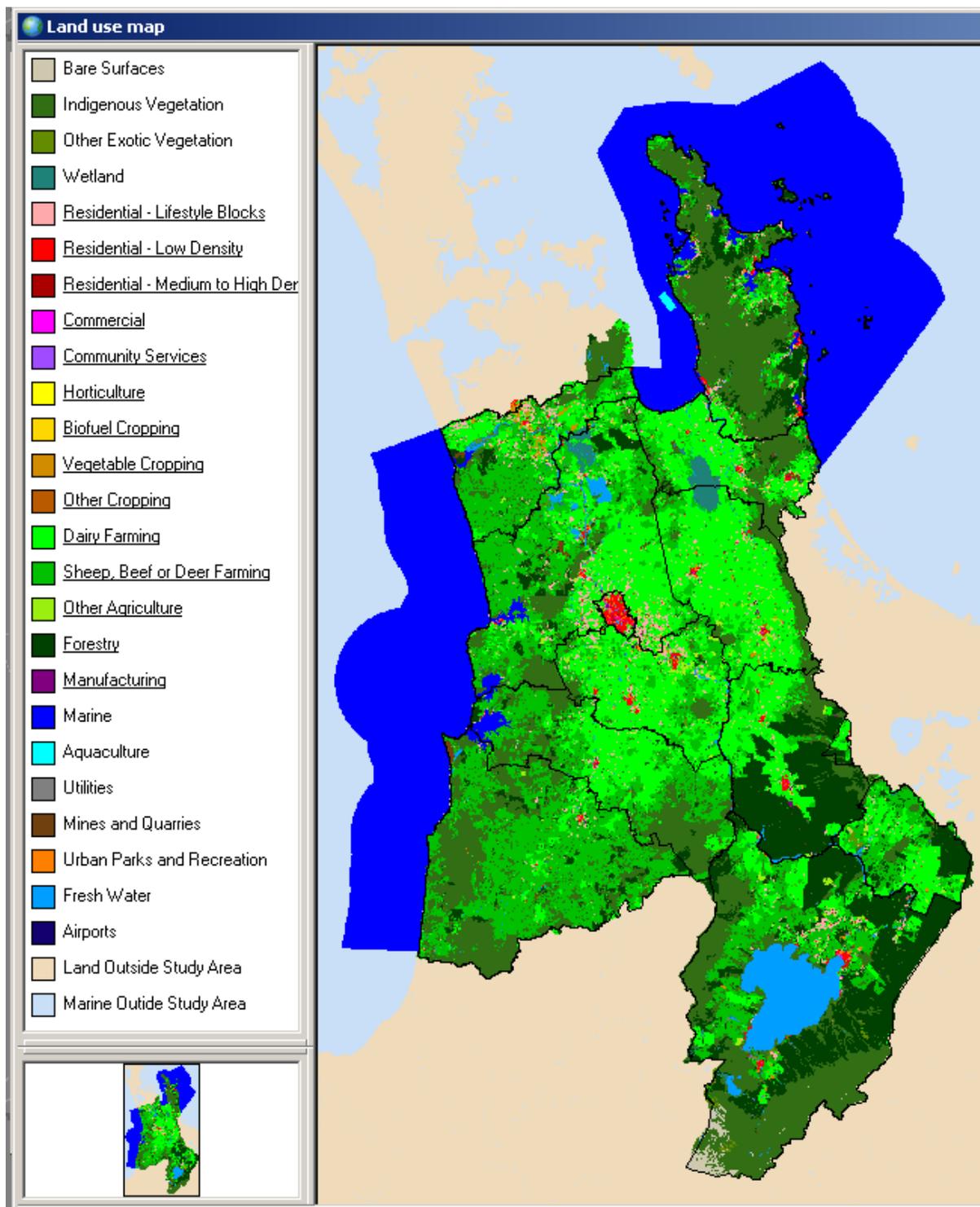


Figure 19 Land-use map for 2013, the start year for simulations in WISE Version 1.6.

Table 20 Land-use classes for the Land Use Change model in WISE 1.4

Cell Value	Type	Class	Code	Description	Examples	Rationale
0	Vacant	Bare Surfaces	BSF	Sand, unvegetated sand dunes, bare rock, ice and snow, large unvegetated erosion scars and alluvial flats, permanent exposed soil not related to Mine or Quarry activities	Beaches and sand dunes on the Coromandel and West Coast, The Volcanoes of Tongariro National Park.	Covers significant parts of Waikato coastline and around mountains. Is a passively dynamic land use of natural causes
1		Vacant – Urban land	VUL	Land that is generally within existing urban areas/boundaries which has been removed from a productive land use and is awaiting development into residential or commercial/industrial use.	Empty sections within residential areas, residential or industrial developments that are underway but haven't been build on and occupied yet. Small lifestyle residential sections with no dwelling.	Land that fits into this class is seen as 'transitory' as it has been removed from a productive land use but has not yet become a new land use that would contribute to either residential use/population densities or commercial economic activities
2		Indigenous Vegetation	IDV	Predominantly native vegetation such as indigenous forest, shrubland, tussock and mangroves	Indigenous forests, mānuka/kanuka, flaxland, fernland, etc.	"Native bush" is an iconic part of the NZ landscape; also indigenous forest has second highest coverage in Waikato region
3		Other Exotic Vegetation	OEV	Predominantly exotic/non-native vegetation not intentionally planted for production of timber products	Wilding pines, willows, deciduous hardwoods, gorse, blackberry, heather, matagouri?	Allows for areas where non-natives exist or can colonise after management for economic gain stops (similar to abandonment in other RIKS models but that concept does not fit as well in NZ)
4		Wetland	WLD	Permanent saline or freshwater wetlands and their associated non-woody vegetation	Whangamarino; Torehape; Kopuatai; Some estuarine margins.	Although officially protected, inclusion as vacant state allows for possibility of further loss or restoration, both of which occur; difficulty with resolution as many wetlands may fall below the resolution of the model

Cell Value	Type	Class	Code	Description	Examples	Rationale
5	Function	Residential – Lifestyle Blocks	RLB	Very low density, detached, private, single-family dwellings on lots >0.25 ha but usually no larger than 8 ha; usually located in peri-urban or rural areas	Developments around Matangi, Tamahere, River Road north of Hamilton and NW of Cambridge.	For the Waikato, 2 classes (low/high) for depicting lifestyle/periurban vs. urban situations would likely suffice; 3 classes are recommended for easier transferability to other regions, such as Auckland or Wellington, where 3 classes better capture the range of densities available or allows for more scrutiny of intensification
6		Residential – Low Density	RLW	Areas with 5–25 dwellings per hectare, typically dominated by detached, single-family dwellings or duplexes; lot sizes typically from 500–1000 ² m but can be up to 2500 ² m	This is typical New Zealand residential development (i.e. "the Kiwi quarter acre dream") built mostly prior to 2000.	
7		Residential – Medium to High Density	RMH	Areas with >25 dwellings per hectare, typically dominated by multi-unit buildings like townhouses, apartment complexes, or high-rises	Sherwood Vale in Hamilton (along Ruakura Road); new developments north of Hamilton; apartment blocks	
8		Commercial	CML	Wholesale and Retail Trade, Accommodation/Restaurants/Cafes, most communication services, Finance/Insurance and Property Services; Services to Agriculture; Hunting and Trapping	The Base, any CBD or shopping centre in Hamilton or other city/town	A key land use class in terms of its influence on other urban land uses. Typically is the centre of any urban area
9		Community Services	CMS	Government Administration and Defence; Education; Public Safety; Health Services; Public Film, Video, Radio and Television services; Libraries, Museums, Arts and services to the Arts	Waikato District Hospital, Waikeria Prison (Buildings), Hamilton Boys High School, Police Station	A key land use in the service of urban areas. Typically borders commercial and is actively dynamic in expanding urban areas
10		Horticulture	HOR	Production of fruits, nuts, seeds and flowers and other ornamental plants; includes nurseries and viticulture	Vilagrads and Mystery Creek Vineyards; Sunfruit Orchards	Pastoral based production is the dominant land use in the Waikato Region, followed by forestry. Cropping and horticulture generally make up a smaller part of the region although they can be significant in terms of their effects on land and water.
11		Biofuel Cropping	CPB	Production of plants for energy supply	Rape seed, Jatropha, Beets, Sorghum, Coppice plantations, maize? (see issues), etc.	

Cell Value	Type	Class	Code	Description	Examples	Rationale
12		Vegetable Cropping	CPV	Production of plants and roots for the purpose of vegetables for human consumption. Typically involves heavy soil disturbance as part of succession cropping	Land around Pukekohe	Biofuel cropping is included to allow for expansion in future scenarios
13		Other Cropping	CPO	Production of other crops such silage, barely, maize, wheat, tobacco, hops; fungi. Usually involve less disturbance of the soil and rotated on an annual basis	Various rural locations around the region	
14		Dairy Farming	DFM	Land used for the pastoral production of dairy milk or for support of that land use	Most of Waikato's low-lying pastoral landscape	
15		Sheep, Beef or Deer Farming	SBD	Pastoral production of sheep and/or beef and/or deer	Predominantly hill country farming such as commonly found around Te Kuiti	
16		Other Agriculture	OAG	Other agricultural activities such as beekeeping, horse, pig, poultry mixed livestock and other livestock farming	Equine industry around Cambridge; Goats, Pigs, Chickens, Ostriches, Alpaca	
17		Forestry	FTY	Land used for the growth and harvesting of wood, primarily Radiata Pine but also may include other exotic or indigenous species	Kaingaroa or Kinleith Forest. Various smaller private forestry blocks on farmland	
18		Manufacturing	MFG	Production and storage of goods such as wood/paper, textiles, clothing, footwear, foods, beverages, petroleum, coal, chemicals, metals and non-metals, machinery, equipment and furniture; Printing and publishing	Kinleith Pulp and Paper Mill; Dairy Factories; Urban industrial areas	

Cell Value	Type	Class	Code	Description	Examples	Rationale
19	Feature	Marine	MAR	Estuarine and open coastal water out to the 12NM regional boundary	West Coast, Firth of Thames, Coast around Coromandel Peninsula, Raglan Harbour, Whangamata Estuary	A significant part of the Waikato region generally deemed static but could change to a vacant state if aquaculture became a function. Has neighbourhood influences on some land uses
20		Aquaculture	AQC	Production and cultivation of aquatic animals and plants; both salt and fresh water	Mussel farms off Thames coast. Huka prawn park	A developing industry in the Waikato Region. Difficult to model as a function at this stage due to a lack of information but could be changed to a function in later versions
21		Utilities	UTL	Infrastructure for generation, transmission, distribution, storage, treatment or manufacture of electricity, gas, water supply and wastewater treatment. Also includes large infrastructure associated with transportation but not airports	Huntly Power Station, Karapiro Dam, Hamilton Wastewater Plant, Wairakei Geothermal Power Plant, Frankton Railway Station	Critical in keeping the built human environment although tends to have only minor interactions with neighbouring land uses
22		Mines and Quarries	MAQ	Mining and quarrying operations and their solid waste products. Includes coal, oil and gas extraction and exploration activities	Huntly Coal Mine, Waihi Gold Mine; various sand & gravel quarries	Covers significant parts of the Waikato Region. A key employer
23		Urban Parks and Recreation	URP	Areas set aside for recreation, leisure activities, or aesthetic enjoyment; includes Parks and Gardens, Sports Fields and facilities, Gambling and Other Recreation services. Excludes conservation estate land such as National or State Forest Parks	Claudlands Park, Cambridge Town Belt, Hamilton Gardens, Waikato University grounds, Waikato Stadium, Te Rapa Racetrack	Has strong impacts on urban land use dynamics

Cell Value	Type	Class	Code	Description	Examples	Rationale
24		Fresh Water	FRS	Permanent fresh water bodies including lakes, reservoirs, dams and ponds over 4 ha and rivers wider than 200 m	Lake Taupo, Lake Karapiro, various smaller lakes and ponds 4ha minimum	Covers significant parts of the region and has some interaction with some neighbouring land uses
25		Airports	APT	Large airports used for domestic or international flights and their directly associated structures and buildings. Excludes small rural airports and airstrips used only for recreational or primary industry purposes	Hamilton, Taupo and Thames Airports	Critical in servicing large urban areas. Has immediate interactions with some neighbouring land uses
26		Land Outside Study Area				
27		Marine Outside Study Area				

12.3.6.2 Suitability

Suitability estimates the potential of a given location to support a particular land use. For WISE 1.6 this means: how suitable is each 100 × 100-m grid cell for each land-use function or vacant state? Suitability is evaluated on a scale from 0 (= completely unsuitable) to 1 (= most suitable) in increments of 0.1. For WISE, a suitability of 0 means a land use cannot occur at that location. In that regard, a suitability of 0 has the same effect as prohibited zoning, i.e. a land use is “not allowed” in such places.

WISE V1.6 includes RIKs “Land Use Suitability Tool”. This tool allows spatial layers of individual criteria (e.g. erosion risk, drainage) to be loaded and applied to a land use type using defined restriction parameters (i.e. slopes over 45 degrees have a suitability of 0 for residential housing). The Land Use Suitability maps were reviewed in WISE V1.4 by Landcare Research in 2014 (Rutledge et al. 2014). These Suitability maps were initially developed by Landcare Research through a process of combining relevant input layers using sets of rules generated via a review by experts with considerable experience in sustainable land management.

This tool allows for targeted individual suitability layers to be loaded and applied, in combination with other layers, to specific land uses (see Appendix D for more detail on the Suitability Tool). This allows for a more flexible and dynamic use of suitability in modelling than was available in earlier versions WISE (i.e V1.3) which used one predetermined suitability layer (combined in a similar way but outside the WISE model by Landcare Research) for each land use type.

As part of the previous version update Landcare Research were contracted to review current methods and data used to generate land-use suitability layers which were used in WISE 1.3 and recommend changes which Waikato Regional Council could undertake for WISE 1.4 (Rutledge et al. 2014). This contract report describes the specific suitability layers recommended and criteria for applying to each land use type in more detail.

The suitability factors are combined in the Land Use Suitability Tool to generate an overall suitability score. The overall suitability scores reflect the minimum score of the lowest factor and can illustrate complex relationships within the suitability layers. The Suitability Tool incorporates a specific selection of combinations for each land use type. For WISE V1.6 all suitability maps were generated using a geometric mean as follows:

$$S_{i,xy} = \sqrt[N]{s_{1,xy} \times s_{2,xy} \times s_{3,xy} \times \dots \times s_{n,xy}}$$

where

$S_{i,xy}$	=	total suitability score for land use i at location x,y
$s_{i,xy}$	=	suitability score for factor n at location x,y
N	=	count of all factors.

Values for the geometric mean vary from 0 to 1. If any one factor score = 0, then total suitability = 0. If all factor scores = 1, then total suitability = 1. Intermediate scores vary depending on individual factor scores and the total number of factors. For example, consider the following two cases:

Case 1:	$s_{i,xy} = \{1,1,0.5\} = 0.79$
Case 2:	$s_{i,xy} = \{1,1, 1,1,1,0.5\} = 0.89$

Overall, suitability scores depend on all three considerations: selected factors, characterisation of relationships, and rules for combining factors. There is no definitive method for defining and characterising suitability. Instead different combinations of attributes, weightings, combinations and methods can be explored to evaluate the impact of different representations of suitability within WISE.

For WISE V1.4-V1.6 the combination method was set as Geometric Mean for all land use types. Different suitability maps could be generated by varying the combination method used to suit specific user requirements.

Figure 20 shows an example combined suitability map for the “Other Cropping” land use.

12.3.6.3 Accessibility

Accessibility layers vary depending upon the relevance of features to different land uses. WISE 1.6 includes accessibility layers for three types of features:

- Transport networks (highways, roads, and railways)
- Major processing facilities
 - Dairy processing plants
 - Timber production plants
 - Abattoirs
- Central business districts and shopping centres
 - Waikato
 - Auckland
 - Tauranga.

Appendix C contains the list of input data layers that provided the basis for the accessibility spatial data layers in the Land Use Change model.

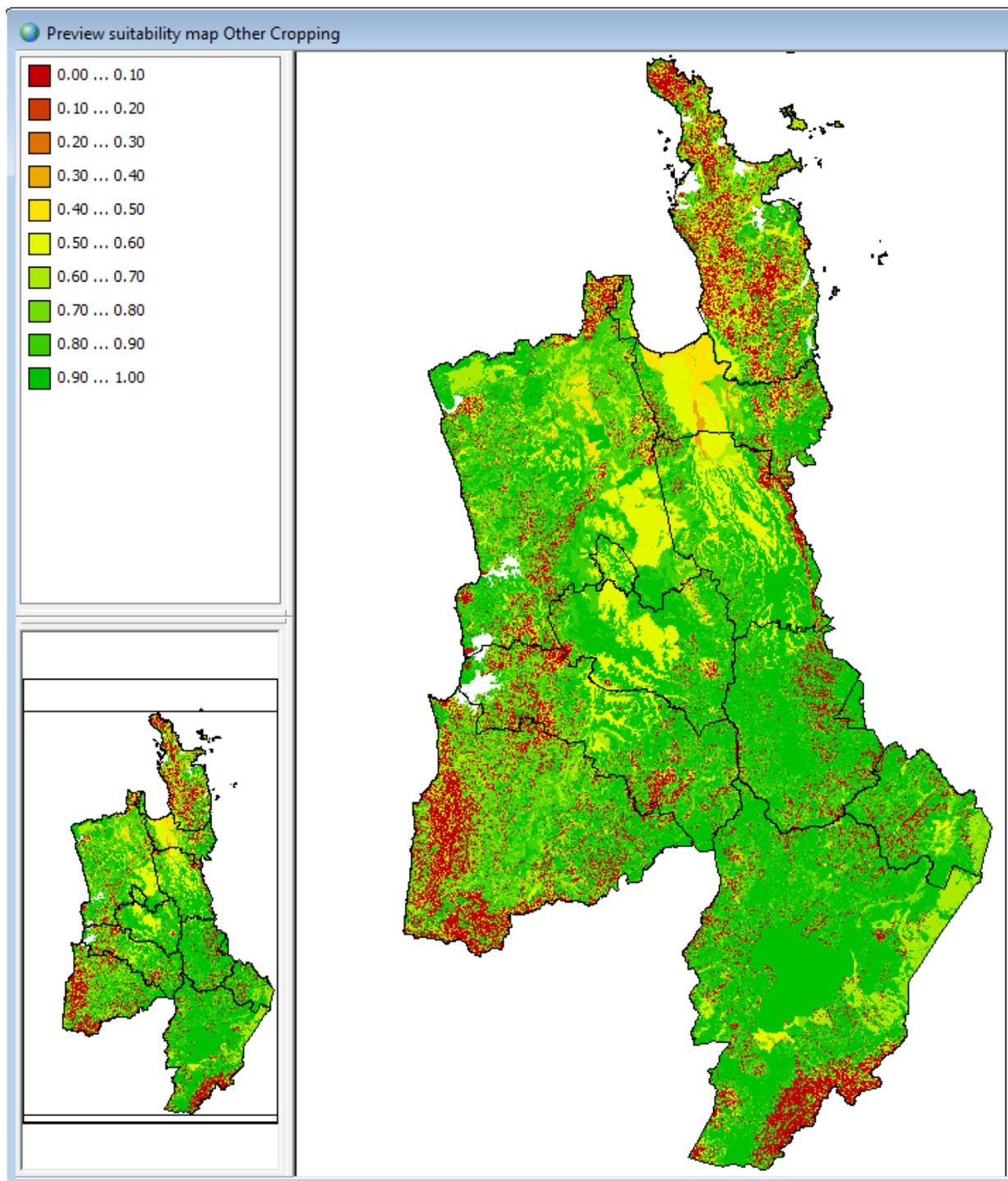


Figure 20 Example of suitability map for Other Cropping land use.

12.4 Equations

12.4.1 Accessibility

Accessibility measures the effect of the nearness and importance of different types of transport networks – such as local roads, highways, railroads, or stations on the possible future occurrence of each land-use function at a certain location. Accessibility in WISE for each land-use function is a composite measure of four types of accessibility:

- local accessibility
- implicit accessibility
- explicit accessibility

- zonal accessibility

Users can alter accessibility by adding or removing layers (usually infrastructure) of interest or by modifying the parameter values defining the accessibility relationships.

12.4.1.1 Local Accessibility

Local accessibility reflects the extent to which the need for a transportation network for a land use can be fulfilled. The network consists of a number of network layers made up of (a) nodes, such as schools or stations, and (b) links, such as roads or railways. Local accessibility is first determined individually for each node or link type and, thereafter, combined into one value for each land use and each cell.

For each land use, the local accessibility for a certain node or link can be either decreasing or increasing over distance, indicated by a positive or negative value for the distance decay parameter, respectively. A positive value indicates the land use needs to be located close to that node or link, whereas a negative value indicates the land use needs to be located away from the node or link. The functional form of this effect is hyperbolic with respect to the distance, where the distance decay parameter determines the rate of the increase or decrease (Figure 21). Note that the local accessibility per link type lies in the range [0, 1].

The *local accessibility* of cell c to node or link s for land use f is calculated as:

$${}^tLA_{s,f,c} = \begin{cases} \frac{a_{s,f}}{D_{s,c} + a_{s,f}} & \text{if } a_{s,f} > 0 \\ 0 & \text{if } a_{s,f} = 0 \\ 1 - \frac{|a_{s,f}|}{D_{s,c} + |a_{s,f}|} & \text{otherwise} \end{cases}$$

where

${}^tD_{s,c}$ = the distance in cells between cell c and the nearest cell that is intersected by a node or link s at time t

$a_{s,f}$ = the accessibility distance decay parameter of node or link s for land use f .

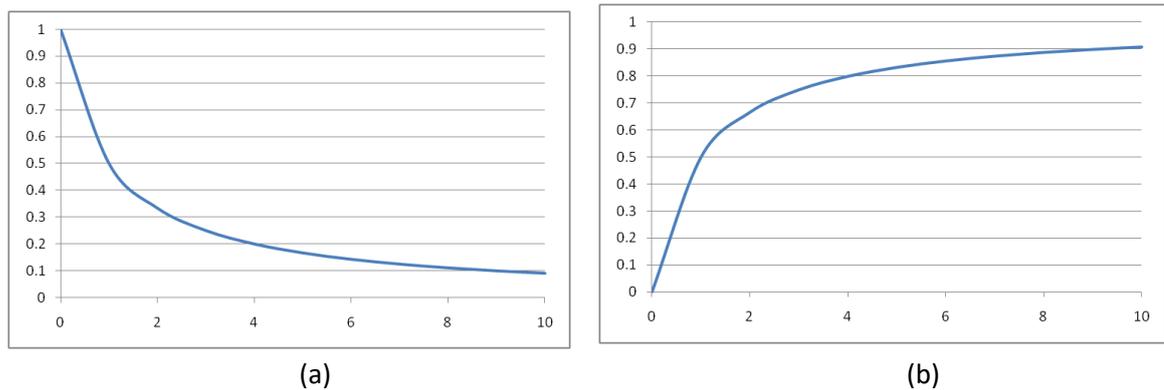


Figure 21 Effect of proximity to the network as a combined function of distance and the distance decay parameter. (a) $a_{s,f} = 1$ (positive distance decay factor) means that a cell is more suitable for land use f if that cell is closer to the node or link of interest; (b) $a_{s,f} = -1$ (negative distance decay factor) means that a cell is more suitable for land use f if that cell is farther from the node or link of interest.

The local accessibility of all nodes and links with negative distance decays is calculated as:

$${}^tLA_{f,c}^{neg} = \prod_{s \in S_f^-} w_{s,f} \cdot {}^tLA_{s,f,c}$$

$$w_f^{neg} = \prod_{s \in S_f^-} w_{s,f}$$

where

- ${}^tLA_{f,c}^{neg}$ = the total negative local accessibility of cell c for land use f at time t
- $w_{s,f}$ = the relative weight of the proximity to the different networks on the total local accessibility
- S_f^- = the set of all nodes and links with a negative distance decay parameter for land use f
- ${}^tLA_{s,f,c}$ = the local accessibility of cell c to node or link s for land use f
- w_f^{neg} = the total weight of the local accessibilities with a negative distance decay parameter.

The total local accessibility of cell c for land use is calculated as:

$${}^tLA_{f,c} = \frac{1 - (1 - w_f^{neg} \cdot {}^tLA_{f,c}^{neg}) \cdot \prod_{s \in S_f^+} (1 - w_{s,f} \cdot {}^tLA_{s,f,c})}{1 - (1 - w_f^{neg}) \cdot \prod_{s \in S_f^+} (1 - w_{s,f})}$$

where

- ${}^tLA_{f,c}$ = total local accessibility for cell c with land use f at time t
- w_f^{neg} = the total weight of the local accessibilities with a negative distance decay parameter
- ${}^tLA_{f,c}^{neg}$ = the total negative local accessibility of cell c for land use f at time t
- S_f^+ = the set of all nodes and links with a positive distance decay parameter for land use f
- $w_{s,f}$ = the relative weight of the proximity to the different networks on the total local (what??)
- ${}^tLA_{s,f,c}$ = the local accessibility of cell c to node or link s for land use f .

12.4.1.2 Implicit Accessibility

Implicit accessibility reflects the fact that when an area is occupied by an urban land use, measures will be taken to assure its accessibility, even if it does not appear so on the network map, e.g., provision of new roads in a subdivision. This is significant because as the cellular automata model changes the land use map, it does not change the network map accordingly.

Implicit accessibility takes one of two possible values for each land-use class: one for urbanised areas and one for non-urbanised areas. A cell is urbanised if its current land use class is flagged as a 'built-up area'. These flags are, therefore, parameters of the accessibility model block.

The implicit accessibility is determined as:

$${}^tIA_{f,c} = \begin{cases} Urb_f & \text{if } {}^t f(c) \in LU_U \\ NUrb_f & \text{otherwise} \end{cases}$$

where

${}^tIA_{f,c}$ = implicit accessibility for land use f of a cell c

Urb_f = implicit accessibility for land use f of a cell c that is occupied by a built-up (urban) land use

$NUrb_f$ = implicit accessibility for land use f of a cell c that is occupied by a non-built-up (non-urban) land use

LU_U = the set of built-up (urbanised) land uses.

In WISE the implicit accessibility for built-up land uses is 1.

12.4.1.3 Explicit Accessibility

When determining the distance from a cell to the nearest node or link, some land uses cannot be crossed. Therefore, the distance cannot be measured in a straight line. In this case, the explicit suitability is set to 0.

On the other hand, some land uses that are impassable for other land uses are actually passable for the same land use, e.g., a military land use. In this case, explicit suitability is set to equal to the implicit suitability of the land use in question. More formally:

$${}^tEA_{f,c} = \begin{cases} {}^tIA_{f,c} & \text{if } {}^t f(c) = f \\ 0 & \text{otherwise} \end{cases}$$

where

${}^tEA_{f,c}$ = explicit accessibility of cell c for land use f at time t

${}^tIA_{f,c}$ = implicit accessibility of cell c for land use f at time t

${}^t f(c)$ = land use occupied by cell c at time t .

12.4.1.4 Zonal accessibility

Zonal accessibility in WISE 1.4 is simply included as a (static) parameter that specifies the multiplication factor for each land use function in each district. These values are used to account for accessibility influences from outside the Waikato region (mainly the attraction of Auckland).

12.4.1.5 Total Accessibility

Local, implicit, and explicit suitability are combined to produce a total accessibility score ranging from 0 to 1 for each land use in each cell. If current land use in a cell is classified as impassable land, then total accessibility = explicit accessibility. Otherwise, the total accessibility equals the product of local accessibility × implicit accessibility.

The total accessibility (A) is defined as:

$${}^tA_{f,c} = \begin{cases} {}^tEA_{f,c} & \text{if } {}^t f(c) \in LU_I \\ {}^tZA_{f,z_c} \cdot {}^tLA_{f,c} \cdot {}^tIA_{f,c} & \text{otherwise} \end{cases}$$

where

${}^tA_{f,c}$ = total accessibility of cell c for land use f at time t

${}^tEA_{f,c}$ = explicit accessibility of cell c for land use f at time t

${}^t f(c)$ = land use occupied by cell c at time t

LU_I = the set of impassable land uses,

${}^tZA_{f,c}$ = the zonal accessibility of cell c for land use f .

${}^tLA_{f,c}$ = the local accessibility of cell c for land use f

${}^tIA_{f,c}$ = the implicit accessibility of cell c for land use f .

Table 21 below lists the full set of inputs, parameters, and outputs in the accessibility model block.

Table 21 Accessibility model block inputs, parameters and outputs

Name	GUI	Type	Description	Source
-	Network maps	Input	The network layers that consist of nodes and links of different types, representing the transport network.	Data
${}^tD_{s,c}$	Distance to road	Input	The distance from a cell to the nearest link segment of a certain link type.	Data
-	Built-up area	Parameter	True/false parameter per land use, specifying if the land use is urbanised or not.	User specified
Urb_f	Implicit accessibility of built-up area	Parameter	The implicit accessibility for a land use on a built-up area.	User specified
$NUrb_f$	Implicit accessibility of non-built-up area	Parameter	The implicit accessibility for a land use on a non-built-up area.	User specified
-	Impassable	Parameter	True/false parameter per land use, specifying if the land use is impassable for other land uses or not.	User specified
$w_{s,f}$	Relative importance	Parameter	The relative weight of the local accessibility for a certain link type and land use in the total local accessibility for that land use.	User specified
$a_{s,f}$	Distance decay	Parameter	The rate at which the local accessibility for a certain link type and land use decreases – for positive values – or increases – for negative values – over distance.	User specified
${}^tA_{f,c}$	Accessibility map	Output	The map that contains the accessibility value for each cell.	Sent to the transition potential model block

12.4.2 Neighbourhood influence

As described above, neighbourhood influence assesses the composition of land use in an 8-cell radius neighbourhood around the cell of interest. Users assign weights to neighbouring cells using influence relationships as discussed earlier (**Error! Reference source not found.17**). Each land use in the neighbourhood has a possible influence on the future occurrence on land use in the cell of interest. Influences are accumulated to produce the neighbourhood effect in each cell for each land-use function, as follows:

$${}^tR_{f,c} = \sum w_{f,f'}(d(a,b))$$

where

- ${}^tR_{f,c}$ = The neighbourhood effect on cell c with land use state f at time t
- $w_{f,f'}(d)$ = The influence function, expressing the strength of the influence of a cell with land use f' on land use f for each distance d in the CA neighbourhood.
- $d(a,b)$ = The Euclidian distance between cell a and cell b

Table 22 Neighbourhood influence inputs, parameters, and outputs

Name	GUI	Type	Description	Comments
$f(c)$	Land use map	Input	The map that contains the land use that occupies each cell.	Data source
$w_{f,f'}(d)$	Rules Influence table	Parameter	The spline that determines the influence of a land use on another land use for each distance in the neighbourhood.	User specified
${}^tR_{f,c}$	-	Output	A map for each land use function containing the neighbourhood effect for that land use for each cell.	Input to the transition potential model block

12.4.3 Suitability

Suitability quantifies the effect that particular factors have on the occurrence of land uses at different locations. In WISE, suitability is pre-determined by users and usually remains fixed for the duration of a simulation. However, users can edit suitability maps within GEONAMICA on-the-fly by pausing a simulation run, editing the map (or maps), and restarting the simulation.

Table 23 Suitability outputs

Name	GUI	Type	Description	Comments
$S_{f,c}$	Suitability maps	Output	A map for each land use containing the suitability of each cell for that land use	Sent to the transition model block

12.4.4 Zoning

Zoning models the influence of policy and planning on the land-use allocation process. As discussed in Section 8, users create categorical zoning maps based on interpretations of various rules, zones, designations, etc., from regional plans, district plans, or other relevant sources. The zones show the RMA activity status of a cell for a particular land use. The Land Use Change model evaluates the overall zoning score for each land-use function f at each cell c at each time step t by looping through zones that apply to that particular land-use function following the precedence rules set by the user. It then converts the resulting categorical zoning values into

numerical zoning values according to the zoning state values assigned by users, e.g., permitted = 1, discretionary = 0.8, etc. More formally, let:

- P the set of all plans
- R the set of all categories in all plans
- F the set of all land-use functions
- Z the set of all activity status values.

Each plan $p \in P$ is represented by a zoning map Z_p that shows the location of all categories r within that plan. Each cell c in map Z_p can have only one category, i.e. no overlaps are allowed. Where categories do not apply, cells have the value 'no data.' For each zone in a plan p , a binary map B_r is created indicating where that category occurs in the plan.

As outlined in the zoning model discussion, users specify several other parameters for each category r in a plan p :

- T_r^{start} = start year of zone
- T_r^{end} = end year of zone
- $S_{f,r}$ = activity status for land-use function f in category r
- O_r = the precedence order for category $r \in R$.

For $r \neq r'$, if $O_r < O_{r'}$ then category r takes precedence over zone r' .

The result of the algorithm will be a time series of zoning maps for each land-use function that indicate for each cell the resulting activity status. Formally, let

$${}^tZ_{f,c} = \text{the activity status of land-use function } f \text{ in cell } c \text{ at time } t.$$

Categorical zoning maps must be converted to numerical zoning maps for use in the calculation of the total transition potential. The Land Use Change Model converts the activity status into the numerical zoning score assigned by the user in the Land Use Change Model. In addition, the model also considers the de facto land-use function. For this purpose we define a matrix that shows on which existing land use a potential land-use function is allowed to develop. Formally let:

- $DF_{l,f} \in \{0,1\}$ the De Facto status of land use function f on land use l , indicating if land use function f is always allowed to develop in areas where land use l occurs,
- $V_{f,s}$ the value that needs to be assigned to zoning status $s \in S$ for land use function $f \in F$ and
- ${}^tZV_{f,c} \in [0, \infty)$ the value used for zoning in the calculation of the total potential for land use function $f \in F$ in cell c at time t .

Table 24 Zoning algorithm for determining precedence among zones

Logic Statement	Comment
Let t denote the current simulation time	
Initialise ${}^tZ_{f,c}$ = 'unspecified' for all cells c and for all land-use functions $f \in F$	Set zoning for all cells as 'unspecified'
For each class r ordered by O_r descending	
If $T_r^{start} \leq t \leq T_r^{end}$	
For each $f \in F$	
If $ZS_{f,r} \neq$ 'unspecified'	
For each c for which $B_{r,c} = 1$	
$Z_{f,c} = ZS_{f,r}$	
End for	
End if	
End for	
End if	
End for	

Table 25 Zoning inputs, parameters, and outputs

Name	GUI	Type	Description
Z_p	Zoning plan	Input	A categorical map that spatially delineates zones in a plan. Zones are specified in an associated legend file
T_z^{start}	Start time	Input	The start time of zone z
T_z^{end}	End time	Input	The end time of category z
${}^tZ_{f,c,z}$	Categorical zoning status	Input	Categorical zoning status for land use f at grid cell c within zone z
O_r	Zone precedence		The precedence order of zone z
$DF_{l,f}$	De Facto zoning		The de facto status of land-use function f on land use l , indicating if land-use function f is always allowed to develop in areas where land use l occurs
$V_{f,s}$	Zoning status value		The numerical zoning value for land use function f with activity status s
$Z_{f,s}$	Zoning maps		A map for each land-use function f that denotes the activity status s
${}^tZV_{f,c}$	Numerical zoning maps		A map for each land-use function f that denotes the numerical zoning value used in the transition potential calculation for cell c

12.4.5 Land-use change

Land-use change is updated based on an analysis of the transition potentials calculated for each cell with either a land-use function or a vacant state. Land-use features do not change and therefore are not modelled. The Land Use Change model aims to meet any external demands for land-use functions as determined by the Waikato region EFM and Population models. Vacant states will be allocated after the required number of cells has been allocated to all land-use functions.

This land-use change procedure can be understood most easily by considering the land-use functions as agents that want to occupy a certain number of cells in the region and by considering the cells in each region as agents that want to be occupied by a land use that has the highest transition potential in that cell. The algorithm attempts to satisfy those conditions such that the accumulated transition potential of the cells occupied by each land-use function is maximised. In that regard, the allocation algorithm (Table 26) yields an equilibrium outcome in which no land use can find a cell that it can occupy, meaning the currently allocated land use has a lower transition potential value in that cell, while vacating another cell and, thereby, increases its accumulated transition potential. At the same time, no cell can find a land use that is willing to vacate another cell and occupy this cell, thus increasing its accumulated transition potential, thereby increasing the transition potential in this cell.

The equilibrium state is found by an iterative procedure, in which the land-use function that has the highest transition potential in an unallocated cell in the region is allocated to that cell, as long as more cells need to be allocated to that land-use function. Thereafter, the vacant land use with the highest transition potential is allocated to each unallocated cell.

Table 26 Algorithm for allocating land use based on calculated transition potentials

for each region

allocate the current land use to all cells occupied by a land-use feature

while some cells have to be allocated to some land-use function

select the land use function for which we still need to allocate more cells that has the highest total potential value in an unallocated cell

allocate the land use to that cell

end while

while not all cells have been allocated a land use

select the vacant land use with the highest potential in an unallocated cell

allocate the land use to that cell

end while

end for

The default calculation determining transition potential in WISE 1.6 is:

$${}^tT_{f,c} = I_{f,c} \times S_{f,c} \quad \text{for land-use vacant states}$$

$${}^tT_{f,c} = (1 - c) \times {}^tN_{f,c} \times {}^tA_{f,c} \times S_{f,c} \times {}^tZ_{f,c} \quad \text{for land-use functions}$$

if ${}^tR_{f,c} \geq 0$

$${}^tT_{f,c} = (1 - c) \times {}^tN_{f,c} \times (2 - {}^tA_{f,c} \times S_{f,c} \times {}^tZ_{f,c}) \quad \text{for land-use functions}$$

if ${}^tR_{f,c} < 0$

where

- ${}^tT_{f,c}$ = transition potential for cell c for land use f at time t
- $I_{f,c}$ = inertia/conversion effect of the current land use in cell c for land use f
- $S_{f,c}$ = suitability score for cell c for land use f
- ${}^tN_{f,c}$ = neighbourhood influence score for cell c for land use f at time t
- ${}^tA_{f,c}$ = total accessibility score for cell c for land use f at time t
- ${}^tZ_{f,c}$ = zoning score for cell c for land use f at time t
- c = random coefficient set by the user.

Users may change the algorithms as desired to explore different combinations or weightings of factors (Table 27). The default value for the random coefficient c is 0.5.

Table 27 Land use model inputs, parameters, and outputs

Name	GUI	Type	Description	Source
-	Land-use map	Input	The land-use map at the start of the simulation	Data
$tP_{f,c}$	Transition potential maps	Input	The transition potential for each land use and each cell	Calculated internally
$tN_{r,i}$	Regional demands	Input	The number of cells that need to be allocated to each land use function in each region	The Waikato region EFM (industrial land uses) and WOW (residential land uses)
$t_f(c)$	Land-use map	Output	The land use that currently occupies each cell in the map	Land Use Change model

12.4.6 Monte Carlo functionality

The land use model has the functionality to perform a Monte Carlo analysis. This means that the integrated model will be run from start to finish a specified number of times and the frequency with which each land use occurs on each location of the map at the end of a run will be counted. In this way, the stochastic nature of the land use change model can be presented much better than with the outcome of a single run. The basic result of a Monte Carlo analysis in WISE will be a set of maps indicating the probability (between 0 and 1) of occurrence of each land use function.

For a useful presentation of the analysis output, these maps need to be combined with each other and with information from the initial land use map. For example, to display the probability of urbanisation the user can sum the probability of occurrence of each urban land use class, depict this against a background of existing (natural) land use classes taken from the initial land use map, and overlay the existing urban land use from the initial land use map (in order to distinguish between existing and new urban areas). Other overlays, such as the road network or district boundaries may be desired as well.

12.5 Links

The Land Use Change model links with the Hydrology, Water Quality, Demography, Waikato region EFM, and Terrestrial Biodiversity (Table 28).

Table 28 Links between the Land Use Change model and other models

Type	Model	Data Passed	Comments
Inputs	The Waikato region EFM	Economic activity	Economic activity determines the amount of land demanded by multiplying economic activity (\$ ₂₀₁₈ m) x the land productivity index
	Demography	Population	Population determines the demand for land (ha) for each of the three residential land use categories
Outputs	Hydrology	Land Use	Land use determines the canopy capacity w_{cm} (mm) via a look-up table
	Water Quality	Land Use	Land use determines the source coefficient (c_i) via a look-up table Land use determines the value of the rain exponent and drain exponent for N loading (α_{ik})
	The Waikato region EFM	Land Use	Amount of land (ha) supplied to the Waikato region EFM
	Terrestrial Biodiversity	Land Use	Land use is passed to the Terrestrial Biodiversity model, where it is reclassified as either native or non-native cover

13 User-defined spatial indicators

13.1 Metadata

1)	Name of Model	User-defined Spatial Indicators
2)	Organisation	RIKS
3)	Contact	Hedwig van Delden
4)	Spatial Resolution	100m (as grid)
5)	Temporal Resolution	Annual
6)	Input Data	Land Use (categorical grid), potentially other grid maps depending on the algorithm selected (e.g. flood map, storm map, protected areas)
7)	Internal Data	Indicators parameters
8)	Output Data	Spatial indicators derived from land use map

13.2 Summary

The spatial indicators model calculates the spatial indicators dynamically with the changing land use on a yearly basis and makes them available in the form of dynamic maps and numeric outputs.

Through this component the user can define spatial indicators on demand by selecting one from a set of available algorithms, when required providing additional input data and configuring indicator parameters.

13.3 Description

An indicator in this context is a measure to make a particular phenomenon perceptible that is not – or at the least not immediately – detectable. On the other hand, indicators can also be set up to verify legislative guidelines or policy goals. Indicators are in fact small model blocks that generally simplify in order to make complex phenomena quantifiable in such a manner that communication is either enabled or promoted.

Clearly, with the system like WISE, which generates evolving land use patterns and the associated high resolution land use/land cover maps, the generation of spatially referenced indicators in a dynamic manner becomes a distinct possibility.

The calculation of indicators can be done as part of a post-processing task on the spatial output written to file and stored during a simulation. The Map Comparison Kit and common GIS are appropriate instruments to produce indicators based on land use changes, respectively composite indicators based on the combination and weighing of land use and ancillary maps. Alternatively, it is possible to incorporate the calculation of spatial indicators in the system and have them calculated dynamically with the changing land use. Like the other variables, indicators are thus calculated on a yearly basis and are available in the model in the form of dynamic maps, time charts and numeric outputs.

The functionality available in the spatial indicator models has the following characteristics.

- a. A set of indicator algorithms has been incorporated to visualise and assess the effects of urban spatial patterns and the possible effects of this in social, economic and environmental terms, but also on floods, forest fires, landslides and other natural hazards. The open architecture of Geonamica enables the straightforward incorporation of additional indicator algorithms at a later stage.
- b. The algorithms that have been implemented perform mathematical operations on the land use map and the output of the regional interaction model generated in the course of a simulation and on external data that can be entered interactively.

- c. The algorithms can be configured interactively (via the user interface) by the end-user of the model on the basis of a number of parameters. In fact, an indicator consists of a generic algorithm, determining the type of indicator, and its set of parameter values, determining the interpretation of the indicator. Within a model, a single algorithm can be employed with different parameter values as often as desired.
- d. In a model run, the user can switch an indicator on or off. All indicators that are switched on are updated after every time step. They are presented in a dialogue window and an associated map window that the user can open and close during the run. Like for all other maps in the model, statistical information relative to the information displayed on the map is available by clicking the mouse in the map – see the User Manual. Indicator maps can be exported in IDRISI format. In addition to the map, for every indicator a synthetic value is calculated over all cells of the map, a sum, weighted sum or average of all cells (depending on the algorithm). This value is represented as an index value in a time chart that is also accessible via the dialogue window.
- e. Finally, the indicator maps can be written to a log file or animated GIF file. The log files can be opened by means of the Map Comparison Kit enabling the analysis of changes in the indicator maps generated within a single run or in different runs of the model. The animations are automatically stored on the hard disk and available after the simulation as animated GIF files that can be opened and viewed with any graphical viewer or internet browser program.

The system includes the pre-defined spatial indicators. From the above, it will be clear that the user can also define a set of new indicators based on the algorithms currently available in the models or he can extend or modify a list of existing indicators. This is done by means of the Spatial indicators dialogue window.

13.3.1 Assumptions

Some indicator algorithms use a search radius or target cluster radius defined in terms of a number of cells. This means that the indicator will work within a neighbourhood of the cell being analysed that has a radius equal to the value of this parameter. The neighbourhood is defined analogous to that of the neighbourhood effect in the land use model. Hence, the resulting area is circular only by approximation as depicted in Figure 22.

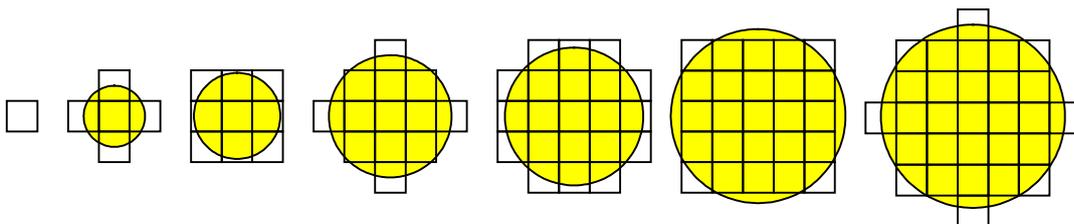


Figure 22 Areas belonging to search radii of 0, 1, 1.42, 2, 2.24, 2.83, and 3, respectively.

13.3.2 Constraints

Some indicators require an additional map (ancillary map) to be specified as one of the parameters.

13.4 Equations

As indicators are model blocks, the outline of each sub-section will follow that of other model blocks. The equations used in the spatial indicator models are described in the sub-sections of this section which give a description of the different indicator algorithms that are currently available in the system. The contents will, however, be more general, since we are describing categories of indicators and not actual indicators, which are comprised of the category of indicator and a set of parameter values for that category of indicator.

Table 29 Parameters used in the spatial indicators component

Name	Description	Source
Search radius (cells) for cluster indicator	The minimum size of a cluster. This can range from 0 to 25. The default value is 0.	User defined
Road is obstacle	Determines whether a road can intersect a cluster (checked) or not (unchecked). By default this is unchecked.	User defined
Target for cluster indicator	Specifies whether a land use contributes to the cluster size (checked) or not (unchecked). By default this is unchecked.	User defined
Search radius (cells) for neighbourhood indicator	The radius in cells within which the algorithm looks for a land use that will be added to the numerator, denominator, or both. By default the minimum value for this parameter is 1 and the maximum is 25. A value of 1 will only count the current cell. The default value for this parameter is 10.	User defined
Numerator	The weight with which the corresponding land use will be added to the numerator. These values can range from 0 to 1000 and are set to 0 by default.	User defined
Denominator	The weight with which the corresponding land use will be added to the denominator. These values can range from 0 to 1000 and are set to 0 by default.	User defined
Target cluster radius for distance indicator	This is the minimum size that a cluster of target cells should have to be considered a target. This value can range from 1 to 25 and is set to 10 by default.	User defined
Role of land use	Per land use you can specify whether it is a source, a target or neither (n.a.).	User defined
Range for counting cells for distance to map indicator	Only count cells with the specific value for distance to map indicator.	User defined
Source for distance to map indicator	Sets for each land use whether the distance to the target areas should be shown or not. By default, all sources are unchecked.	User defined
Area file for distance to map indicator	Specifies the path and filename of a binary map file specifying the areas to which the distance should be calculated. Unless a proper file is specified, the indicator cannot be calculated.	User defined
Disturbance value	The value of the disturbance can range from 0 to 25 and is set to 0 by default.	User defined
Range for counting cells for mask/mapping indicator	Only count cells with the specific value for mask/mapping indicator.	User defined
Search radius for habitat fragmentation indicator	The search radius around the centre cell. The unit of the search radius depends on the cell size.	User defined
Power z	This comes forth from the empirical relation $N = c \cdot A^z$, where N is the number of species, c is a constant and A is the surface.	User defined

Resistance of road	The resistance of a road. If a road crosses through a cell, the resistance of that cell is taken as the maximum of the resistance of that land use and this value.	User defined
Fraction	Signals per land use whether it belongs to the habitat (1) or not (0).	User defined
Resistance	The resistance of the corresponding land use.	User defined
Land use change classification	The value that will be displayed in the result map if the cell has land use <i>from</i> in the base map and <i>to</i> in the current land use map. A value of -1 will result in a 'no data' value.	Pre-defined
Metric	The measure of spatial patterns to use.	User defined

13.4.1 Cluster indicator

Purpose and use

This type of indicator can be used to pinpoint clusters consisting of a certain land use or a certain group of land uses.

Process description

All cells that are occupied by a land use that has target value 0 will be ignored in the algorithm, as will all cells outside the modelling area. In the remaining cells, we then identify clusters of cells and calculate their size.

To identify all clusters, we mark all centre cells – that is, cells that are not ignored and for which all cells within the search radius are also not ignored – and all cells that are within the search radius of a centre cell. We then define a cluster to be a group of horizontally or vertically adjacent cells that are not ignored, where each cluster must contain at least one marked cell. The value of each cell in a cluster is equal to the size of the cluster, which is defined as the sum of the target value of the current land use of each cell in the cluster. The value of all other cells is set to 'no data'.

Algorithm

```
clear all marks from all cells
for each cell c in the model area
    if the current land use in cell c is checked and cell c does not contain a link type
        that is an obstacle
            assign mark I to cell c
        end if
    end for
for each cell c that has mark I or mark II
    if all cells in the neighbourhood of cell c have mark I or mark II
        assign mark II to cell c and all cells in the neighbourhood of cell c
    end if
end for
for each cell c that has mark II
    remove all marks from cell c
     $L = \{c\}, M = \emptyset$ 
     $size = 0$ 
    while  $L \neq \emptyset$ 
        remove the cell d that is first in the list L from L and add it to list M
        increment size with area of cell d
        for each cell e that is horizontally or vertically adjacent to cell d
            if cell e has mark I or mark II
                remove all marks from cell e
                add cell e to the end of list L
            end if
        end for
    end while
    assign the value size to each cell in the list M
end for
```

Parameters, input and output

Table 30 Cluster indicator parameters

Name	Description
Search radius (cells)	The minimum size of a cluster. This can range from 0 to 25. The default value is 0.
Road is obstacle	Determines whether a road can intersect a cluster (checked) or not (unchecked). By default this is unchecked.
Target	Specifies whether a land use contributes to the cluster size (checked) or not (unchecked). By default this is unchecked.

13.4.2 Neighbourhood indicator

Purpose and use

This type of indicator can be used to calculate figures consisting of the ratio of sums of weights associated with land uses in the vicinity of each cell. This type of indicator can present an image of the supply of, or demand for, certain land uses by other land uses within a specified radius.

Process description

Each land use is assigned two weights; one for the numerator and one for the denominator of the values that will be calculated. For each cell, we then accumulate the weight of the occurring land use in each cell within the neighbourhood of the current cell – the size of which is defined by the search radius parameter – for both numerator and denominator. The numerator and denominator are divided to obtain a single value per cell. If the denominator in a cell equals 0, the value in that cell will be set to ‘no data’.

Algorithm

```
for each cell  $c$  on the map
  initialise numerator and denominator to 0
  for each cell  $c'$  in the neighbourhood of cell  $c$ 
    add the weights to the numerator and denominator
  end for

  set the value of cell  $c$  to  $\frac{\text{numerator}}{\text{denominator}}$  if both are positive or else to 'no data'
end for
```

Parameters, input and output

Table 31 Neighbourhood indicator parameters

Name	Description
Search radius (cells)	The radius in cells within which the algorithm looks for a land use that will be added to the numerator, denominator, or both. By default the minimum value for this parameter is 1 and the maximum is 25. A value of 1 will only count the current cell. The default value for this parameter is 10.
Numerator	The weight with which the corresponding land use will be added to the numerator. These values can range from 0 to 1000 and are set to 0 by default.
Denominator	The weight with which the corresponding land use will be added to the denominator. These values can range from 0 to 1000 and are set to 0 by default.

13.4.3 Distance indicator

Purpose and use

This type of indicator approximates the smallest distance from each cell occupied by one of a set of land uses to a cluster of cells that are occupied by a different set of land uses. The minimum size of a cluster can be specified and the measure of distance can be adjusted.

Process description

The distance between each pair of cells is approximated by taking paths from one cell to another that is horizontally, vertically or diagonally adjacent. This approximation overestimates the actual distance by less than 10%.

We calculate for each source cell the smallest distance to a cell that is in the centre of a cluster of target cells. A cell is a source cell if it is occupied by a land use marked as source. Idem for target cells. The centre cells of a cluster are those cells, for which all cells in the neighbourhood are target cells.

Cells that contain a link type that is indicated to be an obstacle are not target cells, even if the land use that occupies the cell is marked as a target.

Algorithm

```
let  $v(c)$  denote the value of cell  $c$ .
set all cell values to 'no data'
for each cell  $c$  that is occupied by a land use indicated as 'target' and does not
contain a link type that is an obstacle
    if all cells in the neighbourhood of cell  $c$  are occupied by a land use indicated as
    'target' and do not contain a link type that is an obstacle
         $v(c) = 0$ 
    end if
end for
put all cells with value 0 in list  $L$ 
while  $L \neq \emptyset$ 
    remove the first cell  $c$  from list  $L$ 
    for each cell  $d$  that is horizontally or vertically adjacent to cell  $c$ 
        if  $v(c) + \text{cellsize} < v(d)$ 
             $v(d) = v(c) + \text{cellsize}$ 
            add  $d$  to the end of list  $L$ 
        end if
    end for
    for each cell  $d$  that is diagonally adjacent to cell  $c$ 
        if  $v(c) + \sqrt{2} \cdot \text{cellsize} < v(d)$ 
             $v(d) = v(c) + \sqrt{2} \cdot \text{cellsize}$ 
            add  $d$  to the end of list  $L$ 
        end if
    end for
end while
for each cell  $c$  that is occupied by a land use that is not indicated as 'source'
    set the value of cell  $c$  to 'no data'
end for
```

Parameters, input and output

Table 32 Distance indicator parameters

Name	Description
Road is obstacle	Determines whether a road can intersect a target cluster (checked) or not (unchecked). By default this is checked.
Target cluster radius	This is the minimum size that a cluster of target cells should have to be considered a target. This value can range from 1 to 25 and is set to 10 by default.
Role of land use	Per land use you can specify whether it is a source, a target or neither (n.a.).

13.4.4 Distance to map indicator

Purpose and use

This type of indicator approximates the distance from a cell with a certain land use to the nearest target cell, specified on an ancillary binary map. As in the distance indicator, one can specify the measure of distance. However, the distance is measured to the closest target cell, not the closest target cluster.

Process description

The distance between each pair of cells is approximated by taking paths from one cell to another that is horizontally, vertically or diagonally adjacent. This approximation overestimates the actual distance by less than 10%.

We calculate for each source cell the smallest distance to a cell that has a positive value in the ancillary map. A cell is a source cell if it is occupied by a land use marked as source.

Algorithm

let $v(c)$ denote the value of cell c .

let A_c denote the value of cell c in the ancillary map.

for each cell c

$$v(c) = \begin{cases} 0 & \text{if } A_c > 0 \\ \text{'no data'} & \text{otherwise} \end{cases}$$

end for

put all cells with value 0 in list L

while $L \neq \emptyset$

remove the first cell c from list L

for each cell d that is horizontally or vertically adjacent to cell c

if $v(c) + \text{cellsize} < v(d)$

$$v(d) = v(c) + \text{cellsize}$$

add d to the end of list L

end if

end for

for each cell d that is diagonally adjacent to cell c

if $v(c) + \sqrt{2} \cdot \text{cellsize} < v(d)$

$$v(d) = v(c) + \sqrt{2} \cdot \text{cellsize}$$

add d to the end of list L

end if

end for

end while

for each cell c that is occupied by a land use that is not indicated as 'source'

set the value of cell c to 'no data'

end for

Parameters, input and output

Table 33 Distance to map indicator parameters

Name	Description
Range for counting cells	Only count cells with the specific value.
Source	Sets for each land use whether the distance to the target areas should be shown or not. By default, all sources are unchecked.
Area file	Specifies the path and filename of a binary map file specifying the areas to which the distance should be calculated. Unless a proper file is specified, the indicator cannot be calculated.

13.4.5 Mask/mapping indicator

Purpose and use

This type of indicator can be used to analyse whether special areas are coinciding with (are disturbed by) certain land uses and display in a particular area.

Process description

For each cell that has a positive value in the ancillary map, the value in that cell is set to the weight of the land use that currently occupies the cell.

Algorithm

let A_c denote the value of cell c in the ancillary map.

for each cell c

if $A_c > 0$

 set the value of cell c to the weight of the land use that occupies cell c

else

 set the value of cell c to 'no data'

end if

end for

Parameters, input and output

Table 34 Mask/mapping indicator parameters

Name	Description
Disturbance value	The value of the disturbance can range from 0 to 25 and is set to 0 by default.
Range for counting cells	Only count cells with the specific value for mask/mapping indicator.

13.4.6 Habitat fragmentation (KOV) indicator

Purpose and use

This type of indicator can be used to analyse the fragmentation or contiguity of combinations of land uses. This indicator gives an indication of biodiversity according to the 'Probability of Occurrence' and is based on the degree of fragmentation. A high probability corresponds to high potential biodiversity.

Process description

This indicator is calculated in accordance with the publication "Stapelning van milieuthema's in kansen van voorkomen" (Klepper, 1997). The indicator calculates the degree to which a location in a natural area is connected to other natural areas. It takes the perspective of an organism and distinguishes land use types that are easy, neutral or difficult to traverse. Easy traversable are all natural areas, neutral are extensive agricultural areas and difficult are sparsely build areas and areas of intensive agriculture, very difficult to traverse are industrial and dense urban areas.

We refer to Klepper (1997) for a description of the method.

Algorithm

The computation is based around a grid cell with a certain land use type, say "nature". The algorithm will consider the neighbourhood of this grid cell and look for locations with the same land use type, and account for the *equivalent surface*. The *equivalent surface* is the sum of cell surfaces, but measured using weights 1 (for class 1); 10 (for class 2) and 1000 (for class 3):

$$A' = \sum w_i a_0$$

where w_i denotes the weights and a_0 the cell surface.

The equivalent radius r' is calculated by:

$$r' = \sqrt{A'/\pi}$$

The cells with nature are weighted according to their distance to the central cell with weight:

$$v = \exp(-r'/r_0)$$

where r_0 is the search radius.

The equivalent radius is now the integral (sum):

$$s = \int_0^{\infty} v f dr$$

where f denotes the fraction of nature in each cell.

The effect of the exponential weight is that the radius does not indicate a crisp boundary, but a gradual decay, where nature cells further away is accounted for increasingly less. When the fraction of nature on the total area is equal to $f = 1$, the integral yields a value for r_0 ; for all other values it yields a fraction of r_0 equal to the distance weighted fraction of nature. The KOV (chance of appearance) is now:

$$KOV = (s/r_0)^z$$

For the full description of the indicator we refer to (Klepper, 1997). The z parameter by default is 0.3 and the resistance values for the different degrees of traversability are 1 (easy), 10 (neutral), 100 (difficult) and 1000 (very difficult).

Parameters, input and output

Table 35 Habitat fragmentation indicator parameters

Name	Description
Search radius r_0	The search radius around the centre cell. The unit of the search radius depends on the cell size.
Power z	This comes forth from the empirical relation $N = c \cdot A^z$, where N is the number of species, c is a constant and A is the surface.
Resistance of road	The resistance of a road. If a road crosses through a cell, the resistance of that cell is taken as the maximum of the resistance of that land use and this value.
Fraction f	Signals per land use whether it belongs to the habitat (1) or not (0).
Resistance w_i	The resistance of the corresponding land use.

13.4.7 Land use change indicator

Purpose and use

This type of indicator can be used to display particular land use changes between a base year and the current year in particular areas.

Process description

The current land use map is compared to the land use map for a base year, which can be entered in the indicator. The resulting value can be specified for each possible combination of a land use in the base year and in the current year. The results can be limited to a specific area with the use of an ancillary map to indicate the area or with the use of the suitability map for a particular land use to indicate suitable areas.

Algorithm

```
for each cell c
  mask = 0
  if suitability is used as mask
    if the value of cell c in the selected suitability map  $\geq$  threshold
      mask = 1
    end if
  else
    if the value of cell c in the mask map > 0
      mask = 1
    end if
  end if
  if mask = 1
    the value in cell c is set to the value in the table for the land use in cell c of
    the base map (from) and the current land use in cell c (to)
  end if
end for
```

Parameters, input and output

Table 36 Land use change indicator parameters

Name	Description
Land use change classification	The value that will be displayed in the result map if the cell has land use from in the base map and to in the current land use map. A value of -1 will result in a 'no data' value.

13.5 Links

The User-defined Spatial Indicator component uses information from the Land Use Change model. Both are part of the Metronamica modelling framework.

Table 37 Links between user-defined spatial indicators and other models within WISE

Type	Model Component	Data Passed	Comments
Inputs	Land Use Change	Initial Land Use Map Current Land Use Map	Initial Land Use Map only required for Land Use Change indicators
Outputs	None		

14 Terrestrial biodiversity – Landcare Research

14.1 Metadata

9)	Name of Model	Terrestrial Biodiversity
10)	Organisation	Landcare Research
11)	Contact	Robbie Price
12)	Spatial Resolution	100m (as grid)
13)	Temporal Resolution	Annual
14)	Input Data	Land Use (categorical grid)
15)	Internal Data	Legally Protected Areas (binary grid) Land Environments of New Zealand Level II (categorical grid) Link Table: Land Use to Land Cover
16)	Output Data	Threatened Environments (categorical grid)

14.2 Summary

The Terrestrial Biodiversity model as shown in Figure 23, assesses the representativeness of native ecosystems in the Waikato region. It performs a combinatorial analysis to identify unique combinations of land environments (Leathwick et al. 2003a, b), legally protected areas (Rutledge et al. 2008), and land cover (Thompson et al. 2003). That analysis in turn provides information on ecosystem condition, assessed as % remaining native cover, and protection, expressed as % of each Level II land environment in the Waikato region. Percentages of remaining native cover and/or legal protection are then transformed into one of six threat categories following Walker et al. (2008).

14.3 Description

The New Zealand Biodiversity Strategy broadly calls for actions to halt the decline of indigenous biodiversity throughout New Zealand (MfE & DOC 2000). Specifically, the Strategy promotes two major goals for indigenous biodiversity:

- Maintain and restore the full range of remaining natural habitats and ecosystems to a healthy functioning state, enhance critically scarce habitats, and sustain the more modified ecosystems in production and urban environments
- Maintain and restore viable populations of all indigenous species and subspecies across their natural range, and maintain their genetic diversity.

Because the full state of biodiversity across all of New Zealand is not – or never will be – fully known, we rely on indicators to help assess our progress in achieving such goals (Lee et al. 2004).

The Terrestrial Biodiversity model combines information on all land cover including vegetation state with information from two other primary data sources to produce an indicator of ecosystem representativeness. The two data sources are land environments that serve as surrogates for ecosystems and habitats (Land Environments of New Zealand or LENZ) (Leathwick et al. 2003a, 2003b) and a database of legally protected areas (Protected Areas Network of New Zealand or PAN-NZ) (Rutledge et al. 2008) (Table 29).

Table 38 Spatial data layers used in the biodiversity model to analyse ecosystem representativeness

Layer	Source	Classes	Description
Land Use	Land Use Change Model	Native (1)	Bare Ground Indigenous Vegetation Water Wetlands
		Exotic (0)	All other land use classes
Land Environments of New Zealand (LENZ) Level II Version 1.0	Ministry for the Environment	1–100	Layer depicting areas with similar environmental conditions across New Zealand based on a combination of climate, landform, and soil conditions
Protected Areas Network of New Zealand (PAN-NZ)	Landcare Research (compilation of other data sources)	Protected (1)	Legally protected areas based on polygon coverage: <ul style="list-style-type: none"> • Conservation Estate (DOC managed) • Queen Elizabeth II National Trust Covenants • Nga Whenua Rahui Covenants • Nature Heritage Fund Covenants • Regional Parks
		Not Protected (0)	All other land

The model overlays information on native ecosystem condition generated by the Land Use Change model with LENZ and PAN-NZ to generate a new spatial data layer whose values consist of a reference to a look-up table containing all unique combinations of vegetation state, LENZ environments, and protected areas. Based on the results of the combinatorial analysis, the model then assigns each environment to 1 of 5 threat categories (Walker et al. 2006) or, conversely, no threat category based on the level of remaining native vegetation or amount of legal protection (Table 30).

Table 39 LENZ environments threat categories, and defining criteria

Category	Criteria	
	Vegetation - Native	Legal Protection
Acutely Threatened	<10%	0-100%
Chronically Threatened	10–20%	0-100%
At Risk	20–30%	0-100%
Critically Underprotected	>30%	<10%
Underprotected	>30%	10-20%
No Threat Category	>30%	>20%

14.4 Equations

Ecosystem representativeness calculates the percentage of native land cover remaining in a land environment that is legally protected. The formula used is as follows:

$$R_{LE_i} = \left(\frac{a_{NLC}}{A} \right)_{LE_i}$$

where

- R = percent of protected native land cover remaining versus total area within the Waikato region
- LE_i = land environment i (1 to 100)
- a_{NLC} = area of native land cover remaining within the Waikato region in land environment i
- A = total area within the Waikato region of land environment i .

14.5 Links

The Terrestrial Biodiversity links to the Land Use Change model (Table 31).

Table 40 Links between terrestrial biodiversity and other models within WISE

Type	Model Component	Data Passed	Comments
Inputs	Land Use Change	Land Use	Land-use change classes are reclassified into Native and Non-native categories as outlined above.
Outputs	None		

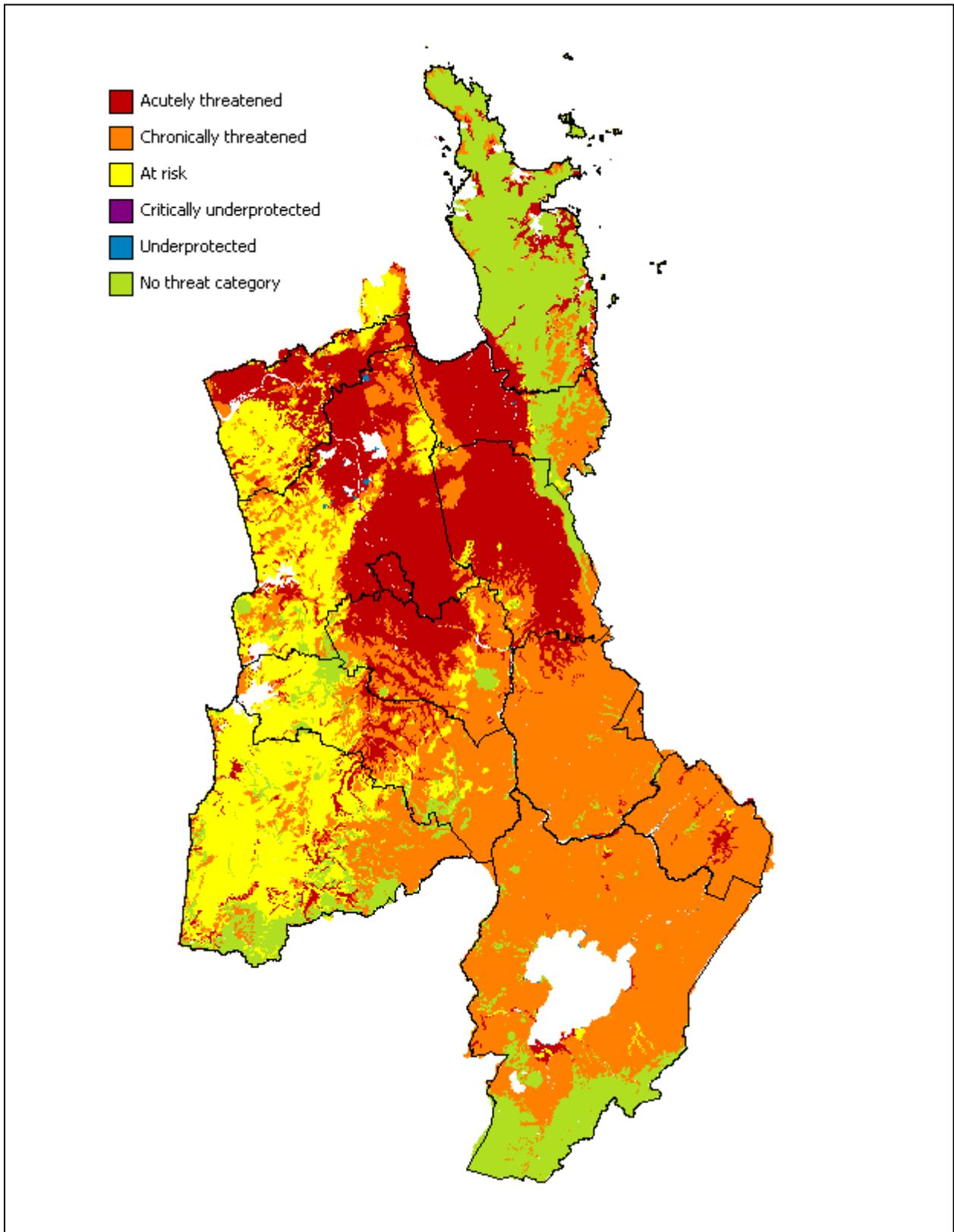


Figure 23 Distribution of threatened environments in the Waikato region at the start of the WISE simulation period.

15 Future development

As part of its LongTerm Plan 2021–2031, the Waikato Regional Council has committed funds for the maintenance, enhancement and upgrading of WISE over the next 10 years.

Recent uses of WISE have centred on developing a set of land use, population, household and economic projections 2018 to 2068 for the Waikato based on the 2018 Census data, at regional, district and local (Statistical Areas 2) level.¹⁶ The current focus is on testing WISE as a tool for integrated spatial planning.¹⁷

During the development of WISE and after its completion, a list of suggested improvements and enhancements was compiled based on conversations among project team members and various end-users including Waikato Regional Council staff, and based on targeted feedback from participants in end-user workshops (Huser et al. 2009; van Delden et al. 2010), and in subsequent discussions on maintenance and update of WISE. Some of those suggestions were incorporated into WISE Version 1.1 (Zoning Tool, various improvements to the graphical user interface or GUI). Further enhancements have been made in WISE Version 1.2 (changes to the integration of hydrology, economic and land use models), WISE Version 1.3 (updated district boundaries, improved calibration of the land use model, addition of Monte Carlo tool and enhancements to the scenario manager), WISE version 1.4 (more detailed spatial resolution, land suitability tool), WISE version 1.5 (user-defined indicators, contingency table tool) and changes incorporated in this update (WISE Version 1.6) documented in this report.

Table 42 contains a compiled list of suggested improvements and enhancements for WISE that have yet to be incorporated. Improvements and enhancements are categorised into one of six types:

1. *New Links* – add new links between models to incorporate new interactions, help explore and address new questions, and improve understanding of feedbacks and trade-offs (improve the dynamic representation of WISE).
2. *Model Enhancement* – make changes, additions, or enhancements to an existing model within WISE to add new analysis capabilities (improve functionality of WISE).
3. *GUI Enhancement* – make changes to the Graphic User Interface to improve the user friendliness and experience.
4. *Usability* - changes that would improve the usability experience for WISE
5. *Indicators* – incorporate new indicators for exploring existing data or combining data in new ways to yield additional information (improve WISE outputs)
6. *Training, Development and Support* – to assist use and further development of WISE

In addition, ongoing efforts are required for data management (collating, storing, analysing and updating model input data).

A review of spatial models used by the Waikato Regional Council was undertaken in 2016 to strategically consider how spatial models can continue to best support decision-making for the Waikato region and inform the applicable outcomes that WRC needs to achieve. Eleven models, including WISE were prioritised for the review undertaken by Landcare Research (WRC doc ID 4113625). Recommendations about the future development of the WISE model include:

- The Waikato Regional Council should retain the vision for an adaptable integrated spatial decision support system for the region.

¹⁶ <http://www.creatingfutures.org.nz/waikato-projections-demographic-and-economic/>

¹⁷ As part of the RMA reform, the Government signalled a requirement for the development of long-term regional spatial strategies to help coordinate and integrate planning and decision-making, <https://environment.govt.nz/what-government-is-doing/key-initiatives/resource-management-system-reform/overview/>

- Based on the systems analysis WISE is not significantly under-used, but council is certainly not using the model to full advantage.
- There is a need for staff strategic investment in both model development and capacity to operate the model and communicate the results.
- WISE is currently being used to analyse population, land-use changes and large-scale economics, as originally intended. Other components of the model, such as water quality, biodiversity, and climate change, are included but currently not fully utilised.
- One potential area of future development would be to link the current population and economics to ecosystem services – primarily provisioning services such as clean water and milk-solids production, or potentially even further to Māori values such as mahinga kai.
- There is also potential for the land-use layers that have been developed as part of WISE – or resulting from model runs – to be used for other purposes within WRC, and potentially for other models.
- Introduce the functionality of the WISE land-use change model in a much simpler guise of either a smaller extent or a hypothetical context and use it as a learning and engagement tool.
- Model development should ideally be carried out in inter-regional collaboration with the other two WISE-type models run by Auckland and Wellington Regional Councils. Joint technical workshops are currently held, but this could be developed further to a national level, integrated spatial group that carries out research and further development, coordinates for national policies, and exchanges experiences.
- Given the critical role of land-use/landscape planning, we recommend that WRC investigate ways to better use the land-use modelling already occurring in WISE.
- Linking land use and infrastructure/transport is critical, the inclusion/coupling of the Waikato Regional Transport Model with WISE will help refine the operation of the WISE land-use change model.¹⁸
- Other aspects of the existing WISE model that could be improved include linking water quality measures directly back into the land-use change model and building nutrient and water accounts¹⁹ that are linked to the economic model to assess water and nutrient allocation (and capping).
- There is potential to better share data and information in WISE and the practical use of the model, for example to benefit from the explicit engagement that is enabled by approaches such as Local Authority Shared Services (LASS) and/or the Upper North Island Strategic Alliance (UNISA).²⁰

The Waikato Regional Council is currently exploring various options for improving and enhancing WISE based on the recommendations received and taking into account its potential application as a tool for (regional) spatial planning.

¹⁸ Work is currently undertaken to couple relevant aspects of the Waikato Regional Transport Model with WISE. .

¹⁹ A provisional Waikato regional water account has been developed including water quantity and quality. The stock and flow accounts will be linked to the economic model component in WISE to assist the spatial evaluation of future demand and supply and efficient use of water.

²⁰ <http://www.waikatoregion.govt.nz/Services/Regional-services/Regional-growth-and-development/Regional-planning-and-forecasting/Upper-North-Island-Strategic-Alliance-UNISA/>

Table 41 Suggested improvements and enhancements for WISE grouped by category (and in a relative order of priority within each category).

Category	Model(s) Affected	Description
New Links	Improved linkages and dynamics between economics and demographics	
	Land Use Change Population WRDEEM	Employment & demography not directly linked, i.e. creation of new jobs does not influence population in a district
	Land Use Change WRDEEM	LUC model does not explicitly distribute jobs per grid cell, i.e. you would assume a mean number of jobs per cell
	Population WRDEEM	Include link from WRDEEM to WOW that allows employment availability to influence population.
	Population WRDEEM	Create ability to change consumption parameters by age class
	Land Use Change WRDEEM	Restrict land use allocation by district
	Hydrology and water quality improvements	
	Hydrology	Validation of the existing hydrology model
	Hydrology Water Quality*	Two models not currently linked. Potential inconsistency between them. The flow rates are not fed into the water quality model. This is not a major concern as the sensitivity of attenuation to flow is not large, and flow rates will probably not change drastically
	Hydrology Land Use Change	New link to model how changes in hydrology affect land-use suitability/productivity
	Hydrology Land Use Change*	New link to model water allocation
	Hydrology Regional EFM*	Linking water quantity to economics
	Water Quality*	There are no links from water quality to economics or land use (such as constraints around Taupo). This could be modified (e.g. driver for land use change reduced if downstream loads or concentrations exceed targets). Also, could specify cost of mitigations/reductions and feed this into economics
	Model Enhancement	Economic Modelling
Regional EFM, Land Use Change, Water Quality*		Water accounts (quantity and quality) to evaluate supply and demand and to link water use to sectors/land use to assess efficiency.
Regional EFM		Incorporate regional EFM model into WISE (operating at district level?)
WRDEEM		Energy use: convert oil equivalents into CO ₂ equiv.
WRDEEM		Restrict productivity not only through exports as the policy lever but also: 1) total area (or %), 2) intensity (e.g., stocking rate), 3) N-cap, 4) water use/allocation, 5) land productivity
	WRDEEM	In addition to the international export, interregional export, and gross fixed capital formation drivers, household consumption by sector needs to be included as a driver. This

Category	Model(s) Affected	Description
		would enable the user to test out changes in domestic consumption. Currently, household consumption is driven purely by demographic change
	Modelling of land use intensification	
	WISE	Use a district boundary layer that shows the district boundaries for those parts of the model that is outside the Waikato political region
	Land Use Change	Control land-use intensity e.g., dairying. Stocking rate per hectare. Dairy industry – 5 classes. Relationship to Sparrow – adjust the nutrient loadings from Dairy?
	Water Quality	Add mitigation parameters to allow exploration of improved management practices
	Other Land Change Model enhancements	
Model Enhancement	Land Use Change	Improve accessibility evaluation by including other possible links and nodes such as rivers, schools, major utilities, train stations, regional bus stops, minor town CBDs and a separate Auckland node
	Land Use Change	Include a factor reflecting ‘ease of transition’
	Land Use Change	Regional boundary effects on land use model (e.g., accessibility, suitability) – can this be improved?
	Land Use Change	Consents’ permission status does not reflect entire story. Some permitted/controlled activities require mitigation measures
	Water Quality	Incorporate a temporal lag in response of stream loads to catchment change arising from lags in groundwater, soils, lakes
	Land Use Change	Include land tenure, e.g. iwi/Maori land
Model Enhancement	Land Use Change	Neighbourhood Rules: potential to include cultural perspectives
GUI Enhancement	WISE	Too hard to distinguish between INPUT/OUTPUT in various windows because it is same font/size as all other text
	WISE	Need titles in the relevant map windows, otherwise it is difficult to know what is being displayed
	Land Use Change	Hovering over a term with a mouse displays the definition of the term
	WISE	In Parameters – Demography – Residential Land Use Demand, list inputs & outputs in units of ‘people/hectare’ rather than ‘people/cell’
	WISE	Display of numbers in the Policy Interface is inconsistent: standardise on showing 2 decimal places, then having access to the full number when you click on any box

Category	Model(s) Affected	Description
	WISE	Allow the user to hover the mouse pointer over, or select, the arrow links in the model system diagram to bring up a window that provides an overview of the relationships between the associated models
Usability	Water Quality	Link the lake outlet loads to a shapefile of lake polygons. This would a) clean up the look of the reaches diagram and b) let people find the lake outlet loading easily
	Water Quality	Add the capability to identify the load values through the map interface so can get hold of reach data over time, and to access to sub-catchment maps
Indicators	WISE	Produce reports that include: 1) summary of baseline, 2) changed assumptions, 3) Use unique identifier for all outputs (i.e. label all results, maps, etc.)
	WISE	Combine all results together in a composite view, e.g., as a spider diagram
	WISE	Improve result outputs – to provide graphs to depict trends over time for more indicators (land use change, population) and more summary indicators under the “Indicator” area of Main Page
	WISE	Show historical data (i.e. before 2013 which is the start year of the simulation) to help the user see past trends
	WDREEM	Add an indicator for inter-regional imports
	Water Quality	Add an indicator(s) that show when nutrient loads exceed a defined threshold
Training, Development and Support	WISE	Ensure availability of relevant experts for consultation when required
	WISE	Plan and implement the installation of WISE on the internet such that external users can access and experts can maintain their models dynamically

Note: * Work is currently underway to produce Waikato regional water accounts, which are envisaged to address these issues.

References

- Alexander RB, Elliott S, Shankar U, McBride GB 2002. Estimating the sources of nutrients in the Waikato River Basin, New Zealand. *Water Resources Research* 38(12): 1268–80.
- Bandaragoda C, Tarboton DG, Woods RA 2004. Application of TOPNET in the Distributed Model Intercomparison Project. *Journal of Hydrology* 298(1–4): 178–201.
- Barredo JC, Lavallo L, Demicheli M, Kasanko M, McCormick N 2003. Sustainable urban and regional planning: the MOLAND activities on urban scenario modelling and forecast Luxembourg, Office for Official Publications of the European Communities.
- Barron M, Targett D 1985. Causal modelling. In: *The manager's guide to business forecasting: how to understand and use forecasts for better business results*. New York, Basil Blackwell.
- BECA Ltd 2019. Waikato Region land use /zoning matrix. Hamilton, New Zealand, Waikato Regional Council.
- Cameron MP 2010. Creating futures WISE: Waikato Integrated Scenario Explorer Model Validation Report WOW Population Model. Population Studies Centre report prepared for Environment Waikato. Hamilton, University of Waikato. WRC document no.2058305.
- Cameron MP, Cochrane W, Poot J 2007. End-user informed demographic projections for Hamilton up to 2041. PSC Research Report No 66. Hamilton, Population Studies Centre, University of Waikato.
- Cameron MP, Poot J 2011. Lessons from stochastic small area population projections: the case of Waikato sub-regions in New Zealand. *Journal of Population Research*. 28(2/3): 245-265.
- Cameron MP, Cochrane W 2021a. 2018-base population, family and household, and labour force projections for the Waikato Region, 2018-2068. Waikato Regional Council Technical Report 2021/22. Hamilton, New Zealand., Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202122/>
- Cameron MP, Cochrane W 2021b. 2018-base SA2-level population, family and household, and labour force projections for the Waikato Region, 2018-2068. Waikato Regional Council Technical Report 2021/24. Hamilton, New Zealand, Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202124/>
- Cheon P, McDonald G 2021. Waikato economic projections 2018 to 2068 (TA and SA2 level). Waikato Regional Council Technical Report 2021/21. Hamilton, New Zealand, Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202121/>
- Chi G, Voss PR 2005. A modest proposal for improving small-area population forecasts. Paper presented at the 52nd Annual North American Meeting of the Regional Science Association International, Las Vegas.
- Choosing Futures Waikato 2006. MARCO Benchmark Indicator Data Report 2006. <http://www.waikatoregion.govt.nz/PageFiles/36757/indicator%20report%202006.pdf> [accessed 12 September 2016]
- Department of Prime Minister and Cabinet 2003. Sustainable development for New Zealand: programme of action. Wellington, Dept. of Prime Minister and Cabinet.
- Dharmalingam A, Pool I 2005. Population projections: Stochastic simulation techniques and applications. Special issue *NZ Population Review* 31(1), Wellington, Population Association of New Zealand.

- Elliott AH, Alexander RB, Schwarz GE, Shankar U, Sukias JPS, McBride GB 2005. Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW. *Journal of Hydrology (NZ)* 44(1): 1–27.
- Elliott S 2009. Creating Futures WISE: Waikato Integrated Scenario Explorer Model Validation Report Water Quality (Sparrow Model). National Institute of Water and Atmospheric Research report prepared for Environment Waikato. WRC document no.2058304.
- Engelen G 2003. Development of a decision support system for the integrated assessment of policies related to desertification and land degradation in the Mediterranean. In: Giupponi C, Shechter M eds. *Climate change in the Mediterranean: socio-economic perspectives of impacts, vulnerability and adaptation*. Cheltenham, Edward Elgar.
- Engelen G, Uljee I, van de Ven K 2003a. WadBOS: integrating knowledge to support policy-making in the Dutch Wadden Sea, In: Geertman S, Stillwell J eds. *Planning support systems in practice*. 513–537.
- Engelen G, White R, de Nijs T 2003b. Environment Explorer: Spatial support system for the integrated assessment of socio-economic and environmental policies in the Netherlands. *Integrated Assessment* 4(2): 97–10.
- Fayad ME, Schmidt DC, Johnson RE 1999. *Building application frameworks: Object-oriented foundations of framework design*. New York, Wiley Computer Publishing.
- Fenton T. 2020. WISE Model – Process for Creation of 2018 land use layer for Waikato Region. Report prepared for WRC by Alchemists Ltd. 28p. Internal WRC doc # 17554847.
- Fenton T, Huser B, van Delden H, and Briggs C. 2021. WISE model update to version 16, reference scenario and Waikato land use projections (TA and SA2 level) 2018 to 2068. Waikato Regional Council Technical Report 2021/31. Hamilton, New Zealand, Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202131/>
- Funtowicz S, Ravetz J 1991. A new scientific methodology for global environmental issues. In: Costanza R ed. *Ecological economics: the science and management of sustainability*. New York, Columbia University Press. 137–52.
- Harris R 2004. Development versus protection, an introduction to RMA and associated laws. In: Harris R ed. *Handbook of environmental law*. Wellington, Forest and Bird Protection Society of New Zealand Inc. 56–76.
- Huser B, Rutledge DT, van Delden H, Wedderburn ME, Cameron M, Elliott S, Fenton T, Hurkens J, McBride G, McDonald G, O’Connor M, Phyn D, Poot J, Price R, Small B, Tait A, Vanhout R, Woods RA 2009. Development of an integrated spatial decision support system (ISDSS) for Local Government in New Zealand. MODSIM 2009 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, 13–17 July 2009. <https://www.mssanz.org.au/modsim09/F12/huser.pdf> [accessed 16 February 2022].
- IPCC 2013. *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA. Cambridge University Press.
- Klepper O 1997. Stapeling van milieuthema’s in termen van kans op voorkomen. Bilthoven, RIVM, ECO-notitie 97-01.
- Leathwick J, Morgan F, Wilson G, Rutledge D, McLeod M, Johnston K 2003. *Land environments of New Zealand: A technical guide*. Auckland, David Bateman.
- Leathwick J, Wilson G, Rutledge D, Wardle P, Morgan F, Johnston K, McLeod M, Kirkpatrick R 2003. *Land environments of New Zealand: Nga Taiao o Aotearoa*. Auckland, David Bateman.
- Lee W, McGlone M, Wright E 2005. *Biodiversity inventory and monitoring: A review of national and international systems and a proposed framework for future biodiversity monitoring*

by the Department of Conservation. Landcare Research Contract Report 0405/122 prepared for the Department of Conservation.

LRIS 2019. Land Cover Database V5. <https://iris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/> [accessed 16 December 2019]

Ludwig D 2001. The era of management is over. *Ecosystems* 4: 758–764.

Maré D, Timmins J 2004. Internal migration and regional labour markets in New Zealand. Wellington, Motu Economic and Public Policy Research.

Market Economics Ltd 2004 Economic Futures Model. Takapuna, New Zealand, Market Economics Ltd.

Market Economics Ltd 2005. Generating regional input–output tables model. Takapuna, New Zealand, Market Economics Ltd.

McDonald G 2010. Creating Futures WISE: Waikato Integrated Scenario Explorer Model Validation Report WRDEEM Waikato Region Dynamic Economy-Environment Model. Market Economics report prepared for Environment Waikato. WRC document no.2058306.

Ministry for the Environment 2004. New Zealand Land Cover Database 2 User Guide. Wellington, New Zealand Climate Change Office, Ministry for the Environment.

Ministry for the Environment and Department of Conservation 2000. New Zealand biodiversity strategy. Wellington, Ministry for the Environment.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenham J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z 2000. Special report on emissions scenarios: a special report of the IPCC Working Group III. Geneva, International Governmental Panel on Climate Change.

Oxley T, Jeffrey P, Lemon M 2002. Policy relevant modelling: Relationships between water, land use and farmer decision processes. *Integrated Assessment* 3(1), 30–49.

Parliamentary Commissioner for the Environment 2002. Creating our future: Sustainable development for New Zealand. Wellington, Office of the Parliamentary Commissioner for the Environment.

Poot J 1986. A system approach to modelling the inter-urban exchange of workers in New Zealand. *Scottish Journal of Political Economy* 33(3): 2–274.

Price R 2010. Creating Futures WISE: Waikato Integrated Scenario Explorer Model Validation Report Terrestrial Biodiversity. Landcare Research report LC0910/109 prepared for Environment Waikato. WRC document no.2059749.

Rutledge D, Price R, Heke H, Ausseil A 2004. National analysis of biodiversity protection status: methods and summary results. Landcare Research Contract Report LC0405/038 prepared for the Ministry for the Environment.

Rutledge D, MacDonald G, Cameron M, McBride G, Poot J, Scrimgeour F, Price R, Phyn D, van Delden H. 2007a. Choosing regional futures spatial decision support system draft specifications. Landcare Research Report 0708/063 prepared for Environment Waikato. WRC document no.1275349.

Rutledge D, McDonald G, Cameron M, McBride G, Poot J, Scrimgeour F, Price R, Phyn D, van Delden H, Huser B, Small B, Wedderburn L, Fenton T 2007b. Development of spatial decision support systems to support long-term, integrated planning. In Oxley L, Kulasiri D eds. MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand. 308–314.

- Rutledge D, Cameron M, Elliott S, Fenton T, Huser B, McBride G, McDonald G, Phyn D, Poot J, Price R, Scrimgeour F, Tait A, van Delden H, Woods R 2008. Choosing regional futures: challenges and choices in building integrated models to support long-term regional planning in New Zealand. *Regional Science Policy and Practice* 1(1): 85–108.
- Rutledge D, Hoffmann N, Briggs C, Price R 2008. Protected Areas Network New Zealand (PAN-NZ): metadata database survey and needs assessment. New Zealand Terrestrial and Freshwater Biodiversity Information System Programme Research Investigation 218.
- Rutledge DT, Cameron M, Hurkens J, MacDonald G, McBride G, Poot J, Price R, Phyn D, Schmidt J, Tait A, van Delden H, Woods R 2011. Creating futures: Waikato Integrated Scenario Explorer technical specifications, Version 1.1. Landcare Research Contract Report LC117 for Environment Waikato Regional Council. WRC document no.1930315.
- Rutledge D, Fraser S, Palmer D, Price R. 2014 Waikato Integrated Scenario Explorer: Land-use Suitability Review and Recommendations. Landcare Research Contract Report LC1819 prepared for Waikato Regional Council. WRC document no.3166478.
- Schenk HJ, Jackson RB 2002. Rooting depths, lateral root spreads, and belowground/aboveground allometries of plants in water limited ecosystems. *Journal of Ecology* 90:480-4.
- Schmidt S 2009. Creating Futures WISE: Waikato Integrated Scenario Explorer Model Validation Report Hydrology. National Institute of Water and Atmospheric Research report prepared for Environment Waikato. WRC document no.23386119.
- Simpson S, Middleton L, Diamond I, Lunn D 1998. Small-area population estimates: a review of methods used in Britain in the 1990s. *International Journal of Population Geography* 3(3): 265–280.
- Smith NJ, Zhang Y, Cardwell RJ, McDonald GW, Kim JH, Murray CF 2015. Development of a regional social accounting framework for New Zealand. ERI Research Report 2015/1. Takapuna, New Zealand, Market Economics.
- Snelder T, Biggs B, Weatherhead M 2004. New Zealand river environment classification user guide. Wellington, Ministry for the Environment.
- Tait A 2009. Creating Futures WISE: Waikato Integrated Scenario Explorer Model Validation Report Climate Change Scenarios. National Institute of Water and Atmospheric Research report prepared for Environment Waikato (Waikato Regional Council). WRC document no.2058118.
- Tayman J, Swanson DA 1996. On the utility of population forecasts. *Demography* 33(1): 523–528.
- Urich P, Li Yinpeng 2015. WISE Climate Change Scenarios Readme File. CLIMsystems report prepared for Waikato Regional Council. WRC document no.3581991.
- Van Delden H 2000. A generic approach for the design of Decision Support Systems for river basin management. Civil Engineering & Management. Enschede, The Netherlands, University of Twente.
- Van Delden H, Gutiérrez E, van Vliet J, Hurkens J 2008. Xplorah: a tool supporting integrated spatial planning in Puerto Rico. Paper presented at International Environmental Modeling and Software Society 2008 Biennial Conference, Ottawa, Canada.
- Van Delden H, Kirkby MJ, Hahn BM, 2009. Towards a modelling framework for integrated assessment in arid and semi-arid regions, in: Anderssen RS, Braddock RD, Newham LTH eds. Proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, Cairns, Australia. 3563-3569.

- Van Delden H, Luja P, Engelen G 2010. Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management, *Environmental Modelling and Software* 22(2): 223–238.
- Van Delden H, Phyn D, Fenton T, Huser B, Rutledge D, Wedderburn L 2010. User interaction during the development of the Waikato Integrated Scenario Explorer. *International Environmental Modeling and Software Society 2010 Biennial Conference*, Ottawa, Canada.
- Van Delden H, Stuczynski T, Ciaian P, Paracchini ML, Hurkens J, Lopatka A, Shi Y, Gomez Prieto O, Calvo S, Van Vliet J, Vanhout R 2010. Integrated assessment of agricultural policies with dynamic land use change modelling. *Ecological Modelling* 221(18): 2153-2166.
- Van Delden H, Hurkens J 2011. A generic Integrated Spatial Decision Support System for urban and regional planning. Keynote presented at MODSIM11 International Congress on Modelling and Simulation, Perth, Australia.
- Van Delden H, Riddell GA, Newman JP, Maier HR, Vanhout R, Zecchin AC, Dandy GC 2015. A framework for the development and use of Decision Support Systems for multi-hazard mitigation, MODSIM, November 29 - December 4, 2015, Gold Coast, Australia.
- Van Delden H, Fleskens L, Irvine B, Kirkby M, Schwilch G, Teixeira da Silva R, Verzandvoort S 2016. Application of a soil-related ecosystem services framework to support European policies, *European Ecosystem Services Conference*, Antwerp, Belgium.
- Van Delden H, Riddell GA, Vanhout R, Maier HR, Zecchin AC, Newman JP, Daniell JE, Dandy GC 2016. A Spatial Decision Support System (SDSS) for understanding and reducing long-term disaster risk, 6th International Disaster and Risk Conference IDRC Davos 2016, Davos, Switzerland. 6th International Disaster and Risk Conference IDRC Davos 2016, Davos, Switzerland, Accepted.
- Waikato Regional Council 2019. WISE Land Use Zoning Matrix from EMS – Excel Master Version. Hamilton, New Zealand, Waikato Regional Council Internal Data. WRC document no.13399832.
- Walker S, Price P, Rutledge D, Stephens T, Lee W 2006. Recent loss of indigenous cover in New Zealand. *New Zealand Journal of Ecology* 30(2): 169–177.
- Walker S, Price R, Rutledge D 2008. New Zealand’s remaining indigenous cover: recent changes and biodiversity protection needs. *New Zealand Department of Conservation, Science for Conservation* 284. Wellington, Department of Conservation.
- Wedderburn ME, Small B, O’Connor M, Barnard T, Rutledge DT, Huser B, Trebilco U, Hood D, Butler M 2009. Combining systems thinking with a qualitative stakeholder process: a case study in regional land fragmentation in New Zealand. *Integrated Agricultural Systems Conference: methodologies, Modeling and Tools*, Association of Applied Biologists, Agricultural Economics Society and the British Society of Animal Science Joint Conference, 2–4 June 2009, Edinburgh.
- Woods RA 2003. The relative roles of climate, soil, vegetation and topography in determining seasonal and long-term catchment dynamics. *Advances in Water Resources* 26(3): 295-309.
- Woods RA 2007. Erratum to “The relative roles of climate, soil, vegetation and topography in determining seasonal and long-term catchment dynamics” [*Adv. Water Resour.* 26 (2003) 295–309]. *Advances in Water Resources* 30(5): 1061.
- Woods RA 2008. Evaluation of a simple similarity index method for estimating global runoff. *Geophysical Research Abstracts*, Vol. 10, EGU2008-A-05892, presented at EGU General Assembly 2008, Vienna.
- Woods RA, Henderson RD 2003. Surface water components of New Zealand’s National Water Accounts, 1995-2001. NIWA Client Report No. CHC2003-074. 50 p. Available on-line via

<https://docs.niwa.co.nz/library/public/CHC2015-013-v2.pdf> [accessed 16 February 2022]

Zeigler B, Praehofer H, Kim T-G 2000. Theory of modeling and simulation. 2nd ed. London, Academic Press.

Appendix A The Waikato region EFM Concordance Notations

A.1 Concordance Relating Industry Notations to the Waikato region EFM Industries

Notation Name <i>i</i>	Industry Code	Industry Name
Ind01	1	Horticulture and fruit growing
Ind02	2	Sheep, beef cattle and grain farming
Ind03	3	Dairy cattle farming
Ind04	4	Poultry, deer and other livestock farming
Ind05	5	Forestry and logging
Ind06	6	Fishing and aquaculture
Ind07	7	Agriculture, forestry and fishing support services
Ind08	8	Mining, quarrying, exploration and other mining support services
Ind09	9	Oil and gas extraction
Ind10	10	Meat and meat product manufacturing
Ind11	11	Dairy product manufacturing
Ind12	12	Other food manufacturing
Ind13	13	Beverage and tobacco product manufacturing
Ind14	14	Textile, leather, clothing and footwear manufacturing
Ind15	15	Wood product manufacturing
Ind16	16	Pulp, paper and converted paper product manufacturing
Ind17	17	Printing
Ind18	18	Petroleum and coal product manufacturing
Ind19	19	Chemical, polymer and rubber product manufacturing
Ind20	20	Non-metallic mineral product manufacturing
Ind21	21	Primary metal and metal product manufacturing
Ind22	22	Fabricated metal product manufacturing
Ind23	23	Transport equipment manufacturing
Ind24	24	Machinery and equipment manufacturing
Ind25	25	Furniture and other manufacturing
Ind26	26	Electricity generation and supply
Ind27	27	Gas supply
Ind28	28	Water, sewerage, drainage and waste services
Ind29	29	Construction
Ind30	30	Wholesale trade
Ind31	31	Retail Trade
Ind32	32	Accommodation and food services
Ind33	33	Road transport
Ind34	34	Other transport, postal, courier, transport support and warehousing services.
Ind35	35	Air and space transport
Ind36	36	Information media and telecommunications
Ind37	37	Finance
Ind38	38	Insurance and superannuation funds
Ind39	39	Auxiliary finance and insurance services
Ind40	40	Rental, hiring and real estate services
Ind41	41	Ownership of owner-occupied dwellings
Ind42	42	Professional, scientific, technical, administrative and support services
Ind43	43	Central government administration, defence and public safety
Ind44	44	Local government administration
Ind45	45	Education and training
Ind46	46	Health care and social assistance
Ind47	47	Arts and recreation services
Ind48	48	Personal and other services

A.2 Concordance Relating Aggregated Industry Notations to Aggregated Industry Names

Notation Name <i>lucacat</i>	Land Use Category Name
LUCat01	Vegetable Production/Market Gardening and Horticulture
LUCat02	Sheep/Beef/Deer
LUCat03	Cropland/Cropping
LUCat04	Dairy Farming
LUCat05	Commercial
LUCat06	Forestry/Planted- Exotic
LUCat07	Mines and quarries
LUCat08	Industry/Manufacturing
LUCat09	Utilities
LUCat10	Air transport
LUCat11	Community Services

A.3 Concordance Relating Socio-Economic Reporting Variable Notations to Full Socio-Economic Indicator Name

Notation Name <i>socce</i>	Socio-Economic Reporting Variable Name
SocEcon01	Value Added
SocEcon02	International Imports by Importing Sector
SocEcon03	Interregional Imports by Importing Sector

A.4 Concordance Relating Employment Reporting Variable Notations to Full Employment Indicator Name

Notation Name <i>emp</i>	Socio-Economic Reporting Variable Name
Emp01	Employment (FTE)
Emp02	Employment (EC)
Emp03	Employment (MEC)
Emp04	Occupation - Chief Executives, General Managers and Legislators
Emp05	Occupation - Farmers and Farm Managers
Emp06	Occupation - Specialist Managers
Emp07	Occupation - Hospitality, Retail and Service Managers
Emp08	Occupation - Arts and Media Professionals
Emp09	Occupation - Business, Human Resource and Marketing Professionals
Emp10	Occupation - Design, Engineering, Science and Transport Professionals
Emp11	Occupation - Education Professionals
Emp12	Occupation - Health Professionals
Emp13	Occupation - ICT Professionals
Emp14	Occupation - Legal, Social and Welfare Professionals
Emp15	Occupation - Engineering, ICT and Science Technicians
Emp16	Occupation - Automotive and Engineering Trades Workers
Emp17	Occupation - Construction Trades Workers
Emp18	Occupation - Electrotechnology and Telecommunications Trades Workers
Emp19	Occupation - Food Trades Workers
Emp20	Occupation - Skilled Animal and Horticultural Workers
Emp21	Occupation - Other Technicians and Trades Workers
Emp22	Occupation - Health and Welfare Support Workers
Emp23	Occupation - Carers and Aides
Emp24	Occupation - Hospitality Workers
Emp25	Occupation - Protective Service Workers
Emp26	Occupation - Sports and Personal Service Workers
Emp27	Occupation - Office Managers and Program Administrators
Emp28	Occupation - Personal Assistants and Secretaries
Emp29	Occupation - General Clerical Workers
Emp30	Occupation - Inquiry Clerks and Receptionists
Emp31	Occupation - Numerical Clerks
Emp32	Occupation - Clerical and Office Support Workers
Emp33	Occupation - Other Clerical and Administrative Workers
Emp34	Occupation - Sales Representatives and Agents
Emp35	Occupation - Sales Assistants and Salespersons
Emp36	Occupation - Sales Support Workers
Emp37	Occupation - Machine and Stationary Plant Operators
Emp38	Occupation - Mobile Plant Operators
Emp39	Occupation - Road and Rail Drivers
Emp40	Occupation - Storepersons
Emp41	Occupation - Cleaners and Laundry Workers
Emp42	Occupation - Construction and Mining Labourers
Emp43	Occupation - Factory Process Workers
Emp44	Occupation - Farm, Forestry and Garden Workers
Emp45	Occupation - Food Preparation Assistants
Emp46	Occupation - Other Labourers
Emp47	Occupation - Not Elsewhere Included

A.5 Concordance Relating Environmental Reporting Variable Notations to Full Environmental Indicator Name

Notation Name e	Environmental Reporting Variable Name
ERV01	Energy - Aviation Fuel
ERV02	Energy - Black Liquor
ERV03	Energy - Coal
ERV04	Energy - Diesel
ERV05	Energy - Electricity
ERV06	Energy - Fuel Oil
ERV07	Energy - Geothermal
ERV08	Energy - LPG
ERV09	Energy - Natural Gas
ERV10	Energy - Petrol
ERV11	Energy - Wood
ERV12	Energy - Total
ERV13	Energy Related Carbon Dioxide - Aviation Fuel
ERV14	Energy Related Carbon Dioxide - Black Liquor
ERV15	Energy Related Carbon Dioxide - Coal
ERV16	Energy Related Carbon Dioxide - Diesel
ERV17	Energy Related Carbon Dioxide - Electricity
ERV18	Energy Related Carbon Dioxide - Fuel Oil
ERV19	Energy Related Carbon Dioxide - Geothermal
ERV20	Energy Related Carbon Dioxide - LPG
ERV21	Energy Related Carbon Dioxide - Natural Gas
ERV22	Energy Related Carbon Dioxide - Petrol
ERV23	Energy Related Carbon Dioxide - Wood
ERV24	Energy Related Carbon Dioxide - Total
ERV25	Energy Related N2O - Aviation Fuel
ERV26	Energy Related N2O - Black Liquor
ERV27	Energy Related N2O - Coal
ERV28	Energy Related N2O - Diesel
ERV29	Energy Related N2O - Electricity
ERV30	Energy Related N2O - Fuel Oil
ERV31	Energy Related N2O - Geothermal
ERV32	Energy Related N2O - LPG
ERV33	Energy Related N2O - Natural Gas
ERV34	Energy Related N2O - Petrol
ERV35	Energy Related N2O - Wood
ERV36	Energy Related N2O - Total
ERV37	Energy Related CH4 - Aviation Fuel
ERV38	Energy Related CH4 - Black Liquor
ERV39	Energy Related CH4 - Coal
ERV40	Energy Related CH4 - Diesel
ERV41	Energy Related CH4 - Electricity
ERV42	Energy Related CH4 - Fuel Oil
ERV43	Energy Related CH4 - Geothermal
ERV44	Energy Related CH4 - LPG
ERV45	Energy Related CH4 - Natural Gas
ERV46	Energy Related CH4 - Petrol
ERV47	Energy Related CH4 - Wood
ERV48	Energy Related CH4 - Total
ERV49	Solid Waste - Landfill - Construction and demolition waste
ERV50	Solid Waste - Landfill - Metal
ERV51	Solid Waste - Landfill - Glass
ERV52	Solid Waste - Landfill - Plastic
ERV53	Solid Waste - Landfill - Paper
ERV54	Solid Waste - Landfill - Potentially hazardous
ERV55	Solid Waste - Landfill - Organic matter - kitchen and garden waste
ERV56	Solid Waste - Landfill - Other
ERV57	Solid Waste - Landfill - Total
ERV58	Solid Waste - Cleanfill - Construction and demolition waste
ERV59	Solid Waste - Total

Appendix B Process for Translating Land Use by Industry ($lu\ wo\ luc_i$) to Land Use by Aggregated Industry ($luc\ wo\ luc_{lucat}$) in the Waikato region EFM

Notation Name	Land Use Category Name	Equivalent Land Use
$lucat$		
LUCat01	Vegetable Production/Market Gardening and Horticulture	$lu\ wo\ luc_{Ind01}$
LUCat02	Sheep/Beef/Deer	$(lu\ wo\ luc_{Ind02} + lu\ wo\ luc_{Ind04}) \times (1 - lu\ split\ crop)$
LUCat03	Cropland/Cropping	$(lu\ wo\ luc_{Ind02} + lu\ wo\ luc_{Ind04}) \times lu\ split\ crop$
LUCat04	Dairy Farming	$lu\ wo\ luc_{Ind03}$
LUCat05	Commercial	$lu\ wo\ luc_{Ind05} + lu\ wo\ luc_{Ind30} + lu\ wo\ luc_{Ind31} + lu\ wo\ luc_{Ind32} + lu\ wo\ luc_{Ind36} + lu\ wo\ luc_{Ind37} + lu\ wo\ luc_{Ind38} + lu\ wo\ luc_{Ind39} + lu\ wo\ luc_{Ind40} + lu\ wo\ luc_{Ind42} + lu\ wo\ luc_{Ind48}$
LUCat06	Forestry/Planted- Exotic	$lu\ wo\ luc_{Ind06}$
LUCat07	Mines and quarries	$lu\ wo\ luc_{Ind08} + lu\ wo\ luc_{Ind09}$
LUCat08	Industry/Manufacturing	$lu\ wo\ luc_{Ind10} + lu\ wo\ luc_{Ind11} + lu\ wo\ luc_{Ind12} + lu\ wo\ luc_{Ind13} + lu\ wo\ luc_{Ind14} + lu\ wo\ luc_{Ind15} + lu\ wo\ luc_{Ind16} + lu\ wo\ luc_{Ind17} + lu\ wo\ luc_{Ind18} + lu\ wo\ luc_{Ind19} + lu\ wo\ luc_{Ind20} + lu\ wo\ luc_{Ind21} + lu\ wo\ luc_{Ind22} + lu\ wo\ luc_{Ind23} + lu\ wo\ luc_{Ind24} + lu\ wo\ luc_{Ind25} + lu\ wo\ luc_{Ind29}$
LUCat09	Utilities	$lu\ wo\ luc_{Ind26} + lu\ wo\ luc_{Ind27} + lu\ wo\ luc_{Ind28}$
LUCat10	Air transport	$lu\ wo\ luc_{Ind35}$
LUCat11	Community Services	$lu\ wo\ luc_{Ind43} + lu\ wo\ luc_{Ind44} + lu\ wo\ luc_{Ind45} + lu\ wo\ luc_{Ind46} + lu\ wo\ luc_{Ind47}$

Where $lu\ split\ crop$ is the fraction of the total land used by the Livestock and Cropping Industry which is used just for the purposes of cropping. This fraction is likely to be determined from data for the base year.

Appendix C Technical Process for Generating Spatial Data Layers Used in the Land Use Change Model

Development of 2018 Land Use Layer

The update of the WISE starting land use layer to 2018 used a different development process to previous land use layers. The new process firstly extracted those land uses that were obvious (native vegetation) or were consistent across input data sets (i.e. dairying coded in both Valuation data base and Agribase). Less clear cut or conflicting data inputs were assessed using additional analysis (assess other codes in Valuation data, assessment against aerial images). Full details of the technical process are provided in Fenton (2020) and a summary of the approach used is shown in Figure 24.

The update process utilised the existing land use classification as defined in Table 20. The process utilises four key data sets: Land Cover Database 4.1 (LCDB4.1); Waikato BioVeg layer; Regional Valuation Database; Agribase (rural land use data) (Table 33).

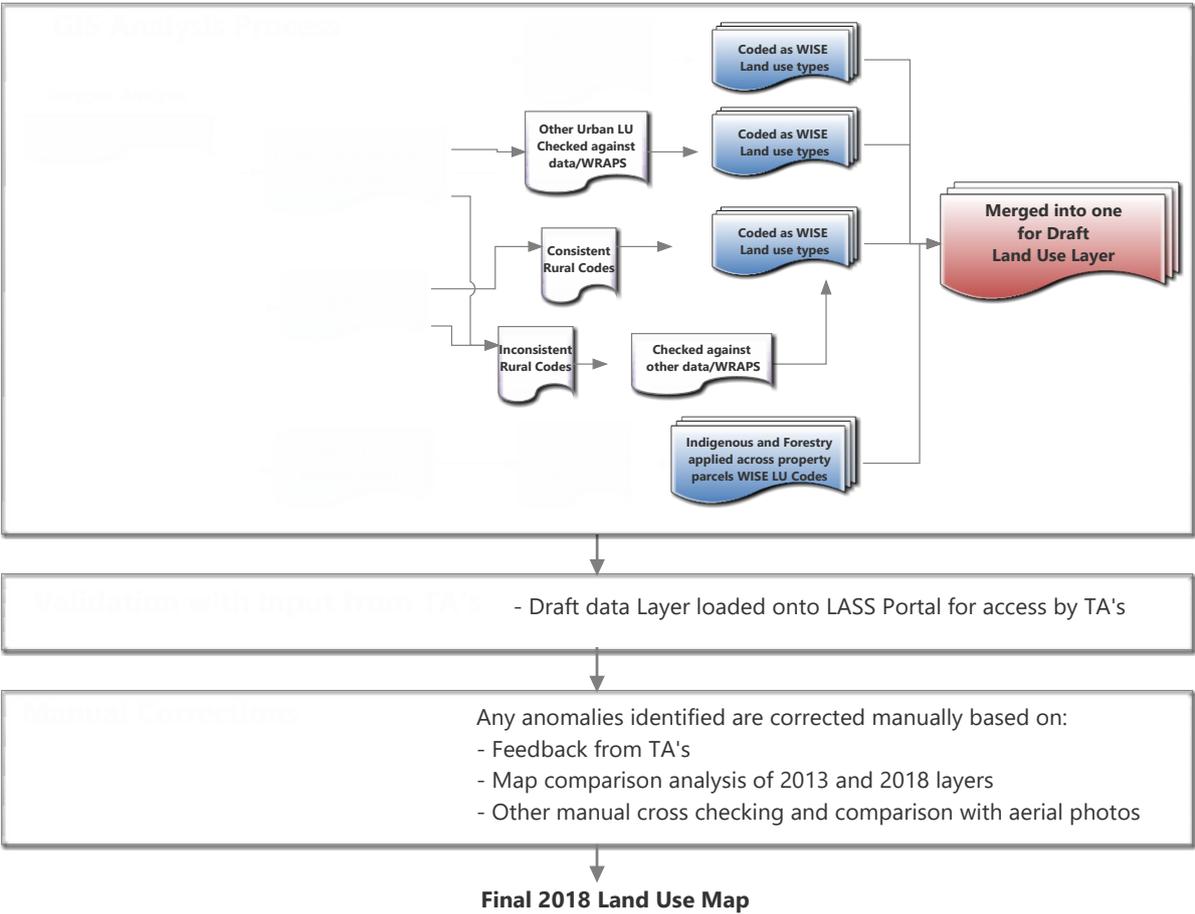


Figure 24 Process diagram for development of 2018 Land Use layer.

The final step was to apply a series of ‘manual corrections’ to the draft land use layer. Identifying these corrections and refining the draft land use layer was assisted by feedback on the draft land use map from regional TA’s. Additional corrections were identified by comparison of the draft 2018 and the 2013 land use map, and through some cross checking with aerial images.

Table 42 Land-use Classification Input Data Layers

Data layer Name	Data source	Timeframe
Property valuation database (VDB)	Waikato Regional Council	Extracted at June 2018
Agribase	AsureQuality	Extract provided August 2018
Waikato Bioveg Layer	Waikato Regional Council	2012 – based on LCDB4 and 2012 WRAPS
WRAPS aerial images - 2017/18	Waikato Regional Council	From summer of 2017/18 to summer 2019/20
LCDB V4.1	LCR	2012
Road Parcel	LINZ	Extracted Oct 2018

Update of Accessibility Layers

The Road Transport layers were updated in 2018 to represent road infrastructure as at 2018 and also to represent planned road construction out to 2051. This process involved sourcing the then current transport network from the Waikato Region Transport Model (WRTM) to update the WISE transport layer to be consistent. This data for 2018 was then compared against 2018 aerial images in areas of recent urban development, particularly in the Future Proof Councils area, to capture any recent additions to the roading network.

Future road construction segments and completion dates were sourced from WRTM. These were used to create future transport networks for 2021, 2031, 2041 and 2051.

In V1.4 it was decided to include a separate layer to represent Private Roads. This was seen as a useful addition as large areas of current and previously forested land had extensive road networks in place that are available to provide accessibility to land uses in these areas. These networks were not reviewed for V1.6.

Zoning data layers

The Zoning data layers in WISE were updated to represent the 'current' active zoning restrictions being applied across the Region and Districts. The Spatial input layers used in this process are outlined in table below. Further detail on the update process is outlined in Fenton et. al. 2020.

Table 43 Zoning Input Data Layers

Data layer	Year of source
Department of Conservation – Waikato Region	2018
Future Proof Industrial allocation	2015
Hamilton City Council Overlay Areas	2015
Hamilton City Council Ruakura Logistics	2015
Hamilton City Council Significant Natural Areas	2015
Hamilton City Council Zones	2018
Hauraki District Council Franklin section	2018
Hauraki District Council Amenity Protection Area	2018
Hauraki District Council Designations	2018
Hauraki District Council Floodway Zone	2018
Hauraki District Council Significant Natural Areas	2018

Hauraki District Council Zones	2018
Indigenous Vegetation Loss – RPS Restriction includes 3 data layers, including Tall forest, Broadleaf forest, and Manuka and Fernland.	LCBD v4.1
Matamata-Piako District Council Designation	2018
Matamata-Piako District Council Development Plans	2018
Matamata-Piako District Council Zones	2018
Nga Whenua Rahui – Waikato Region	2018
Otorohanga District Council Lifestyle Focus	2018
Otorohanga District Council Coastal Policy Area	2018
Otorohanga District Council Country Living Area	2018
Otorohanga District Council Designations	2018
Otorohanga District Council Outstanding Natural Landscapes	2018
Otorohanga District Council Zones	2018
QEII Trust Covenants – Waikato Region	2018
Rotorua District Council Designations	2018
Rotorua District Council Zones	2018
South Waikato Significant Natural Areas	2015
South Waikato District Council Outstanding Natural Features	2015
South Waikato District Council Significant Amenity	2015
South Waikato District Council Designations	2018
South Waikato District Council Zones	2018
Territorial Default Rule	2018
Thames-Coromandel District Council Structure Plans	2018
Thames-Coromandel District Council Foreshore Protection Area	2018
Thames-Coromandel District Council Zones	2018
Thames-Coromandel District Council Designations	2018
Taupo District Council Designations	2018
Taupo District Council Foreshore Protection Area	2018
Taupo District Council Zones	2018
Taupo Variation – Near Shore Zone	2015
Taupo Variation – Taupo Catchment	2015
Waikato District Council Designations	2018
Waikato District Council Zones	2018
Waipa District Council Flood and National Grid overlay	2015
Waipa District Council Policy Areas	2015
Waipa District Council Significant Natural Areas	2015
Waipa District Council Designations	2015
Waipa District Council Residential Priorities	2018
Waipa District Council Zones	2018
Waitomo District Council Special Industry Zones	2018
Waitomo District Council Zones	2018

Appendix D The Land Suitability Tool

Landcare Research was funded by Waikato Regional Council (WRC) to review the land use suitability layers currently used in the WISE 1.3.1 and recommend any changes or improvements. Landcare Research recommended (refer to Rutledge *et.al*, 2014) updated criteria and data used to generate land-use suitability layers for incorporation into WISE 1.4 onwards.

Landcare Research assessed land-use suitability through reviewing the previous data methods, and rules used to generate land-use suitability layers for WISE 1.3. Each spatial dataset used within the land-use suitability model was re-assessed, current methods were reviewed and evaluated against alternatives. As a result recommendations to improve the land-use suitability assessment for the land-use classes were made for WISE 1.4-1.6. This included defining suitability data layers and criteria for their application to specific land uses which could be incorporation into WISE 1.4-1.6. (Rutledge *et.al*, 2014)

The following data layers were used in the WISE 1.4-1.6 suitability tool.

Table 44 Data Layers used in WISE 1.4-1.6 Suitability Tool

Spatial layer	Name	Description	Reference
deficit	LENZ Annual Water Deficit	Where monthly rainfall > evaporation, monthly deficit = zero, but where monthly evaporation > monthly rainfall, the shortfall is accumulated across the year giving annual water deficit	Leathwick <i>et al.</i> 2003a; 2003b
drain	LENZ Soil Drainage Class	Soil drainage class, ranging from 1 (Very Poor) to 5 (Good)	Leathwick <i>et al.</i> 2003a; 2003b
drain_class	FSL Drainage Class	Soil drainage class ranging from 1 (very poor) to 5 (well drained)	Newsome <i>et al.</i> 2008
flood_class	FSL Flood Class	Flood return interval class, ranging from 1 (nil) to 6 (very severe, >1 every 5 years)	Newsome <i>et al.</i> 2008
gdd5	Growing Degree Days	Growing Degree Days above 5°C degrees	Leathwick <i>et al.</i> 2002
LCDB4	Land Cover Database Version 4	Land cover data from 1996 (LCDB1), 2001 (LCDB2), 2008 (LCDB3), and 2012(LCBD4).	Landcare Research 2015. https://iris.scinfo.org.nz
lenz_lvl_4	LENZ Land Environments Level IV	Land Environments of New Zealand Level 4	Leathwick <i>et al.</i> 2003a; 2003b
nz_mar	Mean Annual Total Rainfall	Mean Annual Total Rainfall (mm)	NIWA/WRC 2013
nz_slope25m	LENZ Slope	Slope in degrees	Leathwick <i>et al.</i> 2003a; 2003b
HEL	Highly Erodible Land/LRI Potential Erosion	The Highly Erodible Land (HEL) system identifies land highly susceptible to mass-movement erosion using a combination of the erosion terrains derived from the NZLRI database, a 15-metre digital elevation model (DEM) to determine topography, and land cover mapping. It considers the	Dymond 2014. http://tools.envirolink.govt.nz/dsss/landslide-risk/

		main forms of mass-movement erosion in New Zealand (landslides, earth flows, and massive gullying).	
prd_mid	FSL Soil Potential Rooting Depth	Potential depth to a layer that may impede root extension, ranging from 0.15 to 1.5 metres	Newsome et al. 2008
sdssmask	SDSS Mask	Analysis mask developed for the WISE model	Derived
sal_mid	FSL Soil Salinity	Soil salinity measured as percent soluble salt, ranging from 0 to 1	Newsome et al. 2008
waik_luc	Waikato Land Use Class	Land-use layer developed for the WISE model taken at first time step	Derived

The following table is a list of each spatial grid layer used in the suitability tool for each land use type. Each grid layer used is 100m x 100m resolution for the entire Waikato Region.

Table 45 Grid Layers used in WISE 1.4-1.6 suitability tool for each land use type

Land use type	Spatial grid layer used (100m x 100m)
<i>Dairy Farming</i>	
	FSL - Potential Rooting Depth Class
	Growing degree days
	LENZ - Deficit
	LENZ - Slope
	Mean Annual Rainfall
	FSL - Profile available water
<i>Forestry</i>	
	FSL - Flood class
	FSL - Potential rooting depth class
	LRI - Profile available water class
	LENZ - Deficit
	LENZ - Drainage
	LENZ - Mean Annual Temp
	LENZ - Slope
<i>Sheep, Beef, or Deer Farming</i>	
	FSL - Potential rooting depth class
	LRI - Profile available water class
	Growing degree days
	LENZ - Deficit
	LENZ - Slope
	Mean Annual Rainfall
<i>Other Agriculture</i>	
	LRI - Profile available water class

Growing degree days
LENZ - Deficit
LENZ - Slope
FSL - Potential rooting depth class
Mean Annual Rainfall

Biofuel Cropping

FSL - Flood Class
FSL - Potential rooting depth class
LRI - Profile available water class
LENZ - Deficit
LENZ - Drainage
LENZ - Mean Annual Temp
LENZ - Slope

Vegetable Cropping

LRI - Profile available water class
LENZ - Deficit
LENZ - Drainage
LENZ - Slope
FSL - Flood Class
FSL - Potential rooting depth class

Other Cropping

FSL - Flood Class
FSL - Potential rooting depth class
LRI - Profile available water class
LENZ - Deficit
LENZ - Drainage
LENZ - Slope

Horticulture

LRI - Profile available water class
LENZ - Deficit
LENZ - Drainage
LENZ - Slope
FSL - Flood Class
FSL - Potential rooting depth class

Residential - Lifestyle blocks

FSL - Flood Class

LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Residential - Low density

FSL - Flood Class
LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Residential - Medium to High Density

FSL - Flood Class
LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Commercial

FSL - Flood Class
LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Community Services

FSL - Flood Class
LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Utilities

FSL - Flood Class
LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Manufacturing

FSL - Flood Class
LENZ - Drainage
LENZ - Slope
LRI - Potential Erosion

Using the land use Suitability Model

The land use Suitability Model in WISE 1.4-1.6 is shown in the Figure 25 below. To locate the tool go:

Main window>Land use>Suitability (tab).

Select the chosen 'Land use' type by using the drop down menu at the top left in the suitability tool. The 'Factors and base maps' tab details the suitability factor layers used, by the drop down menu. The layers included here were recommended by Landcare Research (Rutledge et.al 2014). Additional suitability factors can be added or removed here if required to represent specific scenarios.

The 'factor and base maps' illustrate each of the suitability factors used to calculate the overall suitability for each land use class. Selecting the 'Preview suitability map' will show the overall suitability map, derived within WISE by combining the suitability factors.

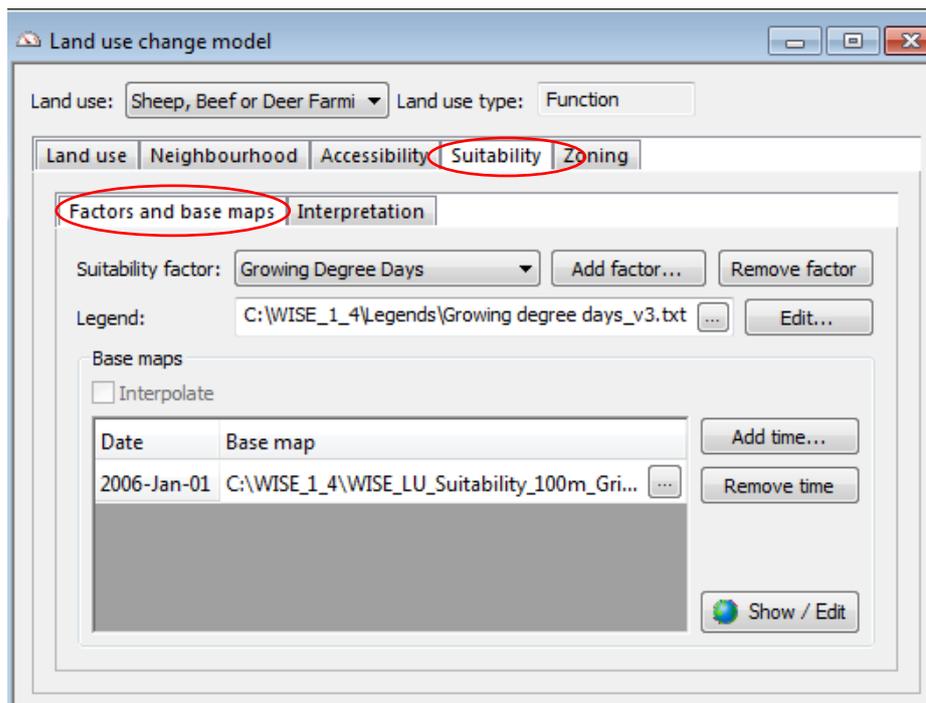


Figure 25 Land Use Change Model – Factors and base maps

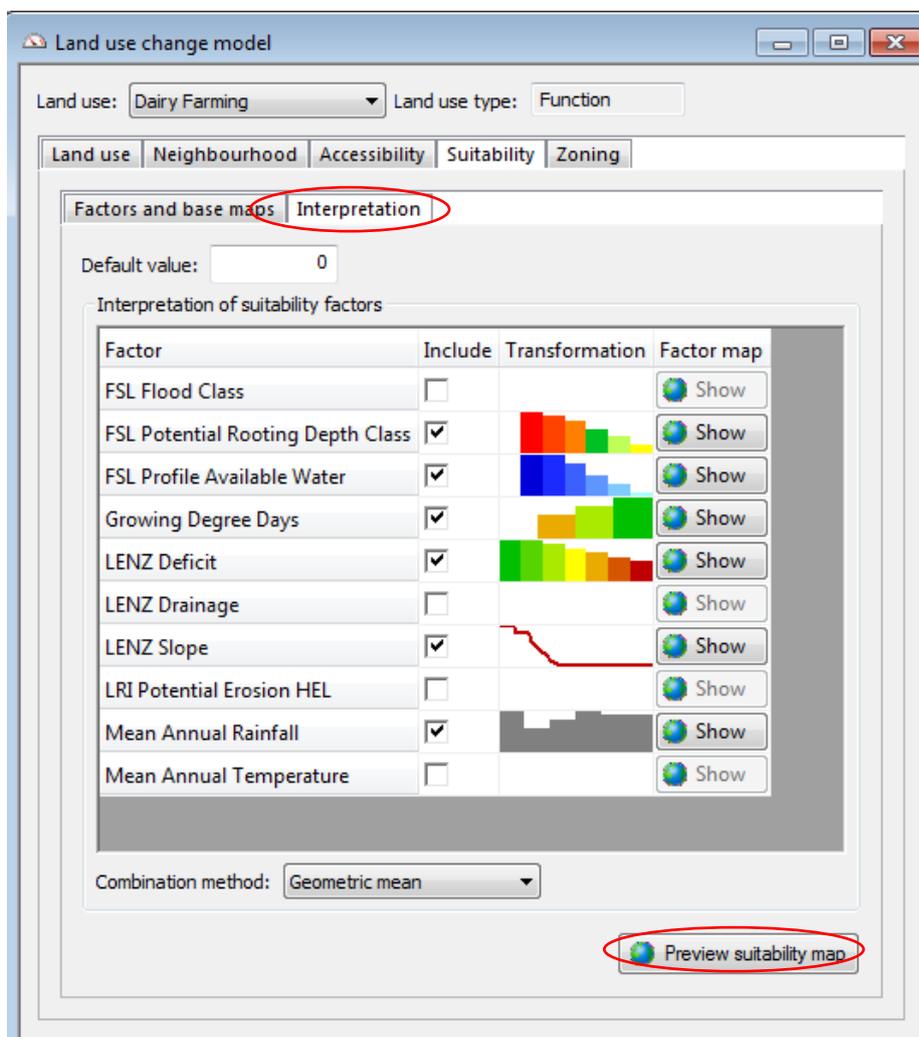


Figure 26 Land Use Change Model - Interpretation

Future Opportunities for the land-use Suitability Tool

A recommendation in Rutledge et.al. 2014 was also for a number of future opportunities to enhance the WISE suitability tool whereby this would increase its functionality and also potentially add to its relevance and value for modelling land-use pressures and issues currently in the Waikato Region. Those recommendations were:

- Future land-use suitability modelling should transition to using data from the emerging S-map database when such data become available for the whole of the Waikato region.
- Nitrogen and Phosphorous leaching risk factors could be developed for future use in WISE land use suitability modelling.
- Two existing land-use classes, Bioenergy Cropping and Other Agriculture, should each be split into two classes to aid suitability assessment and provide more logical representation of land use.
- There is potential to draw on a suite of process models such as water balance, pasture productivity, or forest productivity to improve future land-use suitability assessment in WISE.