Waikato Regional Council Technical Report 2023/10

A Review of spatial planning models

waikatoregion.govt.nz
ISSN 2230-4363 (Online)

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June 2023

Document #: 25606632

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Acknowledgements

This report has benefitted considerably by useful comments and suggestions received by several organisations on an earlier draft. A special thanks to Lesley Baddon/Doug Spittle (Ministry for the Environment), Greg Carstens (Hamilton City Council), Sarah Lomas (Auckland Council, Robert Brodnax (Future Proof), Gill Lawrence (Waikato Regional Council), and Shaun Lion-Cachet (RATA/Co-Lab) for reviewing final draft and providing valuable feedback. Beat Huser (Waikato Regional Council) provided thoughtful guidance and effective coordination throughout the project.

Executive Summary

The New Zealand government is introducing new legislation to replace the Resource Management Act (RMA). The new legislation is intended to address shortcomings attributed to the RMA, specifically: an insufficient affordable housing supply, exceeding of environmental limits, and variation in effectiveness and inconsistency of spatial planning at a regional level across the country.

One of the ways the new legislation intends to do that, is to require more integrated assessment of policies developed under the various new Acts. Integrated modelling will be one of the tools to do so. This report investigates concrete pathways to operationalising integrated modelling to meet the future requirements of said legislation.

WRC has approached [MEResearch] and the [Research Institute for Knowledge Systems (RIKS)] to identify spatial modelling tools suitable to inform the development of the Waikato Regional Spatial Strategy (W-RSS), a mandatory requirement of the proposed Spatial Planning Bill[1]. This report describes the main findings of the study and addresses the following objectives:

1. Identify, prioritise, and evaluate suitable existing (overseas and NZ) models – against the likely requirements of the Spatial Planning Act,
2. Recommend a preferred approach, including assessing the suitability and role of the current WISE model[2], and
3. Identify key datasets and indicators and how they link to each other.

Given these requirements, this report finds that the currently used WISE model most closely addresses the needs identified, due to its integrated nature, focus on both urban and rural dynamics, and its ability to support the planning process. In addition, WISE has demonstrated its ability to operate in the New Zealand context, as it is applied to the Waikato and tested through practical case studies. Nonetheless, some gaps in capability are identified.

The report describes different development trajectories to enhance and complement WISE and lists a preferred implementation pathway. This preferred way forward entails updating the current core components of WISE (economic, demographics and land use) to their latest versions, removing unused and outdated components, and updating WISE to a new start year of 2023 using updated data whenever the new census results become available.

Furthermore, the authors suggest developing integration options for (time series of) data **from other models** to ensure WISE can provide a more integrated assessment of planning and policy options in line with requirements from the new legislation. This includes:

- Incorporation of biophysical (map) data in the local land productivity enhancing the interaction between the macro-economic and land use model,
- Inclusion of zonal accessibility information from WRTM,
- Incorporation of disaster risk components, making use of the current modelling capability of WISE to calculate dynamic exposure profiles.

Likewise, the authors suggest better aligning the information from WISE with those models that (could) use information from WISE, in particular the WRTM and Hamilton Metro models. In addition, when information from WISE is used in combination with information from other models, it is important to streamline the use of these models in the processes in which they are applied.

[1] https://www.legislation.govt.nz/bill/government/2022/0187/latest/LMS545761.html
[2] www.creatingfutures.org.nz/wise/what-is-wise/

The authors strongly recommend using WISE in combination with participatory techniques and see great value in using it for exploring future uncertainties through scenario analysis and in stress-testing different planning and policy options across a range of plausible futures to design robust and/or adaptive strategies.

Finally, the authors note that for a meaningful implementation and use of any model, a well thought-through process regarding its development, maintenance and use is essential. This includes understanding its benefits and limitations, its place and role in the decision context, and designing a use process in which the model, together with other techniques such as participation, contribute to the overall planning questions.

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List of abbreviations used

CAA	Climate Adaptation Act
CCRA	Climate Change Response Act
ISE	Integrated Scenario Explorer
LGA	Local Government Act
LGNZ	Local Government New Zealand
LTMA	Land Transport Management Act
MDRS	Medium Density Residential Standards
MERIT	Measuring the Economics of Resilient Infrastructure
NBE	Natural and Built Environment Act
NPF	National Planning Framework
NPS-UD	National Policy Statement on Urban Development
RMA	Resource Management Act
RSS	Regional Spatial Strategy
SDSS	Spatial Decision Support System
SNZ	Statistics New Zealand
SPA	Spatial Planning Act
WISE	Waikato Integrated Scenarios Explorer
WRC	Waikato Regional Council
W-RSS	Waikato Regional Spatial Strategy

1 Introduction

The New Zealand government is introducing new legislation to replace the Resource Management Act (RMA). The new legislation is intended to address shortcomings attributed to the RMA, specifically: an insufficient affordable housing supply, exceeding of environmental limits, and variation in effectiveness and inconsistency of spatial planning at a regional level across the country.

The Waikato Regional Council (WRC) has received Government research funding to develop an integrated, spatially explicit and dynamic regional model for the Waikato (Creating Futures project 2007-2010)[3]. This model, the Waikato Integrated Scenario Explorer (WISE)[4] has since been further developed and updated to provide planning and decision-support, and to develop demographic, economic and land use projections for the Waikato, its city/districts and smaller scale units (Statistical Units 2, SA2)[5].

The purpose of this report is to identify and evaluate suitable modelling tools to assist the implementation of the Regional Spatial Strategies (RSS) proposed by the RM reform (Spatial Planning Bill, SPA). Given WRC already uses the WISE model, this review focussed on an assessment of WISE and, if considered a suitable tool, to make recommendations for its improvements so it is 'fit-for-purpose', i.e. for the Waikato RSS). This required good knowledge of WISE.

WRC has therefore approached Market Economics Ltd (MEResearch) and the Research Institute for Knowledge Systems (RIKS), both involved in the original research project to develop WISE and in its further development and regular updating, to identify spatial modelling tools suitable to inform the development of the Waikato Regional Spatial Strategy (W-RSS), a mandatory requirement of the proposed Spatial Planning Bill[6]. This report describes the main findings of the study and addresses the following objectives:

1. Identify, prioritise, and evaluate suitable existing (overseas and NZ) models – against the likely requirements of the Spatial Planning Act,
2. Recommend a preferred approach, including assessing the suitability and role of the current WISE model[7], and
3. Identify key datasets and indicators and how they link to each other.

To reach these objectives, we provide a brief overview of the new legislation and the requirements for the modelling capability resulting from this. Using a set of capability criteria, we assess how well existing land use and integrated models can support the requirements. This information is then used to develop a proposed modelling framework listing several possible directions as well as a suggested way forward.

1.1 New Legislation

As part of the new legislation three acts are proposed. Firstly, the Natural and Built Environment Act (NBE), the main replacement for the Resource Management Act (RMA), to protect and restore the environment while better enabling development. Secondly, the Spatial Planning Act (SPA), requiring the development of long-term regional spatial strategies (RSS) to help coordinate and integrate decisions made under relevant legislation. And thirdly, the Climate Adaptation Act (CAA) to address

[3] Development of an integrated spatial decision support system (ISDSS) for Local Government in New Zealand (mssanz.org.au)

[4] Creating Futures What is WISE

[5] Creating Futures Waikato Projections - Demographic and Economic

[6] https://www.legislation.govt.nz/bill/government/2022/0187/latest/LMS545761.html

[7] www.creatingfutures.org.nz/wise/what-is-wise/

complex issues associated with managed retreat. On 15th November 2022 the Natural and Built Environment Bill and Spatial Planning Bill were introduced to Parliament, and on the 22 November 2022 a 1st Reading of these Bills had been completed. Submissions were being sought by 5 February 2023, with reporting back to the overseeing Environment Committee to be completed by 27 June 2023. The Climate Adaptation Bill will be introduced to Parliament in late 2023.

The NBE and SPA are critical documents in the context of this study. It is therefore important to acknowledge the following key objectives for the proposed legislation. These are:

1. to protect and, where necessary, restore the environment and its capacity to provide for the wellbeing of present and future generations.
2. to better enable development within natural environmental limits including a significant improvement in housing supply, affordability and choice, and timely provision of appropriate infrastructure including social infrastructure,
3. to give proper recognition to the principles of Te Tiriti o Waitangi and provide greater recognition of te ao Māori including mātauranga Māori,
4. Fourthly, to better prepare for adapting to climate change and risks from natural hazards and better mitigate the emission,
5. to improve system efficiency and effectiveness and reduce complexity while ensuring local input and involvement.

It is beyond the scope of this study to provide a full review of the legislative requirements of these acts as this is still being worked out through select committee processes. We acknowledge this as a limitation of the study.

1.2 Report Structure

Section 2 describes the legislative context in which integrated spatial planning modelling tools are expected to be used as the new legislation replacing the RMA is enacted.

Section 3 describes the implications of the new legislation for the use of integrated spatial modelling tools and concludes with a set of criteria to meet these requirements.

Section 4 provides an overview of the various models that have been considered and their capability to support the new Spatial Planning Act. These are compared to the WISE model resulting in a preferred modelling approach for the W-RSS.

Section 5 describes the ways in which the recommended modelling approach could be developed to enable achievement of the new legislation's objectives.

Section 6 develops an implementation pathway (or suggested approach) for addressing the gaps and ways to address these outlined in Sections 4 and 5.

Section 7 provides an overview of the main conclusions including the suggested implementation pathway for a spatial modelling approach suitable to inform the development of the Waikato Regional Spatial Strategy (W-RSS).

Appendix A provides a full list of evaluation criteria used to assess the integrated and land use change modelling platforms.

Appendix B provides a full review of each integrated and land use change modelling platform discussed in Section 4.

Appendix C catalogues environmental and urban system models used in the Waikato region.

Appendix D catalogues a selected set of environmental models used throughout New Zealand that could be coupled with the recommend modelling platform to achieve the objectives of the SPA.

Appendix E describes the main input data requirements that are likely to be necessary for an integrated modelling platform whose purpose is to support implementation of the SPA. It furthermore gives an overview of the current indicators in WISE and the potential indicators that could be calculated if some of the suggestions in this report would be materialised.

2 Legislative and Planning Context

Central government is developing three new legislative documents to replace the Resource Management Act (RMA): the Spatial Planning Act (SPA), the Natural and Built Environment Act (NBE), and the Climate Adaptation Act (CAA). Two of these, the NBE[8] and the SPA[9] were introduced to parliament on 15th November 2022. The new legislation was developed with advice from the central government's appointed Resource Management Review Panel (the Panel). The following figure (Figure 1) from the NBE Exposure draft illustrates how the three acts are interrelated.

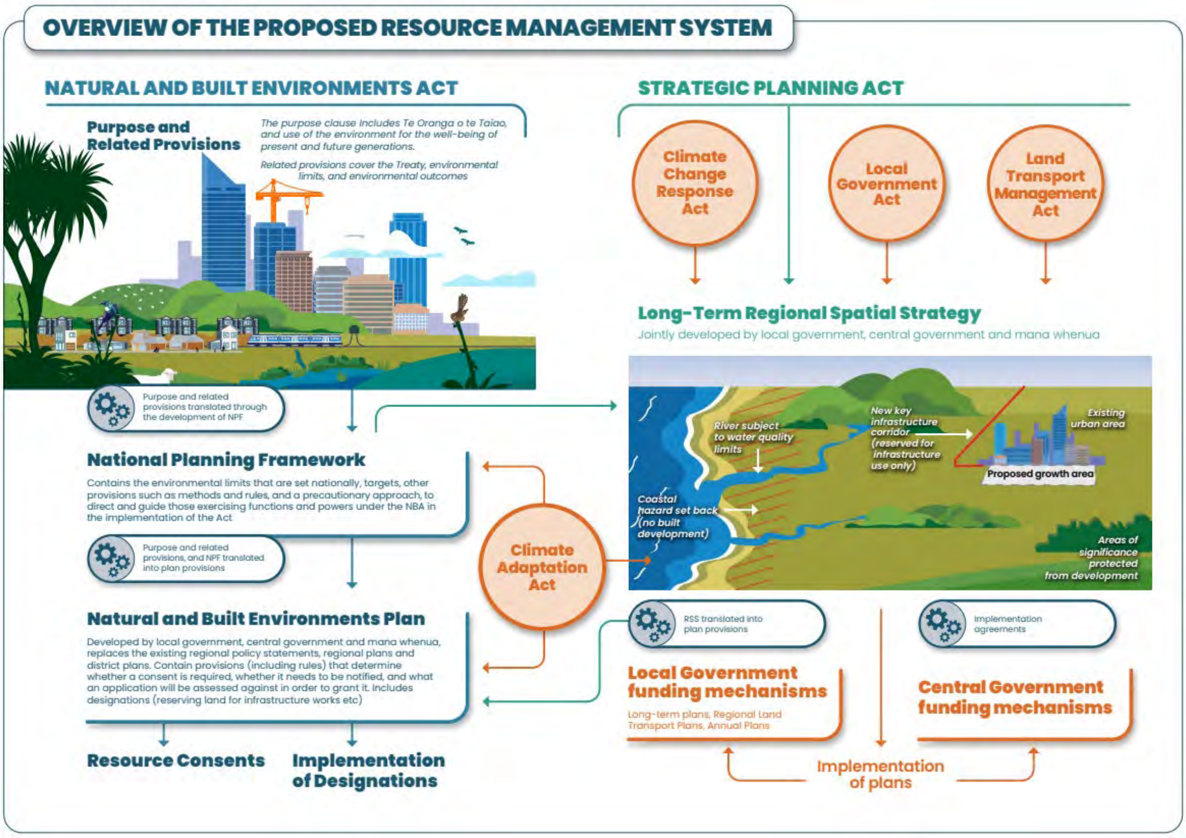

Figure 1: Overview of the proposed resource management system (Parliamentary-Paper-on-the-Exposure-Draft-of-the-NBA.pdf (environment.govt.nz)). Note that prior to 15th November 2022, the Spatial Planning Act was also referred to as the "Strategic Planning Act".

While the new legislation is more evolutionary than revolutionary in nature, it aims to solve several shortcomings with the RMA legislation and current practice. These include:

- Regional and territorial authority planning agencies are not assessing land use requirements in a consistent manner.
- District plans do not appear to be providing sufficient development capacity (supply) to enable a competitive market for developable land, thereby (artificially) increasing land prices, and thus decreasing housing affordability. Local Government NZ (LGNZ) state that, done right, spatial, and strategic planning can reduce the cost of infrastructure investment needed to accommodate future growth as well as improve how land markets operate, thereby creating downward pressure on house prices.

[8] Natural and Built Environment Bill 186-1 (2022), Government Bill – New Zealand Legislation
[9] Spatial Planning Bill 187-1 (2022), Government Bill – New Zealand Legislation

- The RMA does not seem to have protected the environment as well as it was intended to. LGNZ also state that spatial and strategic planning in combination can better protect the environment and public spaces of special cultural value, while being cognisant of constraints such as future climate change adaptation challenges.

Much of the planning that the new legislation foresees, is based on planning developments that are already being implemented in Auckland, Waikato, and Bay of Plenty. In this regard, the legislation will formalize and standardise much of the work already being done so that it can be applied to the rest of the country.

2.1 Natural and Built Environment Act

The Natural and Built Environment Act (NBE) is the primary replacement of the Resource Management Act (RMA). The NBE (in its current form) includes a mandatory requirement for the Minister for the Environment to set environmental limits for air, indigenous biodiversity, coastal water, estuaries, freshwater, and soil to protect their ecological integrity and human health. The NBE specifies a range of outcomes that decision-makers will be required to promote for the natural and built environments:

1. the protection or, if degraded, restoration, of—
    a. the ecological integrity, mana, and mauri of—
        i. air, water, and soils, and
        ii. the coastal environment, wetlands, estuaries, and lakes and rivers and their margins, and
        iii. indigenous biodiversity,
    b. outstanding natural features and outstanding natural landscapes,
    c. the natural character of the coastal environment (including the coastal marine area), wetlands, and lakes and rivers and their margins,
2. in relation to climate change and natural hazards, achieving—
    a. the reduction of greenhouse gas emissions,
    b. the removal of greenhouse gases from the atmosphere,
    c. the reduction of risks arising from, and better resilience of the environment to, natural hazards and the effects of climate change,
3. well-functioning urban and rural areas that are responsive to the diverse and changing needs of people and communities in a way that promotes—
    a. the use and development of land for a variety of activities, including for housing, business use, and primary production, and
    b. the ample supply of land for development, to avoid inflated urban land prices; and
    c. housing choice and affordability, and
    d. an adaptable and resilient urban form with good accessibility for people and communities to social, economic, and cultural opportunities, and
4. the availability of highly productive land for land-based primary production,
5. the recognition of, and making provision for, the relationship of iwi and hapū and the exercise of their kawa, tikanga (including kaitiakitanga), and mātauranga in relation to their ancestral lands, water, sites, wāhi tapu, wāhi tūpuna, and other taonga,
6. the protection of protected customary rights and recognition of any relevant statutory acknowledgement,
7. the conservation of cultural heritage,
8. enhanced public access to and along the coastal marine area, lakes, and rivers,
9. the ongoing and timely provision of infrastructure services to support the well-being of people and communities.

The NBE carries over the RMA's requirement to 'avoid, remedy, or mitigate' adverse effects of activities on the environment. This will ensure a management framework exists for all adverse effects, including those not covered by limits or outcomes. Under the NBE, the new **National Planning Framework (NPF)** will provide strategic and regulatory direction from central government on implementing the new system.

The NPF is a secondary legislation under the NBE that:

- guides the future RM system and influences the content and outcomes of **Regional Spatial Strategies** (RSSs) (required under the SPA) and NBE plans (required under the NBE),
- includes a strategic section that sets out the vision, direction, and priorities for management of the environment and how the wellbeing of present and future generations is to be provided for within environmental limits, and
- gives effect to Te Tiriti principles and reflect te ao Māori.

The NPF must address:

- **the quality of air, indigenous biodiversity, freshwater, coastal waters, estuaries, and soils,**
- **ecological integrity,**
- **outstanding natural features and landscapes,**
- **greenhouse gas emissions,**
- **urban areas,**
- **housing supply,**
- **infrastructure services, and**
- **natural hazards and climate change.**

The NPF will play a critical strategic role, setting limits and outcomes for natural and built environments, and ways to enhance the well-being of present and future generations. Where possible, the NPF will resolve conflicts, or give direction on resolving conflicts across the system.

2.2 Spatial Planning Act

The Spatial Planning Act (SPA) mandates strategic spatial planning and brings together outcomes and functions across several statutes to achieve a longer-term and integrated approach to land use and infrastructure provision, environmental protection, and climate change matters. The purpose of the SPA is to provide for regional spatial strategies that assist in achieving the purpose of the Natural and Built Environment Act and promote integration in the performance of functions under the Natural and Built Environment Act 2022, the Land Transport Management Act 2003, and the Local Government Act 2002.

A significant portion of the review of the RMA undertaken by the Panel looked specifically at Spatial Planning (Randerson et al., 2020) and the challenges that exist for lack thereof. The Panel noted there is currently no consistent framework for spatial planning in New Zealand. Only Auckland Council is legally required to have a spatial plan. Some councils are making progress with developing integrated long-term spatial plans, but there are barriers to achieving their full potential, including:

- insufficient legislative mandate and weight, including formal links between spatial plans and detailed resource management and funding plans,
- fragmented governance and decision-making arrangements (within and between councils) and insufficient central government involvement and coordination,
- infrastructure funding and financing constraints and poor understanding of the costs and benefits of growth,

- poor incentives for councils to join forces to coordinate, provide for, and fund infrastructure to efficiently respond to growth and change.

Furthermore, the Panel identified a range of interrelated factors that hamper strategic integration of the resource management system. Some of these factors include:

- As noted by Infrastructure New Zealand, "the permissive, effects-based orientation of the current system heavily devolves resource management decisions down to affected parties and away from strategic public outcomes".
- Poor alignment of land use and infrastructure plans: misalignment between land use plans under the RMA and infrastructure plans under the Local Government Act (LGA) and Land Transport Management Act (LTMA) has led to poor outcomes both for development and the environment. For example, Local Government New Zealand (LGNZ) argues "the current planning system (comprising RMA, LGA and LTMA) is unwieldy and not well integrated. There is little alignment between strategies, funding, regulation, and decision-making to integrate land use and infrastructure development, set spending priorities, and manage growth".
- Insufficient long-term focus. For example, evidence shows that since the major urban transport plans in the 1960s and 1970s, New Zealand has done little to protect and acquire future infrastructure corridors in advance of planning for development in those areas.
- Lack of engagement and coordination by central government: central government's allocation of the National Land Transport Fund and decisions about education and health infrastructure spending influence land use planning. However, except for the New Zealand Transport Agency (NZTA), central government has generally not been an active participant in strategic land use planning.

The Panel identified three ways in which strategic integration can be improved across the system:

- Strategic direction: ensuring environmental protection and development goals are clearly stated, so we know what we want the resource management system to achieve for New Zealand.
- Vertical integration: ensuring objectives set nationally flow through to local government plans to influence what happens on the ground.
- Horizontal integration: clarifying the intended interaction of plans for development, protection, and funding across the RMA, LGA and LTMA (and the wider resource management system).

RSSs are intended to improve strategic integration by:

- Providing a platform for all three layers of government and mana whenua to agree a shared strategic direction.
- Providing a basis to integrate land use planning, environmental management and infrastructure provision and funding.
- Being required to be consistent with environmental limits and targets that were set under the RMA.
- Flowing into detailed regulatory and funding plans, making the system more cohesive and streamlined.
- Achieving more efficient and cost-effective infrastructure investment and delivery through better coordination between central government agencies, councils, and other infrastructure providers.

- Improving relationships between central and local government, mana whenua and stakeholders.
- Facilitating more efficient land and development markets to improve housing supply, affordability, and choice.
- Regulating land use to address climate change, including both adaptation and mitigation measures.
- Addressing the cumulative effects of land use and other activities impacting the environment.
- Reducing ad hoc decision-making in response to perceived issues as they arise.

Some requirements for spatial planning set out in the SPA include:

- RSSs to set a strategic direction for at least the next 30 years. The level of detail could vary across the time horizon of the spatial strategy as certainty reduces over time.
- A provision for a Ministerial power to direct two or more regions to prepare a joint strategy or to collaborate on cross-boundary issues. Inter-regional spatial planning may be appropriate, for example, where two regions (or parts of regions) function as a single metropolitan area with significant commuter movement across the regional boundary or where two regions cut across a single marine area such as the Kaipara Harbour.
- Spatial planning being mandatory for all regions. Some of its potential benefits apply specifically to urban areas experiencing growth. For example, spatial planning could facilitate an abundance of urban development opportunities, while avoiding areas that are vulnerable to coastal inundation or natural hazards or which have special environmental, cultural, or economic value. However, other benefits could apply equally to urban, rural, and coastal areas. For example, climate change is increasingly going to be a driver of land use change and that will affect all regions of New Zealand. Also, spatial planning could be an important tool to improve the management of cumulative impacts of land use on waterways and harbours.

RSSs are required to include:

- Areas that may require protection, restoration, or enhancement.
- Areas of cultural heritage and areas with resources that are of significance to Māori.
- Areas that are appropriate for urban development and change, including existing, planned, or potential urban centres of scale.
- Areas that are appropriate for developing, using, or extracting natural resources, including generating power.
- Areas that are appropriate to be reserved for rural use, or where there is expected to be significant change in the type of rural use.
- Areas of the coastal marine area that are appropriate for development, or significant change in use.
- Major existing, planned, or potential infrastructure or major infrastructure corridors, networks, or sites (including existing designations) that are required to meet current and future needs.
- Other infrastructure matters, including:
    - opportunities to make better use of existing infrastructure; and
    - the need for other small-to-medium-sized infrastructure required to meet future needs or enable development.
- Areas that are vulnerable to significant risks arising from natural hazards, and measures for reducing those risks and increasing resilience.

- Areas that are vulnerable to the effects of climate change both now and in the future, and measures for addressing those effects and increasing resilience in the region, including indicative locations for:
    - major new infrastructure that would help to address the effects of climate change in the region; and
    - areas that are suitable for land use changes that would promote climate change mitigation and adaptation.
- Areas where any development or significant change in use needs to be carefully managed because the areas are subject to constraints.
- The indicative location of planned or potential business and residential activities and the likely general scale and intensity of those activities.

2.3 Climate Adaptation Act

As noted by the New Zealand Law Society (New Zealand Law Society, 2021) there is little information to glean on what the Climate Adaptation Act (CAA) will provide, i.e., it appears there is currently little information available on the state of development of the CAA. It is clear however that the CAA must work in concert with the NBE and SPA to be effective in implementing managed retreat from coastal and other areas susceptible to climate change hazards. The purpose of the CAA has been described as primarily to address the legal and technical issues associated with managed retreat and to fund some of that work.

3 Implications for integrated modelling capability requirements

3.1 Using integrated modelling and model for policy assessment

One of the main aims of the new legislation is to reinforce a trend towards more integrated (and spatial) assessment of urban development and environmental protection objectives rather than assessing these systems in isolation. The Panel considered whether to recommend new legislation that would separate urban development planning and natural environment management and on the balance of pros and cons decided to recommend legislation that an integrated approach for land use planning and environment protection, encompassing both the built and natural environments should be retained (from the RMA) in the reformed legislation (Randerson et al., 2020). The main arguments for integrating statutory provisions for land use planning and environmental protection were:

- Integration of frameworks for land use and environmental protection is not the cause of poor outcomes associated with the RMA.
- Land use and environmental protection, and the built and natural environments, are inherently interconnected and should be approached through integrated decision-making.
- Separate frameworks would be inconsistent with te ao Māori.
- Developing separate legislative frameworks is likely to result in further complexity and cost.

The Panel recognised that the nature of current and future resource management challenges with freshwater quality, climate change, and urban development will require identifying synergies and interdependencies between environmental protection and urban development. Thus more, rather than less, integrated decision-making will be required in the future.

It follows that an impetus for more integrated decision-making will generate more demand for more integrated modelling. Therefore, we conclude the primary capability by which to compare and assess different modelling platforms is arguably the degree to which they enable integrated modelling of the various systems that fall within the consideration of the three new legislative documents.

It seems reasonable to assume that planning processes under the three new acts will continue to involve the use of most, if not, all the computer simulation models that are currently used in spatial planning processes. Thus, a modelling platform that can make such integration of these models as easy as possible, or at least make the transfer of data between these models easier, ought to offer a considerable amount of value to government and related agencies across statutes (three new legislative documents, as well as LGA, LTMA, and the Climate Change Response Act (CCRA)), scale (national and regional/local), across function (e.g. Central and Local Government), and across outcomes (e.g., social, economic, environmental, cultural).

3.2 Model integration methods

There are numerous ways that models can be coupled and integrated. Table 1 identifies these methods and describes some of their advantages and limitations.

Table 1: Model coupling methods.

Coupling Method	Advantages and limitations
Transferring a static set of model outputs from one model as inputs into another	This method is suitable for situations with weak or non-existent feedbacks between the systems being simulated, e.g., when applying the outputs of a global climate model to a specific region in NZ, the economic and environmental processes within that region will have very little impact on the global climate.
Building a simplified or higher-level version of one model	In some situations, a simplified model of one system can be sufficient to simulate the behaviour of that system. For example, simulation of transport movements across an entire region can be simulated using a four-step transport model, which can be valuable for region-level planning. Although, whereas a state-of-the art agent-based transport model might produce better outputs, it may also be practically too costly to implement, where the four-step transport model will suffice to achieve whatever modelling objectives are at hand.
Loose coupling	Loose coupling is the coupling of models via manually exporting the outputs of one model and transferring them as inputs into another model. Sometimes the data being transferred has a conversion process applied to it. Running simulations using a loose coupling is generally a time-consuming and error-prone process (relative to tight coupling), depending on the number of manual steps involved and the number of feedback iterations required. However, if these steps can be streamlined, and replicating the models concerned requires highly specialised expertise and is otherwise difficult to achieve, loose coupling can be the best alternative among model coupling options.
Tight coupling – automated exchange between models[10]	Tight coupling can be achieved by automating the exchange of data between models. Such automation can be achieved by writing computer scripts to issue commands to the modelling programs concerned and transform and transfer data between them. Alternatively, the core model libraries, along with the data transfer algorithms can be implemented within a single software program. Tight coupling does not require settling for static inputs, simplified models, or the time and cost associated with manually transferring data between models. However, tight coupling can present other challenges. For example, if two or more models must run locally on a single computer, it may be necessary for the agency where the computer is located to secure additional model licences or employ additional people with the expertise to operate and maintain the models. Alternatively, if the models are tightly coupled over the internet, data transfer costs and security may pose other challenges. Investment costs are also highest in this option as there is initial investment (software development) required to enable the integration.

3.3 Relationship between national and regional level modelling outputs

One of the aspects of the new legislation that could influence modelling practice is the form of the relationship between the NPF and the RSSs. One aspect of the NPF is that the SPA will require local councils to use Statistics NZ (SNZ) population projections unless they can demonstrate that alternative

[10] An interesting case is the MONTY model being developed by the Ministry of Transport (MOT). MONTY is an agent-based transport model of all (5 million+) agents in NZ that will run on a dedicated supercomputer. MOT promotes the use of MONTY by all agencies using transport models: PowerPointPresentation (transport.govt.nz).

figures are just as, or more, robust. Indeed, for councils that possess them, tools like WISE tend to provide population projections with better spatial validity. Whereas SNZ's population projections appear to incorporate zoning regulations on an ad-hoc basis, tools like WISE incorporate zoning regulations more explicitly. Tools like WISE also appear to simulate urban development patterns more realistically than do SNZ's national level population projections. For example, it appears that SNZ population projections overestimate population growth of small rural towns (perhaps by assuming people born in such small towns will choose to live in those small towns their whole lives), whereas WISE better captures the behaviour of people moving to larger urban centres. In terms of the relationship between the NPF and the RSSs, this example illustrates that two important modelling capabilities will be important: (1) The ability to simulate spatial allocation of phenomena such as population growth (or environmental effects), and (2) the ability to remain consistent with outputs of national level models, at least in terms of regional totals summing to national level totals.

3.4 Urban development capacity and housing affordability

One of the main issues the new legislation is intended to address, is housing affordability. Factors that influence housing affordability (and price) include:

- Location; proximity to employment opportunities and amenities.
- Supply of developable land (Stephens et al., 2022), including the types of dwelling that are allowed to be built in a given area; i.e., besides allowing development on land with no dwellings, the supply of developable land can effectively be increased by allowing more dwellings to be built on smaller sites where dwellings may already exist, as effected by the MDRS (Medium Density Residential Standards) (Ministry for the Environment, 2022).
- Infrastructure service provision to enable land development.
- Interest rates which affect the cost of servicing mortgages. We note that over the medium to longer term, interest rates may not particularly affect housing affordability. Assuming household incomes are otherwise unaffected, we expect that housing prices will adjust to the mortgage payments that buyers are able to afford. However, such adjustments will not necessarily mitigate all adverse impacts for those who took out large mortgages shortly before large interest rate increases. Furthermore, interest rates can indirectly affect housing affordability by influencing the types of assets that investors prefer to invest in.
- High demand for New Zealand property from foreign investors. Although it is difficult to prove definitively, there is sufficient belief that foreign investment can materially affect housing prices, especially for domestic purchasers, that the New Zealand government, and the governments of various other countries, have enacted laws to curtail foreign investment in residential property markets.
- A favourable tax system for capital investors. Investing in residential property has effectively served as a tax-free way to increase one's wealth in New Zealand. Investing in one's own home also provides the benefit of being able to live in the dwelling as well, having a significant degree of control over the investment.
- Low wages relative to housing capital values. By various measures, New Zealand has a high ratio of housing costs to household incomes, particularly in Auckland. Demographia, for example, rank Auckland 85th on a list of 92 most affordable cities in their survey of metropolitan areas around the world (Cox, 2022).
- A relatively inefficient construction industry. Most houses are one-off builds which means there is little or no standardisation, little or no prefabrication, and limited automation in construction. A substantial minority share of new dwellings are built in small cities and towns, where there is limited opportunity for economies of scale.

Integrated with a suitably capable economic model, transport model, and other infrastructure models, WISE would be able to model and demonstrate the relationships between these factors, which would help stakeholders and decision-makers understand the relative importance of each of these factors in determining housing affordability.

Relevant in this context is the effect of NPS-UD and RMA Amendment Act 2021[11] related to infill and brownfield developments. This act enables people to develop up to three dwellings, each being up to three storeys, on most sites within the greater urban areas of Auckland, Hamilton, Tauranga, Wellington, Christchurch, and Rotorua Lakes district without needing to apply for a resource consent.

3.5 Land use - transport model coupling

Transport model coupling enables significantly improved simulation of urban land use development. This capacity is particularly important for exploring the relationships between the supply of developable land, where development is likely to occur, transport patterns, and - when coupled with a suitably capable economic model- the affordability of new housing.

WRC uses the WRTM transport model[12] which is owned by Co-Lab[13], a Council controlled organisation that delivers council services in a collaborative shared manner across the Waikato Region. The Waikato Regional Transportation Model (WRTM)[14] is a multi-modal strategic model that converts input land use (population, households, and employment per transport zone) and a description of the transport network (road and public transport) to forecast travel patterns for specific forecast years by mode (car drivers, car passengers, public transport passengers, walkers/cyclists).

The WRTM is the single recognised strategic transport model in the Waikato Region and is invaluable as a strategic planning tool for forecasting changes in travel demands based on, amongst others, land use activity. It is therefore critical to couple any integrated modelling capability with the WRTM.

It is also worth noting the transport model being developed by the Ministry of Transport (MoT), known as MONTY.[15] MONTY is an agent-based transport model that is intended to be capable of simulating all of the approximately 5 million residents of New Zealand. MONTY is intended to be accessible via a MoT controlled server, to which users can submit execution requests and submit input data. As well as being capable of highly detailed short-term assessments, we understand that MONTY is intended to be suitable for long-term large scale spatial assessments as well.

3.6 Environmental impacts

The benefits of urban and economic development are relatively easy to estimate and quantify, e.g., changes in housing units, GDP, and employment. However, environmental impacts are more difficult to quantify, e.g., water quality contamination, topsoil loss, and biodiversity loss. Furthermore, short term economic development gains can have environmental impacts that can be significantly net negative in the long term.

Coupling soil and hydrology models with WISE could simulate the feedbacks between land development and the capability of soil and water systems to support various types of agricultural land

[11] Housing intensification enabled by RMA Amendment Act | Ministry for the Environment
[12] https://www.colabsolutions.govt.nz/shared-services/wrtm/
[13] https://www.colabsolutions.govt.nz/
[14] https://www.colabsolutions.govt.nz/shared-services/rata/
[15] https://www.knowledgehub.transport.govt.nz/assets/TKH-Uploads/HubPresentations/Data-event-20-October-2021-Slides.pdf (slides 66-82).

use. Such a model integration could improve the ability to demonstrate long term environmental impacts of land use development.

For example, sheep and beef farming on steep hill country might be economically viable in the short term, but soil erosion could render it unviable in the longer term. As such, WRC may wish to implement policies to incentivise conversion to forestry before there is so much soil loss that even forestry is no longer feasible. Integrating a soil erosion model into WISE could enable WRC to assess changes in soil suitability and productivity, the dynamic relationship with land use, and the potential effectiveness of such policies.

Alternatively, damming a river or significantly increasing water takes upstream could significantly reduce water availability in areas further downstream that are reliant on the river for water supply, thereby rendering certain agricultural land uses infeasible. A hydrology model integrated into WISE could simulate the associated changes in suitability and productivity.

3.7 Incorporation of natural hazards and climate change

As climate change related hazards become more frequent and the CAA is put into effect, it is reasonable to expect that demand for assessing their strategies for managing the impacts of climate change will increase. Likewise, as the impetus to decrease emissions increases, the demand to understand the impacts of emission reduction policies on the environment and the economy will increase. WRC has developed a Climate Action Roadmap (Waikato Regional Council, 2019) that consists of nine climate reduction pathways:

1. **Coastal resilience**: reducing the risk of climate-exacerbated natural hazards on the coastal environment and communities and manage the impacts of sea-level rise.
2. **Agriculture and soils**: working with the agricultural sector to develop integrated approaches to reduce emissions, increase biodiversity and improve water quality.
3. **Water is life**: ensuring fresh water is valued and communities understand how to make the most of every drop using smart ways to capture, store, use and recycle water.
4. **Habitat restoration and planting**: proactively identifying areas for restoration and planting that will deliver climate-related benefits, provide the best return for freshwater quality and habitat for native species, and support community resilience and safety.
5. **Future of transport**: reducing the exposure of the sector to the increasing costs of carbon emissions and enable the transition to low emission transport fuels in a changing climate.
6. **Sustainable investment**: To support sustainability investments that are underpinned by sustainability principles and reduce investments with high climate risk exposure.
7. **Biodiversity and biosecurity**: applying strategies to improve biodiversity at risk from climate change, reduce pest incursion and expansion, and support inter-regional and central government commitment.
8. **Drainage and flood management**: To determine the extent to which current infrastructure and flood protection schemes are fit for purpose and respond accordingly.
9. **Energy**: To facilitate access, development of renewable energy sources within the region and displace the need for non-renewable energy sources.

3.8 Well-being

WRC has developed a "Waikato progress indicators" framework that contains several metrics for measuring the wellbeing of the economy, community, and the environment ("Waikato Progress Indicators - Tupuranga Waikato," 2022)[16] – see Appendix E for a list of the indicators. This indicator

[16] https://www.waikatoregion.govt.nz/community/waikato-progress-indicators-tupuranga-waikato/

framework provides a useful example of a set of indicators that an integrated modelling platform could be expected to calculate values for under the new legislation. We note however that there is no standardised approach to wellbeing assessment. The approach taken in Central Government, for example, has been to adopt the National Living Standards framework. However, concern has been expressed by local government leaders that this framework does not capture well community-based wellbeing impacts and that it is particularly weak from a Te Ao Māori perspective. The indicators in the WPI are arguably by no means comprehensive and would need to be supplemented with other information to provide a more holistic evaluation of wellbeing that communities are asking for.

Furthermore, we note that practical considerations may also determine what sort of well-being indicators can practically be implemented as some are relatively straightforward to derive from computational models, e.g., employment, household income. Others may be more difficult to quantify and simulate, like the percentage of people who agree that the public have 'large' or 'some' influence over the decisions that their council makes. For such indicators other, non-modelling, approaches could be more suitable.

3.9 Alignment of model data and other inputs

When using several different models and comparing their outputs, it is important that where common types of data are used, the same sets of parameters are used. Such a requirement is not necessarily a simple one to implement. For example, it would be insufficient to only specify that climate change scenario RCP4.5 (National Oceanic and Atmospheric Administration, 2022) is being used as there are many parameters within that scenario. To the extent that the new legislation increases demand for integrated modelling tools, so too might it then create the need to rigorously ensure that model parameters are aligned across models.

3.10 Moving from managing for an optimal future to managing for deep uncertainty

Recent literature suggests that there has been a paradigm shift away from seeking decisions that are necessarily 'optimal', and instead to decisions that are 'robust' in the context of 'deep uncertainty' (Groves and Lempert, 2007; Kalra et al., 2014; Maier et al., 2016).

Deep uncertainty is that which occurs where one can enumerate multiple possible futures, but no information about the probability of each can be assigned. Deep uncertainty also occurs where nothing is known about the future, so no possible futures can be specified, let alone simulated.

Robust options or strategies are those that perform well when compared with alternatives across a wide range of different assumptions and plausible futures (Lempert and Collins, 2007).

To the extent that the new legislation's trend towards more strategic planning overlaps with robust decision making and planning for deep uncertainty, models such as WISE that simulate systems at the strategic level will support the development and implementation of robust decision-making methodologies.

3.11 Summary of requirements for an integrated spatial model

Given the implications for integrated modelling capabilities described in the preceding sections, Section 3.11.1 describes a set of criteria by which to assess different models to determine how effectively a given model can meet the model capability requirements described.

In addition to these model criteria there are several other aspects relevant when decided on a modelling capability to support the W-RSS. These are listed in Section 3.11.2.

3.11.1 Model evaluation criteria

The following criteria will be used to evaluate the existing land use and integrated modelling frameworks on:

Potential to address questions across relevant disciplines

In Sections 3.1-3.8 we listed the following key disciplines required for incorporation in a modelling framework to inform the development of the W-RSS:

- Ability to incorporate different spatial scales (local-regional-national) as well as **cross-scale interactions**.
- Ability to address both the **urban and the rural context as well as peri-urban processes**. This requires a set of **various urban and rural land use types** to be included.
- Ability to address urban development capacity, densification strategies, housing affordability and residential choice.
- Incorporation of socio-economic processes, in particular **demographic and macro-economic growth** and implications thereof.
- Ability to address **different types of behaviour** or assess the impacts of interventions of **different societal groups**.
- The ability to include **land use – transport interactions**, both the impact of the land use on transport demand, intensity, and congestion as well as the impact of transport on land use change processes, in particular new urban development.
- Impacts of **climate change** and socio-economic development (population growth, economic growth, urbanisation, agricultural intensification) on the **environment** and **ecosystem services**.
- Assessment of dynamic **disaster risk profiles** as a combination of hazard, exposure and vulnerability, and the changes across those over time, including the impacts of risk reduction options.

Integration of models across many disciplines and modularity of model components

The new legislation asks for a more integrated approach across sectors and in space compared to current practice. Such an approach requires tools that can integrate across the different disciplines listed in the above sections across the four well-beings. In this regard, modularity will be an important feature of the system used as it will make implementing the required models easier and more cost effective.

Spatial resolution and modelling at multiple scales (with a focus on the regional scale)

An important aspect of spatial planning is to assess where in space different activities can best be carried out considering local, contextual factors, as well as overall regional and district demands and processes. The importance of space emphasises the value of a system that can operate across scales and with a high level of spatial detail.

Temporal resolution and horizon

As planning decisions have long-term implications, understanding the impact of actions over multiple decades is critical. Tools that can help to 'stress-test' interventions under various future climate and socio-economic conditions are therefore very useful to support this process, as well as meet the new legislation's 30-year time horizon requirement.

Ability to provide policy support

To be used as a tool for policy support it is important for a model to mature beyond a research phase into a tool with capabilities required to support impact assessment in a governmental organisation. Although this entails several criteria, some of which are described in the next section, it at least requires having the capability to enter different external drivers and policy options and provide information on policy-relevant indicators. Furthermore, it is important for the model to have a graphical user interface to facilitate its use and to have training and support available in the use of the model.

3.11.2 Additional criteria relevant for a modelling capability for policy support

Besides the conceptual considerations listed, it is important to consider factors that determine whether a modelling system will be practical to build, maintain, and embed into decision-making processes. There are a variety of factors that can be broadly classed under *tractability*:

- **Setup time and cost:** Are setup times sufficiently smaller than the assessment cycles in which the tools will be used? Are the setup costs such that local government (with appropriate support from central government if necessary) can afford them?
- **Computational performance:** Model run-times can vary by orders of magnitude. It is important that model run-times occur practically within the timeframes of typical assessments that they will used for.
- **Data requirements:** Some models require more data than others. The ability to implement a model can depend on whether the required data is available, and even if it is available, how much it costs, and how much manipulation of the data is required before it can be included as input into the model.
- **Model calibration and validation:** Model calibration and validation can be considered in terms of deductive validity: how well does the model conceptually represent reality? And inductive validity: how well does the model reproduce historical data? Deductive calibration and validation are generally easier to achieve whereas robust inductive validity can be challenging to achieve.
- **Expertise required:** Some models may require specialist expertise to operate. There may only be a small number of qualified people available to run that particular model. Other models may be implemented in such a way that non-experts can run the model with only occasional support required from experts.
- **Training and support:** Training and support for those using the model now and in the future is a critical aspect for its implementation. With more integrated models, very often different training and support activities need to be designed and developed for different users. It is also important to update any training material when new developments are included in the software and ensure people new to the team receive appropriate training.
- **Ease of coupling with other models:** Data conversion and programming requirements can vary between models, e.g., do two models represent the same information using the same or different units? Do the models being coupled use the same or different standards for data formats and interfaces? Additionally, as models are developed and updated, it will be important to identify whether their compatibility will be affected.
- **Capacity of supporting organisation and/or open-source community, technical documentation:** The capacity of the commercial publisher of the modelling software or community or supporting commercial organisation of open-source software is a critical aspect of whether a given model can be used on an ongoing basis. If sufficient technical support is not available, it is possible that a technical problem could arise that ongoing use of the model becomes no longer possible.

- **Ability to handle uncertainty:** Modelling algorithms and the software within which they are implemented can vary in the degree to which they enable the kinds of modelling processes that can put deep uncertainty and robust decision-making methodologies into effect. Such features can include the ability to set up a model to run several times with a variety of parameters or the ability to set up automatic selection of different options at intermediate stages of a simulation run depending on the state of the model.
- **User interface:** Having a dedicated user interface that allows the more technical user to operate the system (update data and parameters, design and set up scenario inputs, run the model, analyse and compare results) is critical for its use. Ideally the user interface of the (integrated) model is co-designed with the intended users and/or adapted based on feedback from more experienced users.
- **Communication of results:** For any model, sufficient consideration should be given to the communication of the results. This concerns questions such as: What is meaningful to present? and: How can uncertainties be communicated? Visualisation techniques can play an important role in this communication.

4 Review of existing models and integration approaches

We have compared a set of 16 land use and integrated modelling approaches against the set of capability criteria listed in Section 3.11.1. The full list of criteria is provided in Appendix A and an overview of the reviewed models in Appendix B. A summary of this analysis is provided below in Section 4.1 with conclusions being presented in Section 4.2.

4.1 Model comparison

As part of this study two different comparisons were carried out. The first one included a comparison of WISE against other (land use) modelling frameworks on the disciplines included in each framework and their spatial and temporal resolution(s). An overview of this comparison is provided in Table 2. The second comparison (Table 3) involved comparing WISE to other integrated models developed using the Geonamica software environment and/or by the model developers of WISE, as integration of relevant components from these models into WISE would be rather straightforward.

Regarding the first comparison (Table 2), there are several platforms that are capable of modelling regional systems. In searching for different platforms, we considered the criteria listed in 3.11.1. and in supporting the new legislation we strived to include models with a combined urban and rural focus, as we would need to address both in the proposed modelling framework. However, we found that regional system models tend to focus either on simulating urban or rural dynamics and therefore we decided to include models with an urban or a rural focus in addition to combined models, as we wanted to explore their potential for simulation urban, rural and urban-rural dynamics. The second criterion is maturity of development. There are many, perhaps hundreds, of regional system modelling platforms. Usually, land use change modelling is the common modelling approach for integrating various models. However, most of these models exist only as short-lived research projects with a small investment in development and have achieved only a small number of research publications. Some, however, have achieved substantial development and many associated research publications, some even with commercial spin-offs. We consider models with these more substantial levels of development valid candidates for comparison as they have the potential to have sufficient levels of development and support to be implemented by organisations such as Waikato Regional Council.

The sections below provide further detail on the assessment of each of the capability criteria using the information from this table and Appendix B. This appendix also includes references to the information on the models.

Table 2: Comparison of land use modelling frameworks across disciplines and resolutions[17].

Model	**Disciplines included**										**Spatial resolution**	**Temporal resolution**
	Cross-scale	Urban land use	Rural land use	Housing	Population	Economy	Social behaviour	Transport	Climate and environment	Disaster risk		
1. CLUE		+	++								100-1000m. grid	Annual
2. Dinamica EGO[18]		+	++								100-1000m. grid	Annual
3. Land use scanner	+	+	++								100-1000m. grid	Annual
4. Metronamica	++	++	++		++	+	+	+			25-1000m. grid	Annual
5. SLEUTH		+	+								100-1000m. grid	Annual
6. TerrSet[19] (Land Change Modeller)			++						+	+	Various	Various
7. CUBE		+					+	++			Transport zones	Not dynamic[20]
8. DELTA		+					+				Transport zones	Annual
9. UrbanSim	+	++			++	+	+	++			Parcels, transport zones	Annual
10. WISE	++	++	++	+	++	++			+		100m. grid	Annual

[17] Note that WISE incorporates the land use component of the Metronamica Decision Support System but doesn't include the other components included in this system, while it does include dedicated other components from developers that were part of the initial product, which are not included in Metronamica. For this reason, we have included both models as separate entries in the table.

[18] We were unable to confirm what spatial scales and timestep Dinamica EGO implements. We have assumed it uses those that are typical of cellular automata models.

[19] TerrSet incorporates several models with various timescales and spatial resolutions. The land use change model it uses is a cellular automata model. We assume that this model can implement spatial scales typical of cellular automata models.

[20] We were unable to confirm what timestep CUBE typically uses. Based on other features of the model, we assume a calculation is made for a selected future year.

Table 3: Comparison of WISE against other integrated models across disciplines and resolutions.

Model	Disciplines included										Spatial resolution	Temporal resolution
	Cross-scale	Urban land use	Rural land use	Housing	Population	Economy	Social behaviour	Transport	Climate & Environment	Disaster risk		
A. WISE	++	++	++	+	++	++			+		100 m. grid	Annual
B. Xplorah	++	++	+		++	++		+		+	60-240 m. grid	Annual
C. MedAction PSS	++	+	++				+		++		100m. grid	Daily - Annual (+ storm events)
D. SoilCare IAM	++	++	++			++			++		100-500m. grid	Monthly - Yearly
E. Landsim-P	++	++	++				+		++		300m. grid	Monthly – Yearly
F. UNHaRMED		++	++	+						++	100 m. grid	Annual
G. MERIT	+					++	+			++	Region	Weekly – Monthly

4.1.1 Potential to address questions across relevant disciplines

The models in Table 2 have been developed as **land use** (1-6, 10) **or land use-transport models** (7-9). Models that started out as land use models (e.g. Metronamica, CLUE) typically operate at a detailed spatial resolution with grid cells of sizes varying between 50 m. and 1 km., whereby the resolution can be determined whenever the model is applied to a new region. Models with their origin in transport (CUBE, DELTA, UrbanSim) often operate at a coarser resolution (transport zones) and tend to have a less-developed land use component (e.g., a trend extrapolation of selected urban land uses relevant for transport modelling). It is also relevant to note that in transport modelling 'land use' normally equals population, household and employment per transport zone, while in land use modelling it means any kind of land use function (residential, industry, agriculture, nature, water bodies, …) presented on a map, often a grid – indicating the majority land use on the location.

Although some land use or land use-transport models have expanded into modelling frameworks with components from different disciplines, these additional components are in most cases simple and standard approaches. Out of the first set of models, Metronamica (4), TerrSet (6) and UrbanSim (9) and WISE (10) are the most integrated approaches as they include more complex models outside of their original core model component (transport and land use respectively).

- Given that the motivation of the legislation is to achieve more **integrated consideration of urban and rural systems** (maximizing (urban) development capacity while also doing more to avoid environmental limits being exceeded), the primary criteria on which we have assessed the above land use modelling systems is their capacity to achieve integrated simulation of urban and rural systems. We consider that the **Metronamica land use change model** (also incorporated in WISE) has the best capability of achieving this objective both from a theoretical standpoint and from a standpoint of demonstrated capability, as it is included in rural, urban and peri-urban applications (Table 3 A-F). The other models investigated focus on either urban systems or rural systems. As the models with a rural focus (CLUE, Dinamica-Ego, Land use scanner and TerrSet) can include urban land uses in their applications, the potential to further develop urban dynamics in these models is likely higher than the inclusion of (non-economic) rural uses in the models focusing on urban land use (CUBE, DELTA, UrbanSIM). Sleuth is a special case as it only includes two classes, urban and non-urban land, and hence has little detail in its representation of either system.

- Some land use (Metronamica, WISE, and to a lesser extent Land use scanner and UrbanSim) and most integrated models have incorporated cross-scale dynamics. In terms of spatial scales these models incorporated components operating at local, regional and/or national and -in some cases- international level. In most cases the interaction is uni-directional from more global to more local scales, however, Xplorah, WISE, SoilCare IAM and Landsim-P also simulate interaction from local to regional and/or national level. The MedAction PSS and MERIT stand out as they integrate across various temporal scales and resolutions.
- None of the land use models incorporate housing in a detailed way, however, UNHaRMED calculates the number of buildings of different types at each urban location over time, and WISE incorporates a dedicated planning component to plan for different residential densities (the split of the population across different residential land use types as well as the changes in density of each of those types – the latter to e.g. simulate the impact of subdivisions).

The **integrated models** in Table 3 each focus on a different combination of disciplines. From these and the more integrated land use frameworks in Table 2, we conclude that although there is no model or modelling framework readily available that would meet all requirements, they each have one or more components relevant to support W-RSS:

- **Metronamica**, **UrbanSim**, **Xplorah** and **WISE** all include **an age-cohort model** to simulate **population dynamics**. WISE in addition offers the possibility to enter population scenarios (in age-sex-cohorts) at district level, facilitating the use of population scenarios from different sources to be used in the rest of the model. Xplorah includes a feedback loop between its macro-economic and population components and thus allows simulating the impact of economic conditions on migration.
- **Metronamica**, **UrbanSim**, **Xplorah, WISE, SoilCare IAM** and **MERIT** all include a **macro-economic component**, although the component included in Metronamica is a declarative modelling framework that needs to be set up by the user. The different tools include different types of macro-economic models, amongst which econometric (Xplorah), input-output (WISE, Xplorah) and partial equilibrium (SoilCare IAM) models as well as a Computable General Equilibrium (CGE) model implemented using a system dynamics approach (MERIT).
- **Specific behavioural aspects** to mention are the differences in behaviour and preferences of different (mostly urban) household types in **CUBE**, **Delta**, **UrbanSim** and **MERIT** as well as the rural agent-based approach simulating farm households in **MedAction PSS** and **Landsim-P**. **Metronamica** offers the possibility to simulate activity levels in addition to land uses at the local (grid cell) level, and thus allows to simulate the behaviour of different groups in society regarding their locational choices (e.g. where do we expect more vulnerable groups in society to live in future and how are these groups impacted by policy interventions?).
- With their origins in transport modelling, **CUBE** and **UrbanSIM** have the **strongest transport component** out of the land-use transport models (7-10). They also include a high level of detail in the household composition compared to the other approaches. As DELTA was developed

to feed information into a transport model, it provides similar information to the land use components that are part of CUBE and UrbanSIM. On the other hand, the **reciprocal relationship between land use and transport systems** is best represented in **Metronamica** and **Xplorah** as these systems include bi-directional flows of information between both models together with a broader set of land use classes.

- Models with a rural focus, **TerrSet, WISE**, **MedAction PSS**, **SoilCare IAM**, **Landsim-P** all include a **hydrology** component that allows simulating impact of **climate change**. WISE also includes a **water quality** component, while the **other models** focus on **vegetation**, **soil** and **erosion**. **MedAction PSS** also includes **salinization**. The level of detail at which the processes are represented varies between the models, with WISE modelling processes at a rather high level of abstraction and MedAction PSS using the most detailed representation. This has implications for the temporal resolution the models operate on (see Section 4.1.4). The models with a rural focus all give information on one or more **ecosystem services**, food production being a common one, however **TerrSet** is the only model that explicitly mentions having a specific component for this (Ecosystem Services Modeller). **WISE** and **TerrSet** both have a **habitat and biodiversity component** included.
- To model the impact of (changing) biophysical conditions on land use and land management, **MedAction**, **SoilCare IAM** and **Landsim-P** include **a dynamic suitability component** that simulates changes to suitability over time due to climate change and/or land use and management. This enables simulating reinforcing processes such as land management impacting on biophysical conditions which, in-turn, impact land management.
- **Terrset**, **Xplorah**, **UNHaRMED** and **MERIT** all include information on disaster risk, although UNHaRMED and MERIT are most advanced methodologically. Based on external hazard maps (with the exception of an integrated bushfire component), UNHaRMED assesses dynamic risk profiles (e.g. average annual loss, impact per average recurrence interval (ARI)) over time, based on hazard, exposure and vulnerability, while MERIT assesses the impacts of a hazard at a specific point in time (now or in the future) and calculates the direct and indirect economic impacts based on the post-hazard recovery time.

4.1.2 Integration of models across many disciplines and modularity

As can be seen from Section 4.1.1, different integrated approaches exist with specific characteristics useful to support the new legislation. The more integrated approaches (Table 3) are all documented as incorporating separate model blocks and hence we assume the same level of modularity in the software.

For the land use models CLUE, Dinamica-Ego, and Landuse Scanner, we have not found any evidence of them being tightly integrated with other models, and/or serving as the core of an integrated model. There are loose coupling examples with other models available, where information from these models is used in other models or vice versa, but we have not found any studies discussing their technical integration.

Due to their modular structure and their proven technical integration with other models, we assume the more integrated approaches can more easily serve as the basis for a modelling framework to support the SPA.

It is worth noting that integrating models that are developed using the same type of modelling paradigm (e.g. dynamic simulation, optimization, equilibrium) and in the same software environment can be more easily accomplished than integrating models that have vastly different conceptual and technical approaches.

4.1.3 Spatial resolution and modelling at multiple scales

Almost all approaches include a high level of spatial detail. CUBE and DELTA are exceptions as they operate at transport zone level, while MERIT operates at regional level. Most other models operate at a grid at the local scale, with this grid being flexible per application and varying between 25 to 1000m. Rural applications and models with a rural focus often use large grid cells (100 to 1000 meters), while urban applications tend to be more detailed (25 to 250 meters). UrbanSim is different from the other spatially explicit approaches in that it operates at parcel level.

Most integrated approaches include several spatial scales. In general, the larger the area, the more spatial scales are included. SoilCare IAM, as an example, operates at four spatial scales: Europe, Member States, regions, local (grid). Most integrated approaches would be able to operate at regional scale, and hence include processes at regional, district and local level. The only exception being UrbanSim, as this system is specifically developed to simulate urban environments and so far, only applied at city level (and not beyond).

Special consideration is warranted for comparison of parcel-level and cell-based urban models. Given their more exact representation of existing urban land uses, higher resolution, and matching of household agents to specific properties, parcel level models are arguably more capable of simulating urban land use change within existing urban footprints than are cell-based models, at least over shorter time periods. However, over larger spatial scales, growing urban footprints, and longer timeframes, cell-based models can account for important dynamics that parcel-level models have more difficulty with or cannot simulate. Such dynamics include region-wide changes in accessibility, changes in environmental limits, and in particular the interactions in the urban-rural fringe where urban expansion occurs. Parcel-level models can incorporate algorithms to partition (rural) land parcels but are then left with the problem of how to incorporate the effects of proximity of nearby land uses other than by implementing something that looks a lot like a cellular automata algorithm. Given these factors, we consider cell-based models to be more suitable for the region-level scale.

4.1.4 Temporal resolution and horizon

Except for CUBE, all models can capture temporal dynamics. Models with a stronger rural focus tend to simulate the biophysical processes at a more detailed resolution, either to capture the vegetation dynamics throughout the year or to capture specific conditions (e.g. intense rainfalls impacting on erosion). The MERIT model is the only model that simulates socio-economic processes at a more detailed temporal resolution.

Although modelling temporal dynamics is important to support the net legislation, the level of detail depends on the selection of processes to be modelled and their level of abstraction. Once this is selected, the most suitable option for each component can be selected.

4.1.5 Ability to provide policy support

Most of the reviewed tools have the intention to support policy, either as core objective or as one of the objectives. As a result, they incorporate the possibility to assess the impact of various external drivers (e.g. climate change, socio-economic change) and policy interventions. The only exception to this might be Sleuth, as this model heavily relies on historical data through its automatic calibration and uses this information also to project forward, with fewer options to intervene.

The more comprehensive integrated models tend to include more user options in terms of external drivers and policy interventions as they also cover a broader range of disciplines. While the new legislation requires a more integrated approach, with the ability to simulate feedback processes being particularly important, incorporating more models to cover all (more) relevant disciplines, comes with additional challenges such as higher development and maintenance costs, and longer computation times. Furthermore, it impacts the human capacity to operate the system, as more complex systems will require more training and support.

In addition to 'checking the boxes' in terms of the disciplines included, it is important that the software is robust, that it has a user-friendly interface and that there is a support team available. Although all reviewed approaches could potentially meet these criteria over time, WRC would have a head start when selecting components that have evolved beyond the research phase. One indication for this is the number of applications worldwide (CLUE, SLEUTH and Metronamica all have been widely applied across the globe). Another is the use of the systems by government organisations (e.g., Metronamica, WISE and UNHaRMED have such practical use) and the demonstrated availability of a graphical user interface, maintenance, training and support (e.g., CUBE and Metronamica provide this information on their websites).

4.2 Conclusion of model assessment

Assessing the various land use modelling approaches, the Metronamica model seems most suited to be selected for the purpose of supporting the W-RSS as it includes both urban and rural processes, has a modular approach that facilitates its integration with other components and is spatially explicit and dynamic. This model is also already included in WISE and hence already set up with data for the Waikato region and calibrated to the New Zealand context.

There are various integrated approaches that could potentially serve as a starting point for a modelling framework as can be seen from Tables 2 and 3 and the discussion in the previous paragraphs. However, WISE is the only integrated model that has an equal focus on both urban and rural dynamics, and tightly integrates the Economic Futures Model (EFM) developed by Market Economics. It moreover has specific features for incorporating various demographic scenarios and supports the planning process as it allows testing different densification approaches using a dedicated component developed for this purpose. WISE is already applied to the Waikato and tested through practical case studies demonstrating its ability to operate in the New Zealand context.

Nonetheless WISE does not meet all the requirements set out in this document, and therefore we provide various options for improvement. In the next chapter, we first describe the key characteristics of the current version of WISE to support the new legislation (Section 5.1) followed by an overview of the key capabilities of the current version of WISE, and its potential, either by enhancing its existing models, or connecting to new models - be it through technical integration of new models or by loose coupling approaches with other existing models (Section 5.2). Section 5.3 then provides suggestions regarding the model use. In chapter 6 an implementation pathway is proposed.

5 WISE' current ability and potential to support the new legislation

Building on the conclusion from the previous chapter selecting WISE as the preferred system for supporting the new legislation, this chapter focuses of its current ability and potential in doing so. We first discuss some key characteristics of WISE and next focus on its current ability and potential to support different aspects of the legislation. The chapter finishes with suggestions to enhance its use beyond model and software development.

5.1 WISE characteristics relevant for supporting the new legislation

WRC currently deploys WISE as a tool to explore strategic planning decisions, mainly those related to socio-economic growth in both urban and rural areas. WISE is a spatial decision support system (SDSS) that operates across 3 spatial scales (local, district, regional) and provides information at a high level of spatial detail (100x100m) for those processes where the spatial configuration and/or locational characteristics matter. It is designed to support strategic decision-making and operates at a temporal resolution of one year. To facilitate use by practitioners it is equipped with a scenario manager to address different climate change and socio-economic scenarios and allows assessing a range of policy interventions amongst which economic incentives, spatial planning, and infrastructure construction. An overview of the different components incorporated in WISE can be found in Figure 2 below. More information on WISE can be found on http://www.creatingfutures.org.nz/.

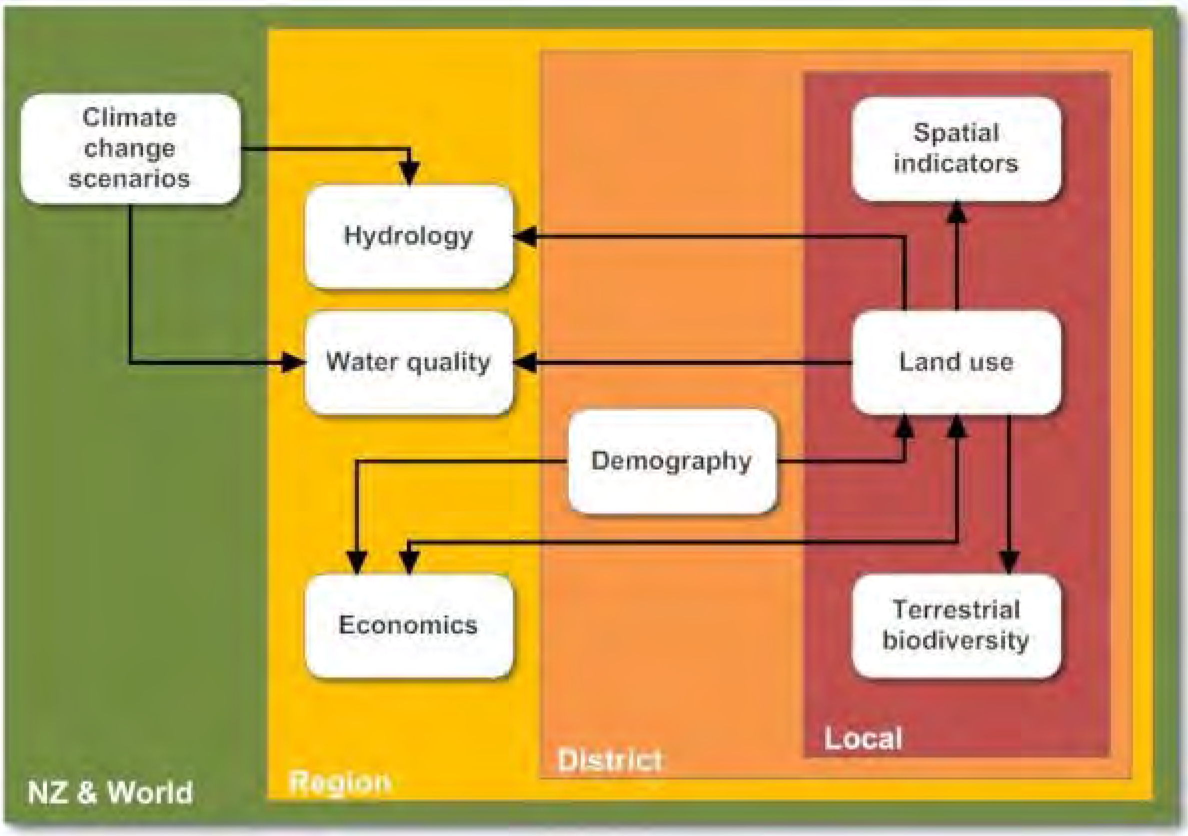

Figure 2: WISE System diagram with main processes operating at each spatial level included in the system.

We suggest using WISE as the core of the proposed modelling framework because of its unique features that fit the requirements:

1) The integrated urban-rural approach: There are many models currently being used to inform aspects of the natural and built environment in New Zealand that will be covered in the NPF. WISE is the only integrated modelling platform that integrates both urban land use change and rural land use change with a reasonable level of capability to simulate change of both types of land use.

2) Ability to integrate various model components: The integrated nature of WISE with both socio-economic and biophysical processes incorporated, offers the potential to address questions across relevant disciplines. The underlying Geonamica software environment is designed to integrate models from different disciplines and developed by different parties. The process followed in the initial development of WISE can be repeated and enhanced to integrate improved or additional components.

3) The spatially explicit nature of WISE: WISE operates at different spatial scales enabling processes as well as policies and indicators to be simulated at these scales. Furthermore, it offers the possibility of operating across scales and its local 100x100 m grid enables addressing the local context and spatial variation relevant for decision making.

4) The dynamic nature of WISE: WISE simulates processes at a yearly resolution up until a selected future horizon, making it possible to understand temporal dynamics and assess the impacts of interventions at different (future) points in time. Moreover, the Geonamica software environment in which WISE is built allows for integrating components operating at different temporal resolutions which facilitates integration with other available models.

5) Ability to provide policy support: WISE is a strategic planning tool allowing assessment of the long-term spatial and temporal implications (covering demographics, economy, land use) of change under different regional development scenarios (or futures). Outputs of WISE have been used to inform the NPS on Urban Development as undertaken by several local authorities (Hamilton, Waipa, and Waikato), development strategies (e.g., Future Proof), and to provide inputs into the Waikato Regional Transport Model (WRTM). In the case of the Future Proof work, land use, population and employment derived from WISE have been used in conjunction with infrastructure assets management plans to help allocate residential and business land use at finer parcel-based scales. Code has already been developed that enables this conversion to be run directly from the WISE-based outputs, GIS layers, and other datasets ensuring rapid assessment of NPS-UD implications.

In addition, adapted versions of WISE have been developed for Auckland and Greater Wellington, demonstrating the generic nature of the approach and the ability to apply it to other regions in New Zealand.

Based on the above features, characteristics, and applied use cases, we suggest WISE to operate as a key tool for the integration of information from different disciplines and hence the core component of the proposed framework.

5.2 Current ability and potential of WISE

To meet the requirements set out in section 3, and by using the findings from Section 4, we suggest a modelling framework with components that can address various disciplines. Based on the requirements and the available resources, a decision will need to be made as to what models to tightly integrate (technical integration of software components) and what models to use within the framework in a more loosely coupled approach (models remain as independent tools) (see Section 3.2 for an explanation of the integration mechanisms).

In the previous section we have provided an overview of the features that make WISE a useful tool for supporting integrated spatial planning and listed a few potential directions. In this Section we discuss how WISE could be used, enhanced, and expanded to (better) address the requirements set out in Section 3. It starts by discussing the cross-scale modelling potential, followed by the important disciplines to be integrated: rural, urban, and peri-urban land use dynamics, housing affordability and choice; socioeconomics and behaviour; land use – transport integration; climate change, environment, and ecosystem services; and disaster risk assessment and reduction. In each of these sections we first discuss how the current version of WISE can support the new legislation, followed by the useful improvements, and how these can be realised. Realisation options include enhancing current models, incorporating new models (tight coupling), or creating integration processes between other models without technically linking the models (loose-coupling). Where relevant we list the various options and their potential and drawbacks. Where available we list options for models that can be integrated. Details of these models can be found in Appendices B (land use and integrated models reviewed in Section 4), C (selected models used by WRC), and D (additional models developed and/or used in New Zealand).

5.2.1 Cross-scale modelling

To facilitate integration between national and regional/local level planning and policy actions, it is beneficial to have a modelling framework matching these interactions. Such an approach is also expected to facilitate the interaction and collaboration between regions and has been discussed previously in the context of developing a model for the Upper North Island[21].

The following key benefits have been listed in the development of a tool that can be applied widely throughout New Zealand and simulating national, regional and local feedback processes:

- Enhanced understanding of interactions between various spatial levels (bottom-up and top-down processes).
- Vertical alignment of policy actions (national – regional – local).
- Use of the same tool across the Upper North Island regions (or even New Zealand) is beneficial in terms of capacity building, maintenance, and robustness of the system through an increase in the user community.
- Funding for further development can be shared and features developed for one region can be used in other regions as well.
- National data layers (e.g., census datasets, employment datasets, slope, soil type, land cover, agricultural land use, climate scenarios, hazards, protected areas, biodiversity, and threatened species) could be easily processed for all regions which facilitates the updating of the information for the various regions.

How can the current version provide support?

[21] Feasibility study "Towards an Upper North Island Integrated Scenario Explorer", report available on Creating Futures Publications.

As WISE incorporates various spatial levels (regional, districts, local), it already enables cross-scale modelling across these scales. Its ability to include multi-scale processes, offers the possibility to develop into an Upper North Island or even New Zealand-wide modelling platform.

What improvements are required?

WISE would need to be linked to other regions and/or national scale processes.

How to realise improvements?

The form in which such a *regional to national approach* would take place can vary based on interest and resources. The most advanced option is to have one system for the entire country. However, great benefits can already be realised by having several regions work with the same software, potentially complemented with a model that simulates interaction between the regions for those processes found relevant, and feeding information to the regional applications and using information from the regional applications in a way that is found appropriate.

In terms of the *regional to local level modelling approach*, we suggest a study could be undertaken to compare the outputs of WISE and parcel-level models for a sample of areas and scenarios, reflecting those that would most commonly be of interest. Such an exercise might also help to inform the implementation pathway for WISE as described in the following section.

Summary of options

Region to national scale:

- A minimum solution entails the use of the same software across the various regions in New Zealand or at least the Upper North Island. Each council would have its own application of the W(ISE) software, with the software building on the current WISE and ISE systems as well as the above listed improvements.
- A medium solution entails the development of a software tool that includes those processes relevant for simulation across the country, such as macro-economics and demographics.
- A maximum solution entails the development of one large software system in which all regions of New Zealand are included and feedback processes (back and forth) between regional and local level are incorporated. Councils would in such an approach be able to update their data and carry out scenario simulations relevant to their interest, while obtaining results considering the interactions with other councils.

Region to local scale:

- Undertake a study to compare model outputs of WISE and parcel-level models, in particular the Hamilton Growth Model to identify opportunities for improvement in both models and/or identify ways in which both models could complement each other in support of planning questions.

5.2.2 Rural, urban and peri-urban land use dynamics

For simulating long-term urban development and understanding the impact of land use changes on the environment, it is important that a modelling framework includes rural, urban and peri-urban dynamics. In addition, a coupling with infrastructure other than transport infrastructure (see dedicated land use – transport integration section for this) could be useful in supporting urban planning.

How can the current version provide support?

The current version of WISE already focuses on rural and urban land uses and simulates peri-urban dynamics resulting from urban expansion.

Already in the current version of WISE the availability of (water) infrastructure can be included in the driving factors of land use allocation as development of certain urban land use classes could be stimulated, limited, or even restricted, based on the availability and capacity of the networks.
Likewise, with the current version, results of future land use scenarios can be used to assess the requirements of the (water) infrastructure by feeding this information into an Urban Water model (e.g. from the DHI suite of water models, although with a loose coupling approach any urban water model could be used).

What improvements are required?

Especially for simulating the urban dynamics, a more detailed simulation of the housing stock including the different housing types would be beneficial as well as the incorporation of infrastructure networks and/or links to models simulating impacts on networks for e.g. water supply, sewage and electricity based on change in land use and households.

How to realise improvements?

Based on a needs assessment, further detailing of land use classes (e.g. further dividing the urban land use classes) would be possible. Another option would be to link to the existing Hamilton Metro Model that models the housing in a more detailed way.

If future developments of WISE include incorporation of the activity-based model, an enhancement of the current land use model in WISE that allows simulating population density at each location in addition to the land use, the above suggestions could be calculated in a more detailed manner as that would allow setting a household/population density per cell based on the availability and capacity of the current or planned networks and also provide the number of households/people per cell to an urban water model. So, in applying the activity-based model there is more granular information: the model then calculates households/people/jobs per cell, instead of an average number of people/households/jobs per cell of a specific land use type per district.

The above approach does not have to be limited to infrastructure but could also be applied to services or green areas. Locations could become more attractive when certain services (e.g. schools, medical services) are nearby or when they are close to green areas. And using information on future land use patterns, level of service indicators (e.g. number of households living within a 1 km radius of a school) or number of people living within a 500 m. radius of a green area of a certain size, can be calculated. The latter could be included as indicators in WISE as they would make use of maps already (calculated) in WISE plus additional (static) maps.

Summary of options

With regards to the urban systems modelling, we suggest that WISE and the Hamilton Metro Model continue to be used as per the areas of relative strength of each; WISE for region-wide rural and urban systems, and the Hamilton Metro Model for local urban areas. If the outputs of these models differ significantly from each other, reconciliation of these model outputs can serve as an exercise to identify important phenomena that one (or both) models may not be sufficiently capturing, or where either model may be mis-calibrated. In this way both models can be used to enhance the overall rigor of the modelling that local government uses to inform their decision-making processes.

Alternatively, it can be investigated if a loose coupling approach in which information from WISE is used in the Hamilton Metro Model or vice versa would be useful. As the two models are rather different in nature, we currently do not recommend a technical integration of approaches.

In addition to coupling WISE with a more detailed urban model, its relevance for supporting urban planning could be increased by incorporating relevant (water) infrastructure information into WISE or by using WISE to feed simulated future land use development scenarios into an urban water model.

5.2.3 Housing affordability and choice

Understanding housing requirements, availability and affordability is critical in supporting sustainable living environments for the future population of the Waikato, together with an understanding of new potential development locations including options for subdivisions.

How can the current version provide support?

The current version of WISE allows for testing different options for urban development, by having a user option to 1) change/set the distribution of people over the different residential classes, and 2) change/set the density of each residential class. Both settings can be provided for different time periods and by district. This way each district can test out time-dependent strategies for the mix of residential development and the densification of the urban areas. These options are unique for WISE and have been developed based on user request resulting from its practical application in the Waikato.

WISE can also assist in providing an understanding of the available land for various land use functions by extracting land use specific zoning information from the incorporated zoning tool and combining this with the land use map for the actual location of various land uses. While running a simulation in WISE, dedicated indicator graphs show for each year and each land use class the difference between land demand (as requested by the economic and demographic models) and land supply (land that is actually allocated). When there is insufficient demand for economic uses, this information is fed back to the economic model and included in its calculations for the next year. So far, we have assumed that all demands for residential areas are met, although this could require developing residential areas with a higher density.

The legislation seeks to achieve an ample supply of developable land, avoid inflated land prices, and provide housing choice and affordability. WISE already has some capability to provide metrics for these objectives such as estimates of supply of developable land and proportion of industry and household income spent on construction.

What improvements are required?

With further development of WISE, even more useful indicators could be achieved such as house and land pricing, and differentiation of residential land use by housing type.

How to realise improvements?

As MERIT contains the main features of a CGE model it can simulate price changes throughout the economy. Hence, its integration into WISE would enable the simulation of land prices and housing affordability. The residential land use class in WISE could be divided into multiple types of residential land use that are of interest, along with the demographic and economic models being used to derive estimates for demand for different choices of housing types.

Summary of options

- ➢ Replace the EFM economic model in WISE with MERIT to be able to simulate housing affordability.
- ➢ Increase the number of residential land use classes in WISE to be able to simulate housing choice.

5.2.4 Socio-economics and behaviour

Dynamic simulation of demographic and economic developments is critical in supporting spatial planning.

How can the current version provide support?

The current version of WISE incorporates a macro-economic model coupled with population projections and thus provides information on the socio-economic dynamics of the Waikato region at regional and district level. These socio-economic models drive the land use demands for residential, (urban) economic and agricultural uses.

What improvements are required?

Economic and land use models - including the ones already incorporated in WISE - have been updated over time and recent developments have enabled the integration of demographic scenarios from different sources to be integrated into WISE. Upgrading existing models or replacing them with newer versions allows simulating processes in more detail and addressing a larger range of issues.

One of the key new features to be addressed is the ability to provide information for social equity and justice questions, as model results can be provided by household type and/or societal group. This allows answering question such as: 'Who is most affected by environmental issues or hazards?' and 'Who benefits from policy interventions?'. A key benefit of being able to identify distributional (rather than average or marginal) impacts is that investment can be targeted at those who are most vulnerable under change.

The original age-cohort population model itself hasn't been updated recently and hence demographic indicators listed in section 3.6 cannot be calculated within WISE currently. This is not necessarily a problem as the information can be obtained through the population models that feed scenarios into WISE. However, a user of WISE currently can't simulate population scenarios or obtain demographic indicators other than those provided through the scenarios that are entered. Also, there is currently no impact of economic activity and employment at district level on the attraction of population as the economic and demographic calculations are now done in parallel without any interaction.

How to realise improvements?

As part of the Economics of Resilient Infrastructure project a more dynamic version of the macro-economic model (Cardwell et al., 2021, 2020; McDonald et al., 2018; McDonald and McDonald, 2020) was integrated with a more elaborate version of the land use model (simulating population and employment densities at grid level in addition to land uses). The macro-economic model, known as Measuring the Economics of Resilient Infrastructure Tool (www.merit.org.nz), has been applied extensively in numerous assessments of infrastructure, natural hazard, climate change, and disruption events to assess socio-economic consequences. MERIT represents a significant step-change over the macro-economic model used within WISE. MERIT can capture non-linear equilibrium effects (e.g., non-linear price change, exchange rate, substitution, transformation effects), but also out-of-equilibrium impacts (e.g., supply chain impacts experienced after COVID-19). MERIT is co-owned by GNS Science, MEResearch and Resilient Organisations. MERIT, which was originally built in System Dynamics, is currently undergoing redevelopment to an Agent-Based Model / Bipartite Network model, providing significant improvements in MERIT's spatial (e.g., from regional to SA1), temporal (e.g., 2 day time step using monthly rather than annual averages) and distributional (e.g., reporting by household types (based-on income, age-sex cohort, family type, ethnicity) reporting. Coded end-to-end capabilities (partial development of an API) linking hazard, risk (through GNS Science Riskscape model), and vulnerability to socio-economic outcomes have also been developed. Extensions to MERIT are currently being developed by various researchers and PhD students (under several MBIE-funded National Science Challenges and Endeavour Programmes) including creation of processes for robust-decision making, uncertainty quantification and communication, improved validation and calibration, and probabilistic assessment of disruption events.

Demographic modelling can be included as external scenarios using the functionality that was recently incorporated into WISE. This allows using results from various demographic modelling studies and assessing their impacts. Furthermore, the incorporated age-cohort model could be updated with new data and/or further developed. Most relevant further developments would be related to the incorporation of interaction between the districts by e.g., using a gravity-based approach and as part of that incorporation of economic information in the attractiveness of the regions. The latter would require the economic model to also operate at district scale.

Summary of options

- As a minimum solution we propose to keep the economic and land use modelling structure as-is and only update the models according to the latest data and model developments.
- A medium solution would be to apply the economic model at a finer spatial resolution (district level instead of regional level), so the economic and demographic components operate at the same spatial subdivision.
- A maximum solution would be to replace the current economic and land use model with newer versions, namely the MERIT economic model and the Activity Based version of the Metronamica model. Including the MERIT economic model would allow for more dynamic economic developments. Including the Activity Based version of the Metronamica model would enable providing annual population and/or employment density information per 100x100 m. cell in addition to (the majority) land use information per cell.

5.2.5 Land use – transport integration

Due to its strong reciprocal relationship, improved understanding of the interaction between land use and transport would be beneficial in supporting strategic planning questions.

How can the current version provide support?

WISE incorporates a transport network which is used for the allocation of (especially urban) land use. The current version can already be used in a loose-coupling approach using the (zonal) accessibility driver in WISE and by converting land use information from WISE into land use information required by a transport model.

What improvements are required?

In the current version of WISE, transport networks are included in the allocation of land uses. Although this type of accessibility is important for spatial development, travel times and costs are equally relevant in regional planning and hence including this information in WISE has high priority. Likewise, current, and future information on where people live, work, shop and socialise is an important driver for transport activity.

Finding a way to incorporate this reciprocal relationship between land use and transport enhances both WISE and WRC's transport model (WRTM, see also Appendix C). There are two key options for this integration:

1. Incorporating a simplified version of the 4-stage transport model into WISE, while ensuring consistency with WRTM.
2. Applying a loose coupling approach in which information from WISE is used in WRTM and vice versa. An example of such an approach is described in Harvey et al (2019).

While the latter approach is more flexible and has less investment costs, it is also more error-prone and requires more time to execute each run due to the manual activities involved.

The same approach could also be taken for WRC to work with MoT to integrate WISE with the Project MONTY transport model when it becomes available.

In each approach aligning the aim of the study as well as the scenarios that will be simulated is of critical importance for its success.

Coupling WISE with WRTM (or another transport model), also offers the possibility to assess current and future emissions.

How to realise improvements?

Some years ago, a feasibility study was carried out to understand the various ways transport could be integrated into WISE[22]. The main directions explored were a loose coupling approach and a tight integration approach. In the former information from WISE would be used as travel demand input into an external transport model and information from both WISE and the transport model could be used to calculate impact indicators relevant for policy support. In the latter a simplified version of the transport model would be integrated into WISE. This would allow simulating the reciprocal relationship between land use and transport but would require more effort as the simple and detailed transport model would both have to be maintained and alignment between results should be ensured.

Is WISE were to be used for simulating future emissions, most of the emissions would be accounted for by the economic model. Emissions attributable to vehicle kilometres travelled (vkt) could easily be derived from a transport model if loosely coupled.

Summary of options

- A minimum solution would entail streamlining WISE output with WRTM (or Project MONTY) inputs and vice versa.
- A maximum solution would entail integration of a transport component into WISE to simulate the reciprocal relationship between land use and transport.
- Potential to assess emissions through the incorporated economics model.

5.2.6 Climate change, environment and ecosystem services

To address climate impacts, and environmental constraints and ecosystem services, the biophysical processes need to be well-represented and integrated with the socio-economic processes.

How can the current version provide support?

[22] Feasibility study "Integrating Transport, Land Use and Economic Modelling", report available on Creating Futures Publications.

The current version of WISE incorporates several environmental components (hydrology, water quality, biodiversity). However, these have not been updated during recent years and effort is required to use them again as part of planning processes. Furthermore, an improved integration between socio-economic and environmental processes would enhance WISE's capabilities as a tool for integrated dynamic assessment.

What improvements are required?

As environmental drivers and impacts are critical to support the new legislative context, it would be useful to enhance this capability. There are various ways in which this could be done:

1. Update the existing models based on new development and new data.
2. Incorporate other models to address the environmental processes.
3. Incorporate information from environmental models as scenarios (driven by climate change) into WISE.

In addition to improving the environmental processes in WISE, their mutual feedbacks as well as their reciprocal relationship with the incorporated socio-economic processes including land use dynamics, need to be addressed. Such development would entail amongst other things:

- Using environmental information on the (economic) productivity of the land and hence improving the simulation of the impact of economic pressures on land demand and allocation, thereby facilitating the discussion what activities should take place where in space.
- Using socio-economic and land use information to indicate the pressures on the environment, including from urban development.
- Using information on land use dynamics as calculated by WISE to assess the impact on ecosystem services as well as the demand for them.
- Addressing the impact of climate change by incorporating (changes in) environment (e.g. water, soil, temperature) on land use dynamics.

Besides information flows from one model to another, having (information from) models integrated in a system like WISE allows for an easy calculation of policy relevant indicators that combine information from various components.

Improving the environmental components and their interaction with the socio-economic and land use change components assist analysts and decision-makers in understanding the relationships between the economic rural and zoning factors that enable land development capacity and stresses on environmental limits.

How to realise improvements?

Given that the original development of WISE was done over 15 years ago, incorporating new models or information from new models (options 2 and 3) would be preferred as this approach will allow selecting the environmental models that best fit the requirements.

The choice for the incorporation of new models (option 2) or the incorporation of results from models (option 3) depends on the interactions between the socio-economic and environmental processes that are found relevant to include, as with feedback between several models, technical integration (option 2) would be required. Option 3 however has the advantage that it is not required to make a choice of a specific model, as any model that can provide the required environmental information can be used.

There are several biophysical models available in New Zealand of which some are already used by WRC. A selection of relevant models to explore further includes hydrological models such as MODFLOW, the Delft3D Suite and the MIKE Suite of models, the CLUES and OVERSEER water quality models, and impact models such as NZeem for erosion impact and InVEST for ecosystem services. Furthermore, there are models that could be used to include biophysical information into zoning options, such as the Land Utilisation and Capability Indicator (LUCI). See appendices C and D for more information on these models.

Summary of options

- A minimum solution is to enter (temporal) biophysical information from biophysical models as maps into WISE and use these for the (changing) suitability and productivity over time due to climate change. Local productivity information (at a 100x100 m resolution) can then be used to improve the interaction between the economic and the land use model as less productive lands would not provide the same agricultural yields and production as more productive lands would.
- A more mature solution entails replacing the biophysical models currently incorporated in WISE with new models, with priority to those models for which a reciprocal relationship with land use and/or economic activity is relevant. A first model to include would therefore be a hydrological model. Water quality models can be used in a conceptual framework where information from WISE is aligned with inputs for one or more water quality models.

5.2.7 Disaster risk assessment and reduction

Socio-economic developments have a large impact on future disaster risk. The ability to better understand future risk would help to design appropriate risk reduction strategies.

How can the current version provide support?

The implications of natural hazards on spatial planning are of critical importance. Natural hazards can be evaluated within WISE through two key avenues. Firstly, zoning or suitability layers can be added that indicate spatial areas of risk e.g., flood prone areas, liquefaction, and landslide susceptibility. Incorporating these layers enables risk-informed decision-making on future land uses. Secondly, natural hazard events can be simulated to understand how risks may play out spatially through time; providing understanding that can inform the dynamics of the so-called 4 R's of 'reduction, readiness, response and recovery' along with 'rebuild' processes. Importantly, this includes understanding multi-hazard events characterised by cascading and coincident hazards.

Scenarios have been stress-tested using WISE to look at the climatic hazards through economy-wide value-at-risk from the exposure of natural capital to climate change and extreme natural climate events (e.g., Monge and McDonald, 2020). The Auckland Integrated Scenarios Explorer (Auckland-ISE), which is built in the same software platform as WISE, has also been used to look at the implications of a volcanic eruption event and its associated recovery within Auckland e.g., Cardwell *et al*. (2021, 2020).

What improvements are required?

WISE currently does not incorporate any hazard components. There are two types of risk assessment that could be carried out using WISE, each requiring different improvements:

1. The first approach entails simulating future conditions (economics, demographics, land use) with WISE, and assess for specific year(s) what the impact of a hazard would be, either expressed as assets affected, or -when combined with damage curves- in monetary terms.

2. The second approach entails the calculation of dynamic risk profiles, by providing a spatially explicit average annual damage assessment by integrating the hazard over various events and the frequency they are expected to occur and combining this information with exposure and vulnerability information.

How to realise improvements?

For the first approach described in the previous section, damage assessment of a current or future event, we suggest an integration or coupling with the MERIT system, already described above (Socio-economics) and an incorporation of indicators to calculate direct damages. Indirect damages and the impact of recovery could be assessed with MERIT.

A spatially explicit prototype of the highly successful Measuring the Economics of Resilient Infrastructure (MERIT, merit.org.nz, see Brown *et al*., 2023; McDonald and McDonald, 2020; Brown *et al*., 2020; McDonald *et al*., 2018) has also been created that is highly compatible with WISE – known as 'Spatial MERIT'. While this prototype is still in development, it demonstrates how WISE might be connected to state-of-the-art risk/loss (Riskscape V2.0) and socio-economic impact (MERIT) modelling toolkits. The benefits associated with the Riskscape/MERIT models can thus be leveraged. MERIT has, for example, been used extensively throughout New Zealand (>50 studies, >100 publications) covering climate change (e.g., Eaves *et al*., 2023; Eaves *et al*., 2019), climatic (e.g., Mattea et al., 2023) and geological (e.g., Cronin *et al*., 2021; Cardwell *et al*., 2021; Cardwell *et al*., 2020; McDonald *et al*., 2018; McDonald *et al*., 2017a,b) natural hazard events. This includes the Wellington Resilience Project, which demonstrated savings of ~$6.0 billion in losses in the face of a Mw7.5 Wellington Fault event, through investment in resilient infrastructure (see Brown *et al*., 2023; Grace *et al*., 2017; Smith *et al*., 2017a). It is worth noting that Monge et al. (2022) provide a framework for achieving this leverage using graphical methods.

For the second approach, calculation of average annual damage, we suggest building on the UNHARMED system, developed for the Australian Bushfire and Natural Hazards CRC. This system is developed using the Geonamica software environment and focuses on natural hazard risk and disaster risk reduction. As these components are already included in the Geonamica environment there are efficiency gains in reusing these for WISE.

For most hazards, an approach using external data for the hazard severity and frequency and combining this in WISE with exposure and vulnerability information into risk indicators would be most suited. However, for hazards with an important reciprocal interaction with land use, such as bushfires and riverine flooding, a more technically integrated approach would add value.

Incorporation of hazard modelling would enable the simulation of natural hazard impacts in a manner that is spatially explicit and dynamic (Cardwell et al., 2021). Furthermore, it would enable the simulation of scenarios with and without managed retreat and the associated costs and benefits.

Potential hazard models that could feed hazard information into WISE are amongst others flood models from the MIKE Suite (Appendix C) and TopNet (Appendix D).

Summary of options

- A minimum solution is the incorporation of risk models which use the information from WISE plus external hazard maps to create spatially explicit risk indicators. The simplest option would be to develop impact indicators showing the area of land of a specific use that is expected to be affected by hazards of a certain magnitude, a more advanced option would be to calculate risk indicators using hazard, exposure (land use) and vulnerability information. The latter would be in the form of damage curves, indicating the damage at certain magnitude levels, and with this information (monetary) damage could be calculated.

- A maximum solution would entail incorporating those hazard models with a reciprocal relationship with the models already incorporate in WISE, such as a bushfire model and a riverine flood model.

5.3 Model use

5.3.1 Visualisation of model outputs for public engagement

WISE and the other modelling systems discussed typically produce model outputs in data formats that are familiar to the expert modellers and policy analysts who have considerable technical expertise and work with the models regularly. These people do not necessarily need further assistance in interpreting this data for it to be sufficiently comprehensible and meaningful. Such data formats include geospatial shapefiles, raster maps, and spreadsheet tables of economic, population, traffic flows, and water quality data. While such data may be meaningful to these experts, its meaning is generally much less intuitive to general members of the public. This difference in ability to interpret the data can limit the potential and efficacy for public engagement of modelling tools such as WISE. This limitation can be unfortunate in such cases, for example, where a modelling assessment of two infrastructure investment proposals may clearly demonstrate that one investment option will perform significantly better than the other, but if the model outputs cannot effectively communicate this difference to the public, public opinion, associated political processes, marketing, and other factors may cause the worse-performing option to be chosen based on less substantial reasons than those that the model can assess.

Relatively recent developments in Digital Twins and 3D animation present an opportunity to overcome this challenge. See, for example, the BuildMedia digital twin of Wellington, https://buildmedia.com/work/wellington-digital-twin. 3D animations can be used to depict the dynamic phenomena that the models simulate. For example, instead of pixels in a raster image changing colour to represent change from one land use class to another, an amination depicting building demolition and new building construction can much easily be understood fully by a general member of the public. Likewise for animations of traffic and water flows versus numbers in a spreadsheet. Animating the impacts of natural hazard events on possible future developments could much more evocatively and effectively communicate the risks of allowing development to occur in geographically risky areas than can numbers in a spreadsheet.

Furthermore, such animations could be made available on the internet to make them widely accessible to the public, and perhaps combined with public feedback processes. In this way, such animation tools could enable a significant means by which the public can engage in regional strategy decision making.

Producing 3D computer animations however requires quite a different skillset to developing computer models of land use change, economic, transport, and other systems and integrating these models. For example, one of the most widely used tools in 3D animation is the Unreal Engine[23]. Use of this tool is quite a different skillset to applying mathematical modelling tools such as R[24] and Python[25] to professional and academic disciplines such economics, hydrology, and transport.

[23] https://www.unrealengine.com/en-US
[24] https://www.r-project.org/about.html
[25] https://www.python.org/

5.3.2 Embedding WISE in a process

Although the focus of this report is on an integrated modelling approach, it is important to realise that a meaningful implementation and use of any model requires a well thought out process regarding its development, maintenance, and use.

As part of the development, it is important to consider the aim and related functions of the model, which relate both to the criteria on which the models are compared (see Sections 3.9.1. and 4.1) as well as the tractability factors listed in Section 3.9.2.

Regarding the maintenance it is important to consider future updates to the software itself (updates to models and the software environment, incorporation of additional models and removal of any components no longer relevant), as well as the data. WISE already has a streamlined process to update the data whenever new census and land use information becomes available, and this approach would need to be expanded to other new models included in the system, as well as models that are more loosely coupled. If the approach for WRC will be reused in other regions or at national scale it is also relevant to design a process to update and maintain national and regional level models, including how to align data preparation processes and model parameters across multiple models.

Finally, it is important to consider how the tool should be embedded in a use process and how it can be complemented with other techniques to best provide support. Similar approaches elsewhere include (for example) the use of narrative, qualitative scenarios to scope plausible future pathways; the implications of which are then modelled using an integrated modelling approach (e.g. Riddell et al., 2019). Such a process can include a range of stakeholder that co-design scenarios through participatory activities. Another possibility is the use of participatory activities to complement the impact of policy interventions on those criteria that cannot be modelled, such as e.g., social or political acceptance of different alternatives.

6 Implementation pathway for WISE developments

Given the likely budget and time limitations, in addition to the interest of moving towards an approach that integrates all the disciplines mentioned in the previous section (economics, demographics, behaviour, land use, biophysics, transport and disaster risk reduction), we suggest first focusing on developing an enhanced version of WISE that incorporates the minimum version of the topics listed above. In short, this option includes **updating the core existing components of WISE (economic and land use)** to their latest version, **removing unused and outdated components**, and **developing integration options for (time series of) data from additional models**:

- The **macro-economic model and land use model** will be updated to their latest (software) versions, with underlying principles remaining unchanged. When new data becomes available these models will be updated to a new start year using the most up-to-date data.
- **Demographic scenarios** will be included as a time series by age-cohort category (already available in the current version of WISE). New scenarios can be included when provided by Te Ngira: Institute for Population Research (University of Waikato).
- **Unused and outdated components**, such as the age-cohort model and the hydrology, water quality and biodiversity models will be removed. This will reduce the maintenance efforts required and facilitate the use of WISE in other regions in New Zealand as the remaining components are sufficiently generic to be applied across New Zealand. In previous projects these components have already been applied in amongst others Auckland and Greater Wellington. Being able to share the same software across different regions will facilitate the development of an Upper North Island model and enhance collaboration across New Zealand.
- **Maps representing biophysical information** relevant for the productivity of the land can be entered through the user interface as a time series. Examples of maps feeding into the land productivity are soil type, (soil) water availability, soil organic matter and nutrients (NPK), which could be provided by existing biophysical models (see appendix C). Within WISE the productivity for agriculture and forestry can be calculated, considering the impacts of climate change as far as this information can be provided by the (external) biophysical models. The calculated productivity information can next be used within WISE to improve the interaction between the economic and the land use component as demand and production can be provided as yield and productive soils and marginal lands can be incorporated in the demand for land and the spatial allocation of activities.
- **Zonal accessibility information from WRTM** can be entered through the user interface as a table with information per transport zone. This information will then be assigned to the local grid within the land use component of WISE. This will allow the integration of congestion and travel times into WISE and as a result improve the accessibility component of WISE, an important driver for land use change.
- **Maps with information on hazard magnitudes and intensities** (e.g., inundation depth for flooding, or Moment Magnitude Scale for earthquakes) can be entered into WISE and within WISE these can be used in the calculation of risk by combining the hazard, exposure (from the land use and economic model) and vulnerability information. For those hazards that change over time, either due to climate change or (structural) mitigation options a (time) series of maps can be entered. Together with the exposure information, which is calculated on an annual basis over time, dynamic risk profiles can be generated.

In turn, WISE can also be used to provide information to other models. Main types of models WISE can provide information to are:

- Models simulating population and employment in a more detailed manner than currently included in WISE. This approach has already been tested and applied for several years as part of Future Proof. A key feature of these models is that they take the more strategic output of WISE and, in turn, disaggregate and allocate this to meet specific requirements under the NPS-UD and Resource Management Amendment Bill 2021 in the short-to-medium term (i.e., up to 20 years, with more resolutions in the 1-to-10-year period). For industry and commercial land uses, this includes *inter alia* floor space requirements, infrastructure provisioning requirements and so on. Similarly, for residential land uses this includes provisioning of building (by type of building) aligned with future growth areas. This work also dovetails into financial contribution policy aligned with development and provisioning of infrastructure.
- Biophysical models, such as hydrology and water quality models, as the land use configuration from WISE will impact on infiltration, roughness of the land and water quality.
- WRTM, through the production and attraction of trips derived from land use change.
- Models simulating hazards that are affected by land use change, such as riverine flooding and bushfires.

An important aspect of the integration described above will be the interaction with the users of the other models to ensure the alignment between model inputs and outputs is scientifically correct and provides support to the new policies in the best way possible.

The use of participatory activities for developing storylines or qualitative scenarios for regional development can be an excellent tool to facilitate the integration across disciplines and facilitate thinking about future uncertainties. Such activities have proven to be useful in the use of models in practice by enhancing the understanding of the models and ensuring their relevance.

Through the above activities we expect key further needs to emerge, which can be used to direct further development. Based on the current study, we already identify potential for the following:

- Replacing the current land use model with an activity-based land use model will allow to simulate population and employment density information on a 100x100 m resolution, in addition to the land use at each location. This improvement will facilitate the link to the transport model as it overcomes issues with the categorical land use classes having a fixed number of people and jobs per class. This option will also improve the calculation of impact and risk due to the enhanced information on jobs and people at each location.
- For simulating reciprocal processes incorporation of relevant models would be important. In WISE such integration already takes place between the economic and the land use model. Additional reciprocal relationships identified are those between:
    - land use and hydrology
    - economics and demographics
    - economic, land use, and transport
    - land use and riverine flooding
    - land use and bushfire.

Although it would be possible to technically integrate additional models in WISE now using a tight-coupling approach[26], we recommend to first use a loose coupling approach for the integration to test the information flow(s) between models. In this option additional models are used as (existing) stand-alone components and only limited software development is required.

[26] See for an explanation on tight and loose coupling Section 3, Table 1.

The decision on tight coupling can be made at a later stage once the model coupling has been tested and once it is established which reciprocal processes are critical to include.

In addition to the above listed model improvements, we also emphasize the importance of the tractability aspects, for which a further explanation can be found in Section 3.11.2:

- **Setup time and cost:** Do the benefits of integrating new models outperform the costs? Or is it sufficient to create 'loose coupling' approaches with existing models? Does 'tight integration' offer better results and/or a more efficient use process? What type of integration with how many model components is feasible given the (development, maintenance and use) budget available?
- **Computational performance:** Does the integration of new model components increase the simulation time more than found acceptable? If so, can pre-calculated simulation runs be entered into WISE as input layers?
- **Data requirements:** Is data of sufficient quality available for the desired new components? If not, can be components be simplified or should non-modelling approaches be taken to include the information?
- **Model calibration and validation:** Are the current calibration and validation practices sufficient, or should time be spent on improving these?
- **Expertise required:** Who should be the user groups of the new system? Does their technical expertise align with what is planned in terms of new developments?
- **Training and support:** Is relevant training material available or can training sessions be provided? What type of ongoing support is required (updating data, software adaptations, running simulations) and is this available?
- **Ease of coupling with other models:** Can procedure be set up so a loose coupling with other models can be facilitated? In which cases is a technical integration of models (tight coupling) required?
- **Capacity of supporting organisation and/or open-source community, technical documentation:** Are the current forms of support and documentation sufficient? Or should additional forms of support be provided?
- **Ability to handle uncertainty:** Is the current ability of WISE to address local uncertainty (Monte Carlo simulation, command line version for setting up sensitivity analysis) and global uncertainty (ability to set up and simulate future scenarios based selecting and setting a range of drivers) sufficient?
- **User interface requirements:** Does the user interface meet the needs of the technical users operating the software?
- **Communication of results:** In what way can results best be communicated? What visualisation techniques can be used to support this?

And finally, we stress the importance of embedding WISE in use process, together with other techniques (participation, data analysis, …) and assessing what it does well and where it can be improved and tailoring further development based on these findings. We strongly recommend using WISE in combination with participatory techniques and see great value in using it for exploring future uncertainties through scenario analysis and in stress-testing different planning and policy options across a range of plausible futures to design robust and/or adaptive strategies.

7 Conclusions and recommendations

This report investigated spatial modelling tools suitable to inform the development of the Waikato Regional Strategy (W-RSS), a mandatory requirement of the proposed Spatial Planning Bill.

Based on the new legislation, a set of criteria was developed to assess the suitability of 16 (inter)national (integrated) land use models, including the WISE model, in addressing the requirements for a modelling framework to support the W-RSS. Particular attention was paid to the WISE model as this model is already used by WRC and able to address several requirements. We concluded that other approaches did not outperform WISE and because of its unique features and proven applicability, WISE would be the preferred system to build new capability on. Key characteristics that led to this decision are WISE's ability to address urban, rural and peri-urban processes, provide a truly dynamic and spatial modelling platform across multiple scales with a finest resolution of 100 m., and integrate model components from various disciplines. In addition, WISE has demonstrated its ability to operate in the New Zealand context, as it is already applied to the Waikato region and tested through practical case studies.

The report describes different development trajectories to enhance and complement WISE and lists a preferred implementation pathway. This preferred way forward entails updating the current core components of WISE (economic, demographics and land use) to their latest versions, removing unused and outdated components, and updating WISE to a new start year of 2023 using updated data whenever the new census results become available.

Furthermore, we suggest developing integration options for (time series of) data from additional models to ensure WISE can provide a more integrated assessment of planning and policy options in line with requirements from the new legislation. This would include:

- Incorporation of biophysical (map) data in the local land productivity, impacting on the supply of agricultural product and forestry and enhancing the interaction between the macro-economic and land use model
- Inclusion of zonal accessibility information from WRTM
- Incorporation of disaster risk components which, using external hazard maps and dynamic exposure information calculated within WISE, would enable assessment of the damage of single events as well as the average annual damage across various events of different magnitudes.

In addition to these further developments of WISE, we suggest better aligning the information from WISE with those models that (could) use information from WISE, in particular WRTM and Hamilton Metro model. Likewise, it is important to streamline the use of WISE in processes where different modelling tools are used, and build e.g., on the work of Future Proof that may best resemble the new planning processes intended under the new legislation. Furthermore, benefits could also be created in using information from WISE in riverine flood modelling, bushfire modelling, or (environmental) impact assessment model addressing issue such as water quality, erosion, soil quality and ecosystem services.

Although we suggest first focusing on the above integrations, we also see benefits in incorporating new model components in WISE in a second step. Worthwhile to further explore in this context are:

- Incorporation of the activity/density-based version of the land use model to facilitate the integration with WRTM and to enhance the capabilities for disaster risk assessment.

- Incorporation of models for simulating reciprocal relationships, e.g., transport, hydrology, bushfires and riverine flooding.

Regarding the use and usability, we have the following recommendations:

- In further developing WISE, or any other framework selected to support the W-RSS, it is important to design and develop a user interface that meets the requirements of the intended users. WISE currently has a dual user interface with dedicated sections for policy analysts and modellers, targeting the needs of these two user groups. Depending on the selected way forward this concept and or the details of both sections might need to be revised.
- As WISE is an analytical tool that requires training and an understanding of the processes incorporated, we do not recommend using the system as-is for the general public. However, we do see great value in linking model results with visualisation techniques to better communicate the results of modelled scenarios to end-users (those that do not have hands-on experience with the model but use its results) and the general public.
- In developing the new support capability, it is important to consider how the tool should be embedded in a use process and how it can be complemented with other techniques to best provide support. Similar approaches elsewhere include (for example) the use of narrative, qualitative scenarios to scope plausible future pathways; the implications of which are then modelled using an integrated modelling approach. Such a process can include a range of stakeholders that co-design scenarios through participatory activities. Another possibility is the use of participatory activities to complement the impact of policy interventions on those criteria that cannot be modelled, such as e.g., social or political acceptance of different alternatives.
- Regarding the maintenance it is important to consider future updates to the software itself (updates to models and the software environment, incorporation of additional models and removal of any components no longer relevant), as well as the data. WISE already has a streamlined process to update the data whenever new census and land use information becomes available, and this approach would need to be expanded to other new models included in the system, as well as models that are more loosely coupled. If the approach for WRC will be reused in other regions or at national scale it is also relevant to design a process to update and maintain national and regional level models, including how to align data preparation processes and model parameters across multiple models.

While implementing the improvements to WISE, we also suggest aligning the WISE and ISE software so various regions can work with the same software. Such a development would facilitate the integration between regions and disciplines, provide benefits in terms of data updates, further development, maintenance, building capacity, and assist other regions in New Zealand in developing the potential to apply these tools to their regions to assist in achieving the objectives of the new legislation.

Finally, we note that for a meaningful implementation and use of any model a well thought-through process regarding its development, maintenance and use is essential. This includes understanding its benefits and limitations, its place and role in the decision context and designing a use process in which the model, together with other technique such as participation, contribute to the overall planning questions.

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Appendix A: Full list of model evaluation criteria considered

This appendix summarises all the criteria that were considered in Section 3.9 and the evaluation of each of models compared in Section 4 (and described more comprehensively in Appendix B below).

- **History**: (Academic) origins of the model up to its current state of development and overall usage
- **Owners / main developers:** Main developers working on current development of the model and owners of the core intellectual property of the model
- **Platform:** Standalone executable, GIS plugin or scripted language. Programming language.
- **Licence type:** Commercial, partially open-source, entirely open-source
- **Model subsystems:** Examples of model sub-models and type:
    - **Demographics:** Age-cohort
    - **Economy:** e.g. input-output or Computable General Equilibrium
    - **Land use change (urban/rural):** e.g. statistics-based algorithms (e.g. logistic regression), cellular automata, agent-based, rule-based (e.g. if-then-else)
    - **Transport:** e.g. four-step or activity-based
    - **Environment:** different subsections of the environment, such as hydrology, water quality, air quality or biodiversity and model types.
    - **Disaster risk:** hazard and/or impact modelling using different model types e.g. event based, average annual damage
- **Integration of models across many disciplines and modularity**: Degree to which different modelled processes are captured as separate components and integrated together
- **Spatial resolution and modelling at multiple scales**
- **Temporal resolution and horizon**
- **Ability to handle uncertainty:** The degree to which a modelling system can handle uncertainty is largely a function of the functions built with the model to support automation of running the model multiple times
- **Understandability:** The degree to which models will be credible as tools for decision support will be influenced by the degree to which they can be explained and understood with a sufficient degree of transparency by as wide a possible a group of stakeholders.
- **Simulation capability:** Degree to which model / model platform can achieve an integrated simulation of all the systems concerned with the new legislation
- **Tractability:** How easy is to set up and embed use of the model into decision-making processes. This includes consideration of factors such as:
    - **Setup time and cost**
    - **Computational performance**
    - **Data requirements**
    - **Model calibration and validation**
    - **Expertise required to use model / ease of use**
    - **Ease of coupling with other models**
    - **Capacity of supporting organisation and/or open-source community, technical documentation**

Appendix B: Integrated and land use change modelling platforms

This appendix provides more comprehensive details on models identified and compared in Section 4.

As Section 3.9 notes, the tractability criteria are difficult to assess without any degree of accuracy without first undertaking significant scoping work. As such, the following descriptions only detail tractability information where the necessary information is available, and it is suitable to make an assessment.

Likewise, a model's ability to handle uncertainty is largely determined by the software it is implemented in rather than the underlying mathematics of the models, i.e., does the software provide functions for the users to set up many of the runs of the model to be undertaken automatically and in sequence or to automatically make decisions midway through a simulation based on the state of the simulation? The degree to which such capabilities can be (easily) achieved will depend on programming language, quality of supporting technical documentation, existing user interface features, and size of supporting model development community.

For an assessment of the structure uncertainty and uncertainty management in four common land use software packages (including Dinamica EGO and Metronamica) we refer to García-Álvarez et al. (2022).

CLUE(-S)

Note that NIWA has a water quality model that uses land use an input and is (confusingly) named CLUES.

History

The original idea of the first CLUE model version was made by Tom Veldkamp and Louise Fresco and published in 1996 (Veldkamp and Fresco, 1996). Later versions were created by Peter Verburg (Verburg et al., 2002) in collaboration with colleagues at Wageningen University and worldwide. ("CLUE model | Environmental Geography," n.d.).

Owners / main developers

Institute for Environmental Studies at Vrije Universiteit Amsterdam ("CLUE model | Environmental Geography," n.d.).

Platform / licence

Open source with acknowledgment of original developers.

Applications

"The different versions of the CLUE model (CLUE, CLUE-s, Dyna-CLUE and CLUE-Scanner) are among the most frequently used land use models globally." ("CLUE model | Environmental Geography," n.d.)

Model subsystems

The **Non-spatial module** models land use demand.

The **Spatial module** models land use allocation.

The allocation of land use is based upon a combination of empirical, spatial analysis, and dynamic modelling. The empirical analysis unravels the relations between the spatial distribution of land use and a series of factors that are drivers and constraints of land use using logistic regression. The results of this empirical analysis are used within the model when simulating the competition between land-use types for a specific location. In addition, a set of decision rules is specified by the user to restrict the conversions that can take place based on the actual land-use pattern. (Verburg et al., 2002).

Spatial resolution and modelling at multiple scales

CLUE-S simulates land use as cells with length of 100m – 1,000m. Models applied at regional and national levels.

Temporal resolution and horizon

CLUES iterates at an annual time step with a time horizon of up to approximately 50 years.

Simulation capabilities

CLUE-S is generally applied to regional and national level assessments focused on agriculture. Its multiple regression model seeks to achieve maximum utility rather than representing competition for space (an important factor in simulating green-field development).

Dinamica EGO

Dinamica EGO is a free, and non-commercial platform for environmental modelling with possibilities for the design from the very simple static spatial model to very complex dynamic ones, which can involve nested iterations, multi-transitions, dynamic feedbacks, multi-region and multi-scale approach, decision processes for bifurcating and joining execution pipelines, and a series of complex spatial algorithms for the analysis and simulation of space-time phenomena.

History

Dinamica EGO originated in 1998 out of the PhD work of Britaldo Silveira Soares-Filho.

Owners / main developers

Dinamica EGO is developed by a dedicated team of software developers and researchers at Centro de Sensoriamento Remoto da Universidade Federal de Minas Gerais – CSR/UFMG. (Dinamica EGO, n.d.).

Applications

Dinamica EGO has been widely applied in Brazil.

Platform / licence

Dinamica EGO is a free and non-commercial platform. It appears the license prohibits derivative works but presumably a discussion with the developers could overcome any licencing issues.

Model subsystems

Dinamica EGO implements a cellular automata Markov-chain land use change model. The software platform enables users to develop and apply their own modelling algorithms including user-developed plugins built in R and Python.

Spatial resolution and modelling at multiple scales

Dinamica EGO implements a grid-cell land use map. Applications can be implemented at the regional and national scale.

Temporal resolution and horizon

Dinamica EGO can simulate land use change at annual time steps across multiple decades.

Simulation capabilities

It is not apparent that the capability to integrate Dinamica EGO with a transport or other urban systems has been demonstrated. It is not clear whether the land use change algorithm would be suitable for simulating urban land use change.

Land Use Scanner

History

Land Use Scanner was first developed in close co-operation with the Netherlands Environmental Assessment Agency (PBL), Geodan and the Agricultural Economics Research Institute (LEI). It has been under constant development since its conception, and most recently by the Netherlands Environmental Assessment Agency (PBL) and Object Vision for several urbanisation studies.

Owners / main developers

The primary developer of Land Use Scanner is the SPIN Lab the Vrije Universiteit Amsterdam (SPINlab Vrije Universiteit Amsterdam, n.d.).

Platform / licence

It appears that software and licenses must be obtained by directly contacting the developers.

Applications

Land Use Scanner has been applied in various locations around Europe.

Model subsystems

The Land Use Scanner is a GIS-based model that produces simulations of future land use, based on the integration of sector-specific inputs from dedicated models. The model is based on demand-supply interaction for land, with sectors competing for allocation within suitability and policy constraints. It uses a comparatively static approach that simulates a future state, in a limited number of time steps.

Unlike many other land-use models the objective of the Land Use Scanner is not to forecast the dimension of land-use change but rather to integrate and allocate future land-use demand from different sector-specific models or experts. External regional projections of land-use change, which are usually referred to as demand or claims, are used as input for the model. These are land-use type specific and can be derived from, for example, sector-specific models of specialised institutes. The predicted land-use changes are considered as an additional demand for the different land-use types as compared with the present area in use for each land-use type.

The total of the additional demand and the present area for each land-use function is allocated to individual grid-cells based on the suitability of the cell. The definition of local suitability may incorporate many spatial datasets referring to the following aspects that are discussed below: current land use, physical properties, operative policies, and market forces generally expressed in distance relations to nearby land-use functions.

Spatial resolution and modelling at multiple scales

Land Use Scanner implements land use maps as cells and is therefore capable of spatial resolutions and scales typical of cell-based models, e.g., cells with lengths of 100m to 1,000m and regional to national scale.

Temporal resolution and horizon

Land Use Scanner does not simulate dynamic change, but is rather an allocation model, and therefore only simulates future scenarios at the future time horizon being considered, e.g., 20 or 30 years from the present.

Simulation capabilities

As Land Use Scanner only functions as a land use allocation model at future dates, it appears that it would not be capable of simulating many of dynamic urban, rural, and environmental processes that would be of interest under the new legislation.

Metronamica

History

Metronamica (Van Delden and Hurkens, 2011; RIKS, 2017, www.metronamica.nl) is a unique generic forecasting tool for planners to simulate and assess the integrated effects of their planning measures on urban and regional development. As an integrated spatial decision support system, Metronamica models socio-economic and physical planning aspects. It incorporates a mature land use change model that helps to make these aspects spatially explicit.

The development of Metronamica started in the 1990s and builds on the seminal work of White et al. (1997). Since then, it has been applied to over 100 cities and regions worldwide and has over time developed from a research model to a flexible and robust spatial decision support system.

Owners / main developers

Metronamica is developed and owned by RIKS. It is provided as a stand-alone executable or integrated in tailor-made systems, such as WISE.

Platform / licence

The software is written in C++ and available through different types of licenses. WRC currently has access to the source code of Metronamica through WISE.

Model subsystems

The Metronamica framework has a high degree of modularity. It incorporates several simulation models that are coupled using the Geonamica software environment. These models start at a certain year in the past for which the required input data is available. The models take annual steps to calculate future states up to a certain end time — this can be up to 50-100 years into the future. The incorporated models work on different geographical scales (national, regional, and local scales, transport zones) to represent the different processes taking place in the real world.

Metronamica can be set up in different configurations. In its simplest form it only includes the local land use component and in this form it is suitable for cities or regions where land use change is the main process of interest. For larger regions, applications can be configured that include both the local land use model and the regional interaction model, a gravity-based model that simulates the flows of activity between different centres (e.g. migration of jobs and people between different cities or countries). Both configurations can be complemented with a demographic model and/or declarative modelling component for macro-economic models to provide regional or national population, employment and/or GDP inputs for the regional and local models. For simulating land use – transport interactions the Metronamica can be set up with inclusion of the transport model that simulates road congestion and regional accessibility. Every application requires at least one of the land use components to be included.

The **land use model** is a cellular automata based model that simulates land use dynamics using a competition for space approach. It simulates land use change based on changes in demand and allocates these to a land use grid based on human behaviour, suitability, zoning, and accessibility drivers.

The **regional model** is a spatial interaction or gravity-based model that distributes population and employment/GDP changes over the different regions and models inter-regional migration of jobs and people. The regional model then translates these figures into surface areas for the different land uses that are fed to the local model.

The **transport model** is based on a classical four-step approach. In the production-attraction step, trip origins and destinations are computed based on the activities in each transport zone. In the distribution step, these origins and destinations are linked to produce an origin-destination matrix. Subsequently, trips are partitioned into different modes of transport, e.g. cars and public transport- in the modal split step. Finally, these trips are placed on the network in the assignment step.

Based on this assignment, transport indicators such as travel time, congestion and accessibility are derived, which are relevant for impact assessment and feed back into the land use and regional model.

The **population model** is an age-cohort model that can be populated to calculate population projections at national or regional level, which will then feed into the other model components.

For macro-economics, Metronamica includes a declarative modelling component, which allows modelers to set up their own model using a set of equations and parameters.

The activity or density-based land use model can be used as a replacement of the local cellular automata based model. It is a more elaborate version of the original local model as it includes population and/or employment densities at cellular level in addition to the land use at each location (grid cell).

Set-up time and costs depend on the number of components selected and the familiarity with the framework.

Spatial resolution and modelling at multiple scales

For simulating land use dynamics, the user can select the number of spatial scales for inclusion in an application, although for all multi-scale applications, including the regional model is required in addition to the land use model. Current applications vary between applications at the local scale (with regional inputs) to applications operating at 4 spatial scales (i.e. Europe, Member States, regions, local).

The spatial resolution at local level can be decided upon by the user. The user is advised to select a resolution between 50-1000 m. depending on the scale of the application. Most new applications have a spatial resolution of 100 m.

The transport model that is incorporated works on the level of transport zones, which are typically smaller than the administrative regions used for the regional model (which are often municipalities, districts or provinces). The transport model includes a wide range of policy-relevant drivers, such as introducing new roads, toll costs, parking costs and public transport policies.

Temporal resolution and horizon

Metronamica operates at an annual resolution. The temporal horizon can be selected by the user. This is commonly 30-100 years into the future.

Simulation capabilities

At the highest geographical scale, trends of future employment, population or surface areas can be entered. For applications with only the land use model, these trends are directly fed to the local model. For applications with the regional and the land use model, the change in employment or population is fed to the regional model. This distributes those changes over the different regions and also models inter-regional migration of jobs and people. The regional model then translates these figures into surface areas for the different land uses that are fed to the local model.

The local model takes care of the spatial allocation of the surface area demands for the different land uses that it receives from either the highest level (for SL applications) or the regional level (for ML applications). This model represents space on a regular grid of cells. Each cell depicts the dominant land use in that area. This land use map is used to calculate a range of spatial indicators that each portray a different aspect of the landscape.

Metronamica allows simulating a wide range of land use classes, and can thus be applied to an urban, rural, and/or peri-urban context. Current applications include those to cities, regions, countries, or larger areas. As a decision support system Metronamica is equipped with external drivers and policy options relevant for policy impact assessment. Drivers and options depend on the selection of model components. For an application with only the local land use model selected, main drivers are land use demands and main options spatial planning, densification strategies, reforestation, and infrastructure development. Metronamica comes with a set of user-defined indicator algorithms to highlight certain aspects of interest (e.g. soil sealing, land abandonment, urban clusters, distance from residential to recreation, habitat fragmentation).

The activity-based version of the model allows to simulate spatially explicit population and employment densities, which are relevant as input into e.g. transport models, but also in simulating dynamic exposure profiles for disaster risk assessments.

SLEUTH

History

The SLEUTH was first developed in 1993 as a cellular automata model for simulating wildfire spread and behaviour (Chaudhuri and Clarke, 2013).

Owners / main developers

University of California, Santa Barbara

Platform / licence

SLEUTH's source code and documentation are open source. The model runs on Unix, Linux and Cygwin (a Windows-based Unix emulator) (Chaudhuri and Clarke, 2013; Project Gigalopolis, n.d.).

Applications

SLEUTH has been applied in many locations around the world, mostly in academic exercises.

Model subsystems

SLEUTH is a cellular automata model that uses five coefficients to control the behaviour of the model and represent the past urbanization trends. These parameters are the dispersion coefficient, the breed coefficient, the spread coefficient, the slope resistance factor, and the road gravity coefficient. These coefficient values determine the growth rate by altering the degree to which each of the four growth rules influences urban growth within the system. The four growth types that determine the probability of a cell becoming urbanized are termed: diffusive growth, new spreading centre, organic growth and road influenced growth. There is a meta level of growth rules called 'self-modification' rules, which help to avoid linear and exponential urban growth in the model. The land use dynamics of the Deliration model also run in sequence and follow a four-step process, which consists of the phases: initiate change, cluster change, propagate change, and age deltatrons respectively. The slope of the land use class also alters the probability of the cells to change. Model execution takes place in the form of a growth cycle (each representing one year) and a series of growth cycles make up the whole simulation process.

Spatial resolution and modelling at multiple scales

SLEUTH cells can vary in size from length of 100m to 1,000m, generally applied at the regional scale.

Temporal resolution and horizon

SLEUTH can iterate with annual time steps up to a time horizon of multiple decades.

Simulation capabilities

While it is available free to download, SLEUTH only implements two land use types: urban and non-urban. Therefore, it has limited use to problem types with which the new legislation is concerned.

TerrSet

History

TerrSet has been developed over a period of 30 years at the Graduate School of Geography at Clark University. Clark Labs released the TerrSet Geospatial Monitoring and Modeling software in 2015.

Owners / main developers

Graduate School of Geography at Clark University (Clark Labs, n.d.)

Platform / licence

TerrSet software is available under commercial licence.

Applications

TerrSet and its subset of models have been applied in numerous research studies globally.

Model subsystems

The TerrSet modelling platform consists of four modelling subsystems:

- **Land Change Modeller (LCM)** simulates the potential of land to experience specific transitions (such as deforestation for agricultural development). Using historical land cover layers along with a set of potential explanatory variables (such as proximity to roads, soil type and slopes), LCM uses empirical modelling tools to establish the relationship between them. LCM supports a Multi-Layer Perceptron (MLP) neural network, SVM (Support Vector Machine), DecisionForest (an implementation of Random Forest), and WNL (Weighted Normalized Likelihoods) – a fast modelling procedure for large numbers of transitions, logistic regression, and a modified KNN (K-nearest neighbour) for model development. Using transition potential models as a foundation, LCM uses Markov Chain analysis to project the expected quantity of change and a competitive land allocation model to determine scenarios for a specified future date. Options exist to incorporate planning interventions such as incentives and constraints, proposed reserve areas and infrastructural changes.
- **Habitat and Biodiversity Modeller** (HBM) provides tools for the modelling of species distributions, habitat assessment, habitat change and gap analysis, biodiversity analysis, and the planning of reserves and biological corridors.
    - At the species level, HBM provides a variety of options for the modelling of species distributions based on observed locations and bioclimatic variables. Options are provided for presence only data (Mahalanobis Typicality and MaxEnt), presence/absence (Logistic Regression and a Multi-Layer Perceptron neural network) and abundance data (Multiple Regression). For individual species, the Habitat Assessment tool allows the mapping of primary and secondary habitat as well as potential corridor areas. Facilities are also provided for the assessment of habitat change and gaps in the protection system.
    - HBM’s Biodiversity tab provides a special utility for working with the IUCN (International Union for Conservation of Nature and Natural Resources) Red List of Threatened Species database. Subsets of species ranges can be extracted based on the Red List threat level, location and endemicity. Given a set of extracted ranges (typically hundreds to thousands of ranges), maps of alpha diversity, gamma diversity, beta diversity, Sorensen’s dissimilarity, and range restriction can be generated.

    - At the landscape level, a facility is provided for landscape pattern analysis that maps normalized entropy, relative richness, edge density, patch area and patch compactness. In cases where land cover maps from two dates are available, the process of change can be mapped. For example, a landscape may not be particularly fragmented, but may be actively fragmenting. Other processes that can be detected include deformation, perforation, shift, shrinkage, enlargement, attrition, aggregation, creation and dissection.
    - For planning, tools are provided for biological corridor analysis and reserve planning. The corridor tool allows you to specify the target width and number of branches as well as produce maps of development suitability and conservation value. It then maps corridors of least biological risk. For reserve planning, we have provided an integrated interface to the well-known Marxan reserve planning tool.
- **Ecosystem Services Modeller** is a spatial decision support system for assessing the value of natural capital for sustainable development. The Ecosystem Services Modeler provides 15 ecosystem service models that are based closely on the InVEST toolset developed by the Natural Capital Project; (1) water yield, (2) Hydropower, (3) Habitat Risk Assessment, (4) Offshore Wind Energy, (5) Aesthetic Quality, (6) Overlapping Use (frequency and importance of human activities), (7) Coastal Vulnerability, (8) Marine Aquaculture, (9) Wave Energy, (10) Water Purification, (11) Sediment Retention, (12) Carbon Storage and Sequestration, (13) Timber Harvest, (14) Habitat Quality and Rarity, (15) Crop Pollination
- **Climate Change Adaptation Modeller** is a suite of tools for modelling future climate and assessing its impacts on sea level rise, crop suitability and species distributions. It includes tools for climate scenario generation using the National Center for Atmospheric Research's MAGICC and SCENGEN models (based on CMIP3/AR4), crop suitability modelling using the Food and Agriculture's EcoCrop database, modelling sea level rise impact, downscaling climate projections, and the derivation of bioclimatic variables.

Spatial resolution and modelling at multiple scales

TerrSet incorporates several models with a variety of spatial resolutions at various scales ranging from regional to global. The Land Change Modeller implements a cellular automata land use change model and therefore can handle a wide variety of cell sizes typical of cellular automata models.

Temporal resolution and horizon

TerrSet incorporates several models that implement various temporal resolutions and time horizons.

Simulation capabilities

While the TerrSet software appears to have a wide variety of environmental modelling capabilities, it does not appear to have capabilities for simulating high resolution urban land use change processes.

CUBE

History

CUBE began as a transport model with the later addition of a land use change model, "CUBE Land". CUBE Land is based upon Dr Francisco Martinez's MUSSA II model (Martinez, 2007).

Owners / main developers

CUBE is developed and maintained by Bentley, an infrastructure software development company based in the USA. (Bentley Systems, 2022).

Applications

The CUBE website appears to mention only one case study, Cape Town, South Africa.

Platform / licence

CUBE is available in a software application under commercial licence.

Model subsystems

CUBE consists of one main application (CUBE) with two additional add-on applications (CUBE Land, CUBE Cargo, and AGENT).

The main CUBE application consists of two programs for simulating transport flows:

- Highway program: Used to estimate zone-to-zone paths for skimming and assigning highway networks through a variety of deterministic and stochastic algorithms.
- Demand modelling program: Includes matrix, generation, distribution, and fratar. Matrix is a calculator designed for demand modelling and matrix manipulation.

CUBE Land leverages an econometric land-use allocation model to bring land-transport interactions into the modelling process. CUBE Land forecasts land use by simulating the real estate market under different economic conditions, as well as considering complex aspects like land use externalities. For a user-defined scenario, CUBE Land forecasts the supply, location, and rents by zone for different types of properties. It also estimates the location of households and non-residential activities for different agent groups.

CUBE Cargo is a freight modelling software that has a library of programs for modelling freight demand throughout a city or at a regional and long-distance scale, to understand or predict the impact of commodity flows. CUBE Cargo offers freight-specific capabilities to represent multiple commodity groups, logistical nodes where transport mode or vehicle may change, a module to model touring vehicles, and a module for local service vehicles. CUBE Cargo consists of three models:

- **Logistics nodes model:** Partitions the long-haul matrices by mode and commodity class into direct flows and transport chain flows.
- **Fine distribution model:** Redistributes from coarse zones to fine zones for each of the matrices.
- **Vehicle model:** Converts the estimated annual commodity flows by truck into the number of heavy trucks and light trucks.

Spatial resolution and modelling at multiple scales

CUBE operates at the spatial scale of transport zones and can be applied at the regional and national levels.

Temporal resolution and horizon

We did not find information on the time resolution and horizon at which CUBE operates.

Simulation capabilities

It appears that CUBE is mainly focused on urban transport modelling and land use change. It is not clear how capable CUBE's land use change model is at simulating greenfield urban development. Nor does it appear that CUBE has any capabilities for simulating rural land use change and associated phenomena.

DELTA (ASP)

History

DELTA is the land use change component of an urban land-use transport model that was developed by David Simmonds Consultancy, The MVA Consultancy, and the Institute for Transport Studies (ITS) of the University of Leeds between 1995 to 1996.

DELTA is notable because Auckland Council has used an implementation of DELTA, called ASP, for a long time. The Auckland Regional Council (ARC) commissioned Sinclair Knight Merz Ltd, in conjunction with Beca Infrastructure Ltd and David Simmonds Consultancy Ltd, to develop new regional transport and land use models for the Auckland Regional Council. This is known as the Auckland Transport Models (ATM2) project.

The transport and land use models are:

- the **Auckland Strategic Planning Model (ASP)**, a strategic land-use model, for medium and long term planning, scenario development and evaluation, and for providing the necessary land use inputs for transport modelling, and
- the Auckland Regional Transport Model (ART), a conventional 4-stage and relatively detailed transport model for medium term project and policy planning and evaluation. Outputs from this will form inputs to the land-use model. (Feldman and Simmonds, 2009)

The commission for ASP3 was based on the use of the DELTA package which DSC has developed and used in a variety of projects [since 1997]. (Feldman and Simmonds, 2009)

Owners / main developers

Systra has recently acquired the rights to the DELTA land use modelling software. DELTA was originally developed by David Simmonds Consultancy which recently went into liquidation.

Platform / licence

As ownership of DELTA has recently changed, it is difficult to find information on current licencing arrangements.

Applications

It does not appear as though Systra have yet listed all the regions in which DELTA has been applied.

Model subsystems

Transition and growth sub-model deals with demographic change and employment growth (i.e. implementing the demographic and economic scenarios within the model). Such changes include singles joining to form couples and couples without children becoming couples with children, migration to and from the modelled area. The transition model also calculates how many households are considering moving, how many must locate anew and how many are not moving.

Employment status and commuting sub-model

- Disaggregates jobs by socio-economic group
- Adjusts travel-to-work matrices and employment status of potentially working residents to ensure that all jobs are filled, and
- Forecasts the number of other (non-working) residents in households.

Development sub-model forecasts the quantities of floorspace completed by zone and development process for housing, retail, office, industrial and warehouse (wholesale) floorspace. For each year, the development sub-model

1. Calculates the total amount of development which developers are forecast to start building
2. Calculates how that total will be allocated to zones and (where applicable) different processes for building the type of floorspace in question.

Area quality sub-model adjusts the quality of the existing stock in each zone (after adjusting the quality for the effect of any new development) by a two-stage calculation. The first stage calculates the "eventual quality", i.e., the level of quality to which the zone would eventually move if occupied indefinitely by occupiers with income levels of the current occupiers. The second stage calculates the actual quality of the zone as it moves a fraction of the way from its current quality towards the eventual quality.

Household location (and residential property market) sub-model calculates the number of households by each type of household located in each zone for each period as a proportion of expected occupiers of a given zone reflecting the stock of vacant floorspace, the characteristics of newly completed floorspace and the number of mobile households.

Employment growth and location (and commercial property market) sub-model deals with the interaction of space and activities

Employment mobility is specified as being 25% of employment in each sector is mobile in each one-year period.

The employment location model is similar in form to the household location model.

Employment growth is determined by the economic scenario that is input into ASP.

Spatial resolution and modelling at multiple scales

DELTA uses transport zones and implements models at the regional level.

Temporal resolution and horizon

DELTA can run at any time specified by the user. The time horizon for modelling can be several decades.

Simulation capabilities

DELTA is an urban land use – transport model that simulates land use and transport at the resolution of transport zones. We are not aware of any capability (theoretical, let alone implemented) for DELTA to simulate rural land use processes and related phenomena.

UrbanSim

History

UrbanSim was developed by Paul Waddell, who is at the University of California, Berkeley.

Owners / main developers

The core UrbanSim model is open source, while the commercial software is developed and maintained by the company of the same name. ("UrbanSim - Smarter Urban Development with AI," n.d.)

Platform / licence

UrbanSim: core model, written in Python, available with open source license

UrbanCanvas: user interface software, available with commercial license

UrbanSim Commons: shared data platform

Applications

UrbanSim has been applied in 22 cities in the USA and another 7 cities internationally.

Model subsystems

Uses discrete choice models, in particular multinomial logit models (MNLs).

Accessibility model: The accessibility model predicts the pattern of accessibility by auto ownership level (Waddell, 2002).

Economic and demographic transition models: The demographic model simulates births and deaths in the population of households. The economic transition model simulates job creation and loss (Waddell, 2002).

Household and employment mobility models: The household and employment mobility models simulate households and employment deciding whether to move. Each household and employee that chooses to move is assigned to an 'in limbo' state (Waddell, 2002).

Household and employment location models: The household and employment location models choose new locations for households and employment that are currently in the 'in limbo' state (Waddell, 2002).

Real estate development model: The real estate development model simulates developer choices about what kind of construction to undertake and where, including both new development and development of existing structures. Variables included in the developer model include characteristics of the grid cell (current development, policy constraints, and land improvement values), characteristics of site location (proximity to transport infrastructure, existing and recent development), and regional accessibility to population (Waddell, 2002).

Land price model: "The Land Price Model simulates land prices of each grid cell as the characteristics of locations change over time. It is based on urban economic theory, which states that the value of location is capitalized into the price of land. The model is calibrated from historical data using a hedonic regression to include the effect of site, neighbourhood, accessibility, and policies on land prices. It also allows incorporating the effects of short-term fluctuations in local and regional vacancy rates on overall land prices. Variables used similar are to those in the Real Estate Development Model." (Waddell, 2002)

Travel demand models are loosely coupled to UrbanSim ("UrbanSim — UrbanSim Cloud Platform 3.12.1 documentation," n.d.).

Spatial resolution and modelling at multiple scales

The UrbanSim land use change model operates at the property parcel level of the input data. It couples with the transport model at the transport model zone scale.

Temporal resolution and horizon

UrbanSim operates on an annual time step with time horizons of multiple decades.

Simulation capabilities

UrbanSim appears to be strong in terms of brown-field urban development, though it is unclear how well it can simulate greenfield urban development which would typically involve splitting up of property parcels in rural areas near a city's urban boundaries. It is also not apparent that UrbanSim has the capacity to simulate or easily integrate rural and environmental phenomena that pertain to the objectives of the new legislation.

Xplorah

History

Xplorah was developed for the Puerto Rican government to address integrated spatial planning issues on the island of Puerto Rico.

Owners / main developers

Xplorah is developed by the University of Puerto Rico and RIKS.

Platform / licence

The software is written in C++ and provided as a stand-alone executable.

Model subsystems

Xplorah includes an age-cohort model, a macro-economic model, a regional interaction model, a land use model, a transport model, and a selection of indicators amongst which hazard impact indicators. Most of the models are part of the Metronamica modelling framework for which details are described above.

Spatial resolution and modelling at multiple scales

At the level of the entire island the model operates at a 240 m. grid. However, there is the possibility to run selected municipalities at a more detailed resolution of 60 m.

Temporal resolution and horizon

Xplorah operates at an annual resolution and has a time horizon 50 years into the future.

Simulation capabilities

Xplorah allows assessing the impacts of a range of economic, demographic, land use (zoning) and transport interventions on social, economic, environmental, hazard and transport indicators.

WISE

The Waikato Integrated Scenario Explorer (WISE) is a dynamic, spatially explicit computer simulation model that integrates economic, demographic, environmental (climate, hydrology, water quality, biodiversity) and land use (suitability, accessibility, local influence, zoning) information to assess the effects and trade-offs of alternative future development scenarios or the consequences of policy options. The modular platform used to build WISE is transferable to other locations or regions and similar models have been developed for Auckland and Wellington (McDonald et al., 2015).

WISE' main use to date has been to support strategic scenario studies, in particular the development of the Future Proof strategy as a collaborative effort of Waikato Regional Council, Hamilton City Council and Waikato and Waipa districts (https://futureproof.org.nz/the-strategy/).

WISE has been adapted and maintained by WRC since the completion of the inception project, the Creating Futures research project (2006-2010) aimed to create tools for improved decision-making.

More information on WISE can be found on http://www.creatingfutures.org.nz/.

History

WISE was developed as part of the Creating Futures project and has since been maintained, updated and used by Waikato Regional Council.

Owners / main developers

WISE is originally developed by WRC and the WISE consortium led by Landcare Research. RIKS and ME Research are currently the main developers of the model.

Platform / licence

WISE is built using the Geonamica software environment for spatially explicit and dynamic model integration. WRC has access to the source code of WISE as part of the license agreement.

Model subsystems

WISE includes a demographic model, an economic model, a land use model, a water quality model, a hydrology model, and a biodiversity model. For more details about WISE refer to Section 5.

Spatial resolution and modelling at multiple scales

WISE operates at three spatial levels: regional, district and local. The economics model operates at regional level, the population model at district level and the other models at local level. The spatial resolution of the local level is the 100 m grid.

Temporal resolution and horizon

WISE operates at an annual time step.

Simulation capabilities

WISE can assess the impact of several economic incentives, zoning regulations, densification strategies and infrastructure development scenarios under conditions of global (climate, socio-economic) change. It includes a series of social, economic, land use and environmental indicators.

MedAction PSS

History

MedAction Policy Support System (PSS) is developed as part of the European research project MedAction. Its main aim is to support regional (rural) development and in doing so it assesses the impact of various strategies on social, economic, and environmental indicators (Van Delden et al., 2007).

Owners / main developers

The MedAction software is developed by RIKS. The hydrological models are developed by King's College London and the socio-economic models by RIKS.

Platform / licence

The software is written in C++ and available through different types of licenses.

Model subsystems

MedAction PSS includes several models, amongst which climate change, hydrology, erosion and sedimentation, salinisation, land use demands, land use allocation, farmer decisions (ploughing, irrigation), natural vegetation, water resources, water demands.

Spatial resolution and modelling at multiple scales

The models incorporated in MedAction mostly operate at local scale (e.g., land use, farmer decisions, hydrology, plant growth, ploughing, irrigation, erosion, sedimentation, salinisation) although a few operate at regional scale (e.g. water demand of non-agricultural uses, land use demands).

Temporal resolution and horizon

Socio-economic processes are modelled at an annual time step (land use change, farmer decisions), while biophysical processes operate at a more detailed temporal resolution (monthly, daily, twice a day, minutes within rainfall storm events).

Simulation capabilities

MedAction allows simulating the impacts of both climate and socio-economic (e.g. land use demand, crop price) scenarios. It has strong capabilities in simulating the reciprocal relationship between land use & management and biophysical processes. Land use and management impact on the hydrology and soil and in-turn the hydrological conditions and soil quality impact on the suitability of the land for various activities and hence are an important driver for land use and land management decisions.

SoilCare IAM

History

The SoilCare IAM has been developed as part of the European Research project SoilCare. It focuses on simulating the impact of climate change and land management scenarios on soil, environment and profitability (Hessel et al., 2022, Van Delden et al., 2021).

Owners / main developers

SoilCare IAM is developed by Wageningen University and Research Centre (WUR) and RIKS and incorporates the PESERA model developed by the University of Leeds. The AGMEMOD model is owned by the Joint Research Centre of the European Commission and loosely coupled with the core of the IAM. SoilCare IAM is provided as a stand-alone executable.

Platform / licence

The software is written in C++ and available through different types of licenses. The PESERA model is also available in FORTRAN.

Model subsystems

SoilCare IAM includes climate drivers impacting on hydrology, crop growth, and soil, as well as a macro-economic model (AGMEMOD) impacting on land use demands, which are subsequently allocated to the local land use grid. At local level, crop yield and profitability are assessed, and environmental impacts (soil organic matter, yield) calculated.

Spatial resolution and modelling at multiple scales

SoilCare IAM includes processes operating at European, Member State, regional and local level. The local level models operate at a 100 or 500 m. resolution.

Temporal resolution and horizon

SoilCare operates at a monthly (biophysical processes) and yearly (socio-economic processes) resolution and simulates developments for 50 years into the future.

Simulation capabilities

The main capabilities include an assessment of land management options on soil, environmental indicators, and profitability indicators under conditions of climate and socio-economic change.

Landsim-P

History

Landsim-P has been developed for the island of Madagascar as part of the 'Land Use Planning for Enhanced Resilience of Landscapes' project.

Owners / main developers

Landsim-P is developed by Wageningen University and Research Centre (WUR) and RIKS and incorporates the PESERA model developed by the University of Leeds. It is provided as a stand-alone executable. Its development is funded through a World Bank contract.

Platform / licence

The software is written in C++ and available through different types of licenses. The PESERA model is also available in FORTRAN.

Model subsystems

Landsim-P includes climate drivers impacting on hydrology, crop growth, and soil, as well as a socio-economic scenario impacting on population and households and related food and nutritional requirements and land use demands. At local level it incorporates a land use model and an agent-based household model to simulate farmer behaviour within the agricultural areas. Based on the household type, farmers have a different behaviour. Farmer decisions impact on crop choice and land management for which implications on crop yield and profitability are assessed and environmental impacts (soil organic matter, yield) calculated (Fleskens et al., 2020).

Spatial resolution and modelling at multiple scales

Landsim-P includes processes operating at national, regional and local level. The local models operate at a 300 m. resolution.

Temporal resolution and horizon

Landsim-P operates at a monthly (biophysical processes) and yearly (socio-economic processes) resolution and simulates developments for 50 years into the future.

Simulation capabilities

The main capabilities include an assessment of land management options on soil, environmental indicators, and profitability indicators under conditions of climate and socio-economic change. It furthermore assesses how households can escape the poverty trap.

UNHARMED PSS

History

UNHaRMED is a software tool for natural hazard risk reduction planning. It was developed through an iterative, stakeholder-focused process to ensure the system can provide the analyses required by policy and planning professionals in the emergency management and risk fields. The process involved a series of interviews and workshops with members of the South Australian, Tasmania, Victorian and Western Australian State and local Governments, NGOs, utility companies, and other stakeholders involved in emergency management, aligning risk reductions to be included, policy relevant indicators and future uncertainties, such that the system can sit within existing policy processes. This has resulted in a tool that considers how land use and related value at stake changes over time, how various hazards interact with these changes, and what the effectiveness of a variety of risk reduction measures is.

Owners / main developers

UNHaRMED is developed by the University of Adelaide and RIKS and funded by the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC).

Platform / licence

The software is written in C++ and available through different types of licenses.

Model subsystems

UNHaRMED consists of a dynamic, spatial land use change model and multiple risk models to consider how disaster risk changes into the future, both spatially and temporally. It includes a land use model, an asset model (building stock, agricultural assets, infrastructure), a bushfire hazard model, and risk models for coastal inundation, riverine flooding, earthquakes, and bushfires. The first three use externally calculated hazard maps, the latter the incorporated bushfire hazard model.

Land use changes are simulated based on several different drivers. First there are external factors, such as population growth or the decrease of natural areas, which determine the demand for different land uses. The land uses for every location are determined based on socio-economic factors (e.g., will a business flourish in this location?), policy options (e.g., are there policy rules in effect that restrict new housing development in this location?) and biophysical factors (e.g., is the soil suited for agriculture here?). Natural hazards are included as the specific application is set up. Hazards can include bushfire, earthquake, coastal inundation, and riverine flooding. Each hazard is modelled differently, depending on its underlying physical processes, as detailed in the UNHaRMED Technical Specification documentation (Van Delden et al., 2022). In UNHaRMED exposure (from the land use and asset models) is combined with hazard and vulnerability information to create dynamic risk profiles. Risk mitigation options impacting on exposure (e.g., land use planning), hazard (e.g. vegetation management, levees) and vulnerability (e.g. building codes, education, and awareness) are then used to calculate the reduction of the risk under present and various future conditions.

Spatial resolution and modelling at multiple scales

In UNHaRMED most processes operate at local level, although there are some drivers that are set either at the level of the entire modelled region or per Local Government Area (LGA) included in the region. Current applications all operate at a 100 m. resolution at local level. Hazard maps however can be included at a finer spatial resolution (e.g. 5 or 25 m.).

Temporal resolution and horizon

The temporal resolution is a year. The time horizon of the current applications (South Australia, Greater and Peri-Urban Melbourne, South-west Western Australia, Tasmania) varies between 35-100 years into the future.

Simulation capabilities

UNHaRMED's main capabilities are to simulate dynamic risk profiles based on changes in hazard, vulnerability, and exposure, and to assess the impact of risk reduction options across these three aspects. It calculates the average annual loss across various average recurrence intervals (ARI) as well as the impact and damage per event. Key risk reduction options include spatial planning, building improvements, vegetation management and structural options such as dams and levees.

MERIT

History

The MERIT macro-economic model, also called the Dynamic Economic Model (DEM), was developed as part of an MBIE funded research project, the Economics of Resilient Infrastructure.

Owners / main developers

MERIT is co-owned by GNS Science, ME Research and Resilient Organisations. ME Research are the main developers of the model.

Platform / licence

MERIT is built using the Vensim system dynamics modelling software. The Vensim model can be converted into C code which can in turn be compiled into a DLL for integration with other models. Use of the MERIT model can be arranged via collaboration with the owners.

Model subsystems

The DEM implements all the main features of a Computable General Equilibrium (CGE) economic model (Hosoe et al., 2010). That is, a model comprised of economic transactions for a given area, output of economic industries, household demand, exports, capital formation, changes in inventory, employee compensation, surpluses, and taxes and institutional transfers, using pricing relationships between these elements to maximise the utility of households, government, and businesses, subject to budgetary constraints. The DEM, however, differs from a normal CGE model in the mathematical basis on which it is constructed. A normal CGE solves a set of equations to find an equilibrium solution (Horridge et al., 2013). The DEM is constructed using systems dynamics modelling so that its variables change with time, and are equilibrium seeking, but do not force an equilibrium solution at every time step (McDonald and McDonald, 2020; Smith et al., 2017b). CGE models typically use an optimisation algorithm to determine at least two equilibrium states, the first a baseline state at the beginning of the scenario period being considered, and a second state that exists some time after a system shock has occurred, based on information about a change in exogenous system variables. The application of optimisation algorithms in this manner does not necessarily inform one about the causal relationships, or transition pathways, of the system's variables between the two assumed equilibrium states.

The DEM uses equilibrium-seeking causal dynamics (price change, substitution and transformation, time lags and delays) to trace the transition pathway through a shock event that occurs to the economy, recognising that for much of the event itself prices may be out-of-equilibrium (McDonald and McDonald, 2020; Smith et al., 2017b). Such capabilities constitute a significant development for solving general economic modelling problems.

Spatial resolution and modelling at multiple scales

MERIT (/DEM) operates at a regional level, typically focusing on a study region, e.g., Waikato region and the Rest of New Zealand.

Temporal resolution and horizon

Unlike typical CGE models which operate at time steps of one year, the temporal resolution of the DEM is typically set at either one week or one month.

Simulation capabilities

As described above, the DEM can simulate regional macro-economic scenarios in a truly dynamic manner. MERIT has also been applied extensively to natural hazard impact assessments and there is therefore a wealth of studies to draw from for application to the climate change adaption act and other natural hazard management policies.

Appendix C: Selected models used by WRC

This section documents a set of existing models used by WRC that could be part of a modelling system to address the new legislation. They have been selected based on their potential to address requirements not yet included in WISE, and the feasibility of coupling them with WISE (either through a loose or tight coupling approach).

The information about these models was obtained from a review of models by Price et al. (2016). Further information on these models can also be found in this report.

The following models have been selected and further described in this appendix:

1. CLUES
2. Delft3D Suite
3. Farmax
4. MIKE Suite
5. MODFLOW
6. OVERSEER
7. WRTM

CLUES

Description

The current CLUES model was initiated in 2004 when the former Ministry of Agriculture and Forestry and the Ministry for the Environment contracted NIWA and subcontractors to develop a regional- and national-scale modelling system to address the effects of land-use change on both water quality and socio-economics (Elliot et al., 2011).

CLUES combines several models into an integrated framework operating within the ESRI ArcGIS software environment. CLUES components consist of a simplified version of the OVERSEER® farm nutrient budget model, the SPARROW water quality model and a farm labour and profitability model.

As a GIS-based spatial model, CLUES allows users to compare different scenarios of static land-use configurations and compositions, including stocking rates, to understand the potential long-term impacts on equilibrium (e.g. 5-year running average) water quality including nitrogen loadings, phosphorus loadings, sediments, and E. coli. For the Waikato region, CLUES is calibrated to long-term data derived from Waikato Regional Council's river and stream monitoring network.

Typical applications are exploratory scenarios around water quality, particularly policy options for water quality improvement in relation to national guidelines. As CLUES is intended for use on a relatively large catchment scale, rather than at property level such as OVERSEER, it is best used to understand general catchment information and the relative differences between catchments.

Delft3D Suite

Description

Deflt3D is a hydrodynamic suite maintained by Deltares in the Netherlands that was released as an open-source codebase in 2011 after 13 years as a licensed product. Being open source, the core software is free to download and use.

Deltares offers users pay-for-service contracting in model development and use. Delft3D enables the study of hydrodynamics, sediment, morphology, and water quality and can be used for some biological related topics. The Delft3D Suite includes models for the study of water flow, and wave effects.

Delft3D Suite is a software shell enabling the integration of different model components. It is a numerical model and could potentially inform monitoring design, and consent-related monitoring in WRC. It is also capable of testing scenarios and can be used for forecasting based on available knowledge.

It can produce 3D imagery that could potentially be more extensively used in a customer service/communication function for example for social learning and priority setting.

Delft3D is open source software and is used by other stakeholders in the field of hydrodynamics. This makes Delft3D a potentially important tool to facilitate working relationships with important stakeholders/collaborators such as the University of Waikato, NIWA, and DairyNZ.

Farmax

Description

The Farmax model was originally launched in 1993 by AgResearch and is designed to assist farmers with on-farm decision-making to improve profitability. There are tools to assist and advise on a range of farming types in the pastoral industries and some cropping components. The model uses farm management data to help inform farm managers of the most profitable farm management practices. There are several Farmax consultants providing commercial services to the client base.

Strictly speaking, Farmax is not a spatially aware model, but as it deals with real entities each farm block can be considered a spatial unit. It can be used to explore future scenarios on hypothetical farms.

Outputs are provided monthly. It is a coupled-components model including farm systems and economics. In WRC, it is used primarily for testing the economic feasibility of proposed policy options for farmers.

Farmax does not include social factors like broader decision support tools like FARMIQ, but the model is used extensively by other agencies and farm consultants providing a common language for discussions with stakeholders and customers about viable policy options. It could also be further used in economic analyses, e.g. what a particular milk solids pay-out might mean for the regional economy.

MIKE Suite

Description

MIKE is a significant commercial player in the hydraulic modelling world. These software packages enable the study of oceans, coasts, rivers, lakes, groundwater, and biological processes. The MIKE suite has its origins in the 1980s and 1990s. In addition to desktop applications, MIKE has recently become available as a rented, portal-based Software Service.

The MIKE suite can be one-dimensional (MIKE 11) or two-dimensional (MIKE 21, Mike21FM – Flexible Mesh), or a recently released three-dimensional component (MIKE3), depending on the data available and the purpose for which it is being used. WRC currently uses Mike11 with the NAM rainfall runoff model, plus Mike21 (rectangular grid), and Mike21FM (flexible mesh).

WRC's flood forecasting system integrates MIKE models with telemetry water level, stream flow, and rainfall information to provide flood forecasts. The one-dimensional model uses surveyed data of a river cross-section to support building of infrastructure such as stop-banks. The two-dimensional functions use LIDAR data and are used to assess spatial hazards such as flooding.

The model is surface-based, assessing rainfall and runoff over a given time period. It incorporates soil characteristics and can predict the effect of a particular change to the catchment, such as removal of a forested area, as well as effects on upstream and downstream areas.

MIKE is used in public meetings and with zone committees to support consultation. It has a good capacity for visualisation tools. It is also used to provide science internally in WRC to the natural hazards team, and is used by regional consultants (Mike 11, Mike 21). It is also used by the IPENZ rivers group and the hydrodynamic society. An annual user group meeting is held by the developers of MIKE.

Regarding other, similar models, Delft3D could fill a similar capacity. There are also other components such as MIKE FEFLOW that can combine ground and surface flows. The groundwater component of this model is similar to that found in MODFLOW.

There is also potential for MIKE to be used for other purposes, for example sediment transport modelling, and it could be used more widely for vegetation/forest clearance assessment. It could potentially be used to assess riverbed degradation. Its uses could also potentially be extended to water quality effects, particularly point source pollutants in surface runoff.

MODFLOW

Description

MODLFOW is an open source, free-for-use three-dimensional groundwater modelling package from the USGS (United States Geological Survey). It was first released in 1984 purely as a groundwater flow simulator but now includes many other capabilities. In New Zealand it is used routinely for groundwater modelling and is often referred to in Statements of Evidence before the Environment Court.

MODFLOW can assess the impacts of land use, drainage, and point source contaminants. It operates on a spatial grid, with highly flexible operation in time and space. It is also possible to bolt on an uncertainty analysis 'pest', which can also be used as an optimiser. Added value comes from the model's capacity to do flux budgets for mass contributions (e.g. Taupo catchment).

Some of the other models are also capable of calculating these but not as well. It could potentially also be used to assess sustainable yields for fresh or salt water. The main limitation is data input related.

While the model is not often used directly in a public communication setting, it has a good capacity for visualisation and is used by the larger regional councils and by CRIs and consultants.

OVERSEER

Description

OVERSEER is a farm-scale systems model that includes a nutrient balance model. It evolved in 2000 from the earlier 1980's Computer Fertiliser Advisory Scheme (Watkins and Selbie, 2015). As with Farmax, its primary role is to assist with farm management. The model enables the user to run scenarios to test the likely consequences of farming practice.

It is used in New Zealand to assist in the regulatory processes associated with managing nutrient losses on farms. The model deals with seven major nutrients and acidity, but primarily nitrogen and phosphorus. The model is actively maintained and developed.

The original purpose of the OVERSEER model was to support decision-making in relation to fertiliser requirements on-farm, rather than to calculate nutrient losses. Its use in a regulatory context is widespread but not unchallenged. The model is continuously being developed, with version changes approximately every 6 months, which can produce different nutrient outputs for the same farm as the information in the model is further refined. This is challenging from a regulatory perspective; for example, the version of OVERSEER written into Variation 5 of the regional plan has now been superseded by more up-to-date versions that account for a wider range of management practices such as cultivation and irrigation.

Driven by a real need for protocols and uniformity due to its widespread use in a regulatory context, considerable investment is now being made in supporting model users, for example through the provision of user manuals and the development of courses.

The model is very important in interactions with stakeholders such as milk companies and DairyNZ as it provides a common platform to discuss nutrients. There is ongoing interaction between WRC and the OVERSEER development group.

WRTM

Description

The Waikato Regional Transportation Model (WRTM) was completed in 2010. The model is developed using the TRACKS10 framework and owned by a limited liability company with seven local authority shareholders (Waikato Regional Council, Hamilton City Council, Thames Coromandel District Council, Waipa District Council, Matamata Piako District Council, Taupo District Council, and Waikato District Council), and includes NZTA, a major funder by way of a service agreement.

The model is built on both quantitative and qualitative data. It is a four-step model (Trip Generation, Trip Distribution, Mode Choice, and Route Assignment). The model currently includes only road transport. The model does not include rail or freight value but does include existing public transport systems – currently limited to buses in the Waikato region.

The model replaces earlier transportation models, the most recent from the 1980s.

Of the LASS11 company owners managing the model, WRC has unique decision-making needs. The RPS, LTP, and public transport investment decision-making are the responsibility of WRC. Responsibility for planning and developing roading infrastructure is largely the domain of NZTA, the district councils, and Hamilton councils.

The TRACKS system is an appropriate abstraction of traffic flow at a regional scale and the WRTM model can be refined locally if required.

Appendix D: New Zealand Models

This section documents a set of existing models developed and/or used in New Zealand that could be part of a modelling system to address the new legislation. They have been selected based on their potential to address requirements not yet included in WISE, and the feasibility of coupling them with WISE (either through a loose or tight coupling approach).

The information about these models was obtained from the EnviroLink database: Decision Support Systems Directory « DSS Home (envirolink.govt.nz).[27] Further information on these models can also be found through this database.

The following models have been selected and further described in this appendix:

8. Cumulative Hydrological Effects Simulator (CHES)
9. Forest Investment Framework (FIF)
10. Highly Erodible Land Model (HEL)
11. Integrated Valuation of Ecosystem Services and Trade-offs (InVEST)
12. Land Utilisation and Capability Indicator (LUCI)
13. Marxan
14. New Zealand Empirical Erosion Model (NZeem)
15. Sediment budgets for river Networks (SedNet)
16. Soil Plant Atmosphere System Model (SPASMO)
17. Suspended Sediment Yield Estimator (SSYE)
18. TopNet

Cumulative Hydrological Effects Simulator (CHES)

Purpose

CHES (Cumulative Hydrological Effects Simulator) estimates the net changes to the flow regime throughout a catchment due to multiple water use schemes. It also quantifies the consequences for both the overall availability and reliability of the water resource and the residual flows that determine the in-stream environmental effects such as physical fish habitat availability.

CHES provides water resource managers with cost-effective, rapid, and flexible assessment of the cumulative effects of complex surface water allocation scenarios. It can even incorporate future climate change.

Forest Investment Framework

Purpose

Forest Investment Framework (FIF) enables decision-makers to identify sub-catchments or regions across New Zealand and assess their viability of purchasing land and its conversion to forestry. It supports policy decisions and strategic planning on the economics of forestry scenarios and the value of ecosystem services provided by future and existing forests (natural or planted).

[27] https://tools.envirolink.govt.nz/

Highly Erodible Land Model (HEL)

Purpose

HEL identifies land that is highly erodible. It identifies steep land that is at risk of mass movement. It identified land that should be under forest to reduce the erosion risk.

Integrated Valuation of Ecosystem Services and Trade-offs (InVEST)

Purpose

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) tool is a suite of free open source software models for the mapping and valuing of ecosystem services throughout terrestrial, freshwater and marine ecosystems. It enables decision makers to assess quantified trade-offs associated with alternative management choices and to identify areas where investment in natural capital can enhance human development and conservation.

Accessibility

Open/closed source: Closed source

Licence type: No licence

Programming language: Python, ArcGIS / QGIS

Land Utilisation and Capability Indicator (LUCI)

Purpose

Land Utilisation and Capability Indicator (LUCI) is a tool that allows users to explore the capability of a landscape to provide a variety of ecosystem services, such as agricultural production, flood and diffuse pollutant mitigation, carbon sequestration, and habitat provision. It allows for the development of alternate scenarios so that different management decisions can be assessed and compared (https://lucitools.org/).

Marxan

Purpose

Marxan is a conservation planning software that allows a systematic approach to the design of efficient conservation areas.

New Zealand Empirical Erosion Model (NZeem)

Purpose

NZeem® is an empirical model that predicts mean annual sediment yield from a given catchment, based on annual rainfall, type of terrain and percentage of woody vegetation cover.

Sediment budgets for river Networks (SedNet)

Purpose

SedNet identifies sources and sinks of sediment and nutrients in river networks and predicts spatial patterns of erosion and sediment load. SedNet constructs sediment and nutrient (phosphorus and nitrogen) budgets for regional scale river networks (3,000 - 1,000,000 km2) to identify patterns in the material fluxes. This can assist effective targeting of catchment and river management actions at the regional scale, to improve water quality and riverine habitat.

Soil Plant Atmosphere System Model (SPASMO)

Purpose

SPASMO models the transport of water, microbes and solutes through soils integrating variables such as climate, soil, water uptake by plants in relation to farm and orchard practices, and any other factors affecting environmental process and plant production.

Suspended Sediment Yield Estimator (SSYE)

Purpose

A New Zealand national GIS 'layer' to enable reconnaissance-scale estimation of suspended-sediment yields from New Zealand's rivers and streams. It has been developed by NIWA in collaboration with Landcare Research. Predicting long-term average suspended sediment loads in rivers and streams is useful for dealing with a variety of issues. These include sediment entrapment rates in potential reservoirs and the vulnerability of estuarine and coastal marine habitats to sediment influxes from the land.

TopNet

Purpose

The hydrological model TopNet was developed at NIWA and is commonly used in New Zealand. Typical applications include flood forecasting, irrigation planning and estimates of climate change impacts on river flows.

Appendix E: Spatial Plan and Modelling Input Data Requirements and Indicators

Data requirements

Land use

- Land use map (as grid / raster image). Note land use map is compiled from property parcel ratings assessments, population, employment, land cover (from Land Cover Database), and agricultural land use (Agribase)
- Land suitability (as grid / raster image). Example of land suitability inputs include slope and soil type (/fertility)
- Zoning regulations (as grid / raster image)
- Transport (/accessibility) network (as shapefile(s))
- Economic land use demand (hectares, from economic module)
- Residential land use demand (hectares, from population module)

Population

- Fertility by age
- Mortality rate by sex by age
- Birth sex bias
- Net in-migration by sex by age

Economics

- Input-Output (IO) table or Social Accounting Matrix (SAM)[28]
- Population (# persons by age, sex)
- Land use productivity ($\$_{2007}$million)

Example of well-being indicators (Waikato Progress Indicators ("Waikato Progress Indicators - Tupuranga Waikato," 2022))

Economy

- Real value of total new building consents issued per annum
- Employment rate
- Read median weekly household income
- Real regional gross domestic product (GDP) per capita
- Water allocation as a percentage of primary allocable flow – Waikato River mouth during summer months

[28] Input-output tables and Social Accounting Matrices are datasets comprising transactions between the industries that make up an economy, consumption by final end users including households, government, and international exports, and primary inputs into the economy including international imports, and value-added, the two main components of which are represented by labour and surpluses generated by enterprises.

Society

- Percentage of people who agree that the public have 'large' or 'some' influence over the decisions that their council makes
- People's reported sense of pride in the way their city/town looks and feels
- Rates of recorded victimisations per 10,000 population
- Level of agreement by survey respondents that New Zealand becoming home for an increasing number of people with different lifestyles and cultures from different countries makes their area a better place to live
- Percentage of school leavers with NCEA level 2 or above
- Ratio of housing costs to household disposable income
- Gini coefficient
- Life expectancy at birth
- Percentage of people who rate their overall quality of life positively
- Percentage of people who rate their overall health good, very good, or excellent
- Percentage of adults who feel safe walking alone in their neighbourhood after dark
- Percentage of people who say they were physically active on five or more of the past seven days
- Public transport volumes per capita
- Estimated annual social costs of road injury crashes per capita
- Percentage of people who agree of strongly agree that they experience a sense of community with others in their neighbourhood
- Percentage of Te Reo Māori speakers in total population
- Average voter turnout in local, DHB and regional council elections

Environment

- Urban air quality
- Traits Based Index (TBI) of the biological traits of sediment-dwelling animal communities
- Average regional NEP (New Ecological Paradigm)[29] Scale score
- Regional annual total greenhouse gas emissions
- Extent of indigenous vegetation on land
- Self-reported prevalence of household recycling
- Area of highly productive land in urban and rural residential land use
- River water quality for ecological health – percentage of unsatisfactory river water samples for ecological water quality
- Percentage of soil monitoring sites meeting five or more soil quality targets
- Estimated tonnage of waste to landfill per annum

[29] The New Ecological Paradigm scale is a measure of endorsement of a "pro-ecological" world view. It is used extensively in environmental education, outdoor recreation, and other realms where differences in behaviour or attitudes are believed to be explained by underlying values, a world view, or a paradigm. The scale is constructed from individual responses to fifteen statements that measure agreement or disagreement. New Ecological Paradigm (NEP) Scale, Anderson.indd (umaine.edu)

Indicators incorporated in the current version of WISE

- Climate
  - Temperature (°C, as grid)
  - Rainfall (mm, as grid)
  - Potential Evapotranspiration (mm, as grid)

- Hydrology
  - Annual runoff for the year (mm/year, as grid)*
  - Minimum monthly summer flow yield per unit area (litres s^{-1} km^{-2}, as grid)*

- Water quality
  - Mean Annual Load of Total Nitrogen by Stream reach (kg N/year)*
  - Mean Annual Load of Total Phosphorus by Stream reach (kg P/year)*

- Economy
  - Final output for approximately 50 economic sectors ($ 2018m NZD)
  - Gross regional product / Added value per economic sector ($ 2018m NZD)
  - International imports per sector ($ 2018m NZD)
  - Land demand by economic sector (hectares)
  - Employment (# of jobs), Unemployment (%)
  - Household consumption per economic sector ($ 2018m NZD)
  - Solid waste per sector (tonnes)
  - Energy use per economic sector (GJ, oil equivalents)
  - Energy related CO2 emissions per economic sector (tonnes)

- Population and residential demand
  - Population × 1-year age/gender cohort (persons per district)
  - Demands (ha) per residential land use class per district
  - Regional labour force (persons)

- Land use
  - Suitability per land use (numerical between 0-1, as grid)
  - Zoning per land use (categorial, as grid)
  - Land Use (categorical as grid)
  - Regional land use demand vs supply (hectares)

- Terrestrial biodiversity
  - Threatened Environments (categorical grid)

- Additional user-defined spatial indicators, e.g.,
  - Urban and natural clusters, habitat fragmentation, …
  - Land use change (soil sealing, land abandonment, de/reforestation), …
  - Distance from residential to work locations, recreation locations, …

Potential indicators based on further development of WISE

- Disaster risk and risk reduction
    - People, employment, land uses (ha) affected by selected disasters
    - Direct damage per disaster event (flood, wildfire, earthquake, volcano, …)
    - Indirect damage per event (flood, wildfire, earthquake, volcano, …)
    - Average annual damage for selected disasters
    - Risk reduction per event based on selected options
    - Reduction in average annual damage based on selected options
- Land use – transport integration
    - Impact on travel behaviour, intensity, congestion (due to land use change)
    - Impact of travel times on land use developments and economy
- Improved biophysical models
    - Dynamic suitability impacting on land use
    - Assessment for additional land required for additional agricultural production
- Improved socio-economic models
    - Social equity indicators
    - Population density per cell (e.g. supporting integration with transport)