Dynamic models for the Waikato River system: Scoping study

Prepared for Waikato River Authority

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Purpose and scope

This report proposes a set of dynamic models to predict water quantity, quality, and ecological responses to these along the Waikato River and its tributaries, including the Waipa River and the associated catchment. This set of models is referred to as the Waikato Dynamic Models.

Management of the Waikato River requires predictions of how land use changes and restoration activities can improve water quality, water resources and freshwater ecological health to assist with achieving Te Ture Whaimana o Te Awa o Waikato – Vision and Strategy for the Waikato River[1] (Waikato River Authority 2019), which is embodied in the Regional Policy Statement for the Waikato Region. To this end, the Waikato River Authority (WRA) along with project co-funders and River Iwi[2] wish to develop a broad and holistic modelling approach that considers a wide range of needs (where a need in this context is an information need or a purpose to which that information might be put). Accordingly, NIWA was contracted to undertake a study to scope a set of models to predict water quantity and quality and associated ecological responses for the entire Waikato-Waipa river system, its tributaries, and catchment, consistent with the needs of the Vision and Strategy. The emphasis of the proposed modelling is on biophysical conditions and processes; modelling social, human or economic systems was not included in the project brief and so is not considered here.

The scope focussed on *dynamic* (temporal or timeseries) modelling, to provide predictions over time, rather than simply time-averaged or static predictions, because:

i. water quality and ecology depend on processes that interact over time;

ii. key metrics of interest are sometimes related to extreme conditions such as floods or low flows;

iii. uses of water depend on timing of critical events (for example, algal blooms at low flow); and

iv. the time of the river to recover via restoration activities is of interest.

These predictions are also required in a spatially-distributed and connected way, because the impacts of activities and uses of water depend on location and those impacts can be cumulative and may occur kilometres downstream from the activities.

A key principle included in our brief from the co-funders was that the proposed modelling approach should result in the development of a co-owned set of models with open access. Currently available models for the Waikato are fragmented in terms of ownership and spatial coverage and are often based on proprietary software available only to a limited set of specialist providers. Co-funders and stakeholders expressed the view that a more open and community-based integrated approach would widen engagement with modelling, support co-management of the river system, and serve a range of stakeholders into the future. To achieve these objectives the system would, ideally, consist of models that are open-source, free, and have freely accessible input datasets.

[1] Te Ture Whaimana o Te Awa o Waikato – Vision and Strategy for the Waikato River. https://www.waikatoregion.govt.nz/Council/Policy-and-plans/Regional-Policy-Statement/RPS2016/Part-A/2/5/1/.

[2] Waikato-Tainui, Raukawa, Te Arawa, Maniapoto, Tūwharetoa

The nature and complexity of dynamic models means that direct users will require a high level of technical skill. Building such capability would be enhanced through a collective project that includes research and education opportunities through the Te Waiora Joint Institute for Freshwater Management, Waikato-Tainui College, Crown Research Institutes (CRIs), and Iwi entities.

The models would inform the activities of a wide range of indirect users, such as for planning by regional government and River Iwi, the design and evaluation of effects of land use changes and restoration activities, and by the public for flow and water quality forecasts.

This study was funded by the Waikato River Authority (WRA) as the cornerstone funder, with co-funding from NIWA, Waikato Regional Council (WRC), University of Waikato, Mercury Energy, the Waikato Tainui-Mercury Partnership, and DairyNZ. The project was led by NIWA, with technical contributions from the funding partners. River Iwi were also involved with development of the plan through engagement during the project. The wide base of parties was intended to set a foundation for broad buy-in and support for the model and its future development and use.

Dynamic models of this scale require considerable investment to set up, run and maintain, including collection of data. Hence, this project identifies and addresses the needs, suitability and benefits of modelling to guide investment decisions. Also, this project aimed to address both long-term aspirations and more pragmatic shorter-term model development.

Process

The overall scoping project went through the following steps:

1. Hold a waananga (workshop) with the project group to discover river modelling needs and goals of key stakeholders in relation to the management and restoration of the Waikato and Waipa River catchment. The needs and goals were organised around Report Card taura (metaphorically, strands of rope interwoven to form a whole) used in the WRA Report Card processes, to ensure that models would be relevant to those taura and driven by the high-level experiential goals reflected in the taura.

2. Writing a main report (this report) providing: a summary of past and existing modelling; identification of model needs and opportunities arising from the waananaga and technical considerations; an evaluation of modelling options against identified needs; and a draft plan for model development (including a development pathway, input data requirements and plan, uptake pathway, timing, and resourcing).

3. Obtain comments on a draft version of this report from the co-funding partners and River Iwi, including general feedback and views on priorities.

4. Finalisation of this report, including preparation of a supplementary document capturing feedback from the project co-funders and Iwi that provided an agreed pathway forward.

Model needs

The waananga identified several high-level aspirations, with key themes of a) providing a holistic, excellent, long-term approach and b) supporting a wide range of uses. Aspects of these themes are listed in this report.

Initial separate discussions with River Iwi identified several approaches or objectives for modelling, including taking a holistic river-centred approach to protect the Mauri (or lifeforce) of the river, identifying effectiveness of restoration projects and iwi planning documents, identifying impacts on customary activities that occur on the river, and considering multiple dimensions of wellbeing (environment, cultural, social and economic).

The waananga used the Report Card taura as a focus for identifying model needs and opportunities. The taura are: kai; ecological integrity; water quality; water security; experience; economics; sites of significance; and mitigation effort. For each taura, Report Card indicators were noted along with additional indicators, and needs and opportunities for dynamic models were listed. This provided a mechanism to link taura, which are based around experiences of the river, to variables that the models should predict, and model requirements.

Following the waananga, model variables were collated and grouped, and then mapped to the six most relevant taura (sites of significance were set aside, and mitigation effort did not involve additional variables). The model variables were then related to types of models that address these variables as shown in Figure i below. In the figure, the boxes on the left are the model types (in bold) and the variables they predict. The model types are matched to the taura shown on the right.

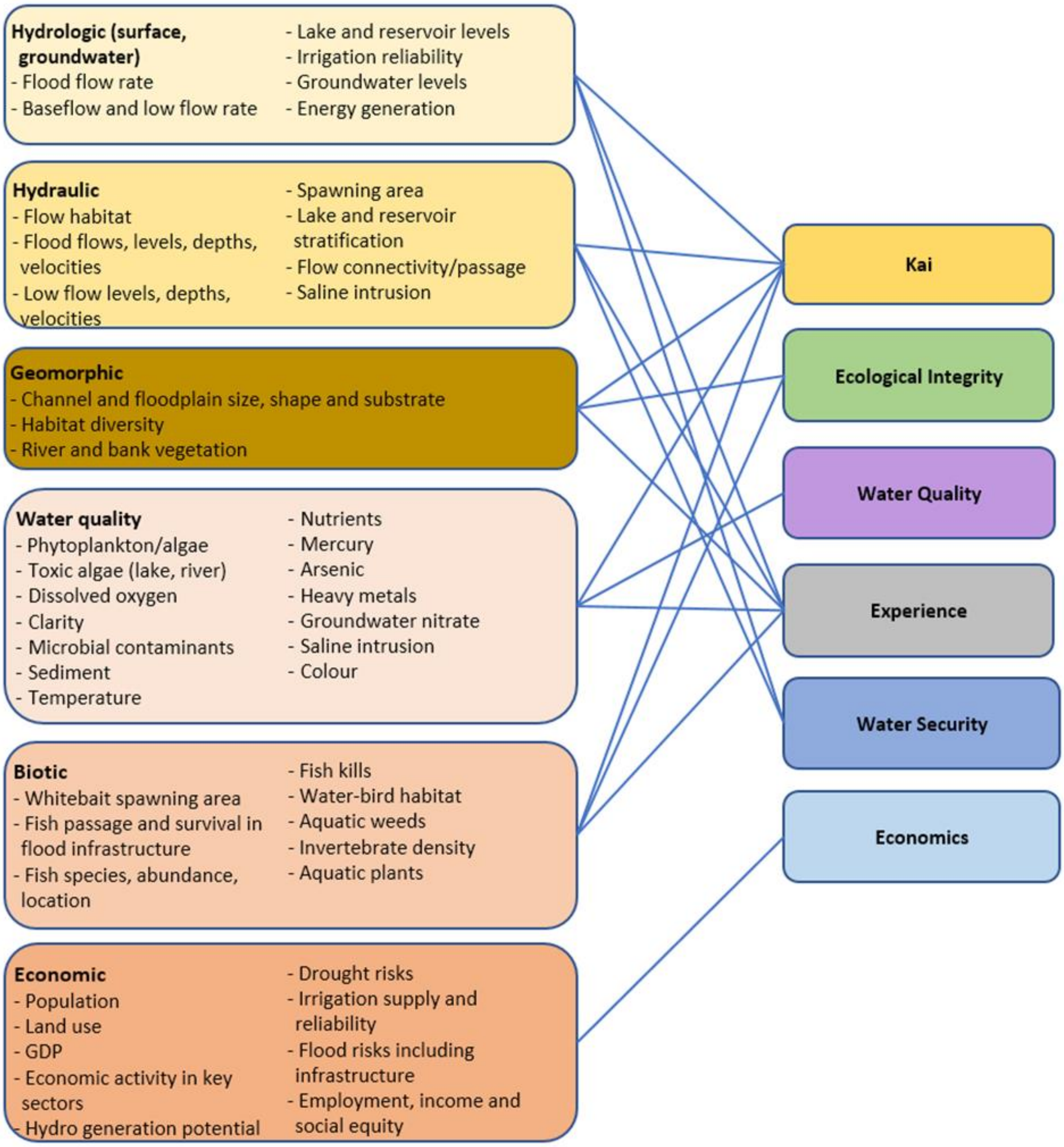

Figure i: **Relationships between model classes (left) and taura (right).**

Although these model variables guide model choice, other factors must be considered when selecting and applying models. These include the temporal and spatial scale and resolution, the specific processes represented, whether the model code is open source, history and prior experience of use, and factors related to user experience such as documentation, parameter guidance and calibration features, user interface, availability of support, and ability to link to operational forecasting. These considerations led to a list of key model types and the technical attributes required to address the needs.

Previous uses of dynamic models in the Waikato were reviewed, because it is desirable to build on existing models to avoid duplication of effort or institutional disruption, provided that the models are able to meet the needs identified by the waananga, and to learn from previous modelling.

Twenty-four previous model applications were identified and summarised, covering many of the main model types. It was found that the collection of past modelling efforts is fragmented and patchy in terms of spatial coverage, model types and providers. We conclude that previous modelling efforts point to the need for the proposed model system to have: a more integrated and consistent open-source approach, complete spatial and temporal coverage, and enhanced ability to simulate key processes occurring in the catchment.

Proposed models

Table i lists candidate models which were selected to address the identified model type requirements.

Table i: Required model types and candidate modelling software.

Model type	Proposed model software
Contaminant generation	SWAT
Groundwater quality and quantity	MODFLOW
Flow routing in mainstem and reservoirs	D-Flow 1D
Reservoir hydraulics and water quality	D-Flow-3D and D-Water Quality
Mainstem water quality model	D-Water Quality
Shallow lakes and Lake Taupō 1-D[3]	GLM-PCLake+
Storm flow generation and routing to streams	D-Hydrology (formerly WFLOW)
Water resources model	Not yet identified. WEAP is a low-cost proprietary option.
Habitat suitability mapping in lower river	D-Flow and mapping
Operational forecasting for flood flows and water quality	FEWS
Cyanobacteria model	Machine learning, R
Fish habitat creation by floodgate modification	D-Flow and mapping

There are some inter-dependencies between models. For example, the mainstem water quality model depends on tributary inputs, which are provided by a contaminant and flow generation model. Hence, some models would need to be run in sequence to represent the full system. These dependencies are addressed in the body of the report.

We have excluded models for fish abundance and movement, and river bio-geomorphology from the list because the capability of models are not sufficiently mature for management applications. We also excluded economic implications of biophysical models, because those assessments can be made when needed based on results of the proposed work, and we excluded land-use evolution spatial modelling (that is, models which simulate the development of land use in time in response to factors such as geographical features, infrastructure, economics, and planning regulations) because we considered it has a lower priority in the current context.

[3] 1-D, 2-D or 3-D models refer to the number of spatial dimensions included. For 1-D model, there is only variation in one dimension. Depending on the context, for a 1-D model the variation may be down the river (averaged across the cross-section), or vertically over the depth of a lake (well-mixed across the lake), so the dimension of variation or type or lateral averaging should be specified in addition to the number of dimensions (except for 3-D models), unless the meaning is clear by the context.

For water quality in the mainstem, we considered a range of models, and compared two of them (CE-QUAL-W2 and D-Water Quality) in more detail, concluding that D-Water-Quality is best suited to meet the identified needs. For reservoirs, however, the 3-D nature of the model may require simplification to be appropriate for use for long-term simulation.

We considered that for cyanobacterial forecasting, machine-learning models may be used instead of mechanistic models, because it is difficult to predict cyanobacterial biomass well using mechanistic models. The machine-learning model can use predictions from other models, such as reservoir stratification models, as part of the model inputs, however.

For rainfall-runoff modelling, some uncertainty about the particular model to use within the D-Hydrology framework persisted. We therefore recommend an inter-comparison of models within D-Hydrology as an initial step in the work programme and selection process.

We anticipate that model computational requirements will be large considering the large catchment area, spatial detail, and long time periods to be covered by some of the planning simulations, so that for at least some applications, the model will need to be implemented on high-performance computing infrastructure rather than a desktop computer.

Proposed modelling and data collection programme

An ambitious staged programme of work (to be undertaken over a 5-year period) was proposed in this report, comprising 15 main tasks. These include development of individual models as well as co-ordination and training of PhD students and management.

Data needs for the models were identified. Some of these data are available freely, other data are available but will need to be purchased or licenced, and further data will need to be collected. The new data includes high-resolution water quality data, vertical reservoir profiles, water use data, and vegetation maps of the lower river.

The system of models will require supporting institutional arrangements associated with ownership of and access to models and data, maintenance, training, management of proprietary data, governance, model coupling, and provision of high-performance computing facilities, all of which in turn will require a centralised 'home' and a co-ordinating agency. In addition, there will be an ongoing need for targeted resources to ensure that the models remain accessible and fit for use by Iwi.

The proposed programme of work has been devised so that components can be selected, and dependencies between models are recognised.

The system of dynamic models involves a large estimated cost – **$8.4 million**. This is a very preliminary estimate which may be subject to significant change. Data collection accounts for approximately $2.8 million of the total cost. This cost is larger than the amount provided in the draft version of this report, due to the addition of Lake Taupō water quality modelling in the revised report. These costs are indicative and should not be used as the basis for detailed planning, procurement or contracting.

The level of funding required is likely to exceed the resources that can be assembled in a short time. Based on feedback of the draft report, it was agreed that further consideration needs to be given to prioritisation and staging of work. To this end, is was proposed that additional funding be used to:

- Prepare a short document summarising the uses and value proposition for the proposed models and data collection.
- Hold facilitated workshops with Iwi and stakeholders with an emphasis on prioritisation of future work, resourcing the work proposed, and governance.

This additional preparatory work is anticipated to lead to more detailed specifications of tasks, more accurate estimates of cost, and a work plan that could be used for procurement and contracting.

Acknowledgments

We wish to recognise the input and guidance from the late Dr John Quinn. John arranged for a team to contribute to this project, which would not have been possible without his standing in the water science and management community. He also provided a structure for the needs assessment, centred on Report Card taura, building on his wide-ranging knowledge of freshwater ecology and management.

We wish to thank and acknowledge the River Iwi – the project has become more holistic in nature due to the advice and direction provided by them.

We also wish to thank the Waikato River Authority, Mercury NZ, the Waikato Tainui-Mercury Partnership, DairyNZ, Waikato Regional Council, NIWA, and the University of Waikato for direct or in-kind co-funding of this work. Individuals who provided advice and information include:

- Tim Manukau (Tim Manukau Consultants)
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- John Hadfield, Derek Phyn, Bevan Jenkins, Ghassan Basheer, Ed Brown, Murray Mulholland and Thomas Wilding (WRC).

1 Introduction

1.1 Purpose and scope

Management of the Waikato River requires predictions of how land use change and restoration activities may improve water quality and freshwater ecological health, and availability of water resources. This information is required to assist with achieving Te Ture Whaimana o Te Awa o Waikato – Vision and Strategy for the Waikato River[4] (Waikato River Authority 2019), which is embodied the Regional Policy Statement for the Waikato Region. To this end, the Waikato River Authority (WRA) along with project co-funders and River Iwi wish to develop a broad and holistic modelling approach that considers a wide range of needs (in this context a "need" is an information need or a purpose to which that information might be put). Accordingly, NIWA was contracted to undertake a study to review relevant models and select a set of models able to predict water quantity and quality and associated ecological responses. These models would operate across the entire Waikato-Waipa river system, its tributaries, and catchment including Lake Taupō[5], consistent with the broader needs of the Vision and Strategy. The emphasis of the proposed modelling is on biophysical conditions and processes – modelling social, human or economic systems was not included in the project brief and so was out of scope.

Rather than using a single integrated 'Waikato River Model', we have determined that a set of models would be required to meet the range of needs, and in some cases it would be best to link different models together. Hence we refer to 'Waikato River Models', to refer to multiple models.

The scope focussed on *dynamic* (temporal or timeseries) modelling, to provide predictions over time, rather than simply time-averaged or static predictions. Several factors favour this approach: a) water quality and ecology depend on process that interact and vary over time; b) some key metrics of interest are related to extreme conditions such as floods or low flows; c) uses of water depend on the timing of critical events (for example, algal blooms at low flow); and d) the time likely to be required for the river to recover via restoration activities is of interest. These predictions are also required in a spatially distributed and connected way, because the impacts of activities and uses of water depends on location, and those impacts can be cumulative and can occur kilometres downstream from the activities. Various applications of dynamic models were anticipated at the inception of this project; for example, dynamic flow modelling can lead to refined flow management such as targeted flow augmentation to enhance inanga spawning success, and hydro reservoir releases could potentially be managed to reduce risks of algal blooms in the river.

Models have already played vital roles in supporting water management and planning for the Waikato River. Examples include the Waikato Catchment Model used in the Waikato River Independent Scoping Study (WRISS, Rutherford et al. 2001; NIWA 2010), simple models used in Healthy Rivers/Plan Change 1 deliberations (Yalden and Elliott 2015), and hydrological models used to forecast river flows (see Appendix A). However, more refined predictions of the response of river flows and water quality to a range of catchment and in-river interventions are needed to support planning and catchment remediation activities. For example, predictions of algae growth down the mainstem of the river used for the Healthy Rivers process did not take temporal dynamics into

[4] Te Ture Whaimana o Te Awa o Waikato – Vision and Strategy for the Waikato River. https://www.waikatoregion.govt.nz/Council/Policy-and-plans/Regional-Policy-Statement/RPS2016/Part-A/2/5/1/.
[5] It was confirmed in feedback on the draft report that Taupō should be included in the scope.

account, and instead relied on simple empirical relationships between nutrient sources and river algae that had considerable uncertainty.

A key principle for the proposed modelling approach is to develop a co-owned set of models with open access. Currently available models for the Waikato are fragmented in terms of ownership and spatial coverage and are often based on proprietary software available only to a limited set of specialist providers. Instead, we propose a more open and community-based integrated approach to widen engagement with modelling, support co-management of the river system, and serve a range of stakeholders into the future. Ideally, the system would consist of models that are open-source, free, and have freely accessible input datasets.

The nature and complexity of dynamic models means that direct users will require a high level of technical skill. Building such capability would be enhanced through a collective project that includes research and education opportunities through the Te Waiora Joint Institute for Freshwater Management, Waikato-Tainui College, Crown Research Institutes (CRIs), and Iwi entities.

It is intended that the models would also be used indirectly by a wide range of users, such as planning by regional government and Iwi, design and evaluation of effects of restoration activities by planning and restoration practitioners, and by the public for flow and water quality forecasts. Links to higher levels of model use, such as for planning or for the public to access forecasts, are expected to be enhanced by the engagement of a wide range of organisations.

This study was funded by the Waikato River Authority as the cornerstone funder, with co-funding from NIWA, Waikato Regional Council (WRC), University of Waikato, Mercury Energy, the Waikato Tainui-Mercury Partnership, and DairyNZ. The project was led by NIWA, with technical contributions from the funding partners. River Iwi were also involved with development of the plan through engagement during the project. The wide base of parties was intended to set a foundation for a broad model of ownership and funding.

Dynamic models of this scale require considerable investment to set up, run and maintain, including collection of data. Hence, this project addresses the needs, suitability and benefits of modelling to guide investment. Also, this project aimed to address both long-term aspirations and more pragmatic shorter-term model development goals.

1.2 Process followed

The overall scoping project went through the following steps:

1. Hold a waananga (workshop) with the project group to discover river modelling needs and the goals of key stakeholders in the management and restoration of the Waikato and Waipa River catchment. The needs and goals were organised around Report Card taura (metaphorically, strands of rope interwoven to form a whole) used in the WRA Report Card processes, to ensure that models would be relevant to those taura and driven by the high-level experiential goals reflected in the taura.

2. Writing a main report (i.e., this report) covering: summary of past and existing modelling; identification of model needs and opportunities arising from the waananaga and technical considerations; evaluation of modelling options against identified needs; and preparation of a draft plan for model development (including a development pathway, input data requirements and plan, uptake pathway, timing, and resourcing).

3. Obtain comment on the draft report from the co-funding partners and River Iwi, including general feedback and views on priorities.

4. Finalise this report, taking comments from funders and Iwi into account, including defining a pathway for future development and implementation of the river models.

This report:

- Describes the waananga process and documents the needs arising from the process.
- Summarises how a set of modelled variables can relate to needs identified in the waananga, translates these quantities into a set of model types, and identifies associated attributes (characteristics) of each of the model types.
- Identifies other factors related to model choice, such as data needs and availability.
- Reviews past dynamic modelling in the Waikato.
- Identifies model software to address each of the model types.
- Proposes model development and tasks and provides an indication of resource requirements.
- Proposes next steps.

2 Model needs and opportunities

2.1 Initial discussion with River Iwi

Tim Manukau met and held discussions with representatives of River Iwi prior to the waananga; he subsequently presented initial ideas arising from those discussions. While Tim Manukau does not represent River Iwi, he is assisting with development of the model by leading River Iwi engagement. A key common question from River Iwi was "

> *How would the proposed model assist iwi achieve their goals and outcomes for their waterways, and help support the restoration initiatives they are currently undertaking or looking to undertake?*

Several roles for modelling were identified. The model should:

- take a holistic approach, representing all well-beings
- identify impacts on customary activities that occur on the river
- identify the effectiveness of the Healthy Rivers Plan Change (River Iwi were heavily involved in the development of this plan) and associated actions
- be suitable for evaluating effectiveness of restoration projects
- aim to also protect the Mauri of the river, not just biophysical components
- link to and help achieve the Iwi Management Plan goals.

It was noted that River Iwi have heavy workloads and their own work priorities, therefore they will determine for themselves when, if and how they input to the project. The project should align with existing iwi management plans and iwi led initiatives, i.e., Report Card and Iwi restoration priorities, rather than re-inventing the goals.

River Iwi stated that appropriate resourcing and support should be made available to ensure the involvement of River Iwi in the next phases of the project, including providing River Iwi with a leadership role.

2.2 Description of the waananga process

A waananga was held at NIWA in July 2018 to: elicit modelling needs from the project partners; identify existing models; and gain input on modelling priorities and aspirations. Those present at the waananga and their affiliations are listed in Appendix B.

Separate discussions were held with River Iwi, led by Tim Manukau in an independent role.

As an organizing aid, the meeting discussions were framed around the eight taura used for the Waikato River Report Card (RC) (Waikato River Authority 2016; Williamson et al. 2016), which in turn built on frameworks developed for the Waikato River Integrated Scoping Study (NIWA 2010). The use of the taura approach provided a link to the holistic approach that had been promoted by River Iwi. For each taura, biophysical indicators related to the taura were listed, opportunities for dynamic modelling were identified, and other needs and opportunities were gathered.

Taura were adopted as a framework for needs elicitation because the higher-level values associated with the taura have been related to biophysical metrics as part of the RC generation, and those metrics can be related to biophysical models (although not all aspects of the taura can necessarily be related to biophysical metrics). The taura, which are described through experiential outcomes and goals, are as follows:

- Kai: Our kai are healthy, have a strong whakapapa, are safe to eat, locally abundant, and can be harvested according to our traditional practices.
- Ecological integrity: Our kai have access to healthy habitats protected from adverse effects due to adjacent land use, and which enhance our associated practices.
- Water quality: Our land use and development practices support water bodies that have water that is safe to drink and physically interact with).
- Water security: Our land use practices, and land development supports communities and taonga species having access to life-sustaining supplies of water.
- Experience: We have a flourishing and nurturing connection with the rivers, and we are empowered to pursue and maintain our positive interaction.
- Economics: Communities are prosperous, as shown by high levels of employment, housing affordability, gross domestic product and income equality.
- Sites of significance: Our sites of significance are forever recognised and celebrated as areas of historical and cultural importance, are safe for us to interact with, and support a healthy Awa.
- Effort: Communities, businesses and individuals are engaged in comprehensive contaminants control and rehabilitation to achieve the Vision and Strategy.

Many aspects of the taura are inter-related. For example, water quality affects kai. Hence, the quantitative metrics related to a particular taura are shared with other taura to form a web of interactions, rather than a clear compartmentalisation. Nevertheless, the taura and associated metrics and model needs serve as a useful initial organising framework.

Notes were taken in Visimap[6] mind-mapping software. The resulting structured list of points have been exported from this software and are presented in Appendix B. Similarly, a mind map was developed for capturing existing available models. Further discussion notes, including assessment of key modelling needs, were captured on post-it notes and whiteboards, and another mind-map was developed to summarise the modelling needs discussion. Extensive meeting notes are included in Appendix B, along with a rich array of ideas and needs. Selected key points are summarised below, followed by further discussion and organisation of the needs.

[6] https://www.coco.co.uk/prodvmpro.html

2.3 Aspirations and opportunities

The waanaga identified several high-level aspirations and opportunities that can be used to set the tone and direction of the modelling. These are summarised below under two themes, relating to: a) aspirations for a holistic, robust model (or set of models) that meets needs for decades to come; and b) potential uses and users of the model.

Holistic, excellent, long-term

- Aim for excellence (a set of models that can be trusted, is scientifically robust, is a leader at a national level, and is a source of regional pride).
- Take an integrated, whole-of-river view rather than piecemeal and fragmented.
- Examine holistic aspects of river health, not just biochemical components.
- Aim to ultimately serve the river as an entity to meet the needs of the river to protect its Mauri.
- Models should support assessments of multiple aspects of wellbeing, such as economic, social and cultural aspects (see the Mauri Model of Morgan 2004).
- Can link models to other dynamic models, such as those that address population pressures and land use change, economics, and social well-being.
- Build a model that can be used in the long term (decades), rather than just to solve immediate needs. This involves allowing for extension and adaptation of the models in the future and including long-term aspirations in model scoping.
- Models that contribute to management actions leading to river protection and enhancement are important for tourism.

Supports a range of uses and users

- Link across spatial scales from farm plan to catchment outcomes, providing confidence for farmers to act.
- Supports the next round of regional planning.
- Models should identify locations to focus restoration and protection efforts:
  - which locations would likely recover easily or are sensitive to pressures
  - which areas would be difficult to fix or are resilient to pressures.
- Modelling could demonstrate cumulative benefits of mitigation and remediation actions and guide further actions.
- Models can both use and drive/guide monitoring and data analysis.

- Models can be used for extended purposes such as nutrient trading and economic optimisation.
- Model system can support multiple needs, such as short-term prediction, tactical farm management, assessment and planning of management measures including flood protection and irrigation schemes, predicting time trajectory of response to interventions, nutrient accounting and allocation including trading, long-term trajectory prediction including effects of climate change, and water allocation and use optimisation.
- A model system should enable visualisation of and easy access to model results in a way that is meaningful to the public.

2.4 Model needs and opportunities associated with the report card taura

This section lists the RC indicators used to assess each of the taura and the needs and opportunities for dynamic modelling associated with each taura.

2.4.1 Kai

RC indicators: abundance, location, size, condition, and recruitment of eel (tuna), whitebait (iinanga, smelt, kooaro, banded kookopu, giant kookopu, shortjaw kookopu), piharau (lamprey), kooura, kaaeo/kaakahi (mussels), trout, and waterfowl.

While not included in the initial RC indicators, mercury concentrations are also a potential concern.

Needs and opportunities for dynamic models:

- Providing flow rates and hydraulic conditions to predict and optimise spawning habitat and migration timing for desirable species, and minimising spawning of undesirable species.
- Predicting water quality and its impact on kai and food sources including dissolved oxygen (D0) and temperature, along with water quality metrics related to broader ecological integrity such as invertebrate abundance, and implications of algal blooms and mercury on food quality and safety.
- Predicting effects of climate change on flow and water quality and associated impacts on kai, and the invasive potential of pest fish.
- Fish abundance modelling through population simulation (this was not discussed explicitly in the workshop, but is implicit in the discussion of aspects such as fishery management and effects of invasive fish).
- Link flows and hydraulic conditions from dynamic models to hydraulic habitat availability [Not mentioned in the workshop].
- Predict lethal water quality episodes for fish.
- Mercury concentrations, including response to de-oxygenation.

2.4.2 Ecological Integrity

The RC indicators: water quality (DO, temperature, ammonium, arsenic in water and sediment, zinc in sediment), extent of riparian planting and shade generated by riparian vegetation, aquatic plants (amount and type including invasives), periphyton cover, macroinvertebrates (including metrics such as MCI, QMCI and EPT [7] metrics), native fish (diversity and abundance), pest fish abundance and types, water birds (scores derived from presence and types), and connectivity (fish passage and natural-ness of hydrology).

Needs and opportunities for dynamic models:

- Water quality modelling.
- Spread of pest biota.
- Fish passage and habitat access in response to changes in infrastructure; trade-offs between flood service levels and habitat enhancement.
- Dynamic river morphometric (channel and floodplain characteristics) and hydraulic modelling to predict habitat diversity.

2.4.3 Water quality

RC indicators: Total nitrogen (TN), total phosphorus (TP), clarity, chlorophyll, and *Escherichia coli (E. coli)*. With the exception of maximum chlorophyll, these indicators are median concentrations.

In addition to these indicators, the National Policy Statement for Freshwater Management (New Zealand Government 2020) includes minimum DO levels. Concentrations of mercury and arsenic are also of interest, as well as cyanobacterial concentrations and temperature, hence we have extended the range of potential water quality indicators beyond the RC indicators.

Needs and opportunities for dynamic models:

- Modelling minimum DO levels in rivers and lakes.
- Modelling temperature variations and maximum temperature.
- Modelling maximum algae levels: occurrence and frequency of blooms.
- Modelling cyanobacterial blooms (frequency, types, prediction).
- Providing improved predictions of median concentrations through better representation of processes.
- Examining opportunities to modify hydro releases (timing, depth) to minimize algal accrual.
- Examining opportunities for mixing structures or devices for stratified lake areas.
- Identifying when and where lake de-oxygenation causes mercury and arsenic release.

[7] Margalef's Diversity Index; Quantiative Macroinvertebrate Community Index; Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies)

- Opportunities to reduce losses of nutrients from farms by tactical management of farming operations (e.g., moving stock, taking paddocks in/out of production, irrigation and fertiliser timing).
- Predicting water quality in response to climate change.
- Predicting swimming quality (including clarity and microbial) to guide recreational activities (cultural, sporting, general recreation).
- Predicting lags in response of water quality to interventions (including establishment of vegetation, reduction of sediment stores, and groundwater load-to-come).
- Predicting hysteresis of water quality response to changes in source loading and rehabilitation efforts.[8]
- Couple with dynamic hydrological models to predict flow/quality interactions.
- Improve understanding of variations of water quality in the lower tidal reaches.
- Understanding how the river was in the past, to serve as a reference condition.

2.4.4 Water security

RC indicators: surface water allocations in relation to available allocable water; groundwater allocations in relation to available allocable groundwater; uptake of irrigation consent conditions; urban water use rates; nitrate in groundwater (relating to drinking water safety).

In the waananga, consideration was given to further aspects such as water supply reliability and flood risk.

Needs and opportunities for dynamic models:

- Prediction of flood risks and response to dam releases, climate change, sea level rise, land surface lowering due to peat shrinkage and modifications to flood infrastructure.
- Assessing the feasibility of land drainage under sea level rise and land surface subsidence.
- Prediction of low flows in relation to water abstraction, hydro power abstraction, land use change, climate change, and associated saline intrusion to water supplies.
- Predicting effects of sea level rise and climate change on flood protection and drinking water abstraction infrastructure.
- Flow predictions are linked strongly to other taura and indicators such as ecological flows for kai and water quality and changes in channel geomorphology.

[8] In this context, hysteresis is a non-linear response of environmental state (e.g., water quality) to pressures (e.g., contaminant loading) whereby the state for a given pressure depends on the history of pressures.

2.4.5 Experience

RC indicators: *E. coli*; cyanobacteria; visual clarity; physical access; navigation; rubbish; signage; sewage.

We suggest that water odour and colour would be further attributes of interest related to experience

Needs and opportunities for dynamic models:

- Predictions of current state and future state at sites of interest and spatially.
- Prediction of low-flow river depth for boating, waka, boat launching and swimming access.
- Prediction of lake levels for recreational access.
- Prediction of river levels, swimming physical safety, river path inundation in floods.
- Water quality related to experience: long-term average conditions and short-term conditions.
- Prediction of algal blooms for aesthetics, health risk, odour, and colour.
- Identify good locations for recreational activity.
- Predict and reduce the incidence of fish kills.
- Model human interactions with rivers – what guides decisions on where and when to use freshwater, perceptions of suitability over time and in response to restoration?
- Need to present dynamic model results in ways that are meaningful to people and that they can access (summary metrics, graphics, web delivery).

2.4.6 Economics

RC indicators: Regional gross domestic product (GDP), employment, house affordability, income, income equality

Needs and opportunities for dynamic models:

- Predict population, land use, urbanization, key economic sectors such as tourism, GDP, export earnings, and socio-economic metrics over time.
- Hydro generation potential and associated optimisation.
- Effects of flood infrastructure on flooding risks and associated optimisation.
- Irrigation reliability and associated optimisation schemes.
- Predict economic implications of climate change related to freshwater.
- Inform assessment of risks to communities and economic shocks associated with floods or droughts.
- Costs to meet water quality goals.

2.4.7 Sites of significance

RC indicators: No indicators are currently in the Report Cards

Iwi expressed a strong preference to discuss and progress assessment of models in relation to sites of significance to Iwi. Therefore the needs of this taura for dynamic models has not been assessed. It was noted at the waananga that there were likely to be some links to biophysical risks such as river erosion. Other potential aspects are Significant Natural Areas (areas of ecological/biological significance).

2.4.8 Effort

RC indicators: Dairy shed discharge consents, farm diffuse pollution controls, stream, wetland, lake and biodiversity rehabilitation, aquatic pest fish and plant control.

Needs and opportunities for dynamic models:

- Predicting magnitude of responses to restoration actions.
- Understanding time lags between restoration actions (e.g., riparian planting/fencing, wetland establishment, conservation tree planting) and responses.
- Understanding timing of responses could be used to prioritize interventions (which should be done first, where to spend money, locations).
- Provide better models to demonstrate cumulative effects of mitigations and rehabilitation done at multiple locations.

2.5 Synthesis of needs for dynamic models arising from the taura

The waananga provided a rich list of model needs associated with the report card taura. We have summarised and re-organised the needs by class of variable that are related to RC taura, and then linked the variables to types of dynamic models. By doing this, we can translate between model types/capabilities and taura, which sets the scene for identifying and selecting dynamic models.

2.5.1 Summary of model variables associated with taura

The variables that can be predicted by dynamic biophysical models with respect to each of the taura are summarised in Figure 2-1. The figure illustrates how quantitative variables such as these can be useful for assessing the current and future status of the taura. The Effort taura is not shown because it does not have dynamic model variables directly associated with it (although responses to mitigation effort is an important use of the models). Likewise, the Sites of Significance taura is omitted because indicators are not yet available.

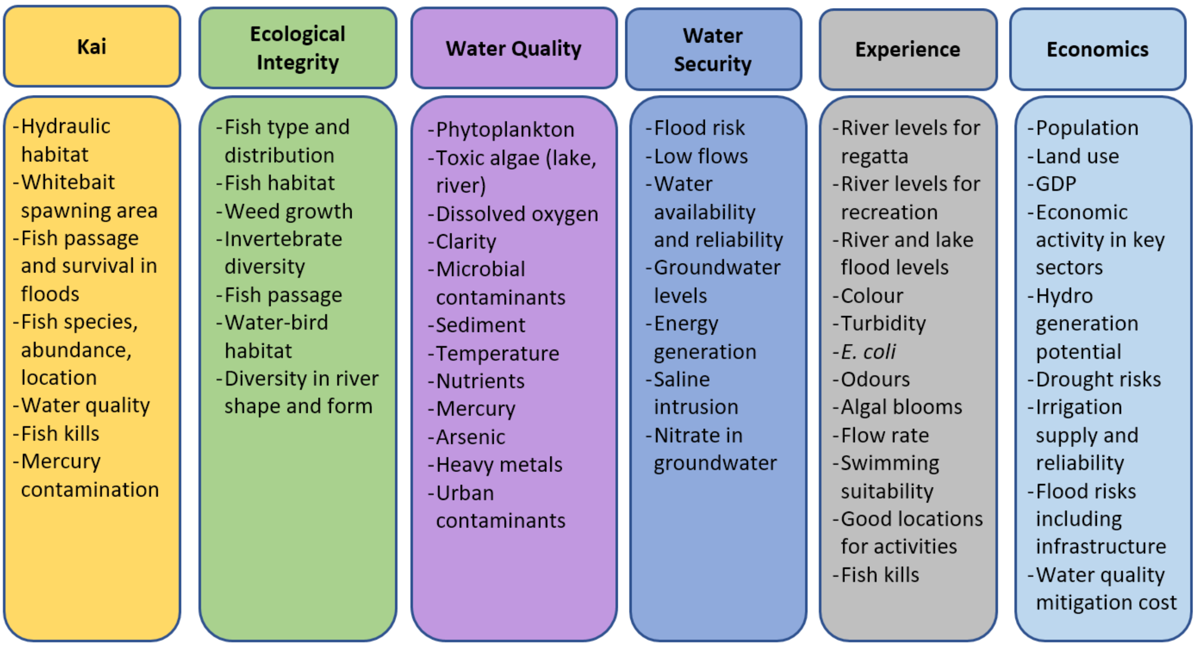

Figure 2-1: Key variables (bottom row) related to taura (top row) that dynamic models can address .

2.5.2 Link from models to predicted variables and taura

Dynamic models are often organized by the type of variables and processes that they represent, such as hydrology; hydraulics; water quality; biota; and economics (although integrated models can address several of these at once). We have therefore grouped model variables and related these groups to the taura, as shown in Figure 2-2. This helps to translate from the taura-derived variables into a model identification and selection process. For the sake of simplicity, some interactions are not shown, e.g., some of the hydrologic variables influence the economic costs of floods, and the taura themselves are interlinked.

As a further step in selecting a system of dynamic models, key dynamic model types were identified and related to the key model variables (Figure 2-3). Again, for the sake of simplicity, not all linkages and dependencies are shown.

When Figure 2-1 is combined with Figure 2-2, a train of linkage between model types and report card taura as shown in Figure 2-3. Model types are addressed further in Section 2.7.

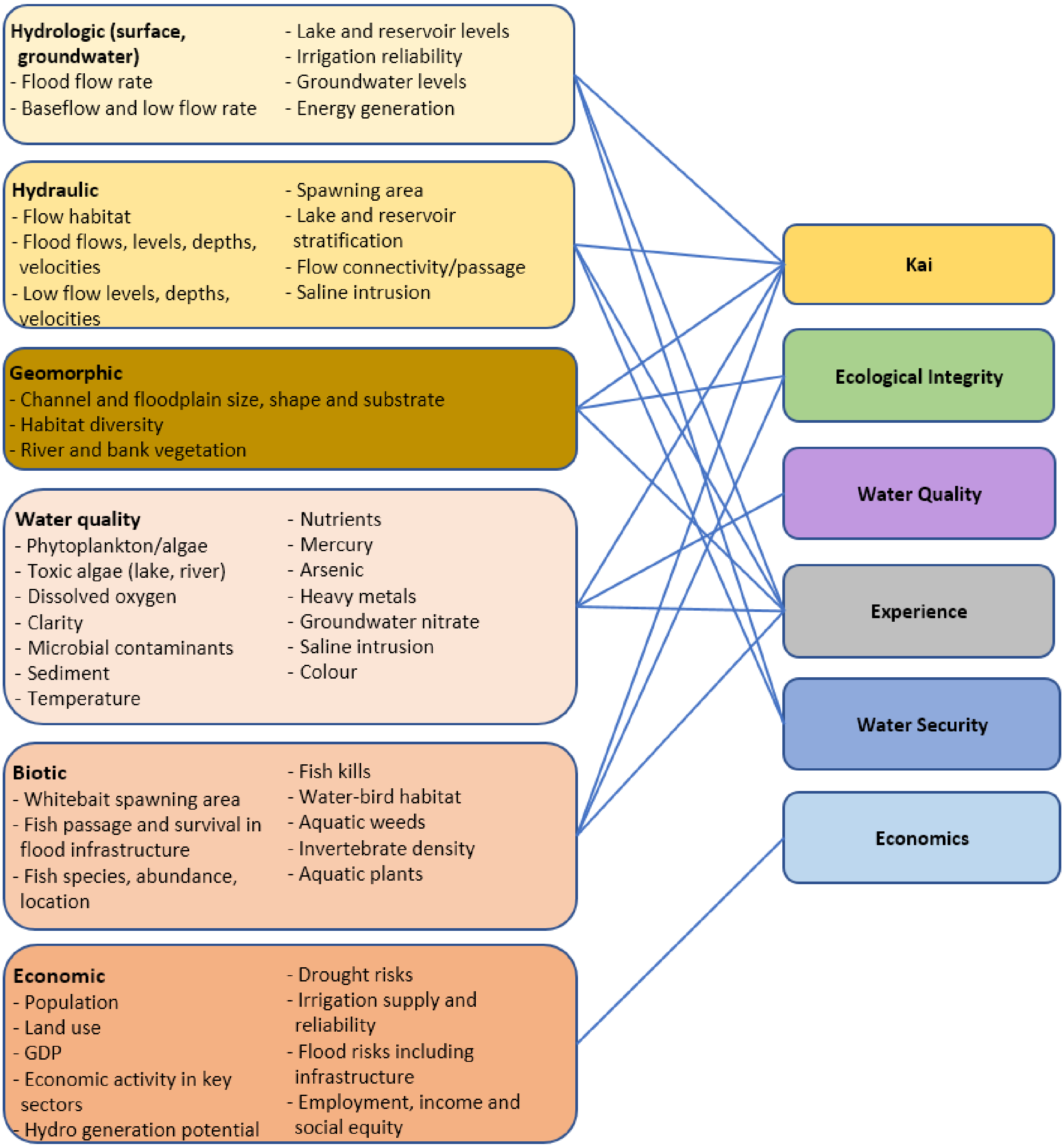

Figure 2-2: Dynamic model variables organised by model type. Direct linkages from variables to taura are also shown.

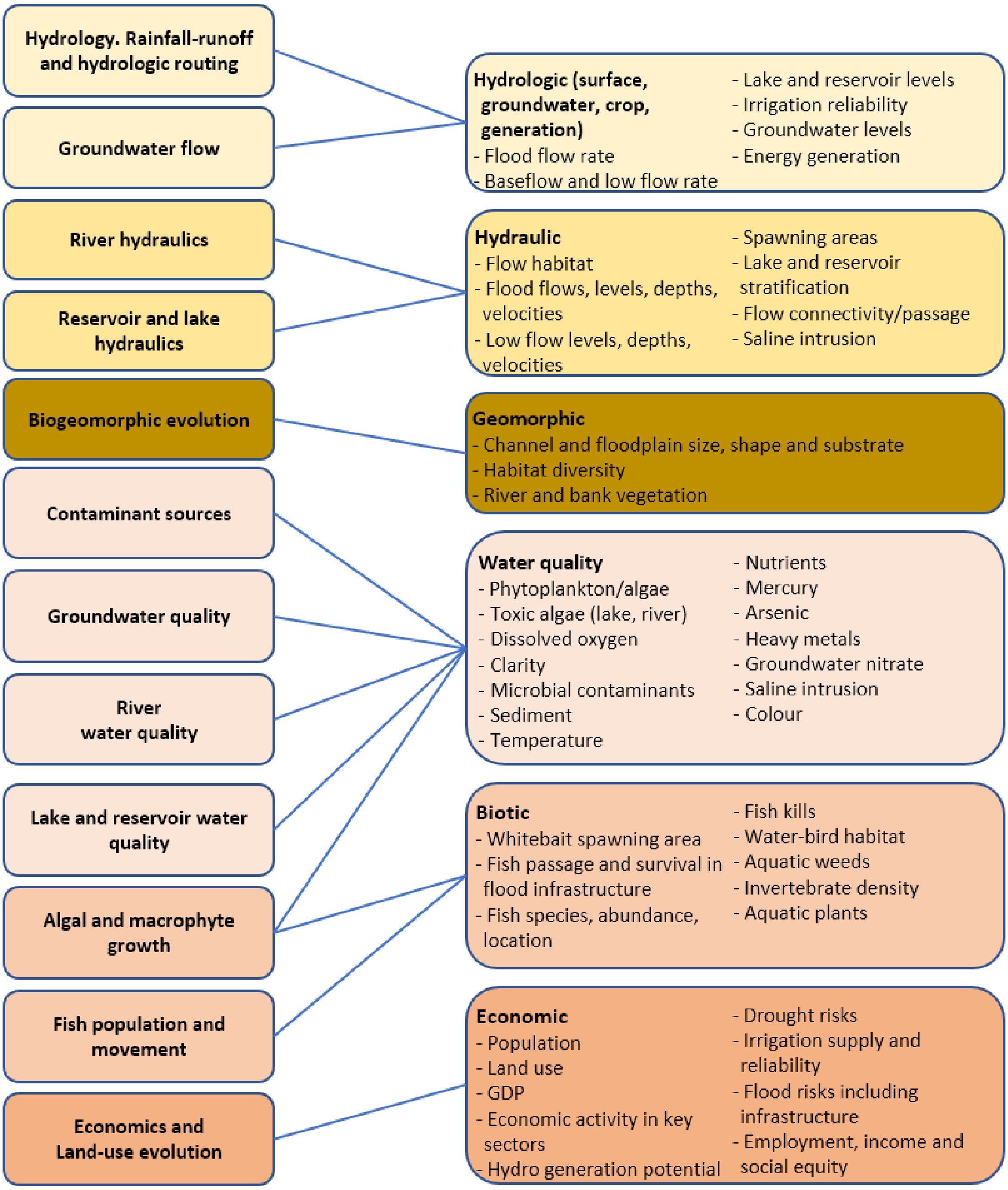

Figure 2-3: Relationship between model types and modelled variables related to taura.

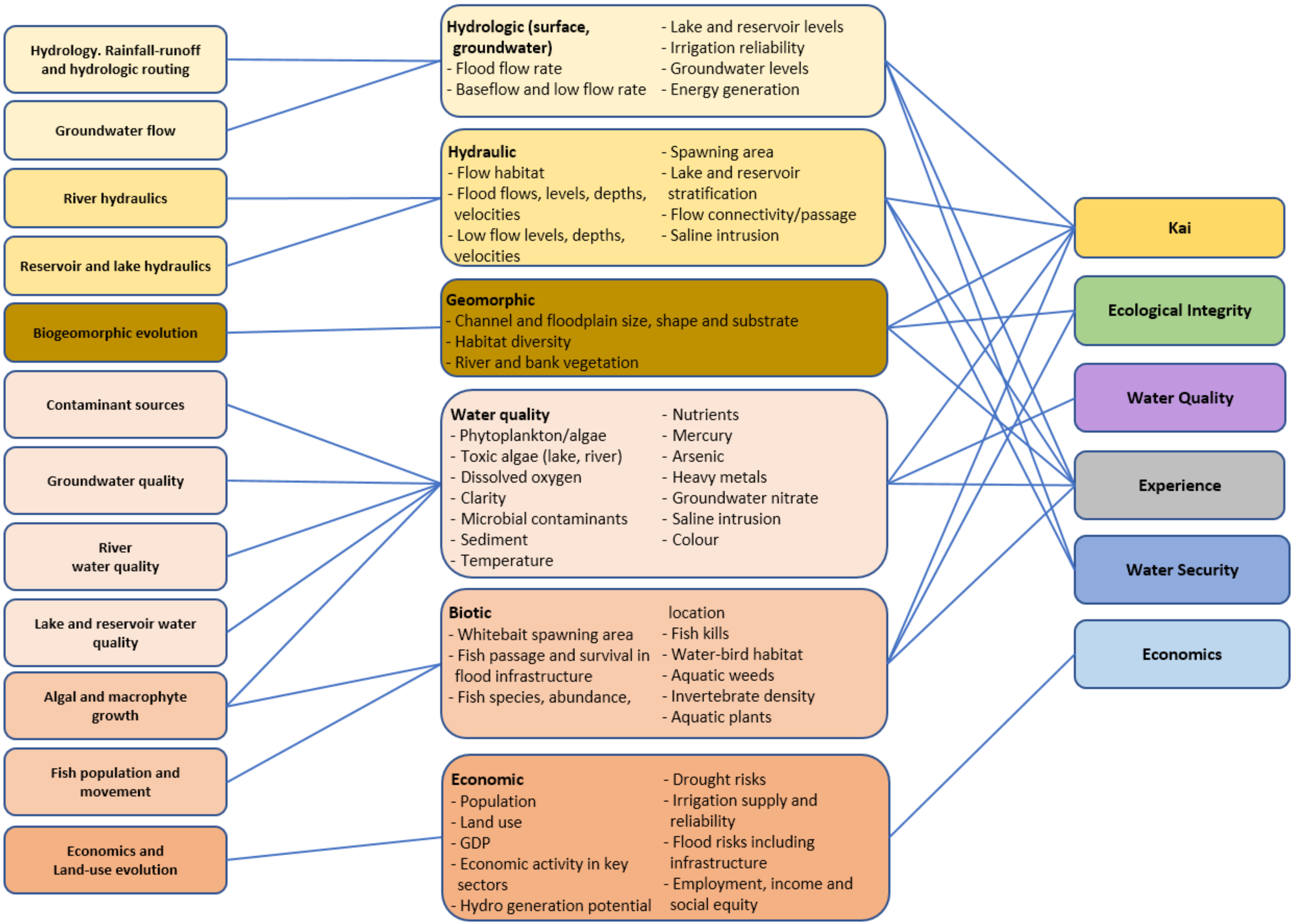

Figure 2-4: Linkage from model classes to taura.

There is also a hierarchy within these models which will help with design of a model development programme. For example, water quality models usually need flow rates and therefore could require coupling to hydrological models; similarly, fish behaviour models may require hydraulic models to identify potential habitats. The hierarchy is somewhat loose – for example, a water quality model does not necessarily require a hydrological or hydraulic model, and economic models do not necessarily need biotic models. Moreover, there can be feedbacks between geomorphic conditions and hydraulics, and between aquatic plants and water quality.

2.5.3 Temporal and spatial resolution and scale

This section defines what is meant by temporal and spatial resolution and scale, and how time and space are represented in models and the interactions between them.

Temporal resolution, or model time-step refers how finely time is divided (i.e., the model time-step). The required resolution will depend on the intended model use.

Dynamic modelling of nutrient generation and transport to a stream network is usually done with a daily time-step. In reality, sources of contaminants associated with sediment can vary on a sub-daily basis in response to runoff events or re-entrainment of streambed materials. Usually, such variations are overlooked or represented in an approximate way. Concentrations in reservoirs and the river main-stem are not likely to respond to sub-daily variations in contaminant inputs, so fine-scale representation of the timing of contaminant inputs to the mainstem may not be important.

Simulation of DO levels in streams and rivers ideally requires representation of processes such as photosynthesis at a sub-daily time-step. For example, DO in streams usually varies over a day, and the minimum daily oxygen level is of interest in terms of effects on biota. Typically, an hourly resolution would be adequate. It is unclear whether such sub-daily variations in DO extend to the mainstem. For lakes, DO in the deeper parts of the lake that are subject to de-oxygenation does not vary through the day, so a sub-daily model is not required.

River flood models also typically require sub-daily resolution (say, hourly), at least for tributaries, because flow can vary on that timescale for the tributaries during and following rainfall. On the other hand, the variations for the mainstem are likely to be slower (see, for example, Jowett 2009). Even so, the mainstem is likely to require sub-daily calculations, because controlled hydro reservoir releases during floods could vary during a day, and settings of flood infrastructure (e.g., gates) could also vary during a day. Prediction of hydraulics and inundation in the lower river would also require a sub-daily model to capture the influence of tides.

Prediction of baseflow and low flow would not usually require sub-daily models, because such flows do not change much over a day. However, hydro reservoir releases routinely vary on a sub-daily basis in response to energy generation demand. Hence, for the mainstem of the Waikato River at least, a sub-daily model would be required.

Groundwater flows and contaminant concentrations usually vary little over a day or week, so groundwater does not need to be modelled at a finer scale than daily.

Modelling of phytoplankton growth would generally require a daily time-step at least. Although there are variations of growth and metabolism within a day, the rates can be averaged over a day (for example, photosynthetic production as a function of daily average solar radiation).

Biotic growth and population models can be simulated with a daily model, although some aspects of fish movement could benefit from a sub-daily model (for example, response to tides or opening of flood gates).

Seasonal variations of contaminants are of some interest. However, dynamic contaminant modelling is usually carried out with a daily time-step or finer, so there is no particular use for a model that would operate at a seasonal scale.

Population, land use change, and economic models would usually not consider sub-annual variations; for example, the WISE integrated model operates at an annual time-step (Appendix A).

While the above considerations set the minimum required time resolution of a model, the model may actually run internally at a finer time-step, for reasons of computational stability and accuracy, especially if a fine spatial resolution exists.

The **time scale** refers to the overall duration or period of time that the model calculations need to cover (e.g., a runoff event, season, year or decades).

Models that are used for short-term prediction of flows might need to run to cover a few days into the future. In reality, a model is also likely to require an additional warm-up period to settle down or stabilise, following which realistic predictions are likely to be produced.

Models intended to predict long-term average conditions and the statistical variations of those conditions may need to run over several years' duration.

Predicting the long-term response time of catchment conditions to interventions (for example, groundwater lags or recovery of biotic populations) requires that the model is run over a time period comparable to the response time of the system – perhaps decades. As an example, capturing the load-to-come for nitrogen associated with the response to historical land use change may require multiple decades of simulation if the groundwater lag time is long (and if little denitrification occurs along flow pathways).

Climate change takes place over decades. Often, rather than simulating the freshwater system over long periods, a model will be run for, say, a decade as an exemplar of the effects of future climate conditions.

If hydrodynamic models are used and flows across the modelled area are stored before calculating water quality, then the storage requirements for long-term simulation can be prohibitive. In such a situation, modelling approaches whereby water quality is calculated in parallel with hydrodynamics are needed (with the downside that hydrodynamics must be recalculated for each water quality simulation).

The desired model use also influences choice of model **spatial resolution and scale** (e.g., small grid cell or an entire catchment). For example, spatial allocation of nutrient sources or abstractions would ideally work at a fine spatial resolution. However, there is typically not enough information at such fine resolution to enable such detail to be captured over the full catchment. This means that various averaging approaches are taken, such as using representative farm types rather than collecting and collating data from individual farms. Some catchment properties, such as soils and land cover, are important for runoff and contaminant generation, so the model will ideally resolve such variation. A common approach is to examine the response of computational units representing unique soil-cover combinations, and then apply the response over space to other locations with the same combinations (this is the so-called hydrological response unit (HRU) approach). Another example is macrophyte growth in rivers or lakes, which varies over space in response to variations in substrate and hydraulics, yet it is impractical to model such fine variations over large areas, necessitating use of reach-average or depth-average conditions.

Hydrologic and contaminant generation models are also categorised according to whether they are lumped, semi-distributed, or fully distributed. Lumped models have single values of parameters across the modelled area. Semi-distributed models have some spatial differentiation of catchment parameters (for example, different sub catchments could have different maximum infiltration rates), while fully distributed models allow parameters to vary spatially down to the limit of model resolution (for example, for each cell in a spatial grid).

The spatial scale of the Waikato Dynamic model has been set at covering the full catchment. However, we consider that it may be appropriate to conduct some aspects of the calculations at a fine spatial resolution for parts of the freshwater system nested within the larger system. For example, there may be parts of the lower river where it is of interest to model variations of hydraulic conditions at meter-scale resolution. Similarly, it would be appropriate to model how stratification varies downstream of some of the hydro reservoirs, requiring fine-scale resolution for those parts of the system. These nested models could be run for specific purposes, with boundary conditions provided by coarser-scale models; also, the full-catchment model could use simplified representations derived from the more detailed simulations to represent the behaviour of the more complex components in an approximate way when simulating the full system.

Time-space consideration. Models that have fine spatial resolution require longer to run. Hence, it is not practical to run fine-resolution models to provide long-term predictions. This is compounded by the typical need to run models at a fine time-step if the model has a fine spatial resolution, for reasons of computational stability or accuracy. Hence, while it is desirable to predict everywhere for all times, careful choices and trade-offs need to be made. Model simplification may play a role in these situations, but such techniques require considerable expertise, as could shifting calculations to a high-performance computing platform (a supercomputer or cluster).

2.6 Other factors affecting model choice and development

Factors other than variables provided, space-time scales and resolution, and model type can affect model choice. Some of these items are listed below.

2.6.1 Processes represented

- The hydro reservoirs have longitudinal variations in water quality and can become partially stratified. This has implications for selection of the lake or river model used. This is most relevant to deeper lakes such as Ohakuri and Maraetai and towards the tail end of Lake Karapiro (Bilinska et al. 2005).
- Within the small lakes, release of nutrients from the lakebed can be important, as can the presence and distribution of macrophytes, so those processes should be included.
- Releases of flows from the hydro reservoirs depend on flood release rules and power generation rules, and the river flow models should be able to represent such release rules.

- Groundwater systems play a strong role in the hydrology of the upper catchment and should be included (directly as a coupled groundwater-surface water model or indirectly through a simplified model) in flow and water quality models, addressing average and low flows.
- Adjustments to historical land use is likely to affect nitrogen sources into rivers, so that representation of historical land use change, future land use, and groundwater lags should be allowed for in a water quality model providing long-term predictions of nitrogen water quality.
- Water quality models need a bank erosion component, especially for the Waipa, and ideally some way of representing inputs from mass erosion events.
- Water resources models used to determine water availability require some representation of water demand, water abstraction, linkages between water abstraction and groundwater/reservoir flow, storage (local and hydro reservoirs) and water restriction rules. Such processes and data would be less relevant to prediction of flood flow.
- Representation of non-native macrophytes in reservoirs is of interest from a nuisance perspective at least (e.g., hornwort affecting hydro operations and recreation), and they should be included both in terms of predicting their abundance and representing their effect on water quality (recognising they probably have limited influence on overall nutrient budgets in the hydro reservoirs, Paul Champion pers. comm.). Inclusion of macrophytes is particularly important in shallow lakes because they affect water quality processes.
- There may be possibilities to reduce stratification and algal growth in reservoirs by constructing structures (e.g., curtain weirs) across the flow, selecting water from different depths for withdrawal, or applying vertical mixing (through bubblers or pumps). Bilinska et al. (2005) were sceptical that hydromodification would affect phytoplankton in the lakes, but Hamilton and Duggan (2010) suggested that this could be important. Hence it would be desirable to be able to represent the influence of artificial mixing and structures in the reservoir models.
- Removal of algae by zooplankton is likely to affect algal abundance and types (Gibbs et al. 2014), so it is desirable to include them in a water quality model.
- Some of the shallow lakes in the lower catchment influence cyanobacteria levels in the lower river, so their effect should be included when modelling cyanobacteria in the lower river.
- The mix of algal types in the river varies over space and time. A model of planktonic algae should represent the main functional classes (diatoms, chlorophytes, cyanobacteria), and preferably their competitive interactions, to improve model performance. We note, however, that models of algal types often have poor predictive performance (Shimoda and Arhonditsis 2016).

2.6.2 Other broader needs related to model use

- "Open source" is called for by some of the intended uses and users. Open source refers to whether the source code of the model is available for inspection and modification. This is desirable for the Waikato Dynamic Models in order to build confidence and credibility, enable modification to build additional features, and to avoid monopolisation by a single software provider. Usually there is a central developer or group of developers who act as gatekeepers for modifications to the reference code, and while these contributors often provide most of the new development, branches of a model may also be developed and ultimately fed back into the reference code by other researchers.

- History and experience of use. It is desirable that a community model have some degree of prior use, to provide confidence that the model is robust, that strengths and weaknesses are known, and guidance can be developed for selection of reasonable model parameters based on past applications. It is also desirable that the model has been used previously in the local setting and by the stakeholders. However, this needs to be balanced against the desirability of using new, relatively untested models that may have improved features and faster solution techniques.

- User experience

  - Documentation, support, training. A community model should have good documentation and support to enable new modellers to learn and adopt the models, rather than relying on a few specialists who have tacit knowledge. It is helpful to have a forum or wiki for sharing experience and obtaining advice.

  - Parameter guidance and calibration. Dynamic models can involve many parameters which can be difficult to set up. It is very desirable for guidance to be provided from model documentation or other means such as a wiki or through a user interface. It is also desirable for the model to be able to be coupled with parameter calibration/conditioning and uncertainty estimation software.

  - User interface. A graphical user interface is desirable to assist users with data entry and pre-processing of model inputs, and post-processing and visualisation of results (maps, plots, summaries). However, high-level users may prefer to edit input files or databases directly, display results through their own software, and run models through a command-line or scripting interface. Both types of interface are desirable.

  - The software developers or third parties may provide paid services to provide professional advice, which can be helpful for users and can provide funds for the developers, while still enabling competent users to access and use the software for free.

- Models should preferably be set up in a way that enables coupling them with other models. For example, using standard file formats and data structures will mean there is less need for translation, enabling models to 'talk to each other'. Ideally, the modelling approach would also conform to interoperability standards (responds to a standard set of model function calls), enabling constituent models to be linked in a co-ordinated way. As a part of model coupling, it is desirable for the model to be able to be run without a graphical user interface (for example, a model executable), even if the setup of the model and display of results happens via a graphical user interface.

- Ability to run on high-performance computing systems (HPC). Dynamic models often require considerable computing resources to run, especially at the spatial and temporal scales envisaged for the Waikato Dynamic Model. Calibration and uncertainty prediction often requires many model runs, which again requires high-level computing capacity.

- Maintenance and updating. If a model is not maintained – for example, due to cessation of funding or retirement of specialist developers - then errors in model code will not be remedied and improvements not made, or the model will not be adapted to keep up with changes in underlying software (for example, changes in ArcGIS have necessitated re-coding of various models at NIWA). This introduces risks and makes such models less attractive for adoption.

- An operational forecasting capability is called for by some of the model needs – (high flows, flow depths for recreation, forecasting risks of algal bloom and deoxygenation events). This usually requires a software infrastructure to enable short-term forecast, incorporation of observations to fine-tune the predictions, and dissemination of forecast data.

2.6.3 Lake Taupō

Model needs for Lake Taupō and its catchment were not addressed in the waanaga, because at that time the main emphasis was on the Waikato River downstream of Lake Taupō. However, in subsequent discussions it was agreed that Lake Taupō should be included in the scope of a Waikato model, because the lake is an integral part of the whole system.

Lake Taupō and its catchment (including imported water derived from the Tongariro Power Scheme) contribute flows to the Waikato River and affect water quality in the river. In past modelling of the Waikato River, Lake Taupō has generally been seen as providing known flow rates and contaminant concentrations which provide an upstream boundary condition for the Waikato River. A model of the complete Waikato system, though, would include: a) inflows to, storage within, and release from the lake, including the representation of the Tongariro Power Development scheme (TPD) and representation of flow release rules, and b) a water quality model of Lake Taupō.

As far as flows are concerned, Lake Taupō and its catchment can be dealt with using the same hydrologic and flow routing that would be used for the rest of the Waikato. Diversions from the Whanganui catchment, and management of the flow diversions and releases in the TPD system, would add some complexity, and some aspects of snow hydrology may need to be introduced. Generally, including flows associated with Taupō is more a matter of extending the spatial extent of the modelling, rather than introducing new types of models.

As far as the influence of Lake Taupō outflows on the *quality* of Waikato River is concerned, it would be suitable as a first approximation to use measurements and empirical relationships, because: a) the lake outflow represents a large source of near-pristine water, which serves primarily to dilute contaminant inputs further down the Waikato River; b) the quality of the outflow varies gradually even if flow rates fluctuate; and c) future changes in water quality are likely to be small, given controls on land use in the catchment of the lake.

There are some potential exceptions, such as the potential for climate change to cause shifts in water quality through effects such as upsetting winter lake mixing (Spigel et al. 2001; Verburg and Albert 2020). Iwi have confirmed that it is very desirable for a lake model to represent impacts of climate change. Restrictions are already in place in the Taupō catchment around protecting the waterways therefore the effects of climate change are seeming to be one of the largest threats to taonga. When assessing long-term water quality risks associated with climate change, it would be appropriate to use a 1-D model of the lake water quality and ecology, because such a model can capture the main changes in stratification and water quality, as demonstrated in previous modelling of the lake. Previous observations have identified that there is little spatial variation in offshore water quality (see references to historical monitoring in Verburg and Albert 2019). Similarly, previous monitoring over a two-year period (Gibbs 2010) showed that there were only small differences between nearshore[9] and mid-lake shallow nutrient concentrations and temperature. Monitoring by Stewart (2018, see Figure 5.7 in that thesis for a summary) showed small differences in concentrations of nitrogen between open water and the littoral zone. Those observations support the use of a 1-D model for predicting changes in nutrient inputs into the Waikato river, as an approximation at least.

Lake Taupō water quality is also of interest in its own right. For example, concerns about deterioration of lake water quality of this high-value oligotrophic system drove development of water quality trading and land use control policies, which had no precedent in New Zealand. Also, issues associated with occasional cyanobacterial blooms in some of the embayments and local microbial water quality degradation associated with stormwater and sewage spills have been identified. Previous monitoring over a two-year period (Gibbs 2010) demonstrated that optical clarity was lower in nearshore areas compared with offshore shallow areas, and that there were higher counts of algae in the inshore areas. These findings suggested that a 3-D model would be best to address clarity and algae in the embayments. Stewart (2018) showed that nutrient transport between nearshore and offshore areas can be important for nutrient cycling, which also suggests that a 3-D model would be best. A 1-D model could still be suitable for exploring overall lake quality and approximate ecological function.

Lake Taupō is large and complex, so a large modelling and data collection effort would be needed to represent the details of ecosystem function and spatial variations in the lake, which are not likely to be necessary for predicting impacts on water quality in the mid- and lower reaches of the Waikato River.

In summary, there are probably three tiers of needs for water quality modelling of Lake Taupō, which can be addressed by different model types:

- For predicting water quality in the Waikato River, use empirical (measurement-based) approaches.

[9]primarily Whakaipo Bay (where 30 m depth occurs), Whangamata Bay (200 m buoy), and some from Acacia Bay (200 m buoy).

- For exploring climate change impacts on lake outflow quality, and overall lake water quality, a 1-D water quality model would suffice.

- For predicting nearshore quality impacts and ecosystem function within the lake, a 3-D model would be best.

Along with the impacts of climate change and algal blooms, Tuwharetoa have identified the following additional issues:

- Understanding the effects of stormwater and accidental wastewater inputs especially around Taupō township and the increased residential developments (e.g. Acacia Bay) and how those can affect the quality and ecology of the area.
- Understanding how taonga species (kōura, koaro, kākahi, smelt and trout) are likely to be affected by changes in water quality, flow, water levels etc.

Additional loading of contaminants due to urban development are likely to be captured in broader models of lake water quality.

Assessing the local effects of discharges is likely to require a model with a fine spatial scale, which would not practicable to implement in a Waikato-scale model.

Water quality and hydraulic models could help assess the implications of water quality, flows and water levels on taonga species. For example, Rowe et al. (2002) assessed the area of lakebed suitable for smelt spawning as a function of lake level; such a model could be linked to a hydraulic model. Temperature predictions, which are usually a part of hydrodynamic models, could be linked to temperature preferences of fish to identify changes in the area or volume of suitable habitat arising from climate change. We note that there is better information on temperature responses for trout than for other taonga species, so that further fundamental experimentation on temperature preferences would be desirable.

We do not consider that there are good immediate prospects for modelling populations of taonga species with accuracy. As an example, ecological modelling of restoration prospects for Lake Waahi (Allan 2018) did not attempt to predict populations. There may be possibilities to link predictions of temperature and primary production to food-energetics models for trout. Overall, further fundamental research on environmental tolerances, preferences and behaviour (including interactions between species) are needed before reliable predictive models could be applied for management purposes (pers. comm. Cindy Baker, NIWA). In the interim, information on habitat and primary production can give clues as to the implications of climate change and lake management.

2.7 Key model types and their required or desirable technical attributes

Based on the relationships between model types and predicted variables related to taura (Section 2.5.2), and following consideration of broader model needs and available types of modelling software, we have derived a list of model types and their requirements, listed below. In some cases, we have provided only a broad description of the model type or needs, while in other cases, where requirements are clearer, we have provided more detail. Some model software can address more than one of these sets of needs, but we have broken the model types down to a level where specialist software that addresses just one component could provide a better solution than a single model that tries to cover all types and needs. These types and needs are used to guide model selection in Section 4.

2.7.1 Hydrology

Hydrologic models convert rainfall to runoff and may optionally route the runoff to streams and down the drainage network. The routing is called 'hydrologic routing' because it does not take account of the details of flow mechanics (for example, interactions between depth, water slope, friction and velocity).

Hydrology related to flood flows may be dominated by different processes and timescales of interest relative to hydrology models targeted more at predicting water supply and availability and water quality. For example, groundwater could play less of a role for flood hydrology. Hence, we have separated models targeted at flood flows from water supply or water quality models. In principle, one model could serve multiple purposes, but in practice separate specialist models may be more appropriate to adequately represent the dominant processes and timescales. The required or desirable attributes of each hydrological model sub-type are listed below.

Hydrology for flood flows

- Provides storm runoff predictions from key land cover classes, and accounts for soil moisture influence on runoff.
- Simulates long-term time series of flows.
- For the river mainstem, tributary inputs vary within a day. Even though flows in the lower river vary fairly slowly, it is highly desirable if not essential to have sub-daily hydrology to represent flood transit and the effects of storm temporal characteristics adequately. Sub-daily models are preferable to account for storm characteristics. Sub-daily time-steps are necessary if flooding of tributaries is of interest.
- Accounts for time lags and attenuation between runoff generation and flow entry to the stream.
- Allows for spatial variability of rainfall.
- Allows for influence of soils and artificial drainage.
- Considers topography, soils, land cover, subsurface drainage and rainfall, so that a spatially-distributed rather than lumped model should be used (even if lumping is only applied at the tributary level).
- Snow hydrology is only likely to be a small part of flood flows, and so could be neglected.

Hydrology for water supply and availability

- Daily resolution is sufficient.
- Capable of long-term simulation.
- Spatial resolution depends on desired refinement of representing water use (individual property/abstraction or lumped catchment), in addition to the need to represent catchment characteristics.
- Allows for variations in land use, soil types, artificial drainage, irrigation and storage.

- Feedback from water availability (including environmental requirements) to water abstraction use is provided.
- Needs to integrate or be able to be coupled with a groundwater model.
- Needs to be able to be coupled with reservoir and mainstem models.
- Desirable to link to economics and allocation tools.

Hydrology for water quality

- Daily simulation is generally sufficient.
- Can be run long-term.
- Sub-daily resolution is desirable for erosion assessment.
- Allows for land use, soils (including drainage).
- Quantifies different flow pathways.
- Incorporates or can be coupled to a groundwater model for N transport.

2.7.2 Groundwater flow

- Weekly predictions are sufficient.
- For water resources assessment, desirable to be able to link to abstraction models.
- Can be run dynamically for multiple years – may require high-performance computing, or model simplification/meta-modelling.
- Three-dimensional (3-D), accounts for major geological features.
- Lateral resolution to 250 m to capture interaction with tributaries and variations in recharge.
- Can be coupled with rainfall-runoff model to derive recharge.
- Supplies flow routing to the mainstem or can be coupled to a tributary routing model.
- Probably not necessary to allow for stream losses, as they are not common in the Waikato (pers. comm. Channa Rajanayaka, NIWA).

2.7.3 River and reservoir flow routing for flood assessment

- The model should be able to be run for long-term simulation to capture flow variations.
- Flood flows in the lower river vary over days, (Environment Waikato 2010), so that sub-daily flood routing might not be necessary. However, tributary inputs fluctuate on a finer scale, flood waves take less than a day to transition down the mainstem between reservoirs, flood releases may vary over periods less than a day, and the operation of flood infrastructure such as a flood may vary within a day. Hence, sub-daily routing is highly desirable, if not essential; generally, models targeted at flood routing would provide sub-daily resolution.

- Hydraulic routing in the main stem. In the lower reaches, backwater effects should be considered.
- For reservoirs, storage, release rules, and some representation of pre-release of reservoir storage is needed.
- Flows in the lower river do not vary much within a day for large floods
- It would be very desirable to represent flood infrastructure such as pumps and gates in the lower river.
- For flood management, the model should be suitable for linking to an operational forecasting system, including data assimilation and rain forecasts.
- It would be desirable for the model to be run in ensemble mode (for example, with different rainfall-runoff models, parameterisation, or reservoir release scenarios).
- Local 2-D or 3-D models might be needed to resolve inundation in some specific locations; that is beyond the scope of the current project, but such models could use results of a 1-D model as boundary inputs.

2.7.4 River hydraulics and reservoir releases other than for flood assessment

Hydraulic models use the physics of water movement (such as pressure gradients, friction, and energy) to determine flow characteristics of interest such as depths, velocities, and turbulence.

- 1-D, longitudinally-varying, flow hydraulic routing would be suitable for establishing river depths and levels for baseflow and low flow conditions. In the lower river, the model would need to operate at sub-daily time-step. This would also be suitable for establishing flow habitat. Reservoir releases vary on a sub-daily basis, so a sub-daily model would be suitable. These are the same requirements as for flood modelling.
- 2-D, vertically-averaged or 3-D models would be needed for representing spawning habitat in the lower river. Such a model would not be suitable for long-term predictions (e.g., a decade) due to the computational cost. The results of shorter simulations could potentially be linked to predictions of 1-D flood models for longer-term evaluation of spawning habitat (for example, relating habitat to flow rate and tide level in a kind of lookup table).
- It would be desirable to represent constructed habitat with specialised flow control devices behind flood gates.

2.7.5 Reservoir hydraulics

- Reservoir hydraulics are not needed for flow routing but may be needed for contaminant routing.
- Some of the deeper hydro reservoirs (Lakes Ohakuri, Maraetai and Karapiro) are known to partially stratify in late summer (Reid 1966; Bilinska et al. 2005), which can affect water quality, especially algal species and numbers, and potentially nutrient forms. Hence representation of stratification and flow variation down the reservoir and with depth is desirable (including modelling temperature, which affects

stratification). Temperature and wind-induced mixing are also important for stratification dynamics.

- It is probably not necessary to model lateral variations in velocity in the reservoirs, although the Whirinaki arm of Lake Ohakuri should be represented as a separate branch, because its water quality is known to differ from that in the main body of Lake Ohakuri.
- The models should be able to represent depth-constrained reservoir inlets, and preferably mixing dynamics of flows entering the reservoir.
- For shallower lakes, a 0-D (level-pool) approach would be sufficient for representing flood passage (although longitudinal variations would still be desirable for water quality).

2.7.6 Contaminant sources

- It would be desirable to provide sub-daily variations, because tributary concentrations vary on a sub-daily basis (at least during storms), and concentrations that are used for calibration re not daily averages but are instantaneous. However, concentration variations in the mainstem vary fairly slowly, so that daily resolution of inputs to the mainstem rivers is sufficient.
- Spatial resolution should be sufficient to represent variation in land use and other drivers within the catchment.
- For some applications, spatial resolution down to the property level may be desirable.
- Addresses nutrients, sediment and *E. coli*.
- Preferably provides accompanying flow rates so that the timing of contaminant loading is consistent with flows.
- Can represent key mitigation measures such as stock type and management, fertiliser type and management, and irrigation management.
- Represents key land uses (pastural types and intensities, urban, lifestyle, pine, horticulture, native forest), soils, climate, slope variations.
- Provides nitrogen recharge rates to groundwater.
- Desirable to represent key processes such as artificial drainage, overland flow, bank erosion in tributaries.
- Preferably provides insights into key mechanisms and processes responsible for generation and transport of contaminants.
- Weekly resolution is sufficient, if not modelling interflow.

2.7.7 Groundwater quality

- 3-D model to represent variations in flow paths.
- Lateral resolution as for the groundwater. Note that it is not possible to represent fine-scale variations in hydro-geochemistry accurately due to unknown subsurface conditions.
- Represents nitrogen attenuation.
- Representation of phosphorus losses from dissolution of minerals is desirable.
- Desirable to represent groundwater deoxygenation and dissolved organic carbon loading to stream.
- Desirable to represent attenuation processes in riparian and wetland areas.

2.7.8 Mainstem river and reservoir water quality

- Daily resolution at least. Desirable to represent sub-daily variations for oxygen dynamics and water quality implications of reservoir releases.
- Can be run for long time periods (decade).
- River model can be run in 1-D longitudinal mode (assume mixing over the cross-section) for computational speed.
- Reservoir model needs to represent longitudinal and vertical variation, and selective withdrawal depth, in the deeper reservoirs that are subject to partial stratification.
- Transports and processes sediment, nutrient, *E. coli*, oxygen, temperature, and algae. Also represents optical clarity and light penetration. For nutrients:
  - Speciation into readily bioavailable forms and less available forms, and the interactions between species, is required.
  - Usually, various forms such as dissolved reactive (ammonium, nitrate, dissolved reactive phosphorus) and dissolved organic forms, algal biomass, plant biomass, detritus, and adsorbed would be modelled, and some of these forms may be split into degradable versus recalcitrant forms.
  - The sediment model should include fine sediment fractions that do not settle readily.
- Desirable for water colour to be represented.
- Represents zooplankton grazing: Bilinska et al. (2005) suggested that zooplankton have a small role in the hydro reservoirs due to their low population densities and high flushing rates, but Gibbs et al. (2014) note that they made a difference to algal levels in Karapiro (from algal growth experiments with varying zooplankton), and Hamilton and Duggan (2010) noted the proliferation of larger zooplankton in the reservoirs, with smaller, faster-growing communities in the rivers below the reservoirs. We therefore consider that it is desirable to represent zooplankton grazing.

- Accounts for interactions with bed material. For reservoirs subject to stratification, sediment flux responsive to DO is required, and shear or wave-driven resuspension is required for shallow parts of the system.
- Lower reaches of the river that are influenced by tides may require representation of salinity, depending on the question of interest.
- Multiple phytoplankton groups should be represented (although earlier caveats regarding predictive capability of models with multiple functional groups should be noted).
- Desirable to represent water quality implications of macrophytes.
- Represents macrophyte growth.
- Represents artificial mixing.
- Can be coupled to models of the shallow lakes (especially the riverine lakes), because they seed algae into the lower reaches.

2.7.9 Tributary water quality

- As for the mainstem, but sub-daily required if high-flow responses and dissolved oxygen are of interest, and with more emphasis on erosion processes.

2.7.10 Shallow lake water quality

- Similar requirements to the mainstem and reservoir models, but a 1-D vertical model is sufficient, and there will be more emphasis on lake-bed interactions (resuspension, internal loads, sediment interaction in the water column) and the role of macrophytes.
- A difficulty with some of the smaller lakes is that loading to the lakes is dominated by subsurface inputs, which can be difficult to measure and model.

2.7.11 Lake Taupō water quality

As discussed in Section 2.6.3, three levels of model that could be needed, depending on the purpose:

i. Empirical and measurement-based, to predict concentrations entering the Waikato River at Taupō. This does not require a simulation model, and simple statistical models could be used.

ii. 1-D model for predicting response of lake outflow quality to climate change, and response of water quality in the lake overall to changes in inputs and climate drivers. Such a model has the same requirements as the shallow lake models, but with less need for representation of bed sediment entrainment. Geothermal heat inputs would need to be represented. It would be desirable for this model to represent the insertion depth of lake inflows depending on temperature. This model could also be used to assess some aspects of lake ecology.

iii. 3-D model, to assess spatial variations of water quality in the lake (such as local algal accumulation in embayments), and for more detailed representation of ecological dynamics. However, we caution that such a model is likely to have difficulty in simulating the dynamics of algal blooms, especially those of toxic cyanobacteria, as discussed earlier for the reservoir and river models. Hence, hybrid mechanistic-statistical models that use predictions of currents and nutrients would be preferable for predicting algal blooms.

2.7.12 Fish and water-bird habitat

A common approach to assessing aquatic habitat is to relate environmental factors such as flow depth and velocity, substrate, and vegetation to habitat preferences for the species of interest, to derive an indication of the quantity of suitable habitat, often expressed as a function of river flow. This can entail detailed observations of those factors and their relationship to flow rates, and hydraulic modelling of selected areas. 2-D or 3-D hydraulic modelling is desirable to support such assessment but can only be conducted over fairly small areas due to data input and computational demands.

Ideally, habitat assessment takes account of the frequency and duration of the driving factors. For example, it may be important to provide suitable hydraulic conditions at times of spawning, or a single protracted period of low flow may have more impact than shorter but more frequent periods of low flow.

River connectivity is a further important aspect of habitat; suitable habitat needs to be accessible, and passage is required for critical life-stages and for migratory species. Currently, most approaches to connectivity address barriers or lethal factors such as culverts, flood gates, dams, pumps and turbines. Static assessments of habitat continuity and patches may also be applied. Generally, such assessments would not take dynamic considerations into account (for example, providing continuity at critical times related to migration).

A limitation of these approaches is that it is difficult to link habitat availability to abundance and condition of fish and mahinga kai.

2.7.13 Fish abundance, location and movement

Ideally, a fish population model would represent: growth; movement, including barriers and response to habitat clues such as velocity; spawning habitat; food sources and availability; shelter; predation and harvest; response to adverse water quality (including temperature); sea migration; and interactions with other species, across life stages and maturity classes, including pest fish invasion and competition. Representing these factors requires understanding and quantifying many behavioural and environmental factors, about which there is often little knowledge. Alternative statistical modelling approaches are possible, but they require considerable observation data over time and space.

2.7.14 River bio geomorphology

This class of models combines information on flow, hydraulics, sediment accretion and removal, and vegetation growth to derive predictions of habitat types and associated ecology over time and space (including factors such as diversity and disturbance), often over long time periods and including the floodplain (Baptist 2005; Camporeale et al. 2013; Coombes 2016); these often also allow for feedbacks between biological and geomorphic features.

This could in principle lead to ecological improvements through modifying hydrological or riparian and floodplain vegetation and hydraulic features and targeting conservations efforts. Typically, a detailed 2-D representation would be applied over long time periods, so that only selected parts of a river system could be modelled with such approaches.

2.7.15 Economics and land-use evolution

Dynamic economic models represent the temporal evolution of different components of the economy in response to drivers such as policy, external markets or environmental change. The economic state and activities over time can depend on the starting point and pathways of change, as well as factors such as lags and variable response of individuals or groups to drivers, so that modelling the evolution of time is desirable. Such models may also be posed in a spatial context, such as a grid of land-uses or transport network, whereby evolution populations and economic activity at a point depends on adjacent conditions, infrastructure, and networks. An example is the WISE spatial model, discussed in the next section.

3 Past and current dynamic modelling of the Waikato River system and catchment

3.1 Summary table of past and current models

This section describes key dynamic models that have been used previously or are currently being used for the Waikato River and its catchment. It is important to be cognizant of these existing models, because it is desirable to build on them to avoid duplication of effort or institutional disruption, provided that the models are fit for purpose. Also, lessons may be learned from the success or failure of application of past models. This list was informed by outputs from the waananga (Appendix B) and was refined by follow-up discussions with key technical staff (reference in the appendix) and a literature search. Key models are summarised in Table 3-1, with further detail in Appendix A. Models that have been developed or applied over a relatively small scale, such as groundwater models around Taupō, have not been included, although we do present models of small lakes due to their regional importance despite their small individual scale.

3.2 Comments on past and current modelling work

The collection of past modelling efforts is fragmented and patchy in terms of spatial coverage, model types, and providers.

For hydrological modelling associated with flood flows, there are several models for tributaries, a model for flow passage through reservoirs, and a separate model for flows in the lower river (i.e., below Karapiro). As far as the mainstem is concerned, there is a break in ownership of models between the upper catchment and lower river, from Mercury to WRC, although the two organisations do exchange information. This makes it difficult to model the hydrology of the Waikato as an integrated whole. Moreover, the catchment of Lake Taupō is not included explicitly, which is a clear gap. The existing hydrologic models are based largely on the proprietary DHI[10] platform plus a custom model for the hydro system; this is counter to the goal of this programme to develop an

[10] https://worldwide.dhigroup.com/

open-source integrated model. Operational flood forecasting does not use 'live' models for the upper catchment (i.e., upstream of the Karapiro outlet).

There was also a previous effort to model the upper catchment with TopNet (proprietary), and HEC-HMS (free but closed-source) for flood predictions, again linking with the reservoir routing and existing models for the lower catchment. TopNet has now been developed into NZWaM (the New Zealand Water Model), which can be run nationally and used for operational flood forecasting.[11]

All of the hydrological models above will have weaknesses in terms of predicting baseflow and low flow, because water sources in the upper catchment are dominated by regional groundwater inputs. The Ruahiwai hydrological models couple a proprietary rainfall-runoff model with a groundwater model (MODFLOW) and eWater Source (Source) to obtain an improved representation of baseflow inputs for the upper Waikato (down to Lake Ohakuri).

Dynamic water quality modelling of the full mainstem Waikato system has not occurred previously, which is a clear gap in modelling capability in relation to the needs assessed in the previous section. While the 'Waikato River Model' represents the full system, it is steady-state (although the model can be run with different input flows). BNZ modelling of Lake Taupō contaminant inputs was conducted two decades ago and relied on NIWA-held code. The Ruahiwai model covers the upper Waikato from the Lake Taupō outlet to Lake Ohakuri but relies on the Source framework and several customisations by Williamson Water Advisory, although it does use some open components such as MODFLOW and APSIM. Hence previous dynamic water quality models of the mainstem address part of the system and are mainly proprietary.

Models of hydraulics and water quality have been developed for several of the small-medium Waikato lakes, mainly by the University of Waikato. These have used a variety of modelling software, and it would be desirable to have a consistent platform in the future. The models generally do not represent biotic components of the system beyond algae and zooplankton. A model of Lake Taupō water quality was developed in the early 2000's using the now-discontinued DYRESM-CAEDEM model, although the model could probably be transferred to successor software.

The only detailed hydrodynamic model of the river is one related to whitebait in the Waikato estuary.

There have been no dynamic modelling studies of biotic components of the Waikato River, nor any dynamic geomorphic studies.

The only dynamic model that we are aware of that addresses wider aspects such as economy and land-use progression is the WISE model, which is built on a proprietary platform.

[11] https://niwa.co.nz/freshwater-and-estuaries/freshwater-and-estuaries-update/freshwater-update-80-march-2019/the-new-zealand-water-model-nzwam-%E2%80%93-a

Hence, previous modelling efforts point to the need for a more integrated and consistent open-source approach and identify several gaps in spatial coverage and model types, which the proposed model system intends to address.

Table 3-1: List of key past and current dynamic models in the Waikato. See Appendix A for further details. Two steady state models have also been listed.

Model	Type of model	Software	Location covered	Owner/Client	Provider
Reservoir flow routing	Hydrologic routing	Custom Fortran code	Upper Waikato River from Taupō outflow to Karapiro	Mercury	Ian Jowett
Rainfall-runoff upper Waikato	Hydrology	DHI, probably NAM	Upper Waikato tributaries from Taupō outflow to Karapiro	Mercury	Not known
Lower Waikato Model	Hydrology and flood routing	DHI: NAM and MIKE-11 and FLOODWATCH/Operations	Lower Waikato (below Karapiro) and Waipa	WRC	DHI, Joynes, WRC
Upper Waikato flood runoff HEC-HMS	Flood hydrology	HEC-HMS	Upper Waikato River from Taupō to Karapiro	WRC	Jacobs
Upper Waikato flood runoff TopNet	Flood hydrology	TopNet	Upper Waikato River from Taupō to Karapiro	WRC	NIWA
Taupō tributary inflows	Flood hydrology	Likely to be DHI NAM	Tauranga-Taupō and Tongariro inflows to Lake Taupō	WRC	Tonkin and Taylor
Maxwell Taupō inflows	Flood hydrology	Now incorporated into LUCI	Lake Taupō catchment	Not known	Victoria University of Wellington
Upper Waikato Regional Groundwater Model	Groundwater flow and nitrogen (steady state)	MODFLOW, MT3D	Taupō outflow to Lake Karapiro	WRC	Aqualinc
Reporoa groundwater model	Groundwater flow and nitrogen	MODFLOW, MT3D	Reporoa basin	WRC	Multiple
Ruahiwai groundwater model	Groundwater flow and nitrogen	MODFLOW, MT3D	Taupō outlet to Lake Ohakuri tailrace	Wairakei Pastoral	Williamson Water and Land Advisory

Model	Type of model	Software	Location covered	Owner/Client	Provider
Ruahiwai Decision Support Tools	Hydrology and water quality	MODFLOW, MT3D, APSIM, eWater SOURCE	Taupō outlet to Lake Ohakuri tailrace	Wairakei Pastoral	Williamson Water and Land Advisory
Waikato Catchment Model (WCM)	Water quality including algae (steady state)	Custom Visual Basic for Applications code in spreadsheet.	Waikato and Waipa from Taupō outlet	WRC/NIWA	Kit Rutherford, NIWA
CREAMS -based inputs to Lake Taupō	Water quality	BNZ, CREAMS	Lake Taupō catchment	NIWA/WRC/Tuwharetoa	Sandy Elliott, NIWA
Lake Taupō 1-D model	Lake hydraulics and water quality	DYRESM-CAEDYM	Lake Taupō	NIWA	Bob Spigel, NIWA
Lake Taupō 3-D hydrodynamics	Lake hydrodynamics	AEM3D	Lake Taupō	University of Waikato	University of Waikato
WISE	Integrated spatial planning	Geonamica	Waikato catchment	WRC	RIKS
Whangape hydrodynamic model	Lake hydrodynamics	Delft3D	Lake Whangape	WRC?	University of Waikato
Waahi hydrodynamic model	Lake hydrodynamics	Delft3D	Lake Waahi	WRC?	University of Waikato
Lake Waikare hydrodynamic model	Lake hydrodynamics	Delft3D	Lake Waikare	WRC?	University of Waikato
Lakes Rotomānuka, Ngāroto, Waahi water quality models	Lake hydrodynamics and water quality	DYRESM-CAEDYM, with lake inputs from CLUES or INCA	Lakes Rotomānuka, Ngāroto, Waahi	WRC?	University of Waikato

Model	Type of model	Software	Location covered	Owner/Client	Provider
Lake Waahi water quality model	Lake hydrodynamics and water quality	PCLAKE and GOTM, with inputs from CLUES/TopNet	Lake Waahi	WRC?	University of Waikato
Whangamarino hydrologic model	Lake levels	GoldSim dynamic system model with SMWBM rainfall-runoff model	Whangamarino system and catchment	DOC	Jacobs
Lake Waikare Flushing	Lake quality	SLAM	Lake Waikare	Waikato District Council	Streamlined Environmental
Waikato estuary spawning habitat	Hydraulic	Delft3D	Mercer to 3 km from coast	WRC	University of Waikato

4 Modelling software to meet key needs

This section identifies models likely to address the needs identified in Section 2. The range of models includes those used previously in the Waikato (Table 3-1) as well as other potentially suitable models Several models in Table 3-1 were excluded because they are proprietary. They include TopNet[12], all DHI software (including NAM and Mike11 as discussed in Appendix A), Overseer[13] and eWater Source[14].

4.1 Hydrology for floods

There are many open-source spatially-distributed flood hydrology models available that are suitable for the scale of the Waikato (for example, see a range of models in Kauffeldt et al. 2016), and it can be difficult to choose between them. Some models, such as the Soil Water Assessment Tool (SWAT; Arnold et al. 1998; Douglas-Mankin et al. 2010; Tuppad et al. 2011) and HYPE (Hydrological Predictions for the Environment, Lindström et al. 2010) operate at a daily time-step and are not well suited for predicting flood hydrology in the Waikato. There has been surprisingly little comparison of such models in the New Zealand context[15] to assist with model selection.

In the Waikato, the SMA (Soil Moisture Accounting) conceptual rainfall-runoff model from the HEC-HMS[16] system has been applied previously to the upper catchment. SMA has options for sub-basin or gridded spatial representation, a variety of hydrological routing methods are available, and it can be run in a sub-daily mode. The model has some capability to represent reservoir releases but would not be able to represent all aspects of the reservoirs – for this reason, it would be better to use a dedicated river routing software for the reservoirs. In the previous application, model parameterisation occurred on a subcatchment-by-subcatchment basis, and an additional storage for slow flow runoff was required. While HEC-HMS is free, it is not open source and would probably be difficult to couple with other models in a flexible automated way. SMA is based on the Precipitation-Runoff Modelling System (PRMS; Leavesley et al. 1983), which is available on other platforms such as the Colorado State University's[17] PRMS/OMS model and through the United States Geological Survey (USGS)[18].

The DHI lumped conceptual[19] rainfall-runoff model NAM (NedborAfstromnings Model, see for example Shamsudin and Hashim 2002) has been used widely in New Zealand, including the lower Waikato (Joynes 2009), and for some of the upper tributary catchments. For the Waikato Dynamic Model, we cannot use NAM because the software is proprietary; but, it would not be difficult to adopt a similar conceptual model within different modelling environments. A further difficulty with NAM is in setting the conceptual parameters based on soil and vegetation parameters, which was found to be difficult in previous applications of NAM to the Waikato (DHI 2006); this creates a strong dependency on calibration (similar difficulties are likely to be experienced as during application of SMA in the upper catchment).

[12] https://niwa.co.nz/freshwater-and-estuaries/research-projects/nz-water-model-hydrology-nzwam-hydro
[13] https://www.overseer.org.nz/
[14] There is a free tier for Source, but terms and conditions are too restrictive for the intended users
[15] See, for example, https://www.waternz.org.nz/rainfallrunoff
[16] https://www.hec.usace.army.mil/software/hec-hms/
[17] https://alm.engr.colostate.edu/cb/wiki/17003
[18] https://www.usgs.gov/software/precipitation-runoff-modeling-system-prms
[19] A conceptual hydrological model represents various storage compartments and flow rates in a spatial unit such as a subcatchment, without necessarily relating the storage and flows to physical characteristics of the soils, plants and aquifers.

Another alternative is the rainfall-runoff routines used within the LUCI model (Land Utilisation and Capability Indicator, Jackson et al. 2013; Maxwell 2013). The routines were recently made available as an open-source model as part of the Interoperable land-water model project[20]. Spatial representation in the model has recently moved from a lumped to a semi-distributed basis, but there is no documentation on the updated version at present. The model is also dependent on a single developer. LUCI could be considered as a candidate in an ensemble modelling approach.

Deltares provide several hydrology models within the D-Hydrology open-source system[21] (previously called WFLOW), including about six rainfall-runoff models and kinematic flow routing within a grid-based spatial arrangement. These models can be coupled to stream routing models and operational forecasting systems available from Deltares.

We recommend that D-Hydrology be used, because it is open-source, flexible, and can interface with river routing models. Within the set of available models, we recommend trialling alternative rainfall-runoff models, including conceptual models that would be similar to SMA/PRMS or NAM (for example, HBV[22]). However, we prefer models where parameters can be related to soil and vegetation conditions, rather than setting conceptual parameters based solely on calibration, so that HBV is less favourable. It would also be possible to couple code representing an alternative preferred model through the software interface provided with D-Hydrology. The models use a Python code platform, which is fairly easy to code. Ultimately, it may be appropriate to use multiple models in an ensemble configuration. D-Hydrology uses dynamic wave routing over a grid surface, which may be computationally expensive, so we recommend trialling this approach in a selected subcatchment. Also, D-Hydrology uses the computational package PCRASTER, and projects are underway to allow PCRASTER models to be run on high-performance computing facilities, including facilities that allow parallel calculations.

4.2 Hydrology for water quality

We recommend using the hydrology routines in SWAT coupled with the groundwater model MODFLOW (Section 4.4) for representing rainfall-runoff and routing to the mainstem when it is not necessary to model large floods. This fulfils all the requirements and can be used for water quality simulation as well.

4.3 Hydrology for water availability

We do not consider that SWAT or the flood model (see previous sections) are well suited to representing water resources, because they do not provide sophisticated representation of irrigation or water abstraction, or links to water availability. Despite modelling of water resources and allocation being common, longstanding requirements, we found surprisingly few comprehensive open-source models, or previous applications of water resources software in New Zealand, beyond the use of groundwater models and Wellington Water's application of the WATHNET model (Kuczera 1997).

Many models are available that represent a catchment as a set of nodes and links, with coupled water demands and abstractions. Such models represent water demands in a fairly simple spatial manner, so they would not be suitable for detailed spatial representation of water users at a catchment scale, or in sophisticated applications where users collectively manage water use in real

[20] https://ourlandandwater.nz/future-landscapes/interoperable-modelling/
[21] https://wflow.readthedocs.io/en/latest/
[22] https://www.smhi.se/en/research/research-departments/hydrology/hbv-1.90007

time to meet water availability constraints. Some examples are WEAP[23], eWater Source[24] and AQUATOOL[25], but they are not free or open-source for the types of users and applications that are contemplated. There is also a need to couple a groundwater model that can represent groundwater abstraction, which WEAP can do (Source uses simplified representations of local aquifers). The RIBASIM software from Deltares[26] does not seem to be part of their open source initiative, and ongoing maintenance of that model is questionable. Despite the long history of water resources model development, we cannot at this stage recommend a free and open source option. Depending on the outcome of consultation with stakeholders, if it is decided to proceed with a water resources model, then further effort will be required to find suitable software, or the requirement for free software will need to be relaxed.

4.4 Groundwater flow

We recommend the use of MODFLOW for groundwater flows[27]. This model is widely used internationally and has been applied in several places in the Waikato. The relatively recent MODFLOW-USG variant allows for variable resolution and also links to a drainage network, although it cannot yet be used for groundwater contaminant transport (we understand that this facility is in development). MODFLOW has been coupled with other models such as SWAT, giving some flexibility. It was previously found that regional modelling for Waikato on a desktop PC (see section 3) required 1 km square grid cells. We therefore anticipate that it will be necessary to use high-performance computing to represent the system at the desired resolution (about 200 m).

4.5 River and reservoir flow routing for flood assessment

We propose that the one-dimensional (1-D) version of D-Flow FM, the hydrodynamic model of the Deltares modelling suite be used for flow routing for flood assessment. The functionality of Deltares' 1-D model (Sobek) is slowly being integrated into D-Flow FM. This model allows for hydraulic modelling of flood transition down a drainage network, including reservoirs and control structures.

The D-Flow FM Real Time Control (RTC) module allows representation of hydraulic control structures. This makes it possible to have the model react to actual or forecast water levels or flows by steering gates, sluices, weirs and pumps. This could be of benefit for the simulation (and possibly further optimization) of the hydropower reservoir and flood system operating rules. The D-Real Time Control module is currently available only under beta testing conditions within Deltares' research programme.

These models can ultimately be linked into operational forecasting tools such as FEWS, through standardised interfaces.

4.6 River hydraulics

We propose that Delft3D Flexible Mesh (FM) be used to represent river and reservoir hydraulics. This is part of Delft3D, a suite of hydrological and environmental modelling tools developed by Deltares. Delft3D consists of several modules, which are linked to and integrated with each other. For much of the system, 1-D hydraulics would suffice. To represent the distribution of velocities in the floodplains, a 3-D model would be desirable, and would allow the effects of salinity to be included. The 2-D and

[23] https://www.weap21.org/
[24] https://ewater.org.au/products/ewater-source/
[25] https://aquatool.webs.upv.es/aqt/en/aquatool-2/
[26] https://www.deltares.nl/en/software/ribasim/
[27] https://www.usgs.gov/software/modflow-6-usgs-modular-hydrologic-model

3-D models can used hybrid meshes composed of rectilinear portions as well as unstructured elements (triangles, quads, pentagons & hexagons), which provides modelling flexibility and the ability to represent complex local features at a finer resolution than used in the rest of the model.

At the time of writing, D-FLOW FM can run 1-D/2-D or 3-D models. While the full 1-D to 3-D functionality is not available yet, river stretches can already be schematized by combining 1-D networks and 2-D meshes that are loosely coupled to 3-D representations of reservoirs. If needed, the resulting grids could be connected at a later stage (when the software allows) to form one fully integrated model of river reaches and reservoirs.

Reservoir hydraulics are required for modelling water quality in some of the reservoirs. This will be addressed in Section 4.9.

4.7 Contaminant generation

We recommend the use of SWAT to model contaminant generation. SWAT models plant growth and nutrient processing and can also be used for microbial runoff and sediment transport. Detailed reviews of SWAT are available in Gassman et al. (2010), Douglas-Mankin et al. (2010), and Tuppad et al. (2011). SWAT is a free and open source model that runs on a daily time-step and with a semi-distributed spatial setup and is suitable for long-term simulation. SWAT has built-in routines to simulate some management practices and has been applied to evaluate the effect of farm best management practices on water quality at catchment scales, (e.g., Strauch et al. (2013), Chaubey et al. (2010), and Ullrich and Volk (2009)). There has been little previous use of SWAT in New Zealand, but it is used widely internationally and is in active development. It was trialled at local scale for the Toenepi catchment in the Waikato region (Hoang 2019b, a), with favourable results.

SWAT meets many of the needs for water quality modelling. However, its erosion component is not very strong in relation to specialist erosion models, so there may be a need to improve that aspect of the model in the long term. SWAT by itself does not represent transport of deep groundwater (it is lost from the system), so we recommend using MODFLOW in conjunction with SWAT, particularly for nitrogen transport. This slows the computations, so we anticipate the need to move to high-performance computing platform, which would also be desirable for representing greater detail in soils, land use, and land management.

We considered the use of the model HYPE, but it is in the same general class as SWAT, and we prefer SWAT because it has a stronger user base and development resources and takes a more mechanistic approach for contaminants.

Another approach that has been used in New Zealand, including for estimating loading into shallow lakes in the Waikato, is to use budget-based models such as CLUES (Elliott et al. 2016)), with the use of flow-concentration curves and flow rates predictions (from another model) to break the mean annual loading from CLUES into a time-series. That approach has some strengths because contaminant budget approaches are relatively simple and can be used to link to Overseer, but establishing a suitable flow-concentration relationship relies on measurements or alternative approximate methods derived from other locations in the area. Fortunately, good records are available for many of the tributaries in the Waikato. We also note that CLUES is not open-source, although it can be used freely for research and regional council applications.

4.8 Groundwater quality

We recommend the use of the MT3D-USGS[28] model coupled to MODFLOW for representing nitrogen transport in groundwater (see section 4.4 for the rationale for using MODFLOW). This can be coupled to recharge from SWAT, which we have recommended for contaminant generation and surface or shallow groundwater transport pathways to streams. Note that MT3D-USGS requires structured grids (not the more modern unstructured grids available in MODFLOW). This model is open-source and has been applied in many locations in New Zealand, including the Waikato.

4.9 Water quality in rivers and reservoirs

We considered a range of models that could potentially be applied to predict water quality in rivers and reservoirs. Below, we first discuss models that were considered but ruled out, and then discuss two remaining alternatives before recommending a model.

4.9.1 Models considered but ruled out

We ruled out the following water quality models for the reasons given below:

- AED2 (Hipsey et al. 2019), this is a flexible open-source Aquatic EcoDynamics model library. It builds on features of the CAEDYM model (Hipsey et al. 2005; Hipsey and Hamilton 2008) which has been used for many lakes in New Zealand. While it addresses many of the water quality model needs and can also be used for shallow lakes, we have ruled this model out for the proposed project because it is hard to use (it is essentially a library of computer modules), fairly new, and is more intended for lakes and marine systems than for rivers (it may be difficult to represent rivers or reservoirs that are mixed laterally or over the cross-section).

- AEM3D[29] (Aquatic Ecosystem Model 3D) is a successor to CAEDYM, but we rule it out because it is proprietary, is not open source (except for development partners), and its future is not certain.

- Qual2Kw[30] is a water quality model which includes many processes and variables of interest, but we rule it out because it is only 1-D (longitudinally varying) and so cannot represent stratification in the deeper hydro reservoirs, and it can simulate only 1 year of time-varying flows.

- EFDC (Environmental Fluid Dynamics Code) (Tetra Tech 2007b, a) includes water quality code as well as hydraulics, but it hasn't been developed since 2007. The manual refers to components for sediment diagenesis and rooted aquatic plants, but the sections are blank.

- WASP[31] (Water Quality Analysis Simulation Program) is a water quality model by the USEPA (United States Environmental Protection Agency) which has arbitrary spatial compartments (segments). While there are some capabilities for calculating flows through a 1-D flow routing model, for more complex situations the flows are calculated through a separate model such as EFDC. While the model represents many processes of interest (for example, luxury uptake by algae, diagenesis), has been used widely, and continues to be developed, the method for specifying the spatial linkages and exchanges is complex and relies on a

[28] https://www.usgs.gov/software/mt3d-usgs-groundwater-solute-transport-simulator-modflow
[29] http://www.hydronumerics.com.au/software/aquatic-ecosystem-model-3d
[30] https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Models-tools-for-TMDLs
[31] https://www.epa.gov/ceam/water-quality-analysis-simulation-program-wasp

hydrodynamic model that has been set up to be coupled to WASP, which we consider would be limiting and frustrating. Also, even though the model is free, we could not find the source code, and documentation of the transport component was not clear. Hence this model was not considered further.

4.9.2 CE-Qual-W2

CE-Qual-W2 (Cole and Wells 2015)[32] is a model for river, reservoir, and estuary hydraulics and water quality. It was originally developed by the US Army Corps of Engineers and is currently maintained by Portland State University. A key feature is that it is laterally averaged (across the river, not necessarily vertically), so does not entail the full complexity of a 3-D model, and it can also be run in 1-D mode (longitudinal down the river). Hence the model spatial representation is suitable both for reservoirs and the mainstem. The model has many features of interest, such as the ability to represent macrophytes and multiple algal species. The model is not well suited for representing model reservoir release rules. The model continues to be maintained and developed (latest release 4.2.1, 2020). CE-QUAL-W2 is open source, and is used widely internationally, but we are unaware of its use in New Zealand.

4.9.3 D-Water Quality

D-Water Quality[33] is one of the Delft3D suite of models from Deltares and is based on the underlying DELWAQ water quality model 'engine'. Substances and processes to be modelled can be selected from a predefined library and modified/extended where needed. The processes library covers many aspects of water quality and ecology, from basic tracers, dissolved oxygen, nutrients, organic matter, inorganic suspended matter, heavy metals, bacteria and organic micro-pollutants, to complex algae and macrophyte dynamics. The process library can be modified to add new processes (although we have found that difficult in an estuarine contexts).

A water quality model can be constructed from hydrodynamic outputs generated by D-Flow FM or any other mass conserving hydrodynamic or hydrologic model. The hydrodynamics can be aggregated to speed up computations. Alternatively, when a tighter coupling with hydrodynamics is required, the water quality simulation can be run in parallel to D-Flow FM (but this coupled mode is only available as a Beta version). In a setup where different hydrodynamic models would be used along the Waikato, their output could still be combined into one continuous water quality model (provided boundary conditions between each water quantity model match each other).

The water quality engine can generate mass balance reports, tracking transport fluxes between, and process contributions within, user defined regions. The mass balance output can be aggregated in space and time.

4.9.4 Choice between CE-QUAL-W2 and D-Water Quality in relation to model needs

The models CE-QUAL-W2 and D-Water Quality are compared against needs in Table 4-1. The comparison shows that D-Water Quality meets more of the needs than CE-QUAL-W2. It is also more flexible in that there is provision for the user to provide their own processes modules (although we have found that this is challenging in practice, and in the current version this functionality is broken)[34].

[32] http://www.ce.pdx.edu/w2/
[33] https://www.deltares.nl/en/software/module/d-water-quality/
[34] pers. comm, David Plew, NIWA, June 2020

A key potential difficulty with D-Water Quality relates to running reservoir or lake models over extended time periods, because a 3-D hydraulic model is required to represent stratification dynamics. Hence, while the model could be used to compare the effect of scenarios over a year, it would be difficult to model multiple years, and it may also be difficult to run short-term operational forecasts without using high-performance computing. Alternative approaches to circumvent this problem include using alternative models for reservoirs and lakes (CE-QUAl-W2, PCLake), investigating simplified grids, and developing meta-models of the full lake (simplified representations of the reservoir by running many simulations with differing inputs and representing the results in statistical or machine-learning terms).

Modelling the main-stem and reservoirs and shallow lakes in one system would require coupling sub-models, with the outflow from one model feeding the inflow to the next model. Deltares is currently developing more integrated 1D-3D coupling mechanisms, but they are not yet available for general use.

Table 4-1: Comparison between CE-QUAL-W2 and D-Water Quality in relation to model needs. Green denotes that the model meets the criterion, red that it doesn't, and yellow that it meets the criterion partially.

Criterion	CE-QUAL-W2	D-Water Quality
Nutrient processing		
Dissolved oxygen		
Multiple algal classes		
Temperature		
Influence of macrophytes on water quality		Not well documented.
Macrophyte growth	Multiple types. Growth equations not well documented.	Not well documented, 1 group.
Implications of fish for water quality (excretion, roiling…)	Except as an additional source.	Except as an additional source.
Zooplankton		Zooplankton biomass is not modelled, but is an input time-series.
Fixed algae/Periphyton	But no internal nutrient stores.	But no internal nutrient stores.
Sediment	Sadeghian (2017) found limitations such as single settling class.	
E. coli	Basic processes such as decay. Generic constituent.	Basic processes such as decay.
Light penetration		
Optical clarity		Limited documentation. Secchi depth.
Colour	Could be derived from bio-optical model (Allan 2018).	Could be derived from bio-optical model (Allan 2018).
Sediment diagenesis		

Criterion	CE-QUAL-W2	D-Water Quality
Sediment resuspension		
Salinity (for lower reaches)		
Suitable for reservoirs		3-D hydraulics required. Flows can be aggregated in 2D to use in water quality modelling.
Sub-daily calculations		
Long-term simulation		No for reservoirs, which require 3-D hydraulic model. Yes for rivers.
Artificial mixing		Coupled abstraction and injection sources.
Reservoir release rules	Some mention of this in development plans for HEC.	
Can be run in parallel on HPC (high performance computing) systems	(Sadeghian 2017). Not set up for parallel computing. Needs re-compilation for Linux. Might not be necessary as does not need 3-D.	Yes, for beta users at least. Unsure whether hydraulics can be run coupled to water quality yet.
Open source		3-D yes, 1-D imminent. https://oss.deltares.nl/web/delft3d/source-code
Previous experience in NZ		No documented river application. Has been applied to coasts/estuaries.
Documentation		Can be difficult to understand
Parameter guidance	Ranges for some parameters are defined.	Was available in earlier versions.
History of use		
Training and support available	Training available. No support.	Training available. Paid support service, usually Deltares.
Visualisation tools	Through WMS proprietary software.	DeltaShell, Quickplot, OpenEarth.
Coupling standards		Can be run through BMI.
Maintained and updated		
Can be linked to operational forecasting	Some mention of this in development plans for HEC.	Not designed for this but probably can be done through FEWS.
Can address shallow lakes	No 3-D or vertical mode.	Only in 3-D mode.

While D-Water Quality could address temperature in the mainstem, a different model may be required for small tributaries, which can be subjected to thermal stress. SWAT has some capability for temperature modelling in a simplified way (Du et al. 2018). NIWA is also scoping dynamic temperature models that could be suitable for tributaries, in a separate project.

4.10 Cyanobacteria modelling

Mechanistic dynamic modelling of cyanobacteria is difficult due to the complex microbial ecology and behaviour (for example, it is difficult to model buoyancy regulation, scum formation, toxin production, conditions for nitrogen fixation, luxury nutrient uptake, species interactions, and temperature response). Bilinska et al. (2005) provided an informative literature review of cyanobacteria, including data on the Waikato reservoirs.

Model predictive performance for phytoplankton is generally poor (Shimoda and Arhonditsis 2016), with a median model efficiency of -0.2 for phytoplankton and 0.02 for cyanobacteria (across all the studies), which is worse than for general water quality, and roughly comparable to just predicting that the concentrations are always equal to the mean observed value. However, Allan (2018) achieved a normalised RMSE (root mean square error divided by standard deviation of the data) of 0.25 for his calibration, which is 'very good' according to criteria in Moriasi et al. (2007), although the model was not validated (assessed against separate data).

After considering the difficulty of modelling cyanobacteria, we advise that mechanistic models should only be used to infer broad directions and magnitude of changes. For predicting temporal dynamics (e.g., for forecasting) we consider that statistical machine-learning models are likely to provide better predictive performance. Such models could be stronger if model predictions of factors such as flows, reservoir concentrations, and stratification, are taken into account, so that dynamic mechanistic models would still have a role. This approach could also incorporate observations of factors such as flow, turbidity, water temperature and rainfall. We note that WRC have long-term records of cyanobacteria derived from routine monitoring, which will be helpful to train statistical models. Although other data on algal species are also available, they have not been taken into an electronic database (but this could be done as a student project).

4.11 Shallow lake water quality

NIWA recently provided advice on selection of models for dune lakes to Auckland Council (Elliott et al. 2020). This is relevant to the Waikato lakes, because the same model needs apply (for example, being able to represent stratification, macrophytes, and algae, with 1-D models being sufficient). Six open-source models were shortlisted for the Auckland application and compared against a set of evaluation criteria. The two most suitable lake water quality and ecological models were AED2 (Hipsey et al. 2013) and PCLake+ (Janse 2005; Janse et al. 2010; Janssen et al. 2019), and they had similar capabilities. PCLake+ was recommended because it has a longer history of use, there are user interfaces for simpler applications, and both NIWA and the University of Waikato have used PCLake+. The model requires a hydrodynamic component, and we recommended the use of the hydrodynamics model GLM (Hipsey et al. 2019) which builds on the now-discontinued DYRESM model (Imberger 1979; Imberger and Patterson 1981) which has been applied successfully in New Zealand. An alternative hydrodynamic model is GOTM (Burchard et al. 1999), which was used for Lake Waahi by Allan (2018). While either hydrodynamic model would be suitable, we recommend GLM because of the history of the precursor model DYRESM.

4.12 Lake Taupō

In relation to 1-D modelling: The DYRESM-CAEDYM model was established around 20 years ago. Support for DYRESM-CAEDYM has been discontinued, so we do not recommend that it be used. Instead, as for the shallow lake models, we recommend that a combination of GLM (for hydraulics) and PCLake+ be used. GLM uses similar hydrodynamics to DYRESM, so aspect of the previous DYRESM model for Taupō could be re-used.

For 3-D modelling, AEM3D has already been set up for hydrodynamics; however, that model is proprietary. Therefore, we recommend a shift to D-Flow 3D and D-Water Quality, as proposed for simulation of the hydro reservoirs. A limitation of such modelling is that long-term simulations (~decade) would be at the limit of feasibility (they would take a long time to run). For predicting algal blooms in nearshore areas, a hybrid mechanistic/empirical approach is recommended, using outputs from the 3-D model, as discussed in Section 4.10. There is also an opportunity to use wind fields calculated with the NIWA 1.5 km weather model (available nationally), rather than relying solely on meteorological stations, which are sparse.

3-D modelling would require a large effort for setup and collecting supporting data. We therefore recommend a staged approach, whereby a 1-D model would be established first.

4.13 Fish and water-bird habitat

One approach to assessing habitat suitability is to spatially map areas with suitable hydraulic conditions (flows, depths) and substrate, and also to summarise the total area of suitable habitat (optionally with weighting functions for the different conditions). This can be done over a range of flow rates. Hydraulic models are one way to assess the hydraulic conditions. Evaluation of the suitability can be performed as a post-processing spatial mapping exercise after the hydraulic calculations are performed. Software such as the Deltares HABITAT software can assist with such calculations.

There are opportunities to extend the analysis of hydraulic conditions already conducted for the lower Waikato for determining habitat availability for spawning under various tidal and flow conditions (Jones and Hamilton 2014a) to take vegetation into account and quantify areas of suitable spawning habitat. This could guide the development of minimum flows. It would also be possible to extend the analysis to investigate the potential to modify the timing of controlled reservoir releases to increase spawning habitat (for example, time releases to coincide with king tides if river levels are low). We recommend that both of these exercises be undertaken.

The dynamic hydraulic models could also be used to identify the frequency and duration of inundation, which could help prioritise locations for vegetation management, and management of flood gates. In general, though, we don't have the data or knowledge to translate inundation areas, let alone frequency-duration, into impacts on species.

Dynamic models could also be applied to assist with the design and operation of flood gates to maximise off-line spawning habitat. Previous reviews have identified the potential for creating habitat behind flood infrastructure, provided that inundation damage and flood damage can be limited. However, water exchange and quality would need to be considered alongside hydraulic habitat, because ponding areas behind gates can suffer from degraded water quality such as depleted oxygen levels. We consider that conducting these studies would not be an immediate priority relative to other modelling exercises but could be suitable for the mid- or long term.

4.14 Fish abundance and movement

First, we note that pest fish have already invaded the lower river and most lakes, so there is limited value in attempting to model their invasion progress in those areas.

In general, it is difficult to create dynamic fish population models for river systems, and we do not consider that such models would be suitable for meeting the needs of decision-makers and resource managers. There are many behavioural factors and parameters that are unknown or poorly quantified – use of these would make the models unreliable. For example, while we know when fish migrations occur, we do not have much information on the relationship between flow and migration, and the relative role of diadromy[35] and use of lakes for spawning. Also, there is typically insufficient data over space or time to drive or constrain the models. There are large natural temporal fluctuations in catch locations, which are difficult to measure and represent in models. At best, such models could build understanding of a system and indicate direction of change over time or space.

While dynamic models are not yet suitable for practical purposes, it is appropriate to further consider fundamental research in this area.

4.15 River biogeomorphology

We consider that river biogeomorphic evolution models are currently at a research stage, and not suitable for practical decision-making. However, as with dynamic fish modelling, there is value in including such models in a broader research portfolio.

4.16 Economics and land-use evolution

Several of the outputs of dynamic models can be used in economic assessments, including:

- Flood risks from dynamic flood models. It would be desirable to link predictions of flood flows to asset inundation and damage through inundation mapping, including 2-D flow mapping in some critical locations. This can also be used to assess the efficacy of flood management infrastructure.
- Drought susceptibility and water supply reliability through the water resources models.
- Water quality mitigation cost.

Other modelling will provide suitable biophysical information for such economic assessments. However we do not propose that these economic assessments be undertaken as part of the work programme, but rather that these assessments are undertaken separately as the need arises, associated with particular economic assessments with specific goals.

In previous work undertaken as part of the Healthy Rivers/Wai Ora programme, water quality mitigation costs were considered through a simplified water quality model embedded in specialist economic optimisation software (Doole 2013; Doole et al. 2015; Semadeni-Davies et al. 2015b; Semadeni-Davies et al. 2015a). Such software automatically evaluates a large number of mitigation scenarios to arrive at an optimum solution (or set of 'best compromises'). Such optimisation requires that the model runs are very fast, which would not be achievable if a full, complex dynamic water quality model were used.

[35] Diadromous fish live part of their life at sea, part in freshwater

Hence, either a scenario approach would need to be used, or approximate representations of the full system would be needed (by running a large number of simulations in advance and modelling the water quality response summary metrics of interest in a statistical or machine learning meta-model).

Dynamic models can also be used to simulate the evolution of land use, population, and associated environmental results over time. Previous work in the Waikato used the sophisticated proprietary Geonamica modelling framework to build the WISE application. Shifting WISE to an alternative non-proprietary platform would be difficult and expensive, and we consider that it has lower priority than other dynamic model development tasks. An alternative software platform may be PCRASTER, although it does not include representation of line features such as transport or drainage networks.

4.17 Note on availability of Deltares models

The preceding sections have identified a useful role for several Deltares models, arising from the sophisticated yet open-source approach adopted by Deltares. However, there are some caveats in the use of these models:

- Cost. While Deltares has an open-source approach for its models, it is often appropriate to make use of their support packages which have an annual fee of approximately $10-40,000, depending on the required level of service. Without such support, it is very difficult to get assistance with troubleshooting, advice on complex model setup, or bug fixes. Although some user community wiki-type services are available, they are not very active.
- Ongoing development. The suite of models has been under transition from older software platforms for some time, and many of the features are only available internally within Deltares or as part of a beta testing programme for associated research partners. This introduces risk into the project, because the rate of development is such that versions may not be available for general use for several years. Key components that are only available under such restricted conditions[36] are real-time control, 3-D water quality, Linux versions, sigma co-ordinates, 1-D models, and 1-3 D integration.
- Currently, the only publicly released version of the 1-D models requires a service agreement (under a banner of the earlier SOBEK software). It is not clear when 1-D capabilities will be incorporated into the open-source version (D-Flow).

[36] https://download.deltares.nl/en/download/delft3d-fm/

5 Proposed modelling approach

The preceding sections have identified multiple model needs and evaluated a range of models for their ability to meet those needs. The following sections propose a staged approach to model setup and implementation, and also address data needs.

5.1 Summary of models selected

The proposed models that were selected in the previous section are summarised in Table 5-1 by model type. Dependencies between models are identified – the dependencies indicate whether one model depends on another one. For example, a mainstem water quality model will generally depend on inputs from a contaminant generation model.

Table 5-1: Summary of main model types and proposed software. Model dependencies are also shown.

Model type	Software	Dependencies
Contaminant generation	SWAT	
Groundwater quality and quantity	Modflow	Recharge, SWAT
Flow routing in mainstem and reservoirs	D-Flow 1D	Flow generation (SWAT, water resources, or flood)
Reservoir hydraulics and water quality	D-Flow-3D and D-Water Quality	Mainstem flow and water quality
Mainstem water quality model	D-Water Quality	Mainstem flow and contaminant generation
Shallow lakes and Lake Taupō 1-D	GLM-PCLake+	Contaminant and flow generation
Lake Taupō 3-D	D-Flow-3D and D-Water Quality	Contaminant and flow generation
Storm flow generation and routing to streams	D-Hydrology (WFLOW)	
Water resources model	Not yet identified. WEAP is a low-cost proprietary option.	
Habitat suitability mapping in lower river	D-Flow and mapping	
Operational forecasting for flood flows and water quality	FEWS	Flow and water quality models
Cyanobacteria model	Machine learning, R	Flow and reservoir models
Fish habitat creation by floodgate modification	D-Flow and mapping	

As noted in Section 4, we have excluded models for fish abundance and movement, and river biogeomorphology because the capability of these models is not sufficiently mature for management applications. We also excluded economic implications of biophysical models, because those assessments can be made when needed based on results of the proposed work. Finally, we excluded land-use evolution spatial modelling because we considered it has a lower priority at present.

5.2 Work programme

The main tasks and sub-tasks and timing are shown in Table 5-2.These tasks represent a 'wish-list' and will need to be refined depending on resources and capacity. Also, the timing and construction of tasks will need to be refined once there is clearer direction on priorities and resourcing. Some modelling needs are related to the next round of Waikato land-water planning (Healthy Rivers or the equivalent), which are a priority. For example, it is acknowledged that better models of mainstem phytoplankton are needed. However, a long-term aim to lift the state and capability of land-water modelling for the Waikato also exists as part of fulfilling the Vision and Strategy, so an ambitious agenda has been proposed.

The tasks can be grouped to some degree as follows:

- Tasks 1-5 are related, being needed for water quality modelling. Task 6 (shallow lake water quality) could also be included in that package, because some of the riverine lakes in the lower system affect water quality. Task 12 also relates to water quality, but with a different style of modelling for cyanobacteria. Tasks 13 and 14 are for water quality in Lake Taupō. Task 11 is for water quality forecasting.
- Tasks 7 and 8 are each independent tasks, aimed at different purposes (floods and water resources). Task 10 relates to flood forecasting.
- Tasks 9 and 15 relate to fish habitat.
- Tasks 16 is for student research, while Task 17 is for programme management and co-ordination. Task 17 includes 0.2 FTE/year related to Iwi: ensuring model results are accessible, fit for use, and meaningful. This item is intended to ensure that model results are accessible to the public and able to be visualised easily.

Most of the main tasks include documentation and training sub-tasks. This will ensure that a range of technical users are able to access, use and develop the models. This includes building modelling capability by Maori.

A further work item relates to funding postgraduate study. We proposed that two PhD students be funded, at least one of them specifically for a Maori researcher.

There are opportunities to undertake key model sub-components as a starting point, without committing to the full programme. For example, a water quality model and associated monitoring could be conducted for a single reservoir, without committing to a full roll-out of water quality modelling across the system. Similarly, algal data for the lower river could be assembled and used to construct a preliminary machine-learning model, and flood flow models could be compared within D-Hydrology. Further tasks could be identified when considered to be suitable interim level of modelling.

Table 5-2: Outline of key tasks and timing. Table continues on following two pages.

Task	Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
1. Contaminant generation	1.1 Set up and preliminary calibration based on available data, No GW					
(SWAT)	1.2 Couple to regional GW model					
	1.3 Transfer to HPC (cluster at least)					
	1.4 Mitigation scenario capability					
	1.5 Collect high-resolution water quality data					
	1.6 Refine SWAT calibration					
	1.7 Documentation		x	x		
	1.8 Training		x		x	
2. Groundwater quality and quantity	2.1 Flow model					
(MODFLOW)	2.2 Historical land use					
	2.3 SWAT-MODFLOW initial model for N					
	2.4 Set up on HPC					
	2.5 Update/refine N model					
	2.6 Documentation		x		x	
	2.7 Training		x		x	
3. Flow routing in mainstem and reservoirs	3.1 Couple to flows from hydrologic models (SWAT, D-Hydrology)					
(D-Flow 1D)	3.2 Set up reservoir models including release rules					
	3.3 Transfer existing models for lower river					
	3.4 Set up and calibrate full system					
	3.5 Transfer to HPC					
	3.6 Documentation			x		
	3.7 Training				x	
4. Reservoir hydraulics and water quality	4.1 Collect reservoir temperature, water quality, chla sensor, velocity and climate data					
(D-Flow-3D and D-Water Quality)	4.2 Set up reservoir models					
	4.3 Transfer to HPC					
	4.4 Calibrate models					
	4.5 Model simplification and meta-modelling					

Task	Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
	4.6 Documentation				x	
	4.7 Training				x	
5. Mainstem water quality model (D-Water Quality)	5.1 Set up model including inflow linkages					
	5.2 Collate river algae data in a database					
	5.3 Preliminary calibration using 1-D representation of reservoirs					
	5.4 Refinement with 3-D reservoir models, including linkage and re-calibration					
	5.5 Documentation					
	5.6 Training					
6. Shallow lakes (GLM-PCLake+)	6.1 Set up 6 key shallow models, building on prior work and monitoring					
	6.2 Calibrate					
	6.3 Couple with mainstem model					
	6.4 Documentation and training					
7. Storm flow generation and routing to streams (D-Hydrology)	7.1 Preliminary setup and testing with three candidate models. Select final model					
	7.2 Refine calibration for selected model for tributaries					
	7.3 Couple with mainstem model					
	7.4 Documentation and training				x	
8. Water resources model (Model choice to be finalised)	8.1 Set up abstraction and flow database					
	8.2 Set up initial irrigation, rainfall-runoff and routing model including control roles					
	8.3 Couple with groundwater model					
	8.4 Refine model setup and calibration					
	8.5 Documentation and training				x	
9. Habitat suitability mapping in lower river (D-Flow and mapping)	9.1 Transfer and refine existing hydraulic model to FM on HPC, including refined DEM					
	9.2 Run model over long forcing conditions					
	9.3 Analyse riparian vegetation from aerial photogrammetry					

Task	Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
	9.4 Combined hydraulics and vegetation to assess area of spawning habitat					
	9.5 Investigate hydromodification implications					
	9.6 Documentation and training				x	
10. Operational flow forecasting	10.1 Set up storm rainfall-runoff model in operational forecasting software, including drivers					
	10.2 Add data assimilation capability					
	10.3 Documentation and training			x		x
11. Operational water quality forecasting	11.1 Set up storm water quality model and inputs in operational forecasting software					
	11.2 Add data assimilation capability					
	11.3 Documentation and training			x		x
12. Cyanobacteria model	12.1 Initial model using measured SOE environmental parameters and modelled reservoir status					
(Machine Learning in R)	12.2 Extension to include continuous water quality monitoring data and quality model predictions					
13. Lake Taupō 1-D model	13.1 Set up and calibrate hydrodynamics					
	13.2 Set up and calibrate water quality					
	13.3 Run climate change scenarios					x
	13.4 Documentation					x
	13.5 Training					x
14. Lake Taupō 3-D model						Post Y5
15. Fish habitat creation by floodgate modification						Post Y5
16 PhD Students x2						
17. Management and co-ordination	17.1 Model steering group meetings and technical workshops	x	x	x	x	x
	17.2 Repository maintenance					
	17.3 HPC management and training					
	17.4 Iwi linkage					
	17.5 Project management and technical leadership					

5.3 Costing

A very provisional costing is provided in Table 5-3, to serve as a guide for selecting and resourcing the models. FTE's are costed on a basis of $300k/FTE. This costing is for indicative purposes only, and does not constitute a proposal for the purpose of procurement or contracting. Detailed price and duration estimates would be needed prior to embarking on a specific task.

Table 5-3: Preliminary costing.

Item	FTE	Data ($k)	Total ($k)
1. Contaminant generation	1.5	640	1090
2. Groundwater quality and quantity	1.5		450
3. Flow routing in mainstem and reservoirs	0.5		150
4. Reservoir hydraulics and water quality	1	600	900
5. Mainstem water quality model	1		300
6. Shallow lakes	1		300
7. Storm flow generation and routing to streams	1.5		450
8. Water resources model	1.5		450
9. Habitat suitability mapping in lower river	0.5		150
10. Operational flow forecasting	1		300
11. Operational water quality forecasting	1		300
12. Cyanobacteria model	0.75		225
13. Lake Taupō 1-D model	0.5	100	250
14. Lake Taupō 3-D model	1.25	500	875
15. Fish habitat creation	1	50	350
16 PhD Students (2, 50k each per year, 3.5 years)		700	700
17. Management and co-ordination	3		950
18. Software support and data licences, HPC		200	200
Total	**18.5**	**2790**	**8390**

5.4 Supporting data

The models require supporting data as inputs and for calibration and testing. These data is summarised in Table 5-4.

Table 5-4: Summary of data needs.

Item	Model supported	Existing/new	Comment
Soils map. SMAP	Multiple	Existing	Will need permissions.
Current land use. AgriBase	Multiple	Existing	Will need permissions.
Historical land use	Multiple	Existing	Has been collated for Healthy Rivers.
Historical distributed climate. VCSN	Multiple	Existing	Will need permissions.
Flow and level data	Multiple	Existing	Will need Mercury permission for some datasets; otherwise or collect new data.
SOE water quality data	Water quality models	Existing	
River algal data	Water quality models	Existing	Hardcopy species/community data needs to be transferred to electronic database.
High-resolution stream/river water quality data	Water quality models	New	Suggest 3 tributaries, 1 lower mainstem. 1 year.
Reservoir stratification and DO	Water quality models	New	Ohakuri, Maraetai, Karapiro. May be able to use some historical data for Karapiro. 3 sites for each reservoir. Temperature, DO, Chl. 1-year deployment. Use instrument strings if possible.
Reservoir velocity distribution	Water quality models	New	Ohakuri, Maraetai, Karapiro. May be able to use some historical data for Karapiro. Measure during stratification.
Wind data	Water quality models	New	Local wind could be different from VCSN. 1 year initially.
Climate forecast	Forecasting models	Existing	Will need to purchase service from NIWA or MetService.
Wind and continuous water quality, ongoing	Forecasting models	New	Not costed.
River channel sections	Multiple	Existing	
Lake morphometry	Reservoir and lake models	Existing	
Lake stratification and DO for 1-D models	Lake models	Existing and new	Existing data for Taupō and some shallow lakes. May need additional data for some additional key shallow lakes. Desirable to continue Taupō buoy.
Nearshore water quality, currents, and profiles.	Taupō 3-D lake quality model	New	These would be in addition to the data from the central Taupō site. Data collection could entail a) profiling current meter deployments at key embayments of interest. b) temperature, DO, and water quality profiles on a monthly basis over a year at key sites c) remote sensing and calibration for optical quality of water, 6 deployments of unmanned aerial vehicles and collection of optical model calibration data. We assumed that wind fields at 1.5 km resolution will be available from NIWA's high-resolution climate models.

Reservoir operating rules	Multiple	?	Unclear on where they are specified and how used.
Lower river riparian vegetation	Spawning habitat	New	Base on aerial photogrammetry.
Velocity distribution in lower river	Spawning habitat	Existing	Use data from previous study. But, will need to review to determine whether salinity data is suitable.
Flood infrastructure location and operating rules	Flood modelling	Existing and new	Current representation in models is limited.
Water consumptive use	Water resources modelling	New	Most data is for consented, not actual, abstractions.
Point source data	Water quality models	Existing	Need to capture temporal variation from monitoring data.
Groundwater geology	Groundwater models	Existing	Needs to be translated into suitable form for models.
Groundwater levels	Groundwater models	Existing	
Groundwater quality and ages	Groundwater models	Existing	

As noted from discussions with Te Arawa River Iwi Trust, there may be opportunities to align data collection with other monitoring initiatives that are being led by Iwi.

5.5 Institutional arrangements

A principle of the proposed programme of work is to have a system of models that is owned and used by a community of users. However, there is still a need for co-ordination and some centralised 'home' for models and data. This includes the following aspects:

- The general requirement around model ownership is that the model software will be free, preferably open-source, and that model data will be made available to all parties. We anticipate that there will still be a need for these arrangements to be formalised, and for agreements to be set up – for example, to avoid one party taking the collective IP and commercialising it. A central agency or organisation will need to facilitate the setup.
- There will also be a need to set up and maintain the code, datasets, and results, and metadata. There are repository systems such as GitHub to facilitate such sharing, but it is best if there is a co-ordinating party to curate the information and, in some cases, accept proposed updates to datasets or model code.
- For various model components, it is proposed that training sessions be held. This will require co-ordination.
- Some of the model datasets are likely to come from proprietary sources. Suitable arrangements need to be set up for licencing the data and to ensure that data are used within the limits of those licences.

- The overall project will require governance – for example, to set priorities, modify the work programme as it develops, guide the best use of resources, distribute resources, check accountabilities are met, and manage links with stakeholders at a high level.
- Several of the models will need to be coupled, requiring co-ordination.

The organisational arrangements for this centralised home have yet to be determined. This could be provided by WRA, NIWA, or the WRC, but would be answerable to the governance group and funders.

The application of models to the needs of Iwi is an important end-goal of this work. Apart from representation on the governance group, we have allowed for a work item to ensure model results are accessible, fit for use, and meaningful to Iwi users.

5.6 Next steps

This report recommends models to meet a range of needs linked to Report Card Taura. A set of work items and indicative costs, and institutional arrangements have been outlined. The proposed work programme is ambitious, as requested, but will need to be tempered by the priorities of stakeholders, given the likely limitations in funding.

Based on feedback on the draft report, it was agreed that further consideration needs to be given to prioritisation and staging of work. To this end (using additional funding), it was proposed that NIWA would:

- Prepare a short document summarising the uses and value proposition for the proposed models and data collection.
- Hold facilitated workshops with Iwi and stakeholders with an emphasis on prioritisation, resourcing and governance.

This is anticipated to lead to more detailed specification of work items and contracting.

6 Concluding remarks

The project has arrived at recommendations for implementation of a set of dynamic models to provide predictions likely to meet the needs of the Vision and strategy. This was achieved by identifying variables associated with Report Card taura, relating these to requirements of various model types, reviewing existing models for the Waikato, and evaluating software alternatives to arrive at a proposed set of model software.

An ambitious 5-year work programme has been proposed, with indicative costings, including costs associated with meeting data requirements.

As next steps, it is proposed that the programme will be workshopped with project partners and stakeholders to identify priorities and funding sources.

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Appendix A Past and current dynamic modelling of the Waikato River system and catchment

Mercury and Waikato Regional Council hydrologic models

Mercury NZ uses hydrological models for assessing inflows to the hydro reservoirs and passage of flows down the reservoir system. An interview was held with David Payne from Mercury NZ, who provided information on the flood models that are used or have been used.

An interview was also held with Ghassan Basheer and Murray Mulholland to obtain information on WRC's dynamic flow modelling. Information from that meeting, supplemented by follow-up reading of materials provided, is below.

Reservoir flow routing model

Mercury has a model developed by Ian Jowett to estimate the passage of floods down the reservoir system. The model takes predicted Lake Taupō inflows, add flows from reservoir tributaries, and routes the flow through the reservoirs using level-pool routing with outflows driven by flood release rules (Jowett 2009) and applies empirical time lags to capture delays of flow in the river between reservoirs. Tributary inflows for flood event analysis are determined from statistical analysis of measured flows. The Jowett model is written in Fortran as a stand-alone programme.

Mercury have separate approaches for managing day-to-day (non-flood) generation, which take account of storage in the reservoirs and simplified routing down the network.

Rainfall-runoff model, Taupō-Karapiro.

Mercury have DHI-based models (presumably NAM hydrological models), for estimating runoff for the tributaries between Taupō and Karapiro, intended to be used in conjunction with the routing model above. There are also flow recorders, which can be fed as inputs to the flow routing model, with ungauged catchments inflows based on scaling relationships. These models are not being used currently but would still serve a useful role in terms of operation of the system. The models could potentially be improved and combined with the reservoir routing model in a common software platform.

Lower Waikato Model

WRC have a 1-D dynamic hydrology and hydraulics model of the lower Waikato River (Karapiro down, including the Waipa and its catchment)(Joynes 2009), which is used for flood forecasting, and establishing the level of protection provided by flood banks in the lower river, and has also been used as part of assessing the effects of land use change in the upper catchment on flows in the lower river. The model is based on the DHI NAM hydrology component for runoff generation from the lower catchment, with Mike-11 hydraulic routing of flows down the rivers. The Mike-11 model includes the major structures in the Lower Waikato-Waipa Control Scheme but does not represent flood gates and pumps (pers. comm. Murray Mulholland). Measured outflows from Lake Karapiro (which is at the upstream end of the Lower Waikato model) are telemetered and incorporated into the forecast using the DHI Mike Operations software, and it is assumed that the outflows remain at the measured rates over the forecasting period for baseflows or small floods. During high flood events, Mercury provides predictions of outflow from Karapiro based on incoming natural flows between Karapiro and Taupō, hydro system storage capacity below design levels, and downstream conditions under certain circumstances set in the High Flow Management Plan.

The hydrological parameters were set at the original calibrated values from DHI (2006), which were calibrated using tributary flows (6 subcatchments, lumped parameters for each subcatchment, with most parameters transferred to ungauged catchments based on means in the gauged catchments, except for lag).

The models are incorporated into the Operations software for forecasting (Van Kalken et al. 2005), which includes data assimilation (adjusting the model to take observations into account), and forecasting of rainfall (it unclear how rainfall is forecast). The models were prepared with a combination of in-house and DHI consulting expertise (WRC developed the Waipa model).

Some 2-D hydraulics models have also been developed are also being developed (as of 2018) around Huntly.

The hydraulic models could be updated with council-measured channel geometry.

WRC Upper Waikato flood model

WRC used hydrologic models to investigate how conversion of pine to pasture between Taupō and Karapiro would change flooding levels and flow rates in the lower Waikato (Environment Waikato 2010), for individual floods. The modelling incorporated several sub-models:

- SKM (now Jacobs) and WRC developed a **HEC-HMS** hydrological model of tributaries in the upper Waikato (SKM 2009) from Taupō down to Karapiro. The SMA conceptual rainfall-runoff model was used (within HEC-HMS) for runoff generation, with parameters assigned on the basis of soil and land cover, with calibration on a subcatchment-by-subcatchment basis. Unit hydrograph methods were used to convert runoff to flows at the sub-catchment outlet, along with additional linear storage components applied to groundwater inflows, representing baseflow recession.
- NIWA prepared a **TopNet** model of the upper catchment (Woods et al. 2009) tributary flows, set up in parallel with the HEC-HMS model.
- Routing through the hydro dams was conducted with the reservoir routing model used by Mercury (discussed above). One difficulty was representing reservoir releases during floods; the releases were based on existing flood rules but could not capture the full complexity of reservoir management.
- The lower river was handled with the DHI NAM and Mike11 models already established for flood prediction (see Lower Waikato Model discussed above).

It was noted that the spatial distribution of rainfall in floods is important, but difficult to obtain.

Taupō tributaries

Further DHI-based models of tributaries in the upper catchment have also been prepared (Tauranga-Taupō and Tongariro). Those models were prepared for WRC by Tonkin and Taylor.

Maxwell/LUCI hydrological model for Taupō

Maxwell (2013) developed a hydrologic model for Lake Taupō inflows (described in Chapter 6 of her thesis). The model is a lumped conceptual model, with a soil store, infiltration- and saturation-excess surface runoff, drainage based on a power law intended to represent a variably saturated catchment, three drainage pathways. The model was applied to five gauged subcatchments, with parameter regionalisation applied to ungauged catchments.

A separate statistical representation of the inflows associated with the Tongariro Power Scheme was used. Data assimilation was used for flow forecasting. The underlying conceptual model is the basis of the dynamic hydrological component of the LUCI catchment model (Jackson et al. 2013), although with allowance for spatial variation of parameters.

Groundwater models

Here we present the main large-scale modelling initiatives in the Waikato catchment. There have been several smaller groundwater models, mainly focussed on local issues, and two medium-sized models of the western Lake Taupō catchment and the Northern Lake Taupō catchment which are not discussed here.

Upper Waikato Regional Groundwater Model

Aqualinc have developed a MODFLOW model of the groundwater system from Lake Taupō to the Lake Karapiro outlet for the Waikato Regional Council (Weir and Rajanayaka 2014). The model is at 1 km resolution with rectangular cells in plan view, and about 20 layers vertically. Recharge is provided by outputs of the Irricalc proprietary rainfall-runoff model, with removal of a proportion of the flow representing quickflow that is transferred directly into the rivers. The flow aspects of the groundwater model are essentially steady-state. The nitrate transport model was also steady state, without decay. Tritium concentrations were simulate using a dynamic model, associated with modelling groundwater ages. The authors of the report called for more data before proceeding to refined modelling. One difficulty was obtaining good inputs of nitrogen leaching.

Reporoa

Sarris et al. (2019) modelled groundwater, including nitrate transport, in the 658 km^2 Reporoa basin as part of a collaborative group. MODFLOW-NWT and the associated transport model MT3D-USGS were used, with a 200m grid resolution and four layers vertically, using a steady-state flow and nitrate transport conditions. It was found that denitrification parameters could not be determined by calibration alone, so that detailed characterisation of denitrification conditions is needed based on field investigations. It was predicted that if nitrogen reductions are focussing on locations that have lower losses between the point of leaching and the river, the required reduction in leaching to achieve a target loading to the river can be halved, compared with spatially-uniform reduction of leaching. The required reduction in leaching depended on assumptions about the spatial distribution of denitrification conditions in the aquifer, demonstrating that the spatial variation of denitrification needs to be considered when regulation strategies are developed.

Ruahiwai groundwater model

Zhao et al. (2019) prepared a dynamic groundwater model of the Waikato catchment from the Lake Taupō outlet to the Lake Ohakuri tailrace (1648 km^2), as part of an integrated surface-groundwater model for the area (see below for more information on the integrated model). MODFLOW was used for groundwater flow with a 300m cells in plan, with four geological layers (computational layers are finer vertically). Recharge was provided from the rainfall-runoff component of the SOURCE catchment model (averaged over each of 415 subcatchments). Particle tracking was used to estimate groundwater age.

Transient MT3DMS transport simulations were as used for nitrate and tritium transport, including spatially varying decay of nitrate. Nitrogen leaching inputs were obtained from the APSIM soil-crop model (Holzworth et al. 2018).

A feature of the setup of the model as an oxic layer in the top 5 m of groundwater, underlaid by deeper anoxic layers; this had implications for the relative role of shallow/young flow-paths versus deep/old flow paths (that would spend longer in the anoxic zone and therefore had grater denitrification losses and less contribution to the river), and the spatial allocation of leaching reduction measures. The nitrogen transport parameters were calibrated to observations of groundwater and baseflow stream nitrogen. The model predicted the order of magnitude of groundwater concentrations correctly, but despite the sophistication of the model, the predictive performance of the spatial distribution of concentrations was poor, which is not unexpected for groundwater transport models where the spatial distribution of subsurface conditions and parameters is uncertain, and the overall difficulty of modelling is high.

Ruahiwai Decision Support Tools

Williamson Water & Land Advisory (WWLA) led the development of an integrated water quality model for the Waikato catchment from the Lake Taupō outlet to the Lake Ohakuri tailrace (1648 km^2), to support land development and management by Wairakei Pastoral (Mawer and Williamson 2019). The model couples the following components:

- APSIM soil-crop model for N leaching. The model was run for different land uses and management practices (e.g., irrigation) and climate conditions. The losses were then allocated spatially depending on where those conditions arise.
- A rainfall-runoff model (Soil Moisture Water Balance Model with Vadose Zone functionality (SMWBM_VZ)), developed by WWLA for recharge and runoff generation, which was set up as an add-in to the Source catchment model.
- MODFLOW and MT3DMS model for baseflow and groundwater transport of leached N.
- eWater SOURCE model (Herron et al. 2015)[37] for routing flow down the stream network, used to model generation and transport of N, P, sediment, and *E. coli* (apart from leached groundwater which was transferred to the stream using the groundwater model)(Williamson and Mawer 2019). Several customisations were used beyond the usual SOURCE approach. For example, quickflow TN concentrations were estimated based on an index that was in turn based on sub-indices slope, stocking density and landcover factors; the relationship between the total index and concentration was determined based on calibration, with a different curve for three groups of catchments. Speciation of TN was based on fractions from monitoring data. Sediment was calculated with the hillslope erosion component of the dynamic SedNet model as implemented in Source, which breaks down mean annual loads over time according to the amount of runoff. The model did not include in-river transport and processing of contaminants (apart from decay in Lake Ohakuri). Within-subcatchment decay of *E. coli* (a function of modelled runoff) was allowed for, however.

Waikato Catchment Model (WCM)

As part of the Waikato River Integrated Scoping Study (WRISS) and earlier work for the Waikato Regional Council and electricity generation authorities, a model of water quality down the Waikato and Waipa rivers was developed (Section 5.3 in Appendix 13 of NIWA 2010) (Rutherford et al. 2001), to estimate the effect of land use, mitigation measures the hydro reservoirs on water quality in the

[37] https://ewater.org.au/products/ewater-source/

mainstem of the rivers. The model addresses nutrients, phytoplankton, suspended sediment, fine clarity-reducing suspensoids, yellow substance, optical clarity and colour. The model is steady-state, but was applied to low flow, mean flow, and high flow conditions in summer and winter to obtain predictions of water quality under different flow conditions. Tributary input concentrations (or yields in the later version of the model) were determined based on simple relationships with land use. The reservoirs were treated like parts of the river network (no vertical stratification or longitudinal mixing). The phytoplankton growth constant was a function of light, temperature, and a carrying-capacity factor which depended on a maximum possible concentration, which in turn was a function of nutrient concentration. Optical clarity was assessed based on estimated fine suspensoids, phytoplankton, and yellow matter. This model was implemented in an Excel spreadsheet.

While the model is not dynamic, it does illustrate the potential to simplify the processes in the main stem. Shortcomings include ignoring storage in the reservoirs and the inability to resolve mixing and stratification in the reservoirs.

CREAMS-based nutrient inputs to Lake Taupō, coupled to dynamic lake model

In the late 1990's a dynamic hydrologic and water quality model was developed for the catchment of Lake Taupō (Elliott and Stroud 2001). The model, Basin New Zealand (BNZ) was based on applying the daily soil-crop model CREAMS to unique combinations of land use, soil, slope and climate in the catchment, and then summarising the results for each subcatchment routing the flow and loads down the drainage network, with flow-dependent attenuation. The model is based largely on runoff from rainfall events and is not particularly targeted at baseflow (percolation is spread out over the time between rain events). The models were applied to TN and TP.

The loads were then used as inputs to a 1-D (vertical) dynamic lake model, DYRESM-CAEDYM, to determine the response to land use change scenarios (Spigel et al. 2001). The lake model predicted annual cycles of periphyton growth and highlighted sensitive factors such as the role of geothermal heat sources, mixing of river inflows, and light extinction on the lake dynamics, including their impact on the critical annual winter mixing.

Lake Taupō 3-D Hydrodynamics model

A 3-D model hydrodynamic model of Lake Taupō was built and run as part of assessing nutrient exchanges between nearshore areas and deep areas (Stewart 2018), which informed separate food web assessment. The AEM3D model was used (Hydrodynamic Inc., Australia), which is the successor to the ELCOM model from University of Western Australia. The model was set up with 500 m by 500 m cells horizontally and run for a 22-month simulation period coinciding with a period of ecological measurements. Measured inflows were used, and model performance was assessed against measurements from a temperature profile in the centre of the lake. The model was not coupled to a dynamic water quality or ecological model. Run-times of the model were in the order of 1 day, precluding automated calibration

WISE

WISE (the Waikato Integrated Spatial Explorer)[38] is a model set up for Environment Waikato by RIKS for simulating land use change patterns, population growth, economics and environmental impacts, including feedbacks between some aspects such as population, economics and land use.

[38] http://www.creatingfutures.org.nz/wise/what-is-wise/

The model is dynamic in the sense that it models changes over time at an annual time step and is spatially explicit (mainly grid-based at 100m resolution) but it does not represent sub-annual variations. The model has been maintained in the last few years, mainly by updating the land use, zoning, economic and transport components. It is built using the proprietary Geonamica framework[39].

Shallow lake models

Hydrodynamic modelling of Lake Whangape and Lake Waahi

Hydrodynamic models of Lakes Whangape and Waahi were developed using Delft3D hydrodynamic model (Jones and Hamilton 2014a) (50 m rectilinear grid). The models were set up in 2D mode (vertically mixed) and run for a year-long simulation period, but were not calibrated, partly due to limits of available calibration data and lake inflow measurements. A simple model was used to estimate lake inflows from rainfall. The model is built in the proprietary GEONAMICA spatial simulation framework.

University of Waikato 2017 modelling of shallow lakes

Lehmann et al. (2017) used the 1-D dynamic lake model DYRESM-CAEDYM coupled with catchment models (either INCA, or the flow model TopNet combined with the budget-based model CLUES) to assess the effects of external nutrient load reduction, hydrological modifications (inflow diversion or increasing water level), and sediment capping or flocculation on water quality (oxygen, nutrients, suspended sediment, diatoms and cyanobacteria) for three shallow Waikato lakes (Rotomānuka, Ngāroto, Waahi). Flows for Lake Waikare were modelled with a 3-D hydrodynamic model, Delft3D. Capping was represented with an assumed reduction in internal loading from the bottom sediment (either by reduced entrainment of sediment or reduction of release rates when the bottom water becomes anoxic), rather than through geochemical modelling. The method for representing flocculation was not presented.

Lake Waahi water quality modelling

Allan (2018) modelled water quality of Lake Waahi using the lake model PCLake coupled to a 1-D hydrodynamics model, the General Ocean Turbulence Model. The project was in a context of improving the broader ecological state of the lake to support hauanga kai (food-gathering). Contaminant sources were provided by the CLUES model with TopNet for temporal disaggregation of loads. Fish were included as a constant biomass that affected nutrients and increased resuspension. Scenarios included nutrient input reduction, pest fish reduction, and macrophyte re-establishment. The higher-level goal of modelling kai was not addressed, despite the model having considerable sophistication, which illustrates the limitations of such lake models.

DOC Whangamarino system hydrologic model

Jacobs have prepared a flow model of the Whangamarino system for the Department of Conservation the system for consenting. It is based on a water balance model using GoldSim generic dynamic system software, with the SMWBM (a conceptual rainfall-runoff model) and simple representation of Lake Waikare and Whangamarino storage and outflows (Streamlined Environmental 2015); that model was not adopted during consents processes.

[39] http://www.riks.nl/products/Geonamica

Lake Waikare flushing

Cox and Cooke (2015) applied the proprietary dynamic lake model SLAM (Simplified Lake Model)[40], to predict the implications of providing flushing flows from the Waikato River to improve water quality in Lake Waikare. Lake inflows from the catchment were determined by applying rating curves to measured Matahuru Stream inflows, and representative concentrations to other inflows. Additional lakebed sediment quality measurements were taken to provide input data for the model. The lake model was developed as an enhanced version of the USACOE BATHTUB (Walker Jr 2006)[41] model operates at daily time-steps with well-mixed zones, and mainly simulates nutrients and hydraulics, with an empirical relationship for summer phytoplankton, with an internal loading (bed nutrient release) sub-model.

Hydrodynamic model of Waikato estuary and delta in relation to iiananga spawning habitat

The University of Waikato developed a Delft3D hydrodynamic model of the Waikato delta, to aid with assessment of iinanga spawning habitat (Jones and Hamilton 2014b). The model included detailed bathymetry and topography collected for the study, and field measurements of water levels, temperature salinity, DO, and turbidity. A rectangular grid of 75m resolution, extending 3km from the coast up to Mercer, was used and predictions were made over a three-month period. The model was run for a range of upstream freshwater inputs and tidal levels over periods to identify areas of inundation and salinity distribution. It was found that spawning habitat at high river flows (as identified by inundation) is small, being affected by stop banks. Vegetation types and salinity were not considered in the habitat suitability assessment, apart from general conclusions about variability in the extent of saline intrusion meaning. Alongside the hydrodynamic results, visualisation of inundation areas based on detailed GIS mapping of elevations in relation to tides was helpful in identifying potential locations for increasing habitat, such as in tributaries. Salinity is a further influence on spawning, but the habitat assessment only considered that factor in a broad sense rather than through specific spawning suitability rules.

The study pointed out the need for improved understanding of mixing process in the estuary and improved representation of salinity, which would also require more targeted field data and better measurement of inlet bathymetry. Vegetation should be considered in future assessment of habitat suitability. It was also suggested that a flexible-mesh hydrodynamic model would be desirable, although that version was not released for free use at the time of the study.

[40] https://streamlined.co.nz/wp-content/uploads/2019/05/SLAM-May-2019.pdf

[41] http://www.wwwalker.net/bathtub/help/bathtubWebMain.html

Appendix B Waikato Dynamic Modelling Waananga: Meeting Notes

Note: Appendices to these meeting notes have been removed for brevity.
These notes were prepared by Tom Evans and Sandy Elliott, NIWA

Background and organisation

A meeting was held with several interested parties at NIWA to identify modelling needs at a high level for a dynamic model of the Waikato-Waipa rivers and catchment, as part of a collaborative project with WRA, NIWA, WRC, University of Waikato, Mercury Energy, the Mercury Energy/Tainui Partnership, and DairyNZ. Separate discussions are being held with River Iwi, led by Tim Manukau in an independent role. Iwi will determine their involvement in the project. Following this meeting, a draft document will be prepared by the project technical team and presented to the broader stakeholders, outlining a proposed modelling approach and associated technical resources.

As an organizing aid, the meeting discussions were organized around the 8 taura (strands) identified for the Waikato River Report Card (RC). Notes were taken in Visimap mind-mapping software. An initial list of indictors and model opportunities was prepared by John Quinn in advance, and this was commented upon in the meeting in an open and uncensored way. The resulting structured list of points have been exported from the software. Similarly, a mind map was developed for capturing existing available models. Further discussion notes, including assessment of key modelling needs, were captured on post-it notes and whiteboards. A further mind-map was developed to summarise the modelling needs discussion.

Raw notes and the Visimap files are archived on the OneDrive shared drive, which project partners have access to.

The initial agenda is shown in Appendix 2.

Initial discussions/comments

John Quinn provided a Power point presentation on Scoping Waikato River Dynamic River Modelling – Co-management context (See Appendix 3).

A handout of modelling needs and opportunities associated with addressing the Report Card taura was tabled, to serve as a starting point for discussions. It was agreed that this would serve as a useful basis for structuring needs assessment in the rest of the meeting.

Initial feedback from River Iwi (presented by Tim Manukau)

Tim had met and held some discussions with representatives of River Iwi, and presented initial ideas arising from those discussions. Tim does not represent River Iwi, he is assisting the project with River Iwi engagement. A key common question from River iwi was how would this proposed model assist in helping iwi achieve their goals and outcomes for their waterways and help support the restoration initiatives they are currently undertaking or looking to undertake.

A number of roles for modelling were identified:

- Should take a holistic approach, representing all well-beings.
- Identify impacts on customary activities that occur on the river.
- River Iwi were heavily involved in Healthy Rivers Plan Change – identify the effectiveness of the plan and associated actions.
- Identifying effectiveness of restoration projects.
- Aim to also protect the Mauri of river, not just biophysical components.
- Iwi Management Plans provide goals -- models need to link to these.
- Iwi have heavy workloads and their own work priorities, therefore they will determine for themselves when, if and how they input to project. The project should align with existing iwi management plans and iwi led initiatives i.e., Report Card and Iwi restoration priorities, rather than re-inventing the goals

The meeting notes and information from the hui were forwarded to River Iwi for their feedback and comments.

Tourism Perspective (Don Scarlet)

- Tourism is an important river-centred economic activity.
- Hamilton & Waikato Tourism want to promote 200km of cycleway "cycling New Zealand's longest River".
- 1 of 5 gamechangers for Waikato Tourism.
- Lake Karapiro -- 2 lake-based high performance centres: cycling and rowing; Karapiro is the most highly used recreational lake in NZ; events can bring 10-20,000 people to lake
- Preventing algal blooms, especially toxic ones, was vital.

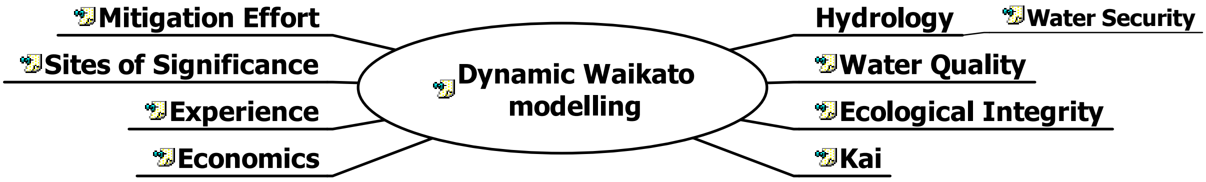
Waikato River Authority perspective (presented by Julian Williams)

- Supports 8 taura as organizing principle.
- Model should identify opportunities for improvement of environment (beyond remediation and maintenance).
- Water allocation interests of Tangata Whenua. [Desirable for the model to address water allocation].

Other

- Gassan Basheer. We might need a tiered or staged approach. Difficult to model hydraulics of the whole system at once.
- Maggie Sullivan. Farmers want to know how their activities affect the river. Attribution of outcomes to action.

Modelling needs and opportunities related to Report Card Taura



For each taura, an initial list of report card indicators and dynamic modelling opportunities were provided, and the meeting participants provided comments.

Hydrology and Water Security

RC indicators: Surface and groundwater allocation, NO_3 in groundwater, Urban use, Irrigation
Dynamic modelling Opportunities:
flood risk in relation to rainfall, antecedent weather, weather forecasts, climate change rainfall prediction scenarios, ENSO climate predictions; sea level rise, peat shrinkage, hydro dam management/ releases, land use change (pasture-urban-forestry)
land drainage sea level rise, peat shrinkage, hydro dam management/ releases, land use change (pasture-urban-forestry); (split from flood risk; originally combined)
low flows, water resource availability, in relation to: water abstraction, water trading, hydro power storage management and energy needs, land use change (pasture-urban-forestry), ENSO climate predictions; rainfall, antecedent weather, weather forecasts, climate change rainfall prediction scenarios, sea level rise/salinity intrusion.
Discussion of needs and opportunities
Need integration of flow predictions across Tongariro Power Development to Waikare
Investigate effects of wetlands and upland storage and other mitigations compared to stop banks, etc.
Link to cost-benefit analyses
Use model to investigate how individual farmer's changes in practice impact the river, providing confidence to act and attribution of outcomes to land uses.
Large scale (time and space) effects of flows on geomorphology and hydromorphology
impacts of land and sediment management, climate change
need to include sediment processes in tributaries
Support assessment of ecological flows to enhance spawning habitat

Water Quality

RC indicators: TN, TP, Chl.a, Clarity, *E.coli*
Dynamic modelling Opportunities: TN, TP, Chl.a, Clarity, *E.coli*, Cyanobacteria, Mercury, arsenic, temperature, dissolved oxygen, in relation to:
hydro lake stratification (Karapiro and Ohakuri), peat lake and riverine lakes stratification,
nutrient inflows, nutrient release,
metal release and Hg methylation,
land use change and management,
restoration actions (farm plans, riparian, pest fish and plant management)

Discussion of needs and opportunities
Align model with measurements and monitoring under NPS-FM. Note that lakes monitoring is increasing to 36 lakes to service NPS-FM.
Use models to extrapolate from measurements (e.g., of cyanobacteria or *E. coli*) to other sites and times. Might include statistical models
Use model to design/optimise monitoring networks
Need to understand sediment particle size distribution and its effects
on ecosystems
water quality indicators -- suspended solids/clarity/turbidity
Link to tourism/recreation impacts (including risk of blooms)
Desirable to have swimmability on daily step for lakes for people planning contact recreation activities
Predict suitability for use at particular times (e.g., clarity and swimmability for triathlon at Taupō)
Support interventions to manage lake mixing and stratification
Plan/predict outcomes (what lags should we expect in response to interventions) Examine long-time trends for nutrients and sediment (N, P)
Different constituents are of interest at different time scales (annual average, daily, restoration trajectory)
Need to integrate groundwater transport and travel times
Need to understanding processes at catchment scale and throughout the catchment (e.g., tributaries), not just monitoring locations
Use models to deciphering/interpret FMU trends (what are the drivers, influence of lags)
Assess effects of invasive species on water quality
Models can be used to provide confidence that interventions are going to produce results (providing landowner and policy support)
A dynamic model can help understand and predict Quality/Quantity interactions, such as effects of altered hydro dam operation on phytoplankton
Flow/DO interactions in lowlands and in tributaries. DO should be added as an attribute of interest.
Improve understanding/representation of tidal zone in lower reaches of the rivers
Model diffuse sources of constituents over the catchment
Nutrient accounting
Potential future use in nutrient/contaminant trading
Economic models to represent trading scheme outcomes (farms cost & catchment gain)
Dynamic/tactical farm management recommendations -- moving stock, taking paddocks in/out of production
Modelling hysteresis effects and lags of system recovery following rehabilitation effects.

Ecological Integrity

RC indicators: DO, Temp, NH_4, As (sed), As (H_2O), Zn (sed), Periphyton, Macrophytes, Macroinvertebrates, Riparian, Native fish, Exotic Fish, Connectivity (hydrology & fish passage), Waterbirds, Emergent plant extent, Invasive Pest Plants
Dynamic modelling Opportunities: Spread/control of pest plants and fish, biota. Responses to changes in connectivity, water quality, habitat, restoration actions. (e.g., if we changed barriers to fish passage, what are the effects. Can we make habitat more accessible to species through infrastructure changes)

Discussion of needs and opportunities
Effects of changes to morphodynamic template
Changes in infrastructure change morphologic processes
Morphologic processes change habitat. Channel form evolution and floodplain interactions. Changes in flow and stage influence channel form.
Channel form influences habitat, sedimentation, flora and fauna How are we managing for different species in different parts of the river Fishery objectives in different part of the basin may compete with one another eels v kooura(eel enhancement co. movements of eel from below Karapiro upstream)
koi v tuna
trout v kooura
pest fish impacts -- koi, catfish
Impacts of importing pest plants (invasive zooplankton)
Impacts of importing pest mussels
Linking dynamic model to statistical models of invasion potential (Kevin Collier)
Can dynamic model represent ecological succession?
Recovery potential
Model as a framework for understanding sensitivity to change in management sense --
Which regions are changeable?
Which would resist change?
Goal is to look at three elements (Quantity, Quality, Kai)
Seeking a modelling framework that supports this
Model potential for re-establishing native macrophytes

Kai

RC indicators: tuna, iinanga, smelt, large galaxiids, lamprey, kooura, mussels, trout, water-birds. As in H_2O
Dynamic modelling Opportunities:
whitebait and tuna fishery management, tuna quota and traditional harvest, recreational harvest effects of invasive fish,
climate change/ temperature/ flow impacts,
fish upstream passage, pump station impacts on downstream migration, HEP impacts on downstream migration,
water quality impacts (DO, T)

Discussion of needs and opportunities
Effects of parasites
Impacts of algal blooms on kai
Access for fishing (health of anglers, how do toxic blooms affect this)
Degraded taste and odour (health of consumers of fish, manaakitanga)
Quota management (guidance and response to change)
Model spawning habitat for desirable and undesirable species
Desirable -- iinanga -> guiding spawning
Pests -- koi spawning to target control
Flow management for kai collection activities
Climate change: how will that affect kai
Implications of morphodynamic changes for kai
Separate modelling of tuna and whitebait fishery management. What is known about whitebait fishery?

Whitebait "passively managed" at present
Model effects of active management (movement, hydro controls…)?
Models could be used to optimise fish passage
Flow speeds around structures w.r.t fish swimmability Can effects be scaled up to basin?
Link flow management and climate change to invasive potential of pest fish
Model "distribution potential" for desirable species
Control of pest plants
Recognize opportunities to re-establish native plants (e.g., through hydromodification, water quality improvements, biological manipulation)

Economics

RC indicators: Regional GDP, Employment, House affordability, Income, Income equality
DP, Employment, House affordability, Income, Income equality, *AU Index of Multiple Deprivation*
Dynamic modelling Opportunities:
Assess population increase,
Predict urban development
Land use change and management effects on employment
Tourism development over time
Regional GDP
Export earnings
Social well-being/deprivation

Discussion of needs and opportunities
Understanding the value of water to different sectors
who uses how much
impacts to regional economy
Ecosystem services
Potential for dynamic model bring process mechanics into ecological/economic effects analysis and intervention
Waikato Vital Signs -- Momentum Foundation
Optimizing hydro operations -- relate to NZ renewable energy goals
Optimizing flood schemes/asset management
Optimizing irrigation schemes
Effects of climate change on hydro/flood/irrigation
Link ecological/connectivity to flood management
Civil Defence and public safety
Optimising water extraction (reduce extraction when WQ makes treatment becomes cost prohibitive)
Forecasting impacts of climate change on economic activities
Salt intrusion -- will water extraction in lower river be feasible in 50, 100 years?
Impacts to water allocations
Sand extraction under same conditions?
Align with Treasury approach to evaluating living standards and plan change 1
natural capital, social capital
living standards and plan change 1
use values -- water fit for use,
Ecological health of the river contribute to tourism
Reputation of region and impact on region's tourism economy
Pride in river -- keeps people in region and impacts primary production
Evaluating "best use of the water"

Model to help science address this question
Cost-Benefit analysis of restoration or management strategies
Evaluating land use suitability
Scenario analysis
Economic vulnerability
Community cost of flood or drought risk
Insurance modelling
WREDA (Waikato Regional Economic Development Agency developed and launched 1/7/18)

Experience

RC indicators: *E.coli*, Clarity, Cyanobacteria, Rubbish, Access, Signage, Sewage consent compliance, Sewage land contact.
Dynamic modelling Opportunities:
River depth for boating, waka, boat launching, swimming access and safety, river path flooding.
Lake levels (Taupō, hydrolakes).

Discussion of needs and opportunities
User-focussed outputs
E.G., which boat ramp should we use for launching (predict and publish)
Wintec project for user communication (*E. coli* in petri dish image)
Algae blooms
Aesthetics
Health risk
Smell
Use indicators
Clarity, odour
Model use potential "What's the best river condition" at a point on the river
Guidelines (relating *E. coli* to water clarity, e.g., -- if > 1.5 meter, little *E. coli* risk)
Predict lethal episodes for fish
Reduce impacts to walkers, swimmers
Enhance sense of place on the river
Links to family, iwi -- interpretive aids on river, marks on bridges
Interpretations along river
Cultural health indicators
Modelling key sub-indicators
There will be diversity in factors contributing to sense of place (e.g., fishers vs duck shooters), which we need to be aware of for modelling, and which modelling might help highlight
Agent-based modelling of interactions with place
Represent the differences in experience for a hunter, an angler, a cyclist...
What drives changes in use?
Model drivers of return to use of lowland lakes (e.g., Puketirini, Waahi). Lost opportunity at lower Waikato lakes in contrast to Rotorua lakes. Reputation of lake lags behind measurable quality.
Hysteresis in lake experience and reputation.
Weeds, which impact on accessibility and experience (feedback to clarity and quality)
Use restoration needs: quality, consistency, story
Tributary experience different from main stem experience
Tributary models at sub-catchment scale, not necessarily in a complete system model
Modelling can be used to show impacts where monitoring is too costly

Citizen science as a contributor (perhaps by providing real-time or training data for models) and an experience
Link model to now-casting and forecasting
Visualise model results in a way that engages lay participants
Serious Games approach
Geospatial tools and VR
Web services to provide "what's going on in my catchment now"
Visualize results of RC monitoring programme
Visualise current state
Model effects of flows on river and lakes access (both positive and negative aspects)
Model accessibility in real time, rather than waiting for static results
Long-term water level effects on access

Sites of Significance

Not currently populated in Report Cards. Iwi to determine relevance to project.
Discussion of needs and opportunities
This taura is for River Iwi to discuss and progress.
Possible identification of unintended consequences to significant sites
Site protection

Further comments about sites of significance for iwi to consider.

Identify areas of significance
Historical and contemporary sites
Include sites of significant to non-Maori
Haukainga sites
Other sites of value to other cultures, or because of ecological/biodiversity significance Include Significant Natural Areas (per RMA)
Cultural knowledge enhances experience of the river. Links to model?
Iwi have been working to map sites of significance
Wāhi tapu sites are often close to river, subject to erosion, pest plants, abstractions, land use change
Sites can be identified as sensitive/significant without necessarily disclosing use/nature of significance

Mitigation Effort

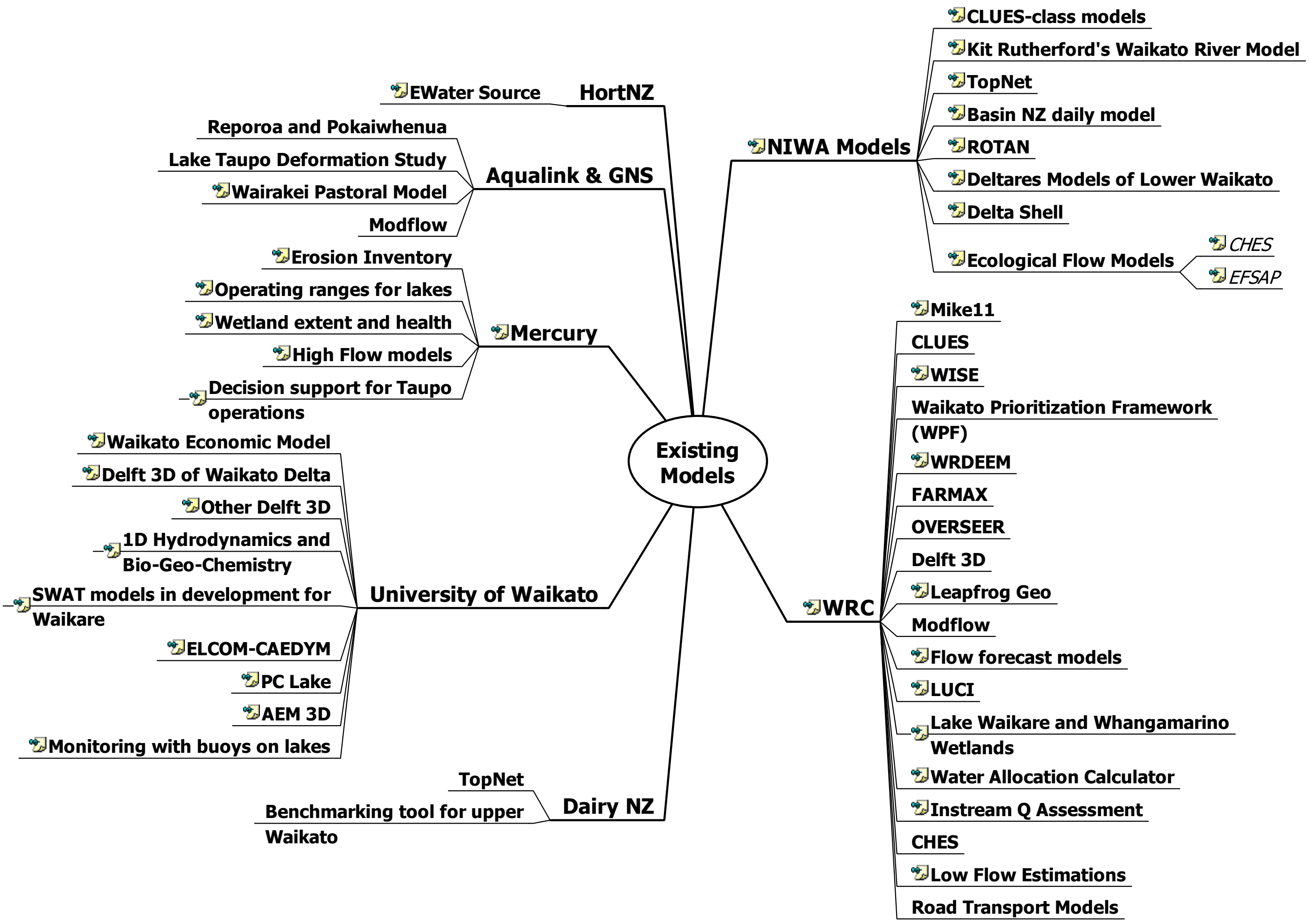
RC indicators: Dairy shed discharge consents, Farm diffuse pollution controls, Stream, Wetland, Lake & Biodiversity Rehabilitation, Aquatic pest fish & plant control
Dynamic modelling Opportunities:
Predicting time scales and magnitude of responses to mitigation actions (WRC Plan Change, Ag Industry Initiatives - farm plans, WRA Restoration activities)
Understanding time lags between actions (e.g., riparian planting/fencing, wetland establishment, conservation tree planting) and responses

Discussion of needs and opportunities
Erosion controls
Time lags in benefit
Support payment for ecosystem service costs in short term to achieve long-term benefit
Analogous to carbon trading
Predicting land use management and costs associated with emissions footprint

Reservoir and flood management systems
Tie benefits to rates expenditures
On-farm management -- e.g., fertiliser timing
Farmers to use participation in sustainability efforts to claim a premium price for their goods
Prioritize funding targets for best benefit
Benefits for cost
Benefits of fish passage enhancements
Dynamics of fish passage
Move across scales to show how small effects add up over the basin to produce desired results
Which problems require dynamic models and which can we cover to 80+% with a statistical/conceptual/static model? Factors such as floods or low flows, algal bloom timing, are not really possible with a static model.
Evaluating at which scale (e.g., flood return period; trees/ha) mitigations are effective
Ghassan: Fundamental model dynamics are hydrology and hydrodynamics

Existing models

Each party at the meeting was asked to list models that they use or know of.



NIWA

CLUES-class models

- Annual average predictions.
- Static or steady-state.
- Spatial scale coarse or by catchment.

Kit Rutherford's Waikato River Model

- Main stem only.
- Low/Mid/Flow flow conditions each modelled as a steady-flow condition.
- Models evolution of water-quality downstream indicators.
- Chlorophyll a.
- Nutrient dynamics.
- E coli.
- Updated for WRISS (NIWA) 2010.

TopNet

- Distributed dynamic hydrology model at sub-day time step.
- Simple representation of reservoirs.
- Simple groundwater component.

Basin NZ daily model

- Long-term dynamic model.
- Calculations on grid with 1-day time step.
- Used for inputs to lake Taupō.

ROTAN

- Rotorua-Taupō Nitrate transport model (daily to annual).
- Simulates GW transport, lag and attenuation of Nitrate from root zone to lakes.
- Uses Overseer outputs as inputs.

Deltares Models of Lower Waikato

- Models of lower Waikato delta and some lakes [Waahi and Whangape],[including detailed bathymetry]Rainfall-runoff and some contaminants [This item probably refers to University of Waikato modelling].

Delta Shell

- Deltares modelling framework.
- Used to couple existing models for interoperable models project.

Ecological Flow Models

- MFE work on abstraction and ecological effects at National scales.

CHES

Cumulative Hydrological Effects Simulator.

ArcGIS extension.

EFSAP

Environmental Flows Strategic Allocation Platform.

WRC

2015 Landcare Research Review identified 80 models in use by WRC.

11 Core models: MIKE suite; CLUES; WISE; WPF; WRDEEM; FARMAX; OVERSEER; Delft 3D; Leapfrog Geo; MODFLOW (one more?)

Mike11
Flood model for lower river (dynamic).

CLUES
WISE
- Waikato Integrated Scenario Explorer.
- Integrated modelling system.
- Runs at 1-year time step.
- Flow, Water Quality, Economics (? Ecosystem).
- Regulation of land use to 2064.
- Terrestrial biodiversity.
- Spatial indicators.

Waikato Prioritization Framework (WPF)
- Spatial framework using multiple model and data information to prioritise areas for conservation works and diffuse pollution control.

WRDEEM
- Waikato Region Economy Environment Futures Model.

FARMAX
OVERSEER
Delft 3D
- A DeltaRes hydrodynamic model.

Leapfrog Geo
Modflow
- Various models in upper catchment.

Flow forecast models
- Flood hydrology in real-time.
- Works in with Mercury.
- 24/7 operation.
- Linked to Mike11.
- DHI admin.

LUCI
- Piako-Waihou river system.
- Victoria University.
- Linked LiDAR (? -- high resolution land elevation) [Have not been able to find a reference to this].

Lake Waikare and Whangamarino Wetlands
- Hydrodynamic model.
- Being scoped by Jacobs.

Water Allocation Calculator
- GIS tool for consenting.
- Web available: http://waterallocation.waikatoregion.govt.nz/
- Tracks consents.

Instream Flow Assessment (for ecological flow setting)
- WAIORA.
- Fish preference curves.
- CHES.
- Lower river with Paul Franklin.

Low Flow Estimations

- Regression models for low flows (regressions out of date?)
- Could be sped up by a reliable dynamic model.

Road Transport Models

Dairy NZ

Benchmarking tool for upper Waikato

- Nutrient sources and effect of mitigations.

TopNet

- For flows, used for temporal disaggregation.

University of Waikato

Monitoring with buoys on lakes

- WRC.
- Buoys in Lakes Ngaroto Waahi Whangape Waikare.

AEM 3D

- Aquatic Ecosystem Model 3D.
- Derived from ELCOM-CAEDYM and supported by HydroNumerics from Australia http://www.hydronumerics.com.au/software/aquatic-ecosystem-model-3d

PC Lake. Part of FABM lake modelling framework

- Hydrodynamic and chemistry linking framework.
- Waahi application.

ELCOM-CAEDYM

- Estuary, Lake and Coastal Ocean Model - Computational Aquatic Ecosystem Dynamics Model.
- Three-dimensional lake, estuary and coastal ocean water quality model.
- David Hamilton, University of Waikato https://teamwork.niwa.co.nz/display/IFM/ELCOM-CAEDYM.

SWAT models in development for Waikare catchment

Not yet calibrated.

1D Hydrodynamics and Bio-Geo-Chemistry

Models of 8 lakes in varying stages of development.

Delft 3D

- Lakes Waahi, Whangape, Waikare.
- Waikato Delta (Hannah Jones).

Waikato Economic Model

- Graeme Doole used for Healthy Rivers.

Mercury

Models used for power supply assurance

Mercury's operating models are part of the NZ electricity market Daily water-balance (now + 12 hrs, + 24 hrs, +48 hrs).

Focussed on delivery of power to Auckland market.

Decision support for Taupō operations
Decision support to keep lake level within top/bottom limits.

High Flow models
Karapiro and lower river.
Rainfall forecasts + wetness = WRC Mike11 model.
Targeting dam safety and lower river flooding.

Wetland extent and health
Monitoring of wetlands affected by hydro lake operations.
Survey of bed degradation from Karapiro to Ngaruawahia.

Operating ranges for lakes
Lakes are required to operate in set ranges of pool level.
Flood conditions invoke flood operation rules operations coordinated with RC.
Low flow conditions have another set of rules to prevent over-draughts.

Erosion Inventory
Taupō to Ngaruawahia.
LiDAR based.
Subject to peer review.

Other parties

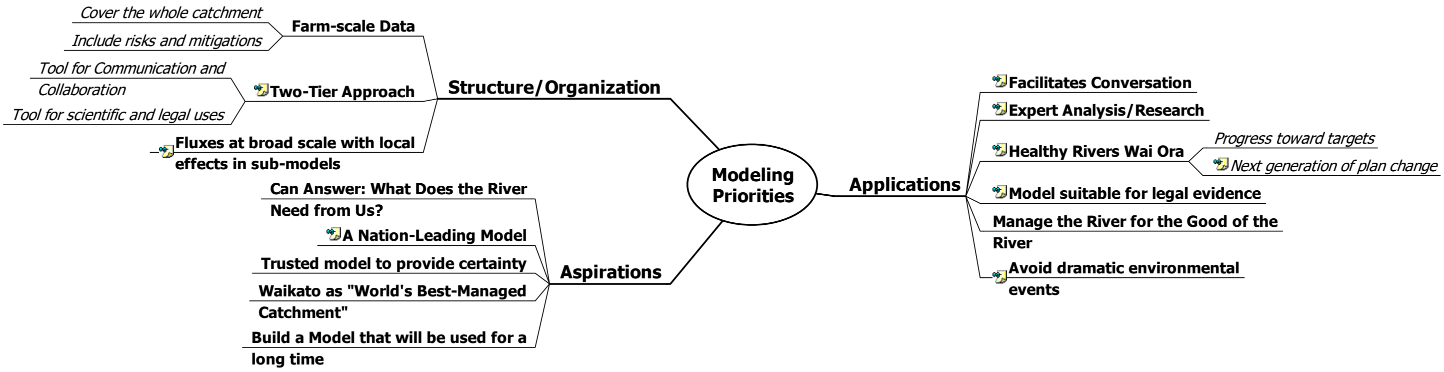
Modflow (Aqualinc, GNS, Wairakei Pastoral)
Wairakei Pastoral Model

- APSim for N generation.
- Modflow.
- eWater Source.
- rainfall/runoff model in eWater Source.
- eWater Source catchment component.
- Taupō to Ohakuri.
- eWater Source (HortNZ)
- Lower Waikato [actually did not proceed with that approach]

Lake Taupo Deformation Study (GNS)
River Iwi may also use models

Further discussion of modelling priorities and aspirations

This section collates and organises various further attributes of models that may be relevant for scoping of the dynamic model, based on general discussions at the meeting. The mind-map was developed after the meeting.



Applications

Facilitates Conversation

- Simple to run on-the-fly.
- Easy to adjust for exploring options.
- Qualitative results.

Expert Analysis/Research

- Farm-scale data?
- Dynamics will require detailed data.
- RC can require farm plans from producers.
- Farm scale mitigation.

Healthy Rivers Wai Ora

- Dynamic models to supplement 80% of the way with static models -- Sandy

Progress toward targets.

Next generation of plan change

- Timelines -- 2020, 2026.
- Need model by 2022-23 for 2026 plan change.

Model suitable for legal evidence

- Tools to help WRC collaborate/use in legal proceedings.

Manage the River for the Good of the River

Avoid dramatic environmental events

- e.g., 2003 Cyano bloom warning.

Aspirations

- Build a Model that will be used for a long time.
- Waikato as "World's Best-Managed Catchment."
- Trusted model to provide certainty.
- A Nation-Leading Model.
- Integrate existing models.
- Go big not piecemeal.
- Can Answer: What Does the River Need from Us?
- Not limited to biophysical.

Structure/Organization

- Fluxes at broad scale with local effects in sub-models.
- Karapiro phytoplankton model example of detailed sub-model.
- Two-Tier Approach:
    - Catchment-wide versus detailed sub-catchments or reaches.
    - Long term evolution versus fine time steps.
    - Scenarios versus short-term forecasting.
- Tool for scientific and legal uses.
- Tool for Communication and Collaboration.
- Uses farm-scale data. Farm plans coming on stream over time.
- Include risks and mitigations.
- Cover the whole catchment.

Attendees

NIWA:
John Quinn (Chair)
Sandy Elliott (Project Lead)
Glen Reeve
Tom Evans
Linh Hoang
Piet Verburg

Iwi facilitator:
Tim Manukau

Dairy NZ:
Christophe Thiange

Waikato Regional Council:
Derek Phyn
Maggie Sullivan
Dominique Noiton
Bevan Jenkins
Ghassan Basheer
Ed Brown

Waikato River Authority:
Julian Williams
Michelle Hodges (apologies)

Mercury:
Stephen Colson
Don Scarlet

University of Waikato:
Chris McBride
James Brasington

GNS:
Zara Rawlinson (apologies)