Te whakawhanake, te urutau me te whakamahi i ngā tauira taiao i roto i te horopaki waeture i Aotearoa

Developing, adapting and applying environmental models in a regulatory context in New Zealand

Guidance document

Ministry for the Environment
Manatū Mō Te Taiao

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Key points

Environmental modelling allows environmental managers and regulators to identify system drivers (causes) and forecast future conditions (outcomes) under a range of different management scenarios, and at a range of spatial and temporal scales. This makes data from environmental models just as important to regulatory environmental management as data from sampling, monitoring, and observation programmes.

A model's design should reflect the context within which the model is being developed to deliver a tool that is 'fit' for its intended purpose. To be considered 'fit for purpose', an environmental model must address the needs of the end user, be aligned with the management or decision-making context, be scientifically credible and operate within the practical constraints of the context.

Environmental models often simulate complex and dynamic systems with processes that are invisible or unknown to us. Every environmental model contains simplifications and assumptions, and requires the modelling team to make judgements. We cannot, therefore, expect a model's predictions to correspond exactly to observed outcomes, either now or in the future. For this reason:

- models should be developed, adapted for use and applied carefully, with a transparent understanding of their scientific foundations, the judgements made by the model builders, the uncertainties inherent in their predictions, and the implications of these factors for resource management and decision making
- when determining how to use model outputs, decision makers should work closely with model developers to ensure they have a clear understanding of how model predictions have been generated and evaluated, as well as a good appreciation of the complexities, areas of contention, degree of predictive accuracy, uncertainties, viable applications, and the inherent limitations of environmental models.

The process of developing or adapting a model for use is not linear. Each of the steps associated with developing or adapting a model are interlinked and, as such, new information; unexpected findings; and the results of peer review, or uncertainty and sensitivity analyses will require modelling teams to reconsider development actions and assumptions.

To ensure problems are defined correctly, and to ensure models provide a useful and credible basis for addressing the environmental issue of concern, those responsible for developing or adapting models should:

- take an iterative approach, routinely revisiting earlier stages in the process and engaging repeatedly with stakeholders, those with local and specialist knowledge, and those who will apply the models
- ensure the conceptual model that underpins the modelling process is well suited to the context and designed to deliver insights appropriate to the issues or management decisions under consideration
- actively create and hold a space for Māori knowledge systems, 'Western' biophysical science and other knowledge systems, to collectively inform environmental modelling processes
- establish appropriate project-management arrangements comprising a clear and well-defined modelling project plan and suitable arrangements for oversight.

When applying an environmental model in a regulatory context, resource managers and decision makers should keep in mind it is generally more appropriate to use models to inform actions and decisions at the 'harder' end of the regulatory spectrum (setting regulatory limits, determining activity status and whether regulatory permissions are required, allocating rights and responsibilities, and establishing compliance or non-compliance with regulatory requirements) where models:

- are well established (mature) and have a longstanding history of effective and reliable use in equivalent contexts
- are underpinned by a comprehensive set of data
- are corroborated by the outputs of other models and evidence
- have been validated by investigations that have demonstrated a strong and reliable correlation between model predictions and sampling results.

On the other hand, it is generally more appropriate to use environmental models to inform actions and decisions at the 'softer' end of the regulatory spectrum (to highlight potential management issues, educate and empower people to make their own decisions, identify where to focus sampling activities, specify thresholds that trigger investigation and/or a greater degree of regulatory scrutiny, and identify a suite of public investments likely to deliver desired outcomes) where models:

- are new (immature) and are being used for the first time or are being used in a significantly different context than the one for which they were initially designed
- are attempting to simulate a highly complex system with many unknowns
- suffer from a paucity of data, or if the model outputs are likely to change as more data becomes available (for example, as understanding of the system increases)
- have not been sufficiently corroborated by investigations, or where they have demonstrated weak relationships between model predictions and sampling results.

It is important to note that it may also be appropriate to use well-established models (that is, models underpinned by comprehensive data, which have been corroborated and/or investigated) at the 'softer' end of the regulatory spectrum, depending on the context.

Where there is the possibility of imminent or irreversible damage to Te Oranga o te Taiao, however, and if an environmental model is the best (or potentially the only) tool available to provide insight into the nature of the situation and consequences of regulatory decisions, decision makers should scrutinise model inputs and draw on model outputs *even if the model is at an early stage in its life cycle or subject to a high degree of uncertainty*.

Releasing a model for use should not be considered the 'finish line' for a modelling process. Effective model application involves an iterative process of continuous improvement and refinement, and requires an ongoing commitment to:

- ensuring decisions informed by model outputs stay within an appropriate scope of application
- ensuring there is enough resource available to continue to evaluate and refine the accuracy of the model after its initial deployment
- actively managing any changes to model outputs by clearly communicating their rationale and evidential basis, evaluating and describing their implications, and giving advanced warning of when changes will come into effect and how they will be implemented.

1 Introduction

1.1 Purpose

This guidance is intended for those responsible for developing and adapting environmental models for use in Aotearoa New Zealand, and for model users and decision makers[1] responsible for determining when and how to apply environmental models in a regulatory context.

Data from environmental models provide crucial insights into the state of, trends in, and progress towards specified targets and desired outcomes for Te Oranga o te Taiao. Environmental modelling also allows environmental managers and regulators to identify system drivers (causes) and forecast future conditions (outcomes) under a range of different management scenarios, and at a range of spatial and temporal scales.

Model developers and model users should work together to ensure the best available information is available when decisions are being made regarding the design, development and application of environmental models. Practical constraints (such as statutory timeframes, availability of data, budget and expertise) may influence the scope of choices available to model developers, or force model users to make trade-offs between the timeliness or accuracy of model outputs.

Those responsible for developing and applying models are required to make choices throughout the modelling process – regarding, for instance, the type of model used, the approach to developing and testing the model, and how the model's outputs should be used. These decisions are an inherent feature of all environmental monitoring and modelling programmes, and they should be made transparently, in a deliberate and informed manner, and should be open to scrutiny.

This guidance sets out a framework that can be used by those responsible for developing and adapting environmental models for use in Aotearoa and those responsible for deciding how to apply model outputs. It presents a framework to inform choices and a benchmark of good practice against which these choices can be assessed.

1.2 Scope

Environmental models come in a wide variety of types, are applied in every environmental domain, and are used in many different applications across the regulatory spectrum,[2] spanning 'softer' and 'harder' uses, including (from softer to harder):

- generating insight into processes and dynamics within and between systems
- educating and empowering people to make their own decisions
- providing guidance on where to focus sampling, measurement and investigations

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[1] Including, but not limited to, policy makers, planners, council operational and regulatory staff, councillors, and iwi decision makers.

[2] Sparrow, MK. 2000. *The Regulatory Craft: Controlling Risks, Solving Problems, and Managing Compliance*. Washington: Brookings Institution Press.

- identifying thresholds that trigger targeted investigation or intervention
- developing and determining plan[3] objectives, policies, rules and limits
- complying with statutory state-of-the-environment monitoring requirements
- determining rights and responsibilities via the granting of resource consents and design of conditions
- informing compliance and enforcement action.

As such, the scope of this guidance is necessarily broad and should be read alongside more detailed technical guidance on the development and application of specific environmental models, and alongside procedural guidance on using models for the implementation of national policy statements and environmental standards.

1.3 What are environmental models?

Environmental models are a simplification of reality, constructed to gain insights into select attributes and processes of physical or biological systems, or both. We use environmental models to improve our understanding of how systems react, or are likely to react, to changing conditions.

Environmental models can be defined in conceptual or physical terms, or by using mathematical or statistical equations. They range in sophistication, from extremely simple spreadsheets reflecting basic interactions, to extremely complex representations of system processes and dynamics.

Environmental managers are routinely required to extrapolate from known facts and predict the future implications of their decisions, or to make judgements at times or in places where there is limited understanding of the environmental state or trends. In these circumstances, environmental models provide an important source of data, because they allow environmental managers to:

- characterise key features and processes of systems that are too complex or large to understand solely through observation or direct measurement (that is, the context within which things happen)
- estimate baseline conditions, diagnose events that have taken place and identify trends (that is, what happened or what is happening)
- examine causes and antecedent conditions (that is, why it happened)
- identify key factors which impact ecosystem health (that is, the contaminants or drivers, in combination and in isolation, that have the most positive or negative impacts)
- predict likely outcomes of development or management actions, and forecast future events (that is, what is likely to happen under certain circumstances)

[3] There are multiple points where decisions are required to determine exactly where and how to use model outputs during regulatory plan-development processes – whether, and how, to mandate the use of a particular model or model version; whether and how to use model outputs to underpin policy design; and the role of model outputs in determining activity status for consenting purposes. Typically, regulators will be more conservative about using model outputs to determine activity status at either end of the activity range (that is, ‘permitted’ and ‘prohibited’), because these decisions remove decision-making discretion and either allow or proscribe activities.

- monitor[4] both the state of the environment and progress towards achieving 'target attribute states and environmental outcomes'.

If developed well and used appropriately alongside other sources of data, environmental models can be powerful tools, capable of synthesising information and generating extremely useful insights into the state of, and trends in, natural and human systems, as well as the dynamics within and between those systems.

However, these systems are complex and variable, and often have processes that are not visible or are unknown to us. For this reason, every environmental model contains simplifications, and requires assumptions and judgements to be made throughout the process of model development, use and output generation. We cannot, therefore, expect a model's predictions to correspond exactly to observed conditions, either now or in the future. Capitalising on the potential contribution of environmental modelling requires the following considerations.

- Models should be developed, adapted for use, and applied carefully, with a transparent understanding of their scientific foundations, the judgements made by the model builders, the uncertainties inherent in their predictions, and the implications of these factors for regulatory decision making.
- Model users and decision makers should work closely with model developers, to ensure they have a clear understanding of how model predictions have been generated and evaluated. They should also have a good appreciation of the complexities, areas of contention, degrees of predictive accuracy, uncertainties, viable applications, and the inherent limitations of environmental models in the context they are being applied.

1.4 Environmental models and monitoring are interdependent

Many factors affect the health of ecosystems, and these factors interact in complex ways – the same mix of contaminants or environmental pressures at different times and in different places can have different effects on the environment.

It is common for people to misinterpret the uncertainty inherent in models as a weakness that invalidates their use or undermines their value, in comparison to sampling data, which some may consider a 'true' reflection of reality. Uncertainty can arise in sample results owing to methodological or sampling error, laboratory error and the sensitivity of equipment. In addition, the complexity, dynamism and natural heterogeneity of many environmental systems mean the 'true' state of a specific environment at any point in time is probably better expressed as a distribution rather than a discrete value. For example, the tendency for some contaminants to mix imperfectly in moving air or water means that samples taken a short distance apart in space and a short period apart in time may return very different results.

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4 'Monitoring' should be interpreted consistently with the Oxford English Dictionary definition, as "observe and check the progress or quality of (something) over a period of time; keep under systematic review". For the avoidance of doubt, data from environmental models are a subset of 'monitoring'. Along with data from other sources (empirical observation and sampling data, the insights and judgement of kaitiaki, and the qualitative assessment of experts) output from environmental models contributes to our understanding of the state of, trends in, and progress towards specified targets and desired outcomes for Te Oranga o te Taiao.

Characterising discrete samples as being able to provide a 'true' reflection of reality may overstate what sampling alone is able to convey. To gain an understanding of the processes that influence ecosystems, determine the current state, identify trends and pressures, and predict future conditions, regional council environmental managers are required to draw on and integrate data from environmental monitoring, field observations, and environmental models.

Environmental models work alongside longitudinal measurement (focussed on identifying trends), and targeted and continuous measurement (focused on gaining insight into processes, identifying correlations, and describing relationships). These sources of information are interdependent. It is often necessary, for instance, to use statistical models to enable calculation of environmental quality indices from monthly field samples, or to use models to explain the results of sampling programmes, identify inter-relationships and reveal systemic processes.[5]

On the other hand, it is essential to have monitoring data to build, train and use environmental models. It is not possible, for instance, to reliably link causes to trends and develop meaningful action plans without gathering samples, taking measurements or making observations. Nor is it possible to rely on model predictions unless they are validated against, and corroborated by, sampling data.

> Models without data are fantasy. Data without models are chaos.[6]

Environmental sampling, observations, and modelling complement each other – data from environmental models are every bit as important to the implementation of New Zealand's regulatory framework for environmental management as data from sampling, monitoring, and observation programmes. Communication of the output of environmental models should clearly explain how modelling and sampling work together to reveal the 'true' state of the environment by allowing the spatial and temporal aggregation of samples and predictions.

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5 For example, the need to quantify land-use intensity to explain increases in monitored nutrient concentrations and calculated contaminant loads in fresh waterbodies.

6 Patrick Crill, Stockholm University, quoted in Nisbet EG, Dlugokencky EJ, Bousquet P. 2014. Methane on the Rise–Again. *Science* (343)6170: 493–495. https://doi.org/10.1126/science.1247828.

2 Models must be ‘fit for their intended purpose’

The process of developing, adapting and using an environmental model requires those responsible to make a series of judgements. The network of data that modellers draw from, the emphasis placed on one source of knowledge relative to another, and the way information is integrated into a model’s design, should all reflect the context within which the model is being developed to deliver a tool that is ‘fit’ for its intended purpose.[7]

An assessment of whether a model is fit for its intended purpose must encompass the entire modelling process, from development to application, and must consider the broader environmental, social, cultural and political context within which the model is to be applied. To be considered fit for purpose, an environmental model must:

- address the needs of the end user and be aligned with the management or decision-making context, including the skills and competencies of those who will be tasked with operating and interpreting the model
- be scientifically credible, deliver an adequate level of certainty or trust, and take appropriate steps to avoid unreliable evidence or unreliable assumptions undermining model predictions and estimates
- operate within the practical constraints of the context, including the level of data and knowledge, as well as the degree of future funding available for developing or adapting a model, validating its predictions, and interpreting and applying its outputs accurately.

Modelling processes often take many years, during which time the context may change and affect whether a model can still be considered fit for purpose. Accordingly, there should be a continuing commitment to maintaining an ‘outcome-oriented’ focus, and there should be processes in place to ensure the model adapts and continues to be fit for purpose throughout its lifecycle (see Box 1). Those responsible for overseeing a model’s development and application should continue to ask whether the model is effectively:

- generating insights that are relevant and applicable to the environmental issue under consideration, and that aid in sustaining and enhancing Te Oranga o te Taiao
- revealing key processes and relationships that enable environmental managers to make informed decisions and act with a reasonable understanding of confidence, risk and uncertainty
- interrogating the effectiveness of actions intended to sustain and enhance Te Oranga o te Taiao.

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[7] Hamilton SH, Pollino CA, Stratford DS, Fu B, Jakeman AJ. 2022. Fit-for-purpose environmental modelling: Targeting the intersection of usability, reliability and feasibility. *Environmental Modelling & Software* 148(February 2022): 105278. https://doi.org/10.1016/j.envsoft.2021.105278.

Box 1: Keeping pace with a changing context

Overseer is one of the most commonly used models in Aotearoa New Zealand for calculating nutrient losses. Overseer was originally developed as a farm-management tool to assist with decisions on fertiliser application. The model has, however, been used increasingly by regional councils to underpin regulation designed to manage the effects of excessive nutrient runoff from farms on the health of waterways.

Using the model for this purpose generated controversy, and in December 2018, the Parliamentary Commissioner for the Environment released the results of an investigation into Overseer, which concluded the model did not meet the levels of documentation, transparency and certainty considered desirable in a regulatory setting. Following this investigation, the Government initiated an independent review of Overseer, which concluded that a user could have little confidence in the accuracy of the model's predictions on nutrient N concentrations in either absolute or relative terms. Despite efforts to refine and validate model predictions, Overseer had not kept pace sufficiently with the context in which it was being applied and was not considered fit for the purpose for which it was being used.

Following the independent review, Overseer's owners undertook to work with the Government to identify how the model could be updated and enhanced, and to clarify the appropriate scope of application for the model in a regulatory context.

Source: Ministry for the Environment, Ministry for Primary Industries. 2021. *The Government response to the findings of the Overseer peer review report*. Wellington: Ministry for the Environment and Ministry for Primary Industries.

3 Core components of a model that is ‘fit for purpose’

Models should be built, or adapted, and applied in a manner that is appropriate to the operating context and intended purpose. Although some flexibility is required when designing processes for developing or adapting models, and when using models, care should be taken to maintain consistency with the core components of fitness for purpose described below. These components are required *regardless of context* to ensure environmental models make a relevant, scientifically sound and useful contribution to understanding, sustaining and enhancing Te Oranga o te Taiao.

3.1 Ensure the model has a sound conceptual basis

A conceptual model is a qualitative description of the most important attributes, relationships and processes of the system relevant to the problem of interest. The conceptual model that underpins the modelling process must be well suited to the context and designed to deliver insights appropriate to the issues under consideration or the decisions required (see Box 2).

When developing the conceptual model, the project team should:

- consider and draw on existing data, scientific or technical literature, Māori knowledge systems and mātauranga, applicable anecdotal evidence, and the results or outputs from prior relevant modelling projects
- clearly describe each element of the conceptual model in words, functional expressions, diagrams and graphs, as necessary, and clearly identify and document the science, research, mātauranga, knowledge and assumptions behind each element.

Where relevant and feasible, the project team should:

- describe assumptions, scale and boundaries, feedback mechanisms and static/dynamic processes reflected in the conceptual model
- describe the rationale and scientific foundations for the project team’s judgements, and an assessment of the strengths and weaknesses of each hypothesis underpinning the conceptual model
- test competing conceptual models/hypotheses and use the results of that testing to inform design decisions and the choice of conceptual model adopted for the modelling process.

Box 2: Ensuring models have a sound conceptual basis

Current management practices are estimated to reduce the average annual rate of sediment loss to the Kaipara Moana (Harbour) by 12 to 13 per cent over approximately 10 to 15 years – a slower and less significant reduction than required to secure the health of the moana. The Kaipara Moana Remediation programme (KMR) aims to halve overall sediment lost to the Kaipara Moana through a concentrated 10-year programme of action. In collaboration with Northland Regional Council and Auckland Council, KMR is building a water quality catchment model, Tātaki Wai, to target investment at key sources of erosion and increase the speed, effectiveness, and efficiency of its actions across the 6,020 square kilometre catchment of the Kaipara Moana.

Tātaki Wai is based on open-source models (LSPC and SUSTAIN), developed by the United States Environmental Protection Agency, which have been used globally to support water management decision making across a wide array of pollutants, catchment conditions and management scenarios. Both LSPC and SUSTAIN are process-based, continuous models able to forecast the effects of different land-use patterns and management interventions on short-term events and long-term water quality. The key relationships between land characteristics, land use, meteorological events, and environmental response are well established, and independent experts have assessed the conceptual model underpinning the design of Tātaki Wai, to confirm it provides a sound basis to support decision making in the Kaipara Moana watershed.

Tātaki Wai is in development now, tailoring modelling to the Kaipara context using local and nationally available datasets (such as state-of-environment monitoring, physiographic layers, land cover and land-use layers, local climate station and virtual climate station networks). Once this is complete, Tātaki Wai will be used to facilitate action planning by farm advisors and landowners, leading to the development of targeted, evidence-based 'sediment reduction plans' that deliver KMR's vision for the least cost. Tātaki Wai's design will also allow KMR to forecast the effect of actions in sediment reduction plans and adaptively manage ongoing investments. Importantly, forecasting actions allows KMR to reward landowners by recognising the future benefits of actions they are taking now – many years (and sometimes decades) before these effects are likely to be observable.

Source: https://www.knowledgeauckland.org.nz/search/?query=fwmt

3.2 Respect te Tiriti o Waitangi and te ao Māori

In most instances, environmental models will be developed and applied against a backdrop of central government legislation and regional or district plans governing the management of te taiao. Accordingly, the principles of te Tiriti o Waitangi should form the foundation of the work to be undertaken. This means there is a fundamental responsibility to place the intergenerational health and wellbeing of te taiao at the centre of decision making, and an obligation for participants to:

- recognise and provide for the protection of customary rights, and for the relationship of Māori and their culture and traditions with their ancestral lands, water, sites, wāhi tapu, and other taonga[8]

[8] Resource Management Act 1991, section 6.

- give effect to Te Mana o te Wai, including by partnering with mana whenua in freshwater management and identifying and providing for Māori values[9]
- find space for Māori knowledge systems, 'Western' biophysical science, and other knowledge systems to collectively inform environmental research, management and decision making.

Decisions based on or informed by the outputs of environmental models can have far-reaching and long-lasting implications for Te Oranga o te Taiao. Similarly, decisions on the scale and nature of resource use and extraction can either threaten or sustain the ability of people to interact with the environment through recreation, fishing and hunting, and to undertake customary practices (such as mahinga kai, harvesting resources for mahi toi, performing rituals, and practising manākitanga and whanaungatanga). If these activities and practices are disrupted, there is a risk people will lose opportunities to undertake important customs and rituals, leading to a loss of cultural knowledge systems, sense of connection to place, and cultural identity, for both Māori and non- Māori.

Ideally, environmental models would be conceived, designed, developed, evaluated and applied in dialogue with people who live in and have a relationship with the area being modelled, and in a way that brings together modellers, technical experts, kaitiaki, and experts in maramataka and mātauranga Māori.

The reality, however, is that many modellers will have a limited understanding of, or appreciation for, Māori knowledge systems. Many Māori will struggle to engage openly with biophysical science, environmental modellers, and associated regulatory and decision-making processes without a strong foundation of understanding, respect and trust, and without adequate resourcing.

In addition, environmental models will often focus on a narrow set of parameters or specific processes within biophysical systems, and will rely on data gathered by environmental scientists using biochemical or laboratory-based sampling methods. In these instances, the outputs of environmental models may be useful inputs to kaitiaki, who may consider the insights generated by environmental models alongside other sources of information when forming judgements about the health of, and pressures on, ecosystems.

Actively creating and holding a space for te Tiriti-based collaboration while participants grow their capacity and understanding will foster trust and create opportunities that allow Māori and non-Māori knowledge systems to grow together and integrate, when it makes sense to do so, and to stand apart but alongside each other when that is appropriate.

Modellers and modelling teams should take deliberate steps towards this goal by first engaging with mana whenua, to establish what partnership looks like in the local context, and to ensure sufficient resourcing is available to facilitate this partnership. In building authentic relationships with mana whenua, scientists and decision makers must recognise and respect the way mātauranga has been generated and held, and must understand and provide for Māori expectations in terms of the sovereignty of knowledge and data.

The resourcing of Māori to participate in environmental decision making and management is a matter that government agencies, regional councils, and local authorities will necessarily engage with as the reform of New Zealand's resource management and water management systems progresses, and as local authorities modify their regulatory plans to implement

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9 National Policy Statement for Freshwater Management 2020.

national legislative and regulatory direction. Discussions on this matter should be expanded to specifically include consideration of ways to facilitate the effective introduction of Māori knowledge systems into or alongside the development, evaluation and application of environmental models.

3.3 Involve a range of perspectives throughout the modelling process

To ensure problems are identified and defined correctly, and to ensure models provide a useful and credible basis for addressing the environmental issue of concern, those responsible for developing and adapting models must draw on the perspectives of the right people with the right skills throughout the modelling process. Environmental models and modelling processes should, to the greatest extent possible, be informed by the views of:

- intended end users, and affected and interested parties
- independent modellers and independent technical subject-matter experts
- regulatory decision makers
- representatives of mana whenua or mana whakahaere
- kaitiaki and experts in mātauranga and maramataka.

Not all modelling projects will require members from all these disciplines or positions to be actively involved at all stages of the process. Matters of practicality – resourcing, availability, time, and the nature of the issue being modelled – will have a bearing on what skillset is needed, how, and when in the modelling process.

The nature of input required will change as a model moves throughout its lifecycle. It may be efficient to have a core team involved in developing or adapting a model, supported by a larger group of specialist contributors who can participate at relevant stages throughout the process. It is essential, however, that from inception to completion the modelling process has easy access to people who can 'translate' and effectively communicate the insights and contributions of different participants.

3.4 Ensure technical and scientific rigour

Modelling processes should draw on the best possible data, and as many sources and types of data as possible, to provide useful insights into the system being modelled. This could include:

- published and unpublished, quantitative, and qualitative data arising from academic research
- data from research conducted outside academia (for example, from sector advocacy groups and NGOs)
- data from different countries and contexts
- expert opinion of scientists and technical specialists
- the opinion of kaitiaki, experts in mātauranga and maramataka, and people with longstanding knowledge of the local environment
- anecdotal information and public opinion.

Environmental models are often required to operate in a data-poor context, where there are significant gaps in the spatial and temporal record of information. Those responsible for building or adapting an environmental model will need to appraise the comprehensiveness and quality of data before deciding whether and how to use the data in the modelling process. The strengths, weaknesses and limitations of data should inform decisions regarding which model type to use and determine how models can be used in a regulatory context.

Modellers are required to make assumptions to account for these gaps in information, and they will often need to make technical and scientific judgements when combining different types of evidence, to build an adequate representation of the system being modelled. Similarly, modellers may choose to place greater or lesser weight on different sources of data, depending on:

- the questions an environmental model seeks to answer
- the insights it seeks to generate
- whether the matter at hand is relatively simple or complex/interconnected and difficult to solve (particularly if it is a 'wicked problem')
- whether the implications of acting or not acting have potentially significant and irreversible implications.

A clear process for interrogating technical and scientific judgements embedded within the model should be agreed at the outset, so that key decisions in the modelling process are subject to appropriate scrutiny – from the design of the conceptual model, to determining the modelling architecture, to applying the model in regulatory processes.

This process of interrogation should aim to determine:

- whether the principles of sound science have been addressed during model development, and whether the assumptions and choices made by the modellers are underpinned by defensible, and scientific or technical, rationale
- whether the choice of model is supported by the quantity and quality of available data
- whether appropriate choices have been made regarding which data are fed into the model, and what data standards have been applied (for example, National Environmental Monitoring Standards)
- how closely the model approximates the real system of interest, or how accurately it represents observed relationships between key model parameters
- whether the important drivers and processes represented by the model are relevant to the assessment being undertaken
- the quality and reliability of insights generated by the model
- the level of certainty associated with its predictions under the full range of conditions the model operates within.

To be most effective and to maximize its value, this process of interrogation should begin as early as possible in the model-development phase and run alongside, and feed in to, model design. Interrogation of technical and scientific judgements early in the process of model development or adaptation can help evaluate the conceptual basis of the modelling process and potentially save time, by:

- redirecting misguided initiatives
- identifying alternative approaches

- providing a strong technical grounding to a potentially controversial model output or application
- avoiding the inappropriate use of a model in regulatory processes.

To facilitate an accurate and timely response to any issues identified, those conducting the interrogation should clearly state their key concerns, the potential implications of those concerns, and options for addressing them.

3.5 Build public trust and confidence

If stakeholders have not been involved in defining the problem and programme objective, if people are not confident in the conceptual model or input data, and if they don't understand or trust models, they will not gain political and social support, be used by decision makers to inform decisions, or be effective in addressing the issues they are designed to identify and help resolve.

Adopting an 'open-source' approach and transparently sharing model code and the rationale for model design, highlighting the strengths and weaknesses of data, and clarifying assumptions invites engagement, facilitates scrutiny, and helps guide further investigations and/or model-development processes. This increases both the quality of modelling and the likelihood that people will understand, trust and have confidence in model outputs.

Explicit acknowledgement of complexities, and areas of strong consensus and contention – particularly where there are fundamental disagreements on key elements of the model or its outputs – is essential for parties attempting to interpret and apply a model's outputs, and important for ensuring well-founded debate and decision making.

To help secure public trust and confidence in models, project teams should make available documentation that:

- clearly describes the problem the model is seeking to address, the objective it is seeking to achieve, sources of data and methods of data collection, mathematical frameworks and algorithms employed, accuracy thresholds used, and quality-assurance processes followed
- acknowledges and describes complexities (that is, due to gaps in data or understanding) and areas of contention
- acknowledges and describes assumptions, limitations and uncertainties, including any evidence gaps, and explains their implications for decision making.

Wherever possible, model data, assumptions and code should be freely available in an open-access repository, to allow stakeholders to interrogate the decisions of the modelling team, and to supplement, extend, reproduce or update the work to incorporate new data. This information should be accessible and understandable – expressed in clear maps, graphs, or figures, and accompanied by a short summary written in plain language. The information should be available for review with sufficient time to allow proper consideration and feedback prior to decisions being made on model design or use.

4 Key procedural steps for developing and adapting environmental models

The following section describes key procedural steps involved in the development and adaption of environmental models. It is important to keep in mind that modelling processes are not linear. Each of the steps associated with developing or adapting a model are interlinked. As such, new information, unexpected findings, and the results of peer review or uncertainty and sensitivity analyses will require reconsideration of decisions and assumptions. Those responsible for developing or adapting models should take an iterative approach, routinely revisiting earlier stages in the process and engaging repeatedly with stakeholders to ensure the model is designed to deliver insights appropriate to the issues under consideration.

Regardless of whether the decision is taken to develop a new model, or to apply or adapt an existing model, environmental modelling processes should go through the following general phases (see Attachment 1 for an overview of two procedural frameworks for developing, adapting and applying environmental models).

- Define the problem, and specify the matter or matters the model is intended to address.
- Specify objectives, and define the context within which the model will operate.
- Develop, test, and confirm the conceptual model.
- Select the model framework, describe the parameters of the model, describe key relationships between components of the model, and build or adapt the model.
- Test and calibrate model performance, and corroborate its predictions.
- Deploy the model, and continue to evaluate and refine its performance.

At appropriate points in the model-development process, the team responsible for building or adapting the model should pause to:[10]

- consider commentary from end users or peer reviewers, and the results of uncertainty/sensitivity analyses
- determine whether it is necessary to revisit earlier stages in the model development process – for instance, to alter assumptions in response to findings, or to modify model design or parameters in response to uncertainty analyses or validation testing
- assess whether progress to date continues to suggest that modelling is an appropriate approach
- assess how confident the team is that the model under development will be adequate for the intended purpose.

This should not be a rigid process – some steps might not be needed in some cases, or some might be more important than others. Modelling teams should be able to tailor their approach

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[10] If the project team does not include regulators and other model users, mana whenua, decision makers and representatives of those likely to be affected by decisions based on the model, the project team should engage with these parties and gain their input at these 'pause points'.

to match the context, but they should do so deliberately and transparently, and they should ensure that, as part of any modelling process, they take the steps laid out in this section.

4.1 Establish whether modelling is appropriate to the context

Before any thought is given to the type of model that could or should be used to inform a decision and the information required to populate it, those responsible for developing or adapting models need to make sure the issue and objective are understood clearly.

Any modelling process should first seek to clarify what question is being asked and why. This will generally involve:

- defining the problem of interest
- clarifying the nature of the problem's effect on people and environments
- reviewing the quality of, and insights that can be gained from, existing data
- determining the scale (temporal and spatial) of analysis
- and defining desired outcomes (that is, the task for which an environmental model is being considered, the decisions it will inform, and the end goal it is seeking to facilitate).

For relatively simple or localised issues with a clear problem definition that is shared by affected and interested parties, and where relatively simple models are likely to be suitable, this process may be able to be undertaken by a single person or small group charged with reporting to a project oversight or governance group. More significant problems and more complex models may require a more comprehensive process of initial scoping, led by a project manager responsible for coordinating the input of a scoping team or advisory group comprising mana whenua, relevant technical experts, stewards, and/or representatives of key stakeholders and affected parties.

Once the project objective has been confirmed, it will be possible to ask the following questions to determine the most appropriate source(s) of information for the specific issue or decision-making process.

- Is the relative mix of current data sources giving decision makers the best possible understanding of Te Oranga o te Taiao – what are the strengths and weaknesses of the status quo, and what insights can the existing information provide?
- Could environmental modelling enhance understanding relevant to the issues or matters facing decision makers, or could other source(s) of data/information make a more valuable contribution?

This process of initial scoping and contextual analysis will enable an assessment of the contribution that environmental modelling could make to the network of information and evidence base that will inform decisions. The process helps answer the question 'can environmental modelling make a valuable contribution in this context?'

If the answer is 'no', then other options should be explored, such as relying on existing data, synthesising existing data and information sources, making greater use of mātauranga and local knowledge, relying on the judgement of kaitiaki or technical experts, or conducting a targeted monitoring programme.

If the answer is 'yes', the next steps are to develop a conceptual model to underpin the modelling project, and to establish whether the context requires a new model to be built or whether it would be more suitable to apply or adapt an existing model.

4.2 Adopt robust project management and oversight arrangements

To help ensure the modelling project remains on track to deliver the desired outcomes, the project team should set up appropriate project-management arrangements, comprising a clear and well-defined modelling project plan and suitable arrangements for oversight. The modelling project plan should:

- explain how the modelling project relates to other projects and decisions (that is, policy design or implementation, plan making or regulatory design, or operational management and capital investment), and describe the role the model will play and the outcome it is seeking to facilitate
- create a clear pathway for evaluation and peer review throughout the modelling project (see Attachment 2 for a checklist/prompts to help guide model evaluation)
- determine whether evaluation undertaken by the project team will be sufficient, or whether formal, independent peer review is necessary (that is, where a model may be used at the harder end of the regulatory spectrum, or where a model is new, is being used in a new way, or is limited by data availability or lack of validation)
- define project stages to allow consideration of reviews, uncertainty, and sensitivity analyses etc, and to determine whether to proceed with, stop or modify the project
- establish structures and processes to aid communication and information sharing between modellers, model users and people affected by model outputs
- specify quality assurance processes and criteria for input data and model acceptance (that is, model performance benchmarks/thresholds)
- specify how decisions will be made and documented to maintain transparency and accountability.

The design and membership of oversight arrangements for the modelling project should evolve to match changing demands as a model moves from the development and/or adaptation phase to application. During the development and/or adaptation phase, oversight arrangements should place greater weight on technical or scientific capabilities. It may be appropriate to reconsider oversight arrangements later in the modelling process, as decisions are made regarding how the model will be used, and as political and strategic capabilities become more relevant. In general terms, however, arrangements for oversight should:

- maintain stable governance and a clear line of sight between the design of the model and the decisions the model is intended to inform
- ensure good practice guidelines are applied appropriately throughout the lifecycle of a model
- create and hold a space for te Tiriti-based collaboration
- maintain timely and effective dialogue between model developers and model users to ensure decisions based on model outputs stay within an appropriate scope of application

- proactively coordinate the process of updating the model, as parameters and processes are modified, to reflect new information
- ensure stable financial arrangements are in place and funding is sufficient to maintain an ongoing commitment to continually improving model performance.

4.3 Assess uncertainty and sensitivity

Model users need to have a clear understanding of how closely the model's predictions approximate the real system of interest. In general, this does not simply involve comparing model results with empirical data, as some attributes and relationships within systems are more relevant than others, and uncertainties are inherent in all aspects of modelling and monitoring processes, including in relation to what is being tested. For these reasons, it is often necessary to deploy a range of mechanisms to estimate the probability of different outputs when assessing uncertainty, including running different model scenarios and deploying Monte Carlo simulations.

Identifying attributes and uncertainties that significantly influence model outputs (either qualitatively or quantitatively), communicating their importance, and identifying model-performance thresholds, are key to successfully designing/adapting models and using their outputs in a regulatory context. This is achieved via sensitivity and uncertainty analyses, both of which should commence as early as possible in the modelling process and should inform iterative decision making throughout the process of developing or adapting a model.

- **Uncertainty analysis** investigates the lack of knowledge about a certain attribute or process or the real value of model parameters. Uncertainty can sometimes be reduced through further study and by collecting additional data. Uncertainty can come in three main forms.
  - **Model framework uncertainty** results from incomplete knowledge about factors that control the behaviour of the system being modelled, limitations in spatial or temporal resolution, and simplifications of the system.
  - **Model input uncertainty** results from data-gathering or measurement errors (including bounds of uncertainty in laboratory results due to the accuracy/sensitivity of equipment), gaps in data, inconsistencies between measured values and those used by the model (for example, in their level of aggregation/averaging), and parameter value uncertainty.
  - **Model niche uncertainty** results from the use of a model outside the system for which it was originally developed, and/or from developing a larger model from several existing models with different spatial or temporal scales.
- **Sensitivity analysis** is the study of how a model's outputs relate to changes in model inputs. Sensitivity analysis is the principal evaluation tool for characterising the most and least important sources of uncertainty in environmental models. If, for instance, sensitivity analysis shows that a specific feature of a system has little influence on model predictions, the project team may reasonably decide that a greater degree of uncertainty associated with that feature is acceptable, and vice versa.

When conducted in combination and communicated clearly, sensitivity and uncertainty analyses help model developers and users understand how confident they can be about model outputs. This is critical to ensuring rigour and plays a key role in determining how, when and for what purpose environmental models can be used to inform decision making in a regulatory context.

4.4 Determine the level of scrutiny required

Models should be evaluated iteratively throughout their life cycle from inception to operation, and the results of this evaluation should inform key assumptions and design decisions, including, for instance, scientific or technical judgements on model type, input data, and model parameters.

The scale and nature of scrutiny should vary in response to the context and intended use of the model. In certain instances, where models may have a significant influence on regulatory decision making, a formal process of independent peer review will be necessary.

There may be a relatively small pool of people qualified and available to conduct a formal, independent peer review of a model, however, which can make these processes costly and time consuming. In some circumstances,[11] a less formal or comprehensive process of scrutiny may be acceptable.

Regardless of the nature and scale of scrutiny considered appropriate, some form of peer review is required, to ensure a model is technically robust, competently developed, properly documented, and that it delivers outputs that are relevant to and can reliably inform decision making. The scope and focus of peer review should be proportionate to the circumstances. However, in general terms, a peer-review process should investigate the:

- appropriateness of input data
- appropriateness of boundary condition specifications
- documentation of inputs and assumptions, calculations, and extrapolations
- applicability and appropriateness of selected parameter values
- documentation and justification for adjusting model inputs to improve model performance (calibration)
- accuracy and robustness of model code
- supporting empirical data that strengthen or contradict the conclusions that are based on model results
- certainty of model predictions and reliability of conclusions drawn from them
- performance of the model against acceptance criteria set in the project plan.

Peer review should be conducted by individuals who collectively have technical expertise at least equivalent to those who have developed or adapted the model. Mechanisms for conducting peer review include (but are not limited to):

- convening a review panel of technical experts, specialists, kaitiaki, scientists, and/or modellers
- facilitating a technical workshop with those who developed or adapted the model, and inviting the input of interested and affected parties

[11] For example, where a model is well established and well accepted, where data are numerous and reliable, where the system being modelled is well understood and relatively simple, and where model outputs are intended to be used at the softer end of the regulatory spectrum.

- using an established external professional or public sector peer-review mechanism (such as a technical panel of experts maintained by a professional institute or government agency).

When determining the extent of scrutiny required, those responsible for building or adapting models should consider that the predictions of environmental models generally tend to become more accurate and less subject to uncertainty over time. More data tend to accumulate over time, making more fine-tuned validation of model outputs and adjustments to model parameters and processes possible. This tends to improve alignment between model predictions and the results of empirical observation or sampling. For this reason, newly built models should be subject to independent peer review prior to their first application.

When adapting existing environmental models for use in a different location or context, modelling teams should consider the scientific and technical complexity and/or the novelty of the circumstances in which the model is to be applied, before determining the appropriate degree of scrutiny. In some cases, provided that internal evaluation processes are sufficiently robust, longstanding models with well-established relationships may be able to be used confidently within agreed parameters without independent peer review.

In all cases, responses to matters raised through internal or external peer-review processes should be reported transparently, to enable effective project guidance and facilitate constructive critique, from model development through to application.

4.5 Choose the right model, or models, for the job

There are many different types of models available to choose from, including, for instance, empirical vs mechanistic, static vs dynamic, simulation vs optimisation, deterministic vs stochastic, and lumped vs distributed. In addition, the level of spatial, temporal and process detail that is modelled can range from very simple to very complex, depending on a range of factors, including problem definition, data availability and resource availability.

Those responsible for developing or adapting models should compare alternative model types and evaluate their ability to meet project objectives, to determine the most appropriate type for addressing the problem within project timeframes and resourcing. This evaluation should consider the data and resources available, the temporal and spatial scale of the application, the scale and nature of the problem, and how the model will be used (see Box 3).

Box 3: Matching model type to intended use

In preparation for a regulatory plan change, Environment Southland commissioned modelling to evaluate the impact of nutrient and sediment loads on the health of 11 of the region's estuaries, coastal lakes, and lagoons. The modelling was designed to give an understanding of the difference between the current state of the environment and current contaminant loads, and the contaminant loads predicted to be needed to achieve the draft objectives. The intent was to characterise the 'size of the gap', to inform the nature of public engagement and scope of additional research required in the lead-up to the plan change.

Ideally, the modelling would have treated each estuary as a dynamic system with multiple contributing catchments and spatially variable mixing, flushing and deposition characteristics that give rise to spatially variable trophic state and sediment accumulation. However, local data were extremely limited in all but two of the region's estuaries (where there were sufficient data to facilitate more complex modelling using a more sophisticated model), and the modellers proposed a simplistic model type that represented entire estuaries as a single basin. This approach produced estimates of trophic state and associated nutrient loads for each whole estuary, and whole-estuary averaged sediment accumulation rates. The decision to opt for a more simplistic model type potentially concealed variation in contaminant inputs from different contributing sub-catchments, or spatial variation in both trophic state and sedimentation due to variable flushing rates and variations in bathymetry and depth. On the other hand, this made it possible to maintain a consistent conceptual model and modelling architecture across all estuaries in the region.

For the first step in its regulatory process, Environment Southland chose to prioritise regional uniformity of approach over opting for a mosaic of different models at different levels of complexity. An independent review of the modelling process concluded the modelling provided a suitable foundation for estimating the reduction of contaminant levels required to achieve draft freshwater objectives, given the purpose of the modelling programme and how its outputs were going to be used to inform discussion and analysis in the lead-up to a plan-change process.

Source: Brown H, Davie T, Fenemor A, Jackson B, Muirhead R, Scarsbrook M, Schollum A, Taylor K. 2022. Science Review Panel memo to Environment Southland, Memo to Environment Southland.

When choosing between alternative model types, it is important to recognise that model complexity can significantly affect the certainty of model predictions. Models tend to become more uncertain as they become increasingly simple (that is, if they focus too narrowly on specific attributes or relationships within a system) or as they become increasingly complex (that is, if they aim to closely represent extremely complex inter-relationships between attributes or system components) (see figure 1).

Modellers and decision makers will need to consider what degree of uncertainty is acceptable within the context of a specific model application, and decide on the optimal balance between simplicity and complexity,[12] as they:

- identify or construct a model framework that matches the context and is consistent with project objectives

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[12] Saltelli A. 2019. A short comment on statistical versus mathematical modelling. *Nature Communications* 10(August 2019): 3870. https://doi.org/10.1038/s41467-019-11865-8.

- identify the environmental domain to be modelled and set boundaries of the system to be modelled
- decide whether there are enough data available, or a sufficient understanding of processes occurring, to justify opting for a more complex or more sophisticated model
- specify the processes and conditions within the system to be modelled, including:
  – the transport and transformation processes relevant to the project objectives
  – the relevant temporal and spatial dimensions of processes within the system
  – any locally relevant conditions of the system that will affect model selection or new model construction.

Figure 1: Relationship between model complexity and uncertainty[13]

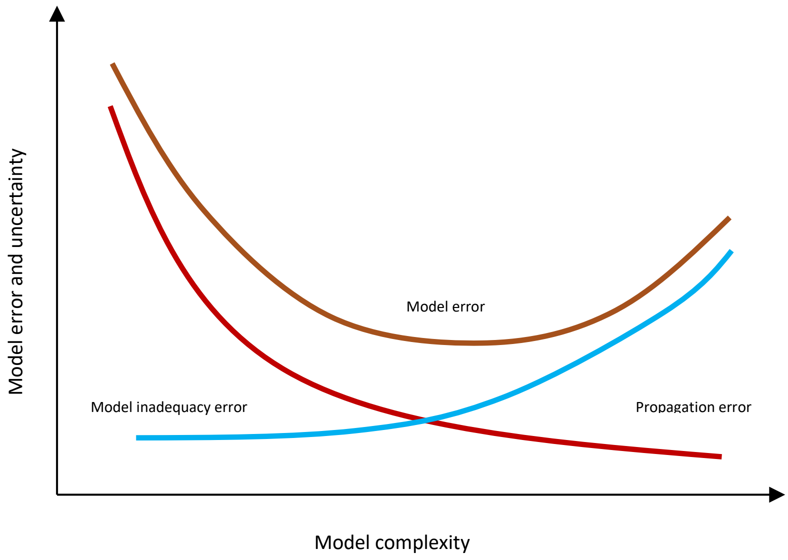


Figure notes:

- **Model inadequacy error** arises when using too simple a model for the problem at hand. This can be reduced by making the model more complex.
- **Propagation error** results from the uncertainty in the input variables propagating to the model output. This increases with model complexity – whenever the system being modelled is not elementary, overlooking important processes leaves us on the left-hand side of the plot, and 'modelling hubris' can take us to the right-hand side.

Environmental managers increasingly need to understand the dynamic interactions between environmental systems, or between natural and human systems. For example, air quality managers need to understand how human activities generate emissions, how these emissions interact with meteorological conditions, and how contaminants in those emissions disperse through the air.

To gain insight into these interactions, and to uncover or infer causal chains in and between systems, modellers may need to 'link'[14] multiple model frameworks, so that the output from one model is used as input data to another model (see Box 4).

[13] Adapted from Saltelli, n 12.

[14] This can vary from 'loosely coupling' models, using the output from one model as an input to another, to 'fully integrating' models to represent complex cascades of causal influence across different aspects of the modelled systems.

If a series of models are to be used in sequence (for example, to estimate contaminant loads and their effects, identify limits or thresholds, allocate discharge allowances, and estimate compliance with those allowances), wherever possible the models used for these purposes should be interoperable, and they should be built using the same basic model architecture and assumptions.

The linking of models to build an integrated system can be a powerful way to gain insight into processes across an entire system. Project teams need to be mindful, however, that uncertainty arising from assumptions or data limitations in one model can propagate throughout a linked modelling system, causing uncertainties across several models to multiply and distort outputs.

Box 4: Linking models to provide insight across systems

A suite of linked models is used in Auckland and Northland to predict water quality at recreational swimming sites.

Wastewater network models predict the location and extent of wastewater overflows during rainfall. These predictions are used as inputs to hydrodynamic models, which estimate the incidence, movement and dispersal of wastewater plumes in the ocean. Water quality models draw on the predictions from the hydrodynamic models to estimate the likelihood of water quality meeting or exceeding thresholds for faecal indicator bacteria set via national guidelines. These water quality models consider the intensity and location of rain, the influence of tide, and the effect of wind speed and direction on the movement of water, as well as the effect of sunlight on the persistence of pathogens. Weather forecasts are integrated into the system, allowing the models to predict water quality, days ahead.

Data from continuous monitors (sensors) on the wastewater network and rain gauges are factored into water quality predictions every 15 minutes, to ensure they reflect actual conditions and to correct for inaccuracies in model predictions (for example, should predicted rain not occur or should it rain unexpectedly, or should a blocked pipe cause an overflow in dry conditions).

An ongoing programme of routine and targeted water quality sampling – building on a 20-year record of weekly sampling programmes – is used to validate and refine water quality model predictions, which are required to meet guidelines for model accuracy published by the United States Geological Survey.

The model results are communicated to the public in real time, allowing them to manage their risk of encountering contaminated water. Network managers use the model results to target monitoring and investigations designed to find and characterise the nature of weaknesses in the water networks.

Source: World Health Organization. 2021. Guidelines on Recreational Water Quality: Volume 1 Coastal and Fresh Waters. Geneva: World Health Organization. pp 50–51.

When employing linked models so that output from one model serves as input for another, those responsible for developing or adapting models should:

- evaluate each component model and the full integrated system of models
- provide a comprehensive explanation of the source and nature of uncertainty, describe the implications of known unknowns, identify areas of potential unknowns, and clearly spell out the implications of uncertainty for model users and for the potential scope of model application

- consider using diagrams to highlight areas of uncertainty and point out how they are likely to propagate through the model architecture and explain the potential implications for the resulting predictions.

In these circumstances, decision makers and those using models need to be particularly careful to avoid using model outputs beyond their intended scope.

4.6 Train and calibrate the model, and corroborate its predictions

It is essential to determine whether a model and its outputs are sufficiently robust and reliable to serve as the basis for regulatory actions and decisions. This is achieved via model 'training' and validation.

As soon as possible after the basic model architecture is in place – whether it has been built from scratch or adapted to meet the needs of the modelling project – the modelling team should generate an initial dataset and begin to populate the model with enough data to enable initial model runs. This will allow the modelling team to:

- test and confirm mathematical/computational methods and the design of algorithms
- corroborate the accuracy/utility of the conceptual model and verify key model components/assumptions
- calibrate model parameters (adjust model parameters within physically defensible ranges until the resulting predictions give the best possible fit to the initial dataset)
- review and verify the robustness and reliability of model code
- conduct a first phase of sensitivity and uncertainty analysis and consider whether the model outputs accord with other lines of evidence, including the reasonable expectations of operational managers, kaitiaki and other expert advisors.

Although it can help to have a backlog of data before commencing model training, this is not essential, as it is possible to gather data, populate and train models concurrently. Data used to populate, train and corroborate environmental models should, however, meet data quality acceptance criteria set out in the project plan, and should conform to methods and standards published by relevant agencies regarding the use of specific environmental models.

For newly developed model frameworks or untested mathematical processes, or where a model is expected to inform decisions at the 'harder' end of the regulatory spectrum (such as determining whether to approve an application for a resource consent), model validation should involve:

- hypothesis tests and thresholds of confidence for model acceptance
- quantitative testing criteria using datasets independent of the model development and calibration dataset
- testing to ascertain that spatial and temporal resolution is appropriate to the application.

When training and validating models, every effort should be made to test model processes against direct measurements of the system of interest. This enables statistical estimates of how closely the model results match samples taken from the real system, under the full range of locations and conditions for which the model is expected to provide predictions. Similarly, model simulations should be run for a sufficient period to enable testing of model predictions under a range of conditions, and to account for long-term variation in driving variables (that is, seasonal or climatic change). The temporal frequency and duration of model simulation should be determined based on the characteristics of the system to be modelled.

For complex mechanistic models, model simulations should typically run for a minimum of one calendar year during the testing phase. It will not always be possible, however, to achieve this. For instance, in complex hydrological systems, there may be long lag times between the generation of contaminants and their impact on water quality. In such circumstances, sampling and year-long model simulations will not necessarily provide insight into the accuracy of model predictions, because the two factors (inputs and effects) are separated by a long period of time.

Where samples are unavailable, too costly to obtain or unobtainable, where data are poor or sparse, or where sampling will not provide timely insight into system processes, the project team may need to rely on a combination of other sources of information to test, corroborate and validate model outputs (see Box 5).

This could involve checking the degree of concordance between the newly developed or adapted model and:

- outputs from other models
- complementary data (such as historical data sets, data from observational studies or targeted sampling)
- expert judgement on whether a model suitably represents a system's behaviour
- the experience and judgements of mana whenua, kaitiaki, and others with specialist or local knowledge of the systems.

Combining monitoring and modelling data, and drawing on 'multiple lines of evidence' to test and corroborate findings, helps those responsible for developing or adapting models to ensure they are providing decision makers with the best available information.

When leveraging multiple lines of evidence to test and corroborate model predictions, the project team should clearly describe the complementary sources of information they have drawn from, the methods used to generate these data, and the degree of 'weight' given to the data or the influence the data have had on model assumptions and conclusions.

Box 5: Using multiple lines of evidence to quantify nutrient loads to Te Waihora

Te Waihora is a large shallow coastal lagoon in the Selwyn catchment, Canterbury. It has exceptionally high value for Ngāi Tahu, primarily related to its traditional pre-eminence as a food source, but it also has high value for the wider community, not least due to its international standing as a wildlife habitat. Lake inflows are dominated by groundwater, which is recharged by rainfall across the central plains and from the Waimakariri and Rakaia rivers. Because of the long distances involved, movement of groundwater from its sources to the receiving environment can occur over multi-decadal timeframes.

Concerns about the impact on the lake from the inputs of contaminants (particularly nitrates from agriculture) have grown in the last two decades, largely because of the intensification of pastoral farming over much of the catchment. In developing policy for the management of water quality, Environment Canterbury needed to understand and quantify current loads to the lake, and to predict future loads – not only in terms of contaminants already in the groundwater system but not yet at the lake, but also in terms of contaminants that might be expected as a consequence of future policy interventions and changes in land management practices.

In making these predictions, Environment Canterbury needed to integrate several types of information, to understand the system and to corroborate its conclusions. A simple groundwater transport model was developed, in which contaminant travel times were based on prior local observations, and attenuation factors were inferred from local and international research. Nitrate inputs below the root zone were calculated from look-up tables that provided for multiple combinations of farm type, climate and soils, and the outputs were used as an input to stream quality and lake modelling.

The performance of the chain of models was tested by back casting, using trends in groundwater and surface water sampling data, along with historic land-use information over timeframes relevant to the time lags in the groundwater system. Modelling assumptions about leaching rates and attenuation were evaluated against lysimeter data from the catchment and with data from similar hydrogeographic settings. Importantly, the aquifers in the Selwyn Te Waihora catchment have been well researched over many years (relative to other Aotearoa groundwater resources). Accordingly, Environment Canterbury was able to draw on a considerable body of expertise to help frame the conceptual model, challenge assumptions and sense-test the outputs. The convergence of all these lines of information was a key factor in building stakeholder confidence in the science, and providing a sound evidential base for scenario testing and discussions about policy options.

Source: Robson M. 2014. *Technical report to support water quality and quantity limit setting in Selwyn Waihora catchment. Predicting consequences of future scenarios: Overview Report*. Report No. R14/15. Christchurch: Environment Canterbury.

4.7 Prepare the model for deployment

Prior to presenting a model as being ready for use in a regulatory context, the project team responsible for developing or adapting a model should consider whether:

- the underlying hypotheses, assumptions, and design parameters are supported by sound science, mātauranga and maramataka, and have clear rationale
- the quality and quantity of empirical sampling data and other evidence available support the choice of model and corroborate its predictions
- the model's complexity is appropriate for the matter at hand
- the model structure reflects all relevant inputs described in the conceptual model
- the model's digital architecture and code have been independently verified and shown to be robust, and can be relied upon to work effectively
- existing platforms for communicating model outputs (the 'user interface') are suitable for the intended task
- the project team supports the application of the model for the intended purpose set out in the project plan.

The results of the project team's consideration should be clearly documented, benchmarked against acceptance criteria set out in the project plan, and submitted as a 'model release report' to the relevant project oversight group or decision maker identified in the project plan.

To facilitate accurate understanding and effective use of model outputs, the model release report should provide written documentation of the model's relevant characteristics and performance in a style and format accessible to mana whenua and kaitiaki, key project partners, stakeholders and the public. It should be as brief and accessible as possible and written in plain language that policy makers and an informed layperson can understand, avoiding jargon and excessively technical language. It should, however, be comprehensive and allow interested parties to access necessary details and underlying data and assumptions, including describing:

- the conceptual underpinnings of the model and its intended uses
- the model equations and assumptions, using clear and appropriate methods to efficiently display key mathematical relationships
- quantitative and qualitative model outputs, using simple tables and graphics to support interpretation of technical data
- the boundaries of the model and its outputs, and its limitations – including when applied outside of intended areas or scenarios
- the relationship of the model to the underpinning data, and the dataset(s) used for training and validation
- how data and other sources of information will be used to evaluate the accuracy of model outputs and confirm the model's ability to reliably support regulatory decisions and actions
- the results of model evaluation and peer review, the stage the model is at in its life cycle, and how its outputs will continue to be refined in response to new data and emerging information
- the factors or events that might trigger the need for major model revisions, or the circumstances that might prompt users to seek an alternative model
- the resources needed to ensure effective operation and continual improvement of the model.

5 Applying environmental models

5.1 Confirm the scope and nature of application

The model development or adaptation process culminates in a formal decision to use the model to inform resource management and decision making in a regulatory context. This decision should be made by the person or group identified in the project plan, involving mana whenua and those charged with making the regulatory decisions or undertaking the operational actions that will be informed by the model's output.

In most instances, the model will underpin or help inform a proposed regulatory decision or intervention. Decision makers should understand the role of the model in supporting the proposal. For this reason, it is essential that those responsible for developing or adapting the model are active participants in this decision-making process. This will ensure that regulatory decisions underpinned by models are made with a full understanding of the assumptions and judgements inherent in the modelling, and of the implications of model uncertainty and sensitivity.

To avoid confusion and potential conflict, a firm decision on the appropriate scope and nature of a model's use should be made before using model outputs to inform regulatory actions or decisions.

When applying a model in a regulatory context, decision makers should keep in mind that it is generally more appropriate to use environmental models to inform actions and decisions at the 'harder' end of the regulatory spectrum[15] (see Box 6) where models:

- are well established (mature) and have a longstanding history of effective and reliable use in equivalent contexts
- are underpinned by a comprehensive set of data
- are corroborated by the outputs of other models and evidence
- have been validated by investigations that have demonstrated a strong and reliable correlation between model predictions and sampling results.

It is important to note that it is also appropriate to use well-established models (underpinned by comprehensive data etc) at the 'softer' end of the regulatory spectrum, should that be appropriate to the context.

[15] For setting regulatory limits, determining whether regulatory permissions are required, determining activity status, allocating rights and responsibilities, and establishing compliance or non-compliance with regulatory requirements.

Box 6: Using air quality models in resource consent processing

Regional councils are often required to consider applications for consents to discharge contaminants to air. Models are an important tool in assessing the likely effects of such discharges on ambient air quality. The use of CALPUFF is particularly helpful in this regard. CALPUFF is a multi-layer, non-steady-state puff dispersion model that simulates the effects of varying meteorological conditions on the transport, transformation and removal of emissions. The model was developed in the USA and is formally endorsed by the USEPA for a range of applications in air shed management.

In Aotearoa, CALPUFF analyses are often submitted with consent applications for industrial-scale discharges, and consent conditions usually reflect the modelled inputs. Where CALPUFF predictions are contested, either during the application process, or in subsequent court appeals, issues relate to model settings or input data, but generally not to the design or architecture of the model itself. CALPUFF has also been used in Canterbury in a prosecution, to help the Court identify the extent of adverse effects arising from a large unauthorised fire that released toxic contaminants to air.

Stakeholders have a high degree of confidence and trust in CALPUFF because it has a long history of use in many jurisdictions, is subject to the USEPA's stringent requirements for the use of models in regulation (including accessibility, transparency, validation testing and regular review), meets end-user and management needs, and is supported by a large community of practice.

Source: Envirolink. *CALPUFF (CALPUFF)*. Retrieved 15 June 2023. http://tools.envirolink.govt.nz/dsss/calpuff/

Generally, it is more appropriate to use environmental models to inform actions and decisions at the 'softer' end of the regulatory spectrum[16] (see Box 7) where models:

- are new (immature), and are being used for the first time or in a significantly different context to the one for which they were initially designed
- are attempting to simulate a highly complex system with many unknowns
- suffer from a paucity of data, or if the model outputs are likely to change as more data becomes available (for example, as understanding of the system increases)
- have not been sufficiently corroborated by investigations, or where investigations have demonstrated weak relationships between model predictions and sampling results.

[16] To highlight potential management issues, identify where to focus sampling activities, specify thresholds that trigger investigation and/or a greater degree of regulatory scrutiny, educate and empower people to make informed decisions, and identify a suite of public investments likely to deliver desired outcomes.

Box 7: Using models to educate and empower the public

Hawke's Bay Regional Council has developed a Drought Risk Indicator to help build drought resilience in the community.

The tool combines live rainfall, soil temperature, soil moisture, and evapotranspiration data from the council's 50 climate stations around the region, to generate a 'traffic light warning system' for drought.

Users of the tool can access specific climate and data sources (rainfall accumulation, soil moisture, soil temperature and potential evapotranspiration), as well as a combined indication of drought risk relevant to their property and surrounding area.

The tool also connects users with resources they can use to help prepare for, or respond to, drought conditions.

Source: Hawke's Bay Regional Council. *Drought Risk Indicator*. Retrieved 15 June 2023.

In some circumstances, there is the possibility of imminent or irreversible damage to Te Oranga o te Taiao, and an environmental model may be the best (or potentially the only) tool available to provide insight into the nature of the situation and the consequences of regulatory decisions. In such situations, decision makers should draw on model outputs to assist with their decisions, *even if the model is at an early stage in its life cycle, or is subject to a high degree of uncertainty*. In these instances, it becomes particularly important to:

- facilitate in-depth discussions between model developers, the model users responsible for applying the model to a particular problem, and those affected by decisions made based on model outputs
- share and discuss the data, assumptions, model code, and information gathered during model evaluation and peer-review processes, including the results of uncertainty and sensitivity analyses
- describe transparently the strengths and weaknesses of the model, and the implications of these, given the context and the intended use of model outputs
- monitor and review the impact and outcomes of regulatory decision in achieving desired objectives
- commit to enhancing the accuracy of the model and corroborating its predictions with monitoring and observational studies.

5.2 Maintain a commitment to continual improvement

Releasing a model for use should not be considered the 'finish line' for a modelling process. Effective model application involves an iterative process of continuous improvement and refinement. The agency using the model should ensure there is enough resource available to continue to evaluate and refine the accuracy of the model after its initial deployment. This implies:

- maintaining an operational project team and a mechanism for project oversight so new data can be obtained, assessed, and incorporated into the model; necessary changes to model processes can be considered and made; and the implications of these refinements can be identified and communicated to decision-makers

- monitoring the modelled system in a range of environmental conditions, and after implementing a remedial or management action, to determine whether the actual system response concurs with that predicted by the model
- conducting formal model reviews at pre-defined milestones after model release, to transparently assess and report on a model's ability to provide valuable input to regulatory and operational management decisions.

The project plan for the modelling process should define ex ante measures that can be used to evaluate the impact of a model's output. These measures can be behavioural, environmental, quantitative, or qualitative, but they should be measurable and designed to reveal the effectiveness of the model in terms of:

- synthesising data and generating information that is relevant and applicable to the environmental issue under consideration
- identifying environmental state and trends that provide useful insights that aid in sustaining and enhancing Te Oranga o te Taiao
- revealing key processes and relationships that enable environmental managers to make decisions and act effectively
- evaluating the effectiveness of actions intended to sustain and enhance Te Oranga o te Taiao.

Transparency and effective communication continue to be of primary importance during model application. The project team tasked with running a model must repeatedly communicate model outputs, conclusions and implications to decision makers, project partners and mana whenua, and stakeholders.

At the same time, the project team must continue to explain the limitations of the modelling process (for example, in terms of accuracy, uncertainty, and appropriate scope of application) to ensure model outputs are understood accurately and used appropriately by affected parties and decision makers. This will require the project team tasked with running a model to document and present technical information in a manner that decision makers and stakeholders can readily interpret and understand, and to address common misinterpretations that can cause people to place too little or too much confidence in model outputs.

To perform these tasks with confidence, the project team tasked with running a model should have easy access to the advice of those responsible for developing or adapting the model for use.

5.3 Establish appropriate arrangements for ongoing stewardship

Environmental models routinely operate in a context of complexity, uncertainty and change. Throughout their life cycle from development to application, many decisions are required in response to the results of evaluation and peer review, as new information comes to hand and as sampling data become available.

Significant time and resources can be invested in the development of a model, and model outputs are often subject to debate and dispute, and can prompt legal challenge, which can be costly and divisive. Inaccurate interpretation and inappropriate use of models can have significant implications for Te Oranga o te Taiao and the wellbeing of society and communities.

Poor or ill-informed decisions can impact the economy and environment and affect societal and cultural wellbeing.

Good governance and oversight of modelling processes and the use of models in a regulatory context is essential, playing a key role in:

- ensuring good practice guidelines are applied appropriately throughout the life cycle of a model
- retaining a clear focus on maintaining and enhancing Te Oranga o te Taiao and consistency with te ao Māori
- ensuring stable financial arrangements are in place, and funding is sufficient to maintain an ongoing commitment to continually improving model performance over a sufficiently long timeframe
- appropriately managing changes to model versions or outputs as model parameters and processes are updated to reflect new information
- ensuring decisions based on model outputs stay within an appropriate scope of application.

5.4 Actively manage the implications of model evolution

During the early stages of their life cycle, models can be expected to go through a succession of version changes as model parameters, assumptions and processes are updated in response to new input data.

In some instances, these changes may have a relatively consistent effect across all modelled conditions or environments. In other situations, the changes may relate only to specific processes and have a focused effect on specific conditions or environments within the modelled system. For example, changes to the subcomponent of a model for predicting nutrient losses in rural environments that relates to dairy cow urine may influence estimates of nitrogen loss for a dairy farm, but the changes will not affect estimates of phosphorus loss arising from an arable cropping farm.

Sometimes, model version changes can have potentially significant implications. For example, if model outputs are used in a plan to define activity status, a model version change that modifies estimates of contaminants associated with a particular activity could alter whether the activity is permitted, requires a resource consent, or is prohibited – without any actual change to the intensity or nature of the activity being undertaken. This may reflect an improvement in the extent to which the model represents reality, but it raises the risk of plan rules being unnecessarily permissive or constraining.

Changes to rights and responsibilities arising from changes in model outputs have proven controversial, especially where models seek to represent complex systems and have a high degree of inherent uncertainty. Decision makers should strive to understand the potential for, and likelihood of, model outputs changing – and the regulatory implications of that – *before* decisions are made on how to apply the model in a regulatory context. If a decision is made to incorporate a model into a plan, then strategies should be adopted to minimise the impact of version change. This could be as simple as being deliberate about how the model is to be used in the plan (that is, at the 'softer' end, in an informative manner, rather than the 'harder' end, in a determinative manner), or being deliberate about what model version is to be used and how (for example, by mandating use of the current model version and standardised long-term average climate conditions to control for variability in driving conditions). Alternatively, it might be through the application of good governance to actively manage any changes to model outputs, by clearly communicating their rationale and evidential basis, evaluating and describing their implications, and giving advanced warning of when changes will come into effect and how they will be implemented.

Glossary of terms

Accuracy: The closeness of a measured or computed value to its 'true' value. Due to the natural complexity, variability and dynamism of many environmental systems, this 'true' value is likely to exist as a distribution rather than a discrete value.

Boundary conditions: Sets of values for state variables and their rates of change along the boundaries of the system being modelled, used to determine the state of the system within the model boundaries.

Calibration: Improving model performance by adjusting model parameters and model forcing within the margins of uncertainty, to obtain a model representation of the processes of interest that complies with pre-defined criteria.

Data uncertainty: Uncertainty (see Uncertainty) that is caused by measurement errors, analytical imprecision, and limited sample sizes during the collection and treatment of data. Data uncertainty, in contrast to variability (see Variability), is the component of total uncertainty that is 'reducible' through further study.

Environmental data: Information about the biophysical environment collected directly from measurements, produced from models, and compiled from other sources such as databases and literature.

Environmental monitoring: Observing, checking, or keeping a continuous record of environmental state, trends, relationships, and progress towards specified targets and desired outcomes – drawing on data generated from observation, sampling and modelling.

Drivers/driving variable: An external factor that influences the state variables calculated within the model. Such factors include, for example, climatic or environmental conditions (temperature, wind flow, rainfall, oceanic circulation etc.) Also called a 'forcing variable'.

Kaitiaki (kaitiakitanga): Tiaki means to guard, preserve, foster, protect and shelter. The prefix kai means someone who carries out an action. A kaitiaki is a guardian or trustee, typically of an environmental area or resource.

Mana whenua: The right to exercise authority over land or territory, vested in the iwi/hapū/ahi kā (Māori landowners) who have jurisdiction over land or territory and who exercise mana whakahaere (authority) and other obligations (kaitiakitanga and manākitanga) in relation to particular whenua (land), wai (water source), space and resource.

Maramataka: Traditional Māori lunar calendar used to guide the planting and harvesting of crops, and fishing and hunting.

Mātauranga: The growing and evolving body of Māori knowledge originating from Māori ancestors, including the Māori worldview and perspectives, Māori creativity and cultural practices.

Model: A simplification of reality that is constructed to gain insights into selected attributes of a physical, biological, economic or social system. A formal representation of the behaviour of a system's processes – can be defined in mathematical, statistical, physical or conceptual terms.

Reliability: The confidence that (potential) users have in a model, and in the information derived from the model, such that they are willing to use the model and the derived information. Specifically, reliability is a function of the performance record of a model and its conformance to best available, practicable science.

Robustness: The capacity of a model to perform well across the full range of environmental conditions for which it was designed.

Scenario: A description of a historical, current, alternative or future system that allows a modeller to vary parameters, assumptions and inputs, to infer how a system will respond in different circumstances and under different conditions.

Scope of applicability: The set of conditions under which the use of a model is scientifically defensible and able to be relied on by decision makers.

Sensitivity: The degree to which model outputs are affected by changes in selected input parameters.

Sensitivity analysis: Calculation of the effect of changes in input values or assumptions on model outputs, to determine the relative importance of parameters in the model.

Training: Involves using calibration data along with the results of model validation analysis to modify model parameters – readjusting model parameters within physically and scientifically defensible ranges until the resulting predictions give the best possible fit to observed data.

Te Mana o te Wai: A concept that refers to the fundamental importance of water and recognises that protecting the health of freshwater protects the health and wellbeing of the wider environment. It protects the mauri of the wai. Te Mana o te Wai is about restoring and preserving the balance between the water, the wider environment, and the community (see clause 1.3 of the National Policy Statement for Freshwater Management 2022 for a comprehensive definition).

Te Oranga o te Taiao: The wellbeing, health and vitality of the natural environment.

Te taiao: The natural environment.

Transparency: The clarity and completeness with which data, assumptions, methods of analysis, model outputs, and conclusions are documented, reported and made available for review.

Uncertainty: Lack of knowledge about models, parameters, constants, data and beliefs. There are many sources of uncertainty, including in the science underlying a model, uncertainty in model parameters and input data, observation error, and code uncertainty.

Uncertainty analysis: Investigation of the effects of lack of knowledge or potential errors on the model (for example, the 'uncertainty' associated with parameter values).

Validation: The extent to which a model performs as expected and delivers outputs that correspond to real properties, characteristics and variations in the system being modelled. Validation involves the use of quantitative and qualitative methods for evaluating the degree to which model outputs correspond to observation and sampling of real-world conditions, or the results of similar models in comparable circumstances. The scope and rigour of these methods will vary depending on the model type and its intended purpose.

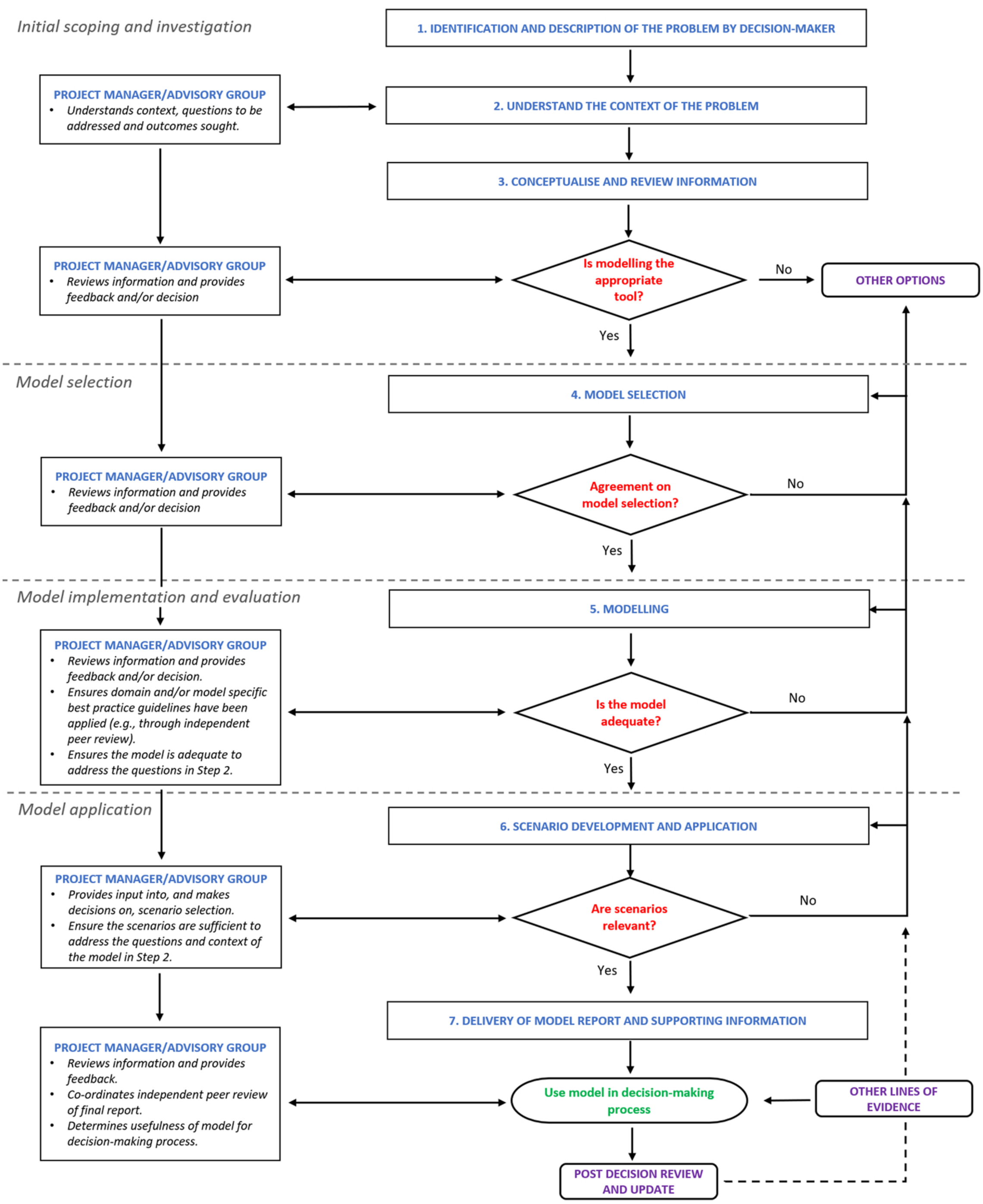
Variability: Observed differences attributable to true heterogeneity or diversity. Variability is the result of natural random processes and is usually not reducible by further measurement or study, although it can be better characterised.

Attachment 1: Overview of two procedural frameworks for modelling

<table>
<tr><th colspan="3">Phases and steps</th><th>Key tasks</th></tr>
<tr><td rowspan="3">Phase 1 – Model foundations: formulating the basis of the model, including problem identification, model conceptualisation and project planning</td><td rowspan="8">Model evaluation – iterative cycle of review, reporting, and refinement throughout the life cycle of the model</td><td>Step 1: Initial scoping, specify context, determine target scope of application, build project team</td><td>Establish modelling objectives, confirm problem scope and definition. Specify decisions to be supported by the model.
Determine model boundaries and scale (spatial and temporal), and target scope of application. Review existing data. Build a project team and establish governance arrangements tailored to the context.</td></tr>
<tr><td>Step 2: Develop and test conceptual model</td><td>Develop scientific/technical foundations, reflect mātauranga and maramataka in conceptual design.
Set initial assumptions and outline the variables and processes to be represented.</td></tr>
<tr><td>Step 3: Develop project plan</td><td>Establish framework for developing, evaluating, and using the model, including:
• communication and decision-making processes
• milestones and pause points
• evaluation plan and process
• performance criteria/thresholds.</td></tr>
<tr><td rowspan="3">Phase 2 – Model development: developing the conceptual model that reflects the underlying science of the processes being modelled, developing the mathematical representation of that science, and encoding these mathematical expressions in a computer program</td><td>Step 4: Determine model type, scope and focus</td><td>Identify a model type that matches the context.
Set the boundaries of the system and confirm the detail of processes and conditions to be modelled.</td></tr>
<tr><td>Step 5: Develop model architecture</td><td>Confirm mathematical/computational methods.
Develop hardware platforms and software infrastructure.
Design model communication platform/user interface.
Populate, calibrate and test model outputs, and conduct initial sensitivity and uncertainty analyses.</td></tr>
<tr><td>Step 6: Confirm scope of potential applicability</td><td>Document evaluation and consideration of model performance against criteria set in project plan.
Recommend appropriate scope of application to project oversight group and/or decision makers.</td></tr>
<tr><td rowspan="2">Phase 3 – Model testing: testing that the model expressions have been encoded correctly into the computer programme and testing the model outputs by comparing them with empirical data</td><td>Step 7: Model training and validation</td><td>Determine whether a model and its outputs are sufficiently robust and reliable to serve as the basis for regulatory actions and decisions.</td></tr>
<tr><td>Step 8: Independent peer review</td><td>Determine whether independent peer review is warranted.
Evaluate the appropriateness of input data, core features of model design, and performance against agreed benchmarks and criteria set in project plan.</td></tr>
</table>

Phases and steps			Key tasks
			Clearly document process, communicate implications, and make available for review.
		Step 9: Decide whether to accept model for use in regulatory context	Determine whether: • the model is suitable for its intended use or whether there is too much uncertainty associated with its outputs • more development is required • the intended use should be changed • the modelling project should be discontinued.
Phase 4 – Model application: running the model and analysing its outputs to inform a decision		Step 10: Model release and use	Produce a 'release report' documenting and presenting technical information in a manner that decision makers and stakeholders can readily interpret and understand. Use the model to estimate the likely outcome of different packages of, or approaches to, regulation, investment or operational management.
		Step 11: Outcome evaluation and continual improvement	Iterative process of continuous improvement and refinement, including: • monitoring the modelled system under a range of conditions, to determine whether the actual system responds in accordance with model predictions • conducting formal model reviews at pre-defined milestones.

Adapted from: US Environmental Protection Agency. 2009. *Guidance on the Development, Evaluation, and Application of Environmental Models*. EPA/100/K-09/003. Washington DC: US Environmental Protection Agency, Council for Regulatory Environmental Modeling. Box 2, p. 6.



Source: Jones HFE, Özkundakci D, Hunt S, Giles H, Jenkins, B. 2020. Bridging the gap: A strategic framework for implementing best practice guidelines in environmental modelling. *Environmental Science & Policy* 114(December 2020): 533–541. https://doi.org/10.1016/j.envsci.2020.09.030.

Attachment 2: Checklist/prompts for model evaluation

Core components	Prompts
Conceptual basis	• The choice of model is supported by the quantity and quality of available data. • The scientific theories that form the basis for models, including their relationship to te ao Māori and the extent to which they draw on mātauranga and maramataka, are appropriate. • The attributes, relationships and processes of the modelled system are relevant to the problem of interest, and the important drivers and processes represented by the model are relevant to the assessment being undertaken.
Respect for te Tiriti o Waitangi	• Mana whenua participation is appropriate. • The role of te ao Māori and degree of focus on intergenerational health of te taiao is appropriate.
Range of perspectives	• The range of perspectives and information sources incorporated into models is appropriate.
Scientific and technical rigour	• The principles of sound science have been addressed during model development, and the assumptions and choices made by the modellers are underpinned by defensible and scientific or technical rationale. • The quality and comprehensiveness of data are appropriate, and appropriate choices have been made regarding which data are fed into the model. • The quality assurance and evaluation processes (including planning, implementation, documentation, assessment and reporting) are appropriate to ensure the model and its components are suitable for its intended use and meet required/reasonable performance standards.
Trust and confidence	• Degree of access to objectives, assumptions, sources of data and methods of data collection, mathematical frameworks employed, accuracy thresholds used and quality-assurance processes followed are appropriate. • The extent to which limitations and uncertainties, including any evidence gaps, complexities and areas of contention, have been identified. • An appropriate process is used to ensure individuals and groups outside the project team (such as decision makers and mana whenua; kaitiaki; policy, regulatory and operational staff in public authorities; and parties likely affected by decisions made on the basis of model outputs) are able to feed into evaluation processes, influence the design of the model, and comprehend its outputs and their implications. • Model predictions and supporting analyses, model evaluation or peer-review reports, and model implications are easy to understand.
Specific elements	**Prompts**
Computational infrastructure	• The mathematical algorithms and approaches used in executing the model computations are appropriate.
Assumptions and limitations	• Important assumptions used in developing or applying a computational model, as well as the resulting limitations that will affect the model's applicability, have been explained and documented sufficiently.

Data availability and quality	• The availability and quality of monitoring and other data is sufficient for both developing model input parameters and assessing model results.
Test cases	• Basic model runs have been undertaken where an analytical solution is available, or an empirical solution is known with a high degree of confidence, to ensure that algorithms and computational processes are implemented correctly.
Validation and corroboration	• Model results have been compared with data collected or observed in the field, to assess the model's accuracy and improve its performance. • Model results have been compared with the results of other similar models where appropriate. • The level of certainty associated with model predictions has been assessed under the full range of conditions the model operates within, at a range of spatial and temporal scales. • The extent to which the model approximates the real system of interest, or how accurately it represents observed relationships between key model parameters has been assessed.
Sensitivity and uncertainty analysis	• The parameters or processes that drive model results, as well as the effects of lack of knowledge and other potential sources of error in the model, have been investigated sufficiently. • The implications of the results of sensitivity and uncertainty analyses for the proposed scope of model application have been identified and explained adequately.
Model resolution capabilities	• The level of disaggregation of processes and results in the model match the resolution needs from the problem statement or model application – the resolution includes the level of spatial, temporal or other types of disaggregation.