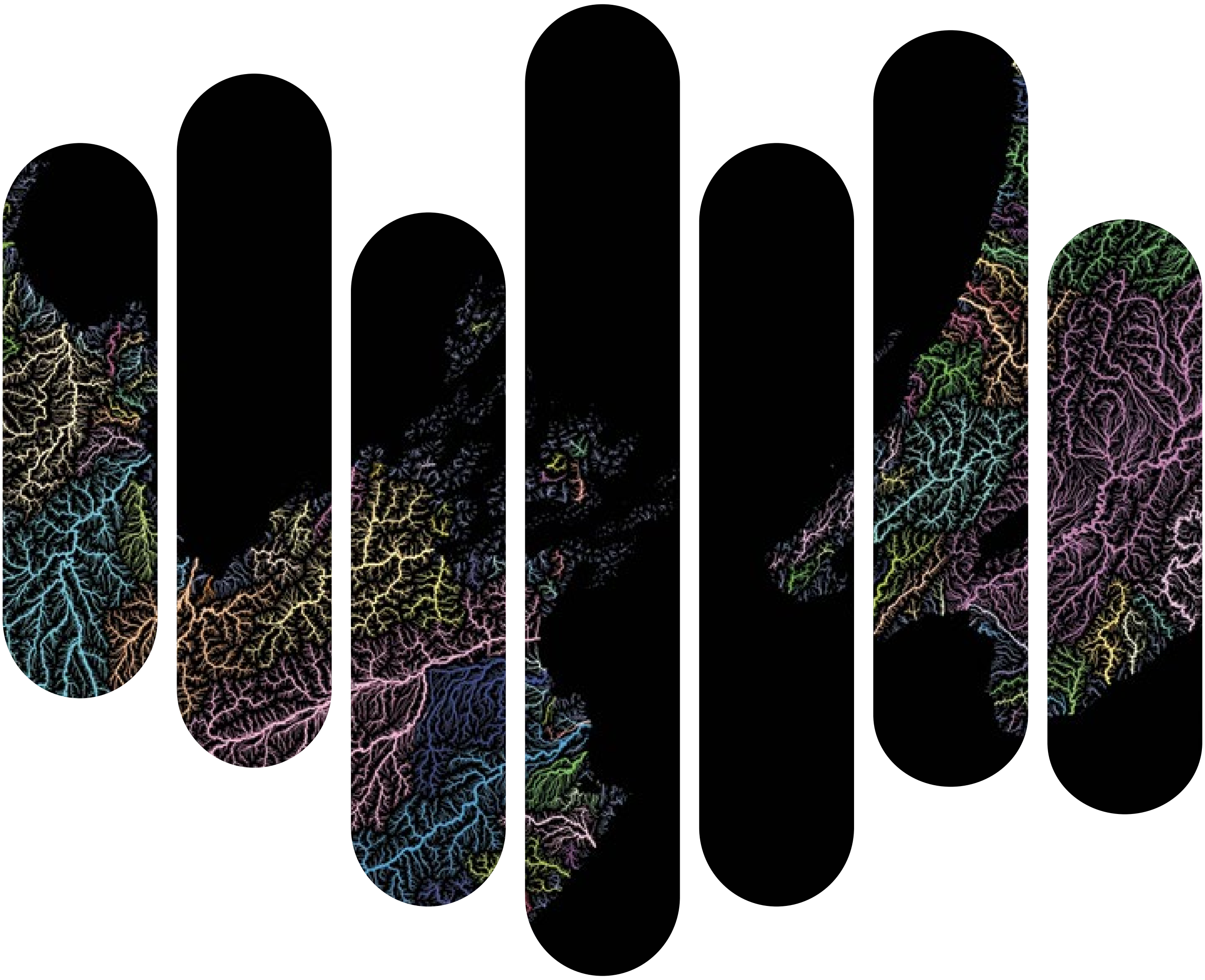
A review of freshwater models used to support the regulation and management of water in New Zealand

June 2024



Parliamentary Commissioner for the Environment
Te Kaitiaki Taiao a Te Whare Pāremata

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June 2024

ISBN
978-0-947517-46-5 (print)
978-0-947517-47-2 (electronic)

Photography
Cover image: Catchments in the top of the South Island and bottom of the North Island. Source data: MfE Data Service (data.mfe.govt.nz) and LINZ Data Service (data.linz.govt.nz). Analysis and visualisation: Toitū Te Whenua Land Information New Zealand.

Chapter header images: *Deparia petersenii* ssp. *congrua*, Ian Armitage, iNaturalist NZ; *Cyathea colensoi*, Pat Enright, iNaturalist NZ; *Abrodictyum elongatum*, Joe Dillon, iNaturalist NZ; *Hymenophyllum dilatatum*, jesse_bythell, iNaturalist NZ; *Tmesipteris sigmatifolia*, Hannah Rogers, iNaturalist NZ; *Asplenium polyodon*, David Hutchinson, iNaturalist; *Polystichum oculatum*, joooom, iNaturalist NZ; *Gleichenia alpina*, naturewatchwidow, iNaturalist NZ; *Pellaea calidirupium*, Chris Ecroyd, iNaturalist NZ; *Hymenophyllum minimum*, chrismorse, iNaturalist NZ.

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Acknowledgements

The Parliamentary Commissioner for the Environment, Simon Upton, is indebted to a number of people who assisted him in conducting this review. Special thanks are due to Dr Anna Hooper and Dr Rogier Westerhoff, who co-led the project, supported by Leana Barriball, Dr Maria Charry, Dr Geoffroy Lamarche, Charlotte Lee-Smith, Megan Martin, Matt Paterson and Rebecca Thornley.

The Commissioner would like to acknowledge the following organisations for their time and assistance during the preparation of this report:

- Alluvium Consulting
- Aqualinc Research Limited
- Traverse Environmental
- Auckland Council
- Bay of Plenty Regional Council
- Cawthron Institute
- Collaborations
- Dairy NZ
- Deltares
- Environment Canterbury
- Environment Southland
- E Oho! Awakening Aotearoa
- Gisborne District Council
- GNS Science (Institute of Geological and Nuclear Sciences Limited)
- Greater Wellington Regional Council
- Hawke's Bay Regional Council
- Horizons Regional Council
- Intera
- Land River Sea Consulting
- Land Water People
- Land & Water Science
- Marlborough District Council
- Manaaki Whenua – Landcare Research
- Ministry for the Environment – Manatū mō te Taiao
- Ministry of Business, Innovation and Employment – Hīkina Whakatutuki
- Ministry for Primary Industries – Manatū Ahu Matua
- National Institute of Water and Atmospheric Research
- Nelson City Council
- Northland Regional Council
- Otago Regional Council
- Our Land and Water National Science Challenge
- Poipoia
- Puhoi Stour
- RMA Science
- Taranaki Regional Council
- Tasman District Council
- Te Uru Kahika
- Victoria University of Wellington
- Waikato Regional Council
- West Coast Regional Council.

The Commissioner wishes to thank the following individuals for reviewing earlier drafts of the report:.

- Andrew Fenemor
- Stephen Lamb
- Tina Porou
- Ton Snelder
- Tony Weber.

While he has benefited hugely from their insights, any errors, omissions or opinions are entirely his own.

Simon Upton

Parliamentary Commissioner for the Environment
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Deparia petersenii ssp. congrua

Executive summary

Freshwater is essential to human wellbeing, our economy and environment. Modelling is an important tool to support robust, evidence-based freshwater management. Models provide insights about things that may be hard or impossible to measure – they fill gaps in monitoring data, identify trends, and provide predictions. Models can also provide robust information that can be used in setting specific regulatory requirements.

A range of water quality and quantity models is currently used in New Zealand to support regulatory tasks such as managing contaminant discharges and water takes. Most models are used by regional councils and unitary authorities. Others have been – and are being – developed by mana whenua, or by industry and community groups to inform their roles in water management.

Those who use models, or are affected by their use, need to know how much confidence can be placed in their outputs. Regulators must be able to defend their decisions to communities and ultimately in the courts, so they need to be sure that models used to reach those decisions are robust and reliable.

This report reviews the suitability, strengths and limitations of water resource models that predict freshwater quantity and quality, and the way they are being used to support the regulation and management of water in New Zealand. The investigation involved an extensive literature review, wide-ranging stakeholder engagement, a survey of regional councils and unitary authorities on their use of freshwater models, and the commissioning of a report on freshwater models developed by, or in close collaboration with, mana whenua.

While this report is being released at a time when the Government has signalled changes to the current policy framework for managing water in New Zealand, the analysis of the models remains relevant, as robust models and data will be needed to manage freshwater in almost any policy framework.

Key findings

- A large number of water models exist. At least 75 biophysical freshwater models are used by regional councils and unitary authorities in a regulatory context. A further 33 freshwater models developed by, or in close collaboration with, mana whenua were found.
- Many of these models have overlapping functions, meaning they are used in the same environmental domain, sometimes for the same purpose. For example, 13 different models are used by various councils to assess sediment in rivers and streams, and 19 river water quality models are used to estimate nutrient loads in river and streams. As different models use different assumptions, principles and data sources, when multiple models are used for the same purpose within the same domain, they can produce divergent results. Divergent results can lead to very different management decisions.
- Model development is siloed and fragmented, hindering collaboration efforts. Development often takes place in isolation inside different institutions, and there is often a strong reluctance to share model codes. Collaboration has suffered at the hands of a competitive desire to 'own' the model code and underlying data. The result has been the development of competitive models. That approach does not lead to well-supported, collaborative modelling work or more transparent models.
- Many models are opaque, and the data underpinning models are frequently non-transparent or inaccessible. This makes it difficult to link models or evaluate and verify them and their outputs.
- Models are not systematically evaluated even though criteria for evaluation exist. This makes it hard to judge which models are best for particular circumstances or if models are fit for their intended purpose. As part of this report, a technical evaluation of the 24 most widely used models (in use by three or more councils) was undertaken. The evaluation found that most models have a good scientific basis (model structure, algorithms, peer review and validation). However, it also found many shortcomings with respect to transparency, uncertainty and computational infrastructure. Combined, each of the weaknesses stands in the way of the comparability and interoperability of models, including the potential to reuse them.
- Guidance on model use – including judging if a model is fit for purpose – falls short of what is useful. Practical implementation support is also lacking. Council staff are looking for help to support on-the-ground freshwater management. Lack of guidance, experimentation in model use, and poor collaboration, sharing and reuse of models have led to the creation of many 'single-use' models – models that are built for a specific purpose for a specific council and only used once.

- The use of models to support the regulation and management of water in New Zealand varies across the regional councils. The choice of models – and whether to use them at all – is determined by a range of factors, including resourcing and expertise, confidence in using models, previous experience and the specific task or regulatory requirement at hand. Further examination found that while some councils are using multiple models with some overlapping functions to address the same regulatory requirements, others are using only one custom-built model. While most councils often use models in a regulatory context, a small number of councils have reported limited use of models.
- Resourcing is thin and expertise is in short supply among model developers and model users. An overall shortage of skills means that model development, application or maintenance is often left to one person, which is risky for the future use of that model.
- There is a lack of commitment to and investment in mana whenua developed models and associated processes to involve mana whenua in the development and application of freshwater models. While Māori freshwater models exist, the use of Māori models in the regulatory context is virtually non-existent. While some are in pilot stages, none of the 33 freshwater models identified in this investigation are in use by councils to support the full implementation of the National Policy Statement for Freshwater Management.
- The large number of models, combined with inadequate guidance on their selection and use and a lack of systematic model evaluation, creates an elevated risk of legal challenge to council decisions, which are based on modelling outputs.

Rather than adding value, the proliferation of models confronts regulators with the quandary of having to choose the 'best' model and then defend that choice, which is not an easy task. It is a choice made harder when models lack transparency and are not systematically evaluated, and when there is a lack of guidance. Looked at nationally, New Zealand's modelling resource is dispersed and unevenly spread amongst regional councils, publicly funded research institutions and some businesses.

Recommendations

The shortcomings identified in this review, including weak leadership and lack of coordination and collaboration, are in no small part a consequence of New Zealand's highly devolved approach to environmental regulation, where each council has responsibility for managing freshwater in its region and using models to do that. Councils are looking to central government for help, but the guidance currently available is generalised and not specific to the challenges that are raised by the use of freshwater models. Further, there is a lack of practical implementation support to turn any guidance into practice and ensure a much more robust and confident use of fit-for-purpose models. In short, on a national scale, freshwater modelling is not organised in a way that can best support the regulation and management of freshwater in New Zealand.

Better national-level coordination and support for freshwater modelling is needed if it is to be used effectively and robustly. New Zealand cannot afford to waste scarce modelling resources on forays into multiple, expensive, and often ineffective model developments and applications.

The recommendations outline steps needed to ensure freshwater modelling can be used effectively to support robust, evidence-based water regulation and management. The first four recommendations focus on solutions that could be implemented in the short-term. While they can be progressed immediately, they would benefit from the establishment of a national freshwater modelling support centre, which is the most effective and efficient way of carrying the desired improvements into the future – the fifth recommendation.

Recommendation 1: The Ministry for the Environment (MfE) should further develop national guidance on the use of models in a regulatory context to support freshwater management across the country.

Recommendation 2: MfE should establish a rōpū of experts to support the development and implementation of Māori freshwater models.

Recommendation 3: MfE should ensure an evaluation of existing freshwater models against guidance on the use of models in a regulatory context is undertaken.

Recommendation 4: MfE should lead the selection or development of a preferred suite of models adaptable to local circumstances.

Recommendation 5: The Minister for the Environment should establish a national freshwater modelling support centre with a mandate to support regional councils, unitary authorities and mana whenua. The Secretary for the Environment should prepare a report advising the Minister for the Environment on where and how such a centre could fit into existing institutional arrangements.

Cyathea colensoi

Whakarāpopoto matua

He waiwai te wai māori ki te oranga tangata, tō tātou ohaoha, taiao hoki. He taputapu hira te whakatauira hei tautoko i te whakahaere wai māori pūtake taunakitanga. E whakarato ana ngā tauira i ngā māramatanga e pā ana ki ngā mea he uaua te ine, tē taea rānei – ka whakakī ēnei i ngā āputa i ngā raraunga aroturuki, tautuhi i ngā ia, me te whakarato i ngā matapae. Ka whakarato hoki ngā tauira i ngā mōhiohio pakari e taea ai te whakamahi kia whakarite i ngā herenga whakaritenga tauwhāiti.

He whānui ngā tauira kounga wai me te rahi e whakamahia ana ināianei i Aotearoa hei tautoko i ngā mahi whakarite pērā i te whakahaere i ngā whakaruke tāhawa me ngā rironga wai. E whakamahia ana te nuinga o ngā tauira e ngā kaunihera ā-rohe me ngā mana whakahaere whakatōpū. I whakawhanaketia ētahi atu – ā, e whakawhanaketia tonutia ana – e te mana whenua, e ngā rōpū ahumahi, ā-hapori rānei kia whaimōhio ai ā rātou mahi i roto i te whakahaere wai.

Me mōhio te hunga e whakamahi ana i ngā tauira, e pāngia ana rānei e te whakamahi, te nui o te ngākau titikaha e taea ana ki ā rātou putanga. Me wawao ngā kaiwhakarite i ā rātou whakataunga ki ngā hapori, ki ngā kōti anō hoki, nā reira, me mōhio rātou he pakari, he tika hoki ngā tauira e whakamahia ana kia tae ki aua whakataunga.

Ka arotake tēnei pūrongo i te tika, ngā kaha me ngā ngoikoretanga o ngā tauira rauemi wai e matapae ana i te rahi me te kounga o te wai māori, ā, te āhuatanga e whakamahia ana hei tautoko i te whakaritenga me te whakahaerenga o te wai i Aotearoa. Kei roto i te whakatewhatewha he arotake mātātuhi whānui, he whakapāpā kaiwhaipānga whānui, he uiui i ngā kaunihera ā-rohe me ngā mana whakahaere whakatōpū mō ā rātou whakamahinga tauira wai māori, me te kirimana i te pūrongo mō ngā tauira wai māori i whakawhanaketia e te mana whenua, i te hunga rānei e mahi ngātahi ana me te mana whenua.

Ahakoa e whakaputaina ana tēnei pūrongo i te wā kua tohu te Kāwanatanga i ngā panoni ki te anga kaupapahere onāianei ki te whakahaere wai i Aotearoa, e hāngai tonu ana te tātaritanga o ēnei tauira, nā te mea ka hiahiatia ngā tauira me ngā raraunga pakari ki te whakahaere i te wai māori i roto i te nuinga o ngā anga kaupapahere.

Ngā kitenga matua

- He maha ngā tauira wai onāianei. Kāore e iti iho i ngā tauira wai māori koiora ā-tinana 75 e whakamahia ana e ngā kaunihera ā-rohe me ngā mana whakahaere whakarōpū i roto i te horopaki whakarite. E 33 ngā tauira wai māori anō i whakawhanaketia e te mana whenua, e te hunga e mahi tahi ana me te mana whenua rānei i kitea.
- He maha ēnei tauira me ngā āheinga e inaki ana, nā reira, e whakamahia ana i roto i te whaitua taiao kotahi, i ētahi wā mō te take kotahi. Hei tauira, 13 ngā tauira rerekē e whakamahia ana e ngā kaunihera rerekē ki te aromatawai i te para i roto i ngā awa me ngā awa iti, ā, 19 ngā tauira kounga wai awa e whakamahia ana kia mōhio ki te whakatau tata o ngā kawenga taiora i roto i ngā awa me ngā awa iti. Nā te mea e whakamahi ana ngā tauira rerekē i ngā pūmāramarama, ngā mātāpono me ngā mātāpuna raraunga, nā reira, ina whakamahia ana ngā tauira huhua mō te take kotahi i roto i te whaitua kotahi, ka whakaputaina pea ngā hua rerekē. Ina rerekē ana ngā hua, ka puta pea ngā whakataunga whakahaere tino rerekē.
- He taratahi, he kongakonga te whakawhanake tauira, e ārai ana i ngā mahi ngātahi. I te nuinga o te wā ka taratahi te whakawhanake i roto i ngā whakanōhanga rerekē, ā, he manauhea te tuari i ngā waehere tauira. Kua raru te mahi tahi nā te hiahia whakataetae kia 'puritia' te waehere tauira me ngā raraunga tūāpapa. Ko te hua he whakawhanake i ngā tauira whakataetae. Ehara te putanga o tēnā ahunga i te mahi whakatauira mahi tahi, e kaha tautokohia ana, i ngā tauira pūataata ake rānei.
- He maha ngā tauira e puata-kore ana, ā, i te nuinga o te wā ko ngā raraunga hei tūāpapa mō ngā tauira he puata-kore, he āhei kore rānei. Nā reira, he uaua kia tūhono i ngā tauira, kia aromātai me te hāpono i ēnei tauira me ngā putanga.
- Kāore ngā tauira e aromātaihia pūnahanahatia ana ahakoa tērā ngā paearu hei aromātai. Nā reira, he uaua ake te whakatau ko ēhea ngā tauira tino pai mō ngā āhuatanga motuhake, tērā rānei e tika ana mō te take i whakaritea ai. I mahia te aromātai hangarau o ngā tauira 24 tino mahia whānuitia (e ngā kaunihera e toru, neke atu rānei), hei wāhanga o tēnei pūrongo. I kite te aromātai he tūāpapa pūtaiao pai o te nuinga o ngā tauira (anga tauira, hātepe, arotake aropā me te whakatūturu). Heoi anō, i kitea hoki he maha ngā hapa e pā ana ki te pūataata, te rangirua me te tūāhanga ā-rorohiko. Ki te whakatōpūtia, ka tū tēnā ngoikoretanga me tēnā ngoikoretanga hei ārai i te whakatairite me te mahi tahi o ngā tauira, tae atu ki te torohū kia whakamahia anōtia.
- He ārahi mō te whakamahi tauira – tae atu ki te whakatau mēnā e rite ana ana mō te kaupapa – kāore anō kia whaitake. Kāore i te pai hoki te tautoko whakatinana whai kiko. E rapu ana ngā kaimahi kaunihera i te āwhina kia tautoko i te whakahaere wai māori ki ngā wāhi hāngai. Nā te iti o te ārahi, te whakamātau o te whakamahi tauira, me te mahi tahi, te tuari me te whakamahi anō kino o ngā tauira i puta mai ngā tauira 'mahi kotahi' maha – he tauira e waihangatia ana mō te take motuhake mō te kaunihera motuhake, ā, e whakamahia ana i te wā kotahi.

- He rerekē te whakamahi i ngā tauira kia tautoko i te whakaritenga me te whakahaere o te wai i Aotearoa puta noa i ngā kaunihera ā-rohe. Te kōwhiringa o ngā tauira – ā, mēnā me whakamahi ngā tauira – e whakaritea ana e ngā āhuatanga whānui, tae atu ki ngā rauemi me ngā mātanga, te ngākau titikaha ki te whakamahi tauira, te wheako o mua me te mahi tauwhāiti, te herenga whakature rānei kei mua i te aroaro. He mātaitanga anō i kite ahakoa e whakamahi ana ētahi kaunihera i ngā tauira huhua me ētahi āheinga inaki ki te urupare i ngā herenga whakarite, e whakamahi kē ana ētahi i te tauira i waihangatia motuhaketia. Ahakoa he maha ngā wā e whakamahi ana te nuinga o ngā kaunihera i ngā tauira i roto i te horopaki whakaritenga, he iti ngā kaunihera e pūrongo ana i te whakamahinga tepenga o ngā tauira.
- He iti ngā rauemi, ā, kāore i te nui te mātanga o ngā kaiwhakawhanake tauira me ngā kaiwhakamahi tauira. Nā te iti rawa o ngā pūkenga e waiho ana te whakawhanake, te whakatinana me te whakatika o te tauira ki te tangata kotahi, he mea tūraru mō te whakamahinga o taua tauira ā muri atu.
- He iti rawa te takohanga me te whakangao ki ngā tauira kua whakawhanaketia e te mana whenua me ngā hātepe hāngai kia whai wāhi atu te mana whenua i roto i te whakawhanaketanga me te whakatinanatanga o ngā tauira wai māori. Ahakoa tērā ētahi tauira wai māori Māori, kāore e tino kitea ana te whakamahi i ngā tauira Māori i roto i te horopaki whakaritenga. Ahakoa kei roto ētahi i ngā wāhanga whakamātau, kāore ētahi o ngā tauira wai māori e 33 e whakamahia ana e ngā kaunihera ki te tautoko i te tino whakatinanatanga o te Tauākī Kaupapa Here Ā-Motu mō te Whakahaere Wai Māori.
- Nā runga anō i te tino maha o ngā tauira, me te ārahi kāore i te rawaka me pēhea e kōwhiri me te whakamahi, ā, me te iti rawa o te aromātai tauira pūnahanaha, ka waihangatia te tūraru nui ake o te wero ā-ture ki ngā whakataunga kaunihera, ka puta mai i ngā putanga whakatauira.

Ka whakararu te huhua o ngā tauira i ngā kaiwhakarite kia kōwhiri i te tauira 'tino pai' me te wawao i taua kōwhiringa, ehara i te mahi ngāwari. Kāore tēnei e hiki ana i te uara. He uaua ake te kōwhiringa mēnā he iti rawa te pūataata, ā, kāore i te aromātaihia pūnahanahatia, ā, mēnā he iti rawa te ārahi. Ina tirohia ā-motu, ko te rauemi whakatauira o Aotearoa e noho marara ana me te horahanga pāhikahika i roto i ngā kaunihera ā-rohe, ngā whakanōhanga rangahau whai pūtea tūmatanui me ētahi pakihi.

Ngā tūtohu

He tukunga iho ngā hē i tautuhia i roto i tēnei arotake, tae atu ki te hautūtanga ngoikore me te kore o te reretahi me te mahi tahi, i te ahunga tino whakawhiti o Aotearoa ki te whakaritenga taiao. Kei tēnā kaunihera, kei tēnā kaunihera te kawenga kia whakahaere i te wai māori i roto i tana rohe me te whakamahi i ngā tauira kia mahi pērā. E hiahia ana ngā kaunihera kia āwhinatia rātou e te kāwanatanga matua, engari he whānui rawa te ārahi onāianei, ā, kāore i te tauwhāiti ki ngā wero e hīkina ana e te whakamahi i ngā tauira wai māori. Waihoki, he iti rawa te tautoko whakatinanatanga ā-ringa hei huri i te ārahi ki te mahinga me te whakatūturu he whakamahi pakari, ngākau titikaha hoki o ngā tauira rite mō te kaupapa. Hei whakapoto ake, mō te rahinga ā-motu, kāore te whakatauira wai māori i te whakaritea kia tino tautoko i te whakaritenga me te whakahaerenga o ngā wai māori i Aotearoa.

E hiahiatia ana te reretahi me te tautoko taumata ā-motu pai ake mō te whakatauira wai māori e whakamahia ai kia whakaaweawe, kia pakari hoki. Kāore e taea e Aotearoa te moumou i ngā rauemi whakatauira pūhore ki ngā haerenga ki ngā whakawhanaketanga tauira, taupānga huhua, nui te utu, me te korekiko hoki i ētahi wā.

E whakahuatia ana e ngā tūtohu ngā whetoko e hiahiatia ana kia whakatūturu e whakamahia whakaaweawetia ana te whakatauira wai māori ki te tautoko i te whakaritenga me te whakahaerenga wai kia pakari i runga i te tūāpapa taunakitanga. E arotahi ana ngā tūtohu tuatahi e whā ki ngā whakatikahanga ka taea te whakatinana i te wā poto. Ahakoa ka taea te ahu whakamua ināianei, ka whai painga i te whakatūranga o te pokapū tautoko whakatauira wai māori ā-motu, te ara tino whaitake, whāomo hoki kia kawe i ngā whakapai ake ki anamata – te tūtohu tuarima.

Tūtohu 1: Me whakawhanake anō te Manatū Taiao (MfE) i te ārahi ā-motu anō e pā ana ki te whakamahi o ngā tauira i roto i te horopaki whakaritenga kia tautoko i te whakahaerenga wai māori puta noa i te motu.

Tūtohu 2: Me whakatū MfE i te rōpū mātanga hei tautoko i te whakawhanaketanga me te whakatinanatanga o ngā tauira wai māori Māori.

Tūtohu 3: Me whakatūturu MfE e whakamahia ai te aromātai o ngā tauira wai māori onāianei ki te ārahi mō te whakamahi o ngā tauira i roto i te horopaki whakaritenga.

Tūtohu 4: Me ārahi a MfE i te kōwhiringa, te whakawhanaketanga rānei o te rōpū i tino hiahiatia o ngā tauira e āhei ana te urutau ki ngā āhuatanga haukāinga.

Tūtohu 5: Me whakatū te Minita mō te Taiao i te pokapū tautoko whakatauira wai māori ā-motu me te mana kia tautoko i ngā kaunihera ā-rohe, ngā mana whakahaere whakatōpū me te mana whenua. Me whakarite te Hēkeretari mō te Taiao i tētahi pūrongo e tohutohu ana i te Minita mō te Taiao ki hea, āhea hoki tētahi pokapū pērā e uru ai ki ngā whakaritenga whakanōhanga onāianei.

1

Abrodictyum elongatum

Background and context

Why this report?

While Aotearoa New Zealand has plenty of freshwater, we are heavy users of it. Intensification from urbanisation and agricultural land use, particularly dairy farming and horticulture, has in recent years contributed to water bodies becoming polluted in many catchments. We are degrading the mauri of freshwater and its life-supporting capacity.

Many regions have over-allocated freshwater or are close to doing so. Less water means more pressure on freshwater species, and higher concentrations of contaminants in our waterways. Changing the flow and quality of water through water take, fertiliser application, drainage, land use, diversions and water storage has consequences for the health of the ecosystems that water supports. Finally, climate change is re-dealing all the cards. It will have complex feedback effects on all these existing pressures and will drive further land-use change.[1]

There is currently a requirement in national policy to better manage New Zealand's freshwater and to work to achieve Te Mana o te Wai, a concept that acknowledges the rights of water to be protected from harm, while recognising the health and wellbeing that healthy freshwater provides. It protects the mauri of the wai by placing the health and wellbeing of water first, the health needs of people (such as drinking water) second, and the ability of people and communities to provide for their social, economic and cultural wellbeing third.[2] The application of this concept is currently under review by the Government.

Responsible management of our freshwater requires clear outcomes, sound processes, robust information and the use of a range of tools. Models have an important role to play.

Given that a range of models is currently used to help manage contaminant discharges and water takes across the country, this investigation reviews water resource models and how they are used in water management across New Zealand. When making management decisions based on modelling, the modellers and those dependent on model outputs must have confidence in this information. Not only must these decisions be defensible to both communities and the courts, but also the Resource Management Act 1991 requires councils and central government to evaluate the costs and benefits of their proposed remedies. Decision makers need to be sure that models used in reaching those decisions can convincingly support proposed measures.

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1 More information can be found in reports produced under the Environmental Reporting Act 2015, including MfE and StatsNZ (2020, 2022, 2023). Note that PCE is currently working on a report that examines how an integrated approach to land use management can achieve multiple outcomes at the landscape-scale. This report will be published in the first half of 2024.

2 Poipoia, 2022a.

It is important to emphasise that this review is about the suitability of models in a regulatory context. The scope of this review covers models that predict freshwater quantity and quality and have been or are being used to support freshwater management and regulation.

Specifically, the scope of this review:

- focuses on water resource management models that estimate the effects of resource use (e.g. land, water, nutrients) on freshwater
- includes water resource models dealing with both water quantity and quality in all water bodies that have been used to support a range of regulatory freshwater management requirements[3]
- excludes hazard management models (e.g. flood management models) and farm economics models
- excludes models that are used in the design of infrastructure for the provision of water services (e.g. drinking water pipes, stormwater channels, wastewater pipes).

The analysis of biophysical models in this report focuses essentially on the ‘model software’ – that is, the technical components and computational infrastructure that models need in order to produce robust results. It also addresses good modelling practice.

This report builds on my 2018 review of the farm-scale model Overseer, in which I recommended a review of the many models and databases that inform our understanding of catchment-scale dynamics.[4] This review stressed the need to examine what is happening beyond the farm gate in the wider catchment. As although nutrient pollution may originate in a paddock, its environmental consequences will be felt beyond the farm boundary in distant receiving water bodies.

I release my findings at a time when the Government has signalled changes to the current policy framework, including the National Policy Statement for Freshwater Management (NPS-FM) 2020.[5] Regardless of the policy framework, robust models and data are needed to manage freshwater. So, this analysis of the models, including their strengths and limitations, remains relevant.

Finally, while this report focuses on models, it recognises that models are just one tool in the much broader toolbox of decision-making processes. Models can assist in exploring options and associated consequences, but they cannot make decisions for the decision makers.

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3 These include biophysical models as well as models developed by or in close collaboration with whānau, hapū and iwi. Given the holistic nature of te ao Māori models, they may stretch beyond freshwater management to cover broader system models and other types of ecosystems, which are largely excluded from this report.

4 PCE, 2018, p.124.

5 McClay et al., 2023.

Evidence base for this report

The findings presented in this report have been informed by an extensive literature review, wide-ranging stakeholder engagement and a commissioned report on freshwater models developed by, or in close collaboration with, mana whenua.

The literature review included a model stocktake and technical assessments of the most commonly used biophysical models. These are available as appendices to this report.

We engaged with model developers and model users as follows.

- Meetings were held with model experts, including the developers of key models widely used in a regulatory context to assist with the management of freshwater. Additionally, a workshop was held in Christchurch with a group of modellers, where several current shortcomings and possible solutions were identified.
- Meetings were held with the 16 regional councils and unitary authorities, followed by requests to provide information on past and current model use in a regulatory freshwater management context. This information formed a critical part of the model stocktake.
- Two in-depth workshops with Environment Canterbury and Waikato Regional Council provided additional insights on the challenges of models used to support decisions in a regulatory context.
- Online surveys with members of two regional sector special interest groups (Groundwater Forum and Surface Water Integrated Management) provided information on model and data accessibility, and availability of freshwater modelling skills at councils.

A report, *Te Mana o te Wai, Te Oranga o ngā Tāngata*, was commissioned to review current models developed by, or in close collaboration with, mana whenua and Māori entities to manage freshwater. The report identifies models that could support the implementation of the NPS-FM 2020, including the fundamental concept of Te Mana o te Wai. It comprises an analysis of the use of models developed by Māori groups, including for regulatory purposes. The report includes a stocktake of Māori freshwater models, and three case studies that provide details on the development, engagement and use of Māori models. *Te Mana o te Wai, Te Oranga o ngā Tāngata* is a separate piece of analysis that focuses on the views of tangata whenua about the development and use of freshwater models.[6]

The remainder of this chapter explains some of the concepts and language that this review encompasses. Experts familiar with the use of water models in catchment settings can move directly to the following chapter. The matters briefly elaborated in this chapter are as follows:

- the fundamentals of freshwater
- different definitions of models
- why we need models
- model fitness for purpose and good practice
- technical terms used in this investigation.

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6 The report, referred throughout as Taylor (2023), was prepared by Lara Taylor (E Oho! Awakening Aotearoa) and is available on the PCE website. See https://pce.parliament.nz/publications/a-review-of-freshwater-models-used-to-support-the-regulation-and-management-of-water.

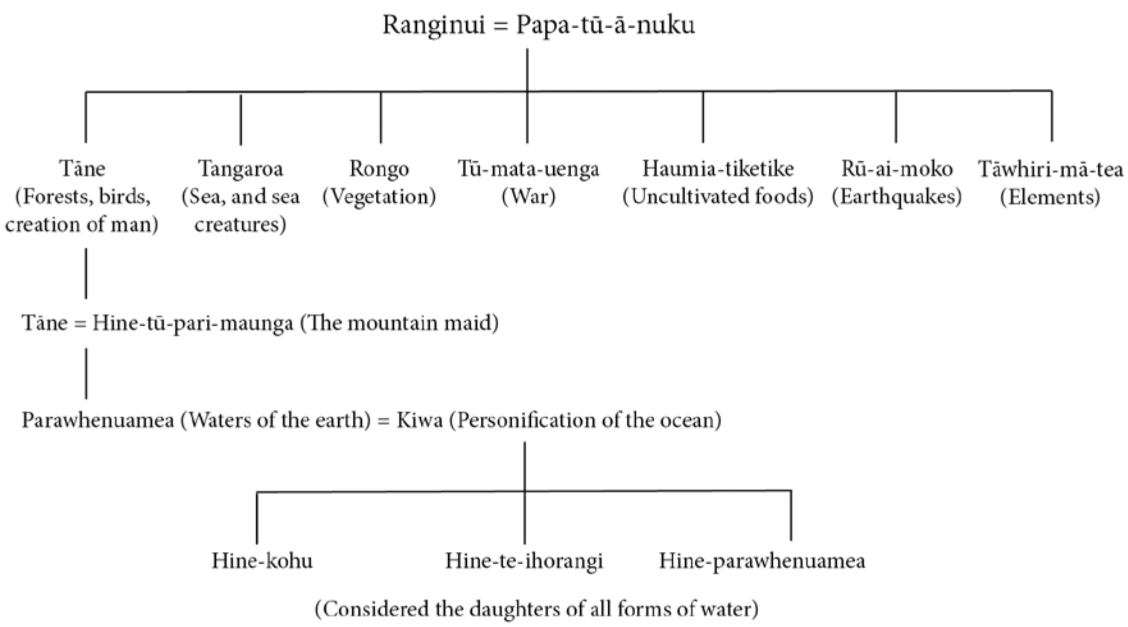
The fundamentals of freshwater

"E kore tātau e mōhio ki te waitohu nui o te wai kia mimiti rawa te puna. We never know the worth of water until the well runs dry."

– Te Wharehuia Milroy (Ngāi Tūhoe)

Whakapapa of water

Whānau, hapū and iwi understand water and the water cycle through the lens of whakapapa. Water is an integral part of survival so there are many atua (guardians, deities, ancestors) associated with it, making up a very large component of whakapapa (Figure 1.1). Water is essentially protected by Tangaroa, although other atua also provide protection. Like all things in the environment, Māori have a familial relationship with water, where the environment is as a tuakana, an older sibling that should be cared for and respected, and who in return provides resources.[7]



Source: Phillips, 2020, p.3

Figure 1.1: Whakapapa of water, with atua responsible for certain types of water (not all water types are represented here).

As whakapapa sets the frame for how water moves through space, locally specific pūrākau (stories) hold what is known about how the water behaves in certain seasons or areas. For example, a waiata from Ngāti Pāhauwera tells where the awa comes from, its flow path, its behaviour twisting and turning, its entrance into the marae, and its exit out to a taniwha in the sea, the guardian of Ngāti Pāhauwera – Paikea.[8]

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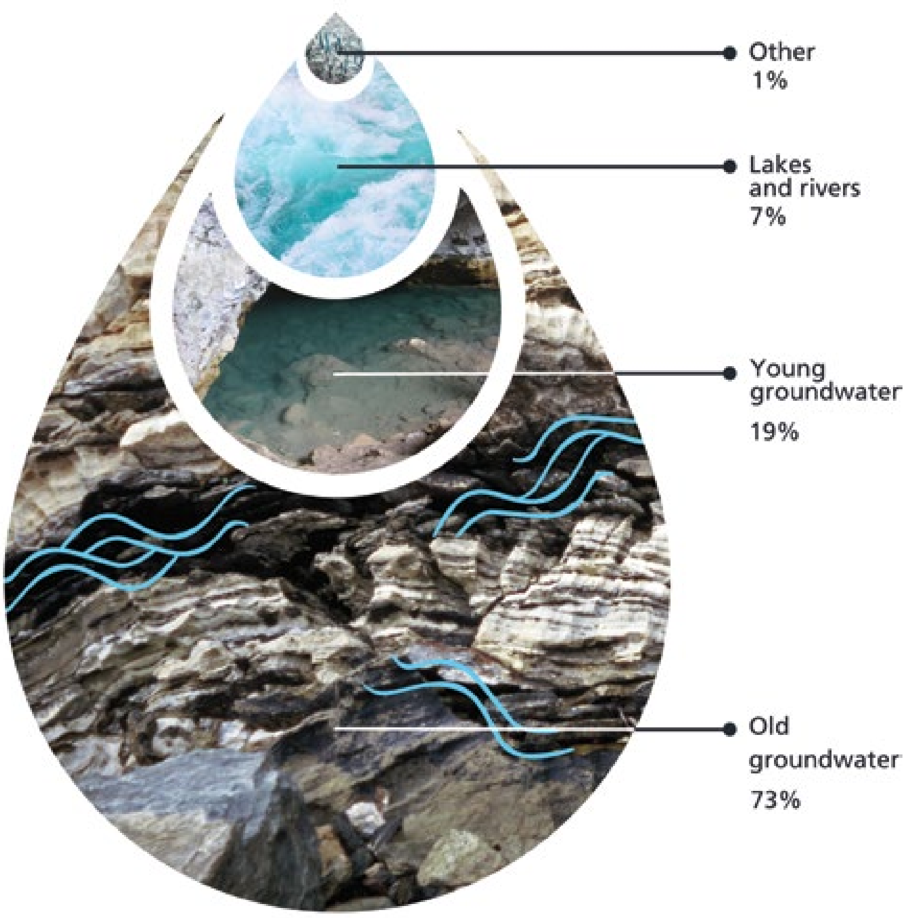
7 Taylor et al., 2020; Reid, 2021.

8 Taylor, 2023, p.68.

The water cycle: Its stocks and flows

Freshwater is part of the water cycle, which describes where water is on Earth and how it moves. Only by taking account of all the factors that impinge on the water cycle – including human consumption of water, land use and climate change – can decision making about water resource management hope to work towards sustainable water use.[9]

Across the globe, terrestrial freshwater – water on or above the land surface – has been estimated as making up less than 2% of all the water on Earth.[10] The vast majority of that terrestrial freshwater is old – deep groundwater that does not interact much with the surface (Figure 1.2).



Source: PCE; photos by Flying Kiwi Tours, Flickr; Coen Versluis, Flickr; Larry Koester, Flickr; GNS Science

Figure 1.2: Estimated components of terrestrial freshwater for New Zealand. The blue squiggly lines show old groundwater 'hiding' in the cracks between the rocks. Total estimated volumes: old groundwater: 4,500 cubic kilometres; young groundwater: 1,200 cubic kilometres; lakes and rivers: 418 cubic kilometres; other (snow, ice, biomass water content and interception, soil moisture): 73 cubic kilometres. More details in Table 1.1.

[9] For more information, see USGS (2022).

[10] Seawater accounts for 96%, and icesheets another 2% (Dorigo et al., 2021, p.1899).

This investigation largely covers young terrestrial freshwater: surface water that is hours to days old before it washes out to sea, and relatively shallow young groundwater that is days to tens of years old. Young groundwater interacts with the land surface through processes that see it discharge into lakes, streams and springs (Table 1.1).

Globally and in New Zealand, young groundwater represents approximately three-quarters of young terrestrial freshwater.[11] Because groundwater moves much slower than surface water, it provides a buffering capacity: groundwater systems absorb water in wet times, filter out contaminants and provide consistent flow to our rivers, even in dry times when rivers are described as being at baseflow. Estimates vary, but more than half of all New Zealand surface water flows are provided by young groundwater as baseflow. This is a national average – flows vary spatially across the country.[12] We still do not fully understand the risk to groundwater from unsustainable use, but it is very likely to affect future generations. Making this relatively invisible resource more visible has been a challenge for decades (Figure 1.3).[13]

Table 1.1: Estimates for terrestrial freshwater stocks and flows for New Zealand.

Stocks	km^3	Flows	km^3/yr
Ephemeral and permanent snow and ice	58[a]	Precipitation	500[c,e]
Vegetation, biology	2[a]	Evapotranspiration	150[d,e]
Soil moisture	13[a]	Flow	350[b,c,d,e]
Lakes and rivers	418[a]	Note: over half of flow consists of young groundwater as baseflow; the other part is runoff [b,c,d,f]	
Young groundwater	1,200[a,b]		
Old groundwater	4,500[b]		

Sources: (a) Toebes, 1972, p.137; (b) Westerhoff et al., 2019; (c) Tait et al., 2006; (d) Zhang et al., 2019; (e) Stats NZ, 2022; (f) Singh et al., 2019, p.646. These estimates are expected to be uncertain by up to 25%.

[11] Young groundwater (estimated as approximately 1,200 km^3) is the groundwater that interacts with surface processes, e.g. as baseflow. It covers a larger volume than readily extractable groundwater in New Zealand's known aquifers, estimated at approximately 700 km^3 (Moreau and Bekele, 2017). See also Toebes (1972, p.137), Gleeson et al. (2016, p.1) and Westerhoff et al. (2019, p.176).

[12] Toebes, 1972, p.129; Singh et al., 2019, Fig. 10; Westerhoff et al., 2019, p.176.

[13] Rosen and White, 2001, p.1. In addition, the theme of United Nations World Water Day in 2022 was 'Groundwater: Making the invisible visible'.

Freshwater carries a range of materials and life forms. These include:

- sediments
- minerals (e.g. sand, silt, salts, heavy metals)
- organic matter and contaminants (e.g. nitrogen, phosphorus, *Escherichia coli* (*E. coli*))
- vascular plants and algae
- living organisms (e.g. insects, small invertebrates, stygofauna)
- synthetic compounds (e.g. detergents).[14]

The most comprehensive New Zealand study to date has estimated the total load of four constituents commonly found in freshwater (nitrogen, phosphorus, *E. coli* and sediment) for New Zealand as a whole and by region (Table 1.2).[15] In addition, it calculated how much those loads were in excess of a national bottom line for each of the contaminants.[16] However, we do not have nationally consistent stock and flow estimates of contaminants, nor of other materials in the water. That is largely because there are still evident research gaps on what ratio of each contaminant moves where (e.g. land, soil, groundwater, river, lake, estuary), how these contaminants behave (e.g. denitrification of nitrates in soil), and how they are influenced by human activity.[17]

Table 1.2: Load estimates of four contaminants, and load reduction required to achieve a national bottom line for New Zealand.[18] Values in brackets indicate the range, defined by 90% confidence intervals.[19]

Constituents	Total load	Load reduction required
Total nitrogen (kilotonne per year)	172 (157–190)	19% (15–22%)
Total phosphorus (kilotonne per year)	24 (20–28)	6% (4–12%)
E. coli (petatonne per year)[a]	3,034 (2,407–3,765)	73% (60–84%)
Sediment (megatonne per year)	223 (170–324)	33% (21–44%)

[a] Peta denotes a factor of 10^{15} (one thousand million million).

[14] Stygofauna are any fauna that live in groundwater systems or aquifers such as cavities and fissures.

[15] Snelder, Smith et al., 2023.

[16] Based on national bottom-line criteria in Appendix 2A of the NPS-FM 2020. For a summary of the legislative framework, see Appendix 4.

[17] McDowell et al., 2013, pp.393–394; Snelder et al., 2018, pp.356–357; Larned et al., 2022, p.142.

[18] Based on national bottom-line criteria in Appendix 2A of the NPS-FM 2020. For a summary of the legislative framework, see Appendix 4.

[19] Snelder, Smith et al., 2023.

Source: Lloyd Homer, GNS Science

Figure 1.3: Groundwater is often invisible, unless it flows out of an artesian well, as in this photo.

Different definitions of models exist

While models are used widely, there are varying definitions of what a model is and what it may represent. Models can be described as:

- representations of processes[20]
- a simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system[21]
- an example for imitation or emulation[22]
- a simple description of a system, used for explaining how something works or calculating what might happen.[23]

[20] Beauséjour and Mac-Thiong, 2020.
[21] US EPA, 2009, p. vii.
[22] Merriam-Webster, no date.
[23] Oxford Learner's Dictionaries, no date.

Models answer everyday questions such as what time will my Uber arrive, when should I go fishing, will it rain tomorrow, or how high will inflation be next year. Life would be a lot less predictable without such models.

Models are a deduced relationship between observations. In other words, models and observations are inextricably linked: "Data without models are chaos, but models without data are fantasy."[24] Observations enable us to understand a process and formulate a relationship between observations. Models can interpolate between observations, or extrapolate from the last known observation, to make predictions.

Models come in many shapes and forms – conceptual, numerical, empirical, mechanistic, deterministic, stochastic, steady state and dynamic.[25] With this variety comes a wide range of complexity. While using a simple model is sometimes sufficient, models such as those used for the simulation of a biological or hydrological system (with mathematical formalisations of the physical and chemical properties of that system) are often complex. Many environmental models, including freshwater ones, come with a fair degree of complexity and might be described as belonging to a family of numerical environmental biophysical models.

Weather forecasts are a classic, widely understood application of models that range from the very simple to the very complex. They are used by everyone, everywhere, every day and have been researched for millennia. Weather lore such as "red sky at night, shepherd's delight; red sky in the morning, shepherd's warning" can be traced back to the Bible.

Māori also have weather lore embedded in mātauranga and their own models. Ngāi Tahu remember approximately 50 known kā tohu huarere (weather indicators).[26] For example, tahupokai means that a red sky all around the horizon at dusk indicates fine weather is expected for Ōtautahi (Christchurch). 'Kā hihi kanapa o te rā' means that when sunrise above Hikuika (Mount Sinclair) is preceded by red streaks, rain is imminent.[27] These are simple yet accepted models: The weather is deduced from empirical research based on repetitive, carefully recorded and correlated observations. Weather is deduced from observations of sky colour, the time of day and the location.

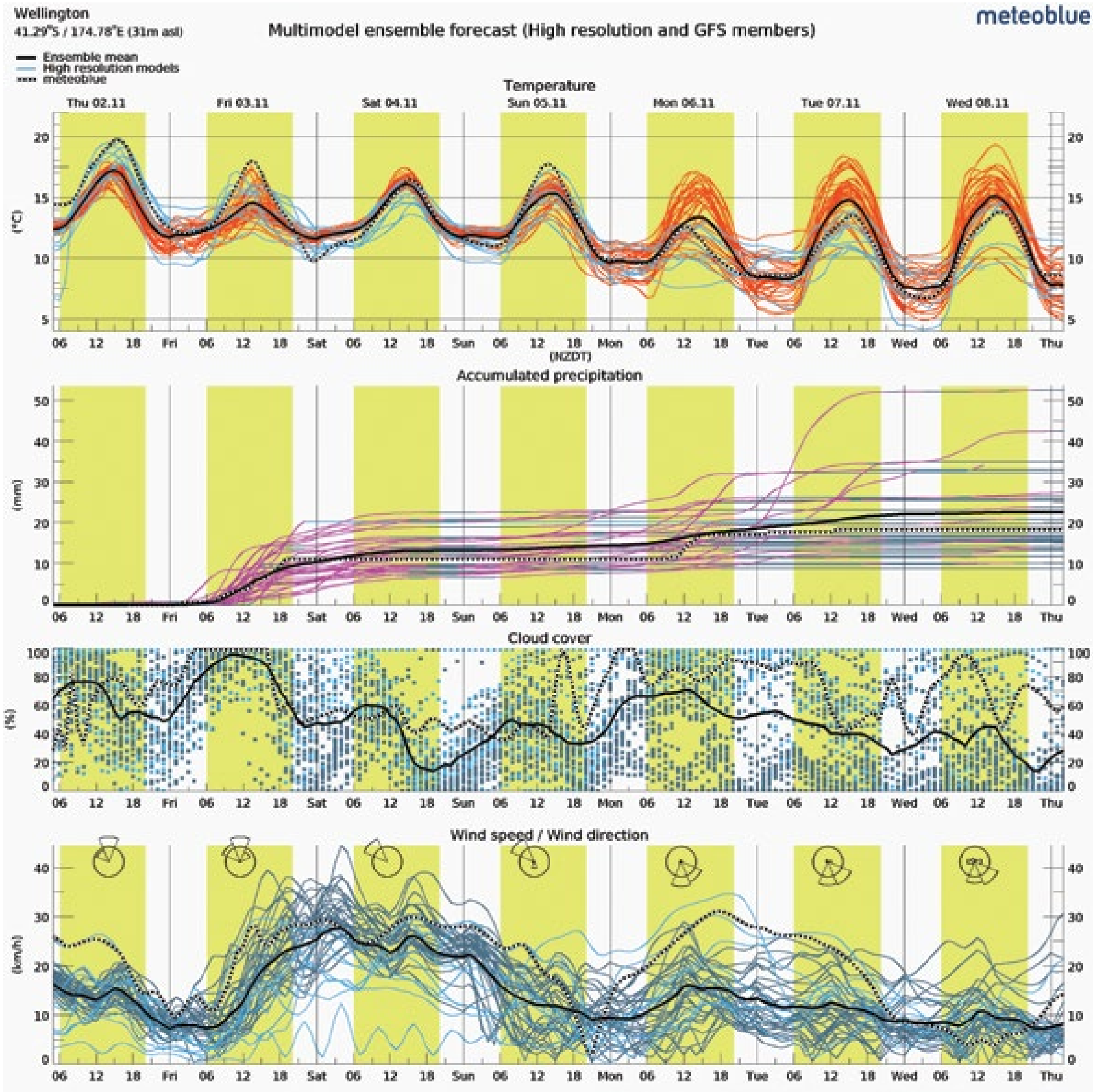
Technically advanced weather models are at the other extreme of the complexity spectrum. Numerical weather model predictions are built from a combination of empirical relations and mathematical equations that describe complex physical processes and account for numerous input components (e.g. air pressure, ocean current, wind speed, wind direction, atmospheric and soil moisture, time scale) on a variety of scales, from minutes to months and from local to global (Figure 1.4).

[24] Patrick Crill, Stockholm University, according to Nisbet et al., 2014, p.394.

[25] A detailed account of these different model types can be found in PCE (2018) and further in this chapter.

[26] Skipper, 2020, pp.313–323.

[27] Skipper, 2020, pp.314–315.



Source: Meteoblue, 2023

Figure 1.4: Advanced multi-model ensemble forecast of temperature, precipitation, cloud cover and windspeed for Wellington, November 2023.

Why do we need models?

Many people may see models as inferior to observations and measurements. But modelling and monitoring (i.e. field data and measurements) are interdependent.

Models provide information about things that may be hard or impossible to measure. They can fill gaps in monitoring data, identify trends, gain insights into processes going on within the catchment system and provide critical predictions. At the same time, it is essential to have monitoring data to build, calibrate and use environmental models.

In the freshwater resource management context, models can help fill important gaps in knowledge, such as:

- assessing trends
- estimating current water body health
- estimating required contaminant reductions
- establishing cause–effect relations between resource use and the health of water bodies
- estimating the effect of freshwater improvement actions
- estimating the effect of climate change on water quantity and quality
- exploring scenarios and future outlooks.

By interpolating between observations, models can generate virtual observations in areas where none are available, whether it be in time or space (e.g. trends or maps, respectively) (see Box 1.1).

Box 1.1: How models help us understand freshwater and its sustainable use in a data-sparse environment

Estimating river flow is a critical component of understanding the effects of human water takes and variations in climate on the quantity and health of the water and its living species.

River flow is measured by streamflow gauges, but these will often only be at a few locations in a catchment. Hydrologic models can simulate streamflow in non-gauged parts of the catchment based on monitoring data and other (climate, catchment and river) properties. Understanding critical processes in the subsurface, such as groundwater storage and flows in aquifers, can help decision makers better understand how much water can be taken sustainably.

The level of groundwater across an aquifer, including the way it varies both spatially and over time, can be assessed in multiple ways. Drilling many boreholes across a large area could be hundreds of times more expensive than a combination of a few strategically placed boreholes with, for example, well-conceived hydrogeological models, aerial geophysical surveys,[28] and numerical groundwater models.

Models can provide an efficient way to understand large-scale groundwater systems, thereby improving access to controlled and sustainable sources of drinking or irrigation water.

Models help us understand and unpick the complexity of what is observed by revealing the primary drivers of change. For example, weather models identify trends and help explain weather patterns. A better understanding of trends and patterns can provide early warning of adverse weather and water-related events such as floods, contaminant outflows into swimming locations, and approaching droughts. Early warning of such events helps water managers, mana whenua and communities make better preparations to minimise any impacts.

[28] Hawke's Bay Regional Council, 2024.

The same applies to the use of models to understand the effects of future climate scenarios on freshwater resources. These will typically look at the effects of climatic variation on water stocks and flows,[29] or on water quality.[30] Being able to explore several future climatic outlooks helps us prepare for potential adverse outcomes.

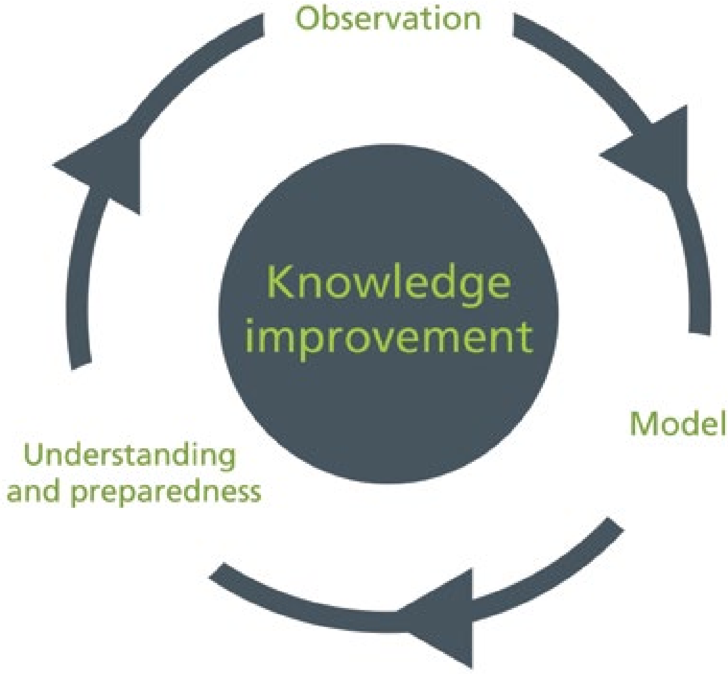
Models enable us to interpret what-if scenarios. For example, a model can quantify the effects of proposed land use changes on freshwater contaminant load in a catchment. Models can help catchment managers to explore what land use change scenarios are best suited to achieve a desired outcome and the magnitude of change needed to reach that outcome. More simply, modelling can illuminate the difference between action and inaction. For example, what happens to a river if the level of pollution is maintained compared with what happens if mitigation actions are undertaken? What range of groundwater levels would occur if you turned off all the pumping?[31] Choosing what mitigation actions deliver the best value for effort will require yet more modelling.[32]

Models are needed to illustrate what the cause of an effect may be (cause–effect relationships). Freshwater management models can, for example, be used to simulate:

- the effect of improvements in local farm management practices (e.g. the effect of riparian planting at the property scale on contaminant concentrations at the outlet of the catchment)
- the effect of changing land uses on the loads of nitrogen contamination carried in groundwater to streams and estuaries down-gradient[33]
- the effect of increased water takes on the health of aquatic species.

Deployed carefully, modelling can play a central role in continuous knowledge improvement in environmental research. Observations help build a model; the model can deepen understanding of a process; and deeper understanding incentivises better and more detailed data collection. This in turn enables further model improvements and a further deepening in understanding (see Figure 1.5).

[29] Mourot et al., 2022; Booker and Snelder, 2023.
[30] Snelder et al., 2021.
[31] Weir et al., 2023.
[32] McDowell et al., 2021; Monaghan et al., 2021.
[33] For example, see Fenemor et al. (2023).



Source: PCE

Figure 1.5. The process of continuous knowledge improvement. Observations help build a model; the model can deepen understanding of a process; and in turn deeper understanding incentivises better and more detailed data collection.

Fitness for purpose and good modelling practice

Freshwater models developed for decision-making processes need to be technically robust. This means that attention needs to be given to transparency, complexity, scale and uncertainty. A significant part of this report focuses on these technical aspects.

A model is 'fit for purpose' if it appropriately addresses both technical aspects and wider decision-making processes, including good modelling practice. Frameworks and think pieces for decision making using models exist, both internationally and in New Zealand.[34,35]

Freshwater models are one tool used in freshwater management. Decision making must also take into account governance arrangements, stakeholders and their disciplines or cultural backgrounds, Te Tiriti o Waitangi, and hapū and iwi involvement, as well as management options and other issues of concern.[36] It is therefore critical that the models used for decision making fit into those wider processes.

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34 For example, see Voinov et al. (2016).

35 Robson, 2014; Fenemor, 2022; Taylor, 2023.

36 For example, see Hamilton et al. (2015).

Another important part of good modelling practice is that there needs to be room for innovation. Hanging on to a specific model approach is understandable, certainly if the approach was proven. However, good modelling practice also includes looking at potential improvement of the scientific basis over time and adopting new models when those have been proven to be superior to older models.

Technical terms used in this investigation

Unavoidably, assessment of the fitness for purpose of models for regulation of freshwater requires some technical analysis. While most of that technical detail is confined to the appendices of this report, technical terms do surface throughout the main body. Set out below are definitions of some of the terms that are used in the report's findings.

Transparency

This report follows United States Environmental Protection Agency (US EPA) guidance, which summarises **transparency** as follows.

> "Model transparency is achieved when the modelling processes are documented with clarity and completeness at an appropriate level of detail. When models are transparent, they can be used reasonably and effectively in a regulatory decision."[37]

The guidance outlines how a transparent model application should include clear and well-explained documentation that explains how the model relationships were applied to the scenario, including limitations. It also explains how effective communication should include the concise explanation of results at an appropriate level of sophistication for the audience.

The term **open source** should not be confused with transparency, as is often the case. Open source refers to the model code being available to be used and adapted by anyone.[38] Open-source model code can be incomprehensible in the absence of any clear documentation, or without an understandable interface, assistance or support. Open-source code is important, but it takes more for a model to be transparent.

Proprietary software is not open and usually requires payment of a licence fee. In return, the user gains access to model software that is commonly easy to navigate, often with good documentation, and usually some degree of support. Proprietary software cannot, in general, be easily adapted to situations outside of what the model was original designed for. Proprietary models can be considered transparent if they are properly documented, including guidance for use and input data that are available in the public domain, and if an independent, scientific verification of the model is available. Considering transparency, US EPA guidance addresses proprietary models in this way:

> "To promote the transparency with which decisions are made, EPA prefers using non-proprietary models when available. However, the Agency acknowledges there will be times when the use of proprietary models provides the most reliable and best-accepted characterization of a system."[39]

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[37] US EPA, 2009, p.37.

[38] Open-source code is often freely available, but not always.

[39] US EPA, 2009, p.31.

In between open-source and proprietary software, there is **open-access software**. This can be used free of charge but cannot be adapted without the developer's involvement. Examples include freely available web interfaces, spreadsheets with hidden or locked macros, or purpose-built apps that can run a model without showing the underlying code.

There is a lot of variation within this spectrum of model types. For example, proprietary software can provide a variety of assistance levels, depending on licence cost, or an open-access version of the software could be provided freely for research purposes only.

In a regulatory context and given the above, for any model to be transparent it at least needs to satisfy the following technical requirements.

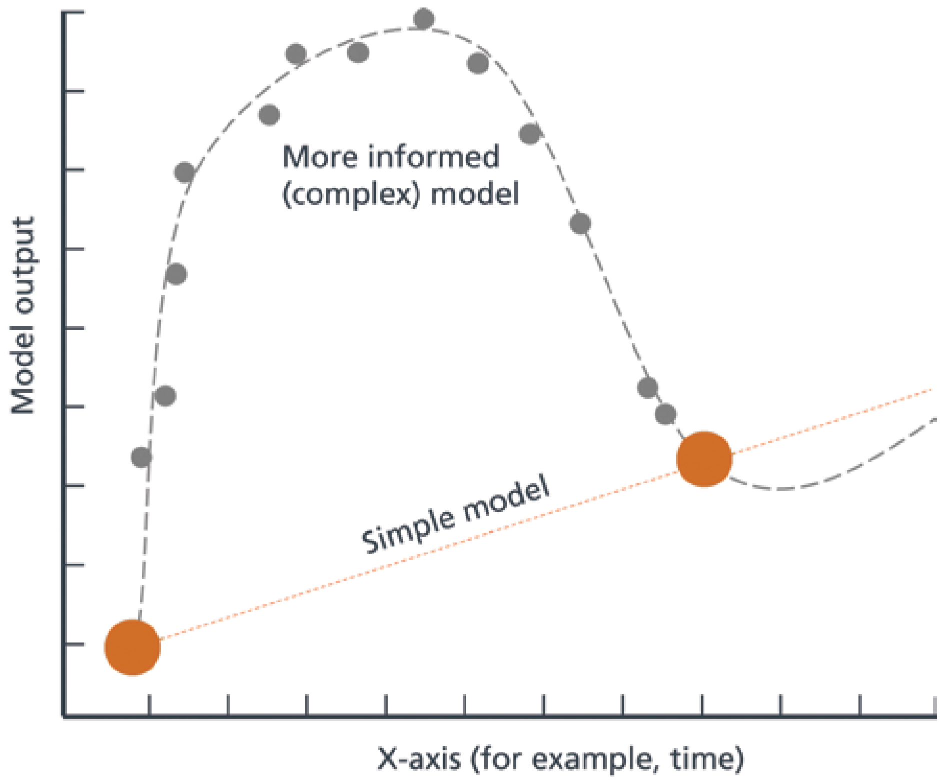
- Model results should be made openly available to those involved in decision making. Importantly, intellectual property should not stand in the way of being able to convey all model results to those involved in the decision-making process.
- Comprehensive model documentation should be available and easy to follow.
- Support for the model software (e.g. assistance by experts when needed) should be available.
- Model software should be maintained so that bugs are fixed, improvements implemented regularly and new versions are easily accessible.

Another aspect of model transparency is **data transparency**. The data used in modelling processes should be readily available to the decision maker, and preferably be publicly available. When data are not made available it becomes impossible to replicate model results or verify differing outputs produced by the same model. A corollary is that data are less likely to be used in modelling if they are not available, or only available with extra cost or effort.

Model complexity and model scale

An example of a (very) simple model is a straight line between two observations with only one parameter that informs the model (e.g. time; Figure 1.6). However, a process often has multiple drivers and therefore a straight line might not represent reality. A model will almost invariably become more complex as it attempts to better represent reality, and as more parameters are used in a rigorous and substantiated way.

Model complexity is sometimes mistakenly perceived as how *complicated* it is to run the model, which in turn often depends on how navigable the model user interface is. Models that can be run with one click of a button are considered simple; models that require many additional inputs (e.g. through a computer coding interface) are often considered more complicated. However, this perceived simplicity might not always reveal the true complexity of the model: After all, the one click might initiate the running of a large set of complex equations.



Source: PCE

Figure 1.6: Representation of model simplicity and complexity. There are simple models, e.g. a straight line between a minimal set of two observations (orange dots). With more information – e.g. more observations or system knowledge (grey dots) – more complex models can be developed, which can incorporate more model parameters to better represent reality.

Real-world environmental processes are mostly dynamic; they vary over time. For example, temperature varies throughout the day, the seasons and over the years. **Dynamic models** are built to predict these diurnal or seasonal environmental variations. In theory, these models represent real-world processes more precisely, but they come with increasing computational demands, which is why simplified versions are often used.

Steady-state models are simpler than dynamic models in that they work with the assumption that there is no variation over time. Most water quality models, largely because of insufficient temporal data, calculate mean annual values of water quality attributes, such as nitrogen, phosphorus or sediment discharged. Some water flow models assume a steady-state flow rate because it is acceptable for long-term water balance calculation.

Dynamic models are not necessarily more complex than steady-state models. At very fine temporal scales, the dynamics can sometimes be associated to physical processes in better and simpler ways. Complexity often comes from combining dynamic processes with steady-state models. For example, human processes are often a response to dynamic processes. Freshwater extraction from streams or groundwater is higher over the summer than in winter; erosion from land surfaces is generally more substantial in wet times than in dry times and could be amplified by processes such as winter forage grazing.

In terms of spatial scale, freshwater models applied at the catchment scale are usually the sum of smaller steady-state and/or dynamic models, which should be representative of the catchment as a whole. In general, the increased representation of processes over different spatial scales increases the model's complexity.

Model types[40]

Empirical models rely on correlations that have been observed, either experimentally or in the field. They do not rely on complex theory that may be difficult to model. Nor do they attempt to fully describe the real-world implications of these correlations. They simply try to model the 'best fit' for available observations.

Statistical models, a form of empirical models, make predictions based on statistical inference with observations. Statistical models are data driven. Although they are often developed with a theory that describes a postulated process or relationship, they do not need any prior knowledge on how the system that is predicted really works. Almost all artificial intelligence and machine learning algorithms can be classed as statistical models. A simple statistical model falling under that category is a 'regression'. **Regression models** aim to find the best fit with observations using certain criteria, such as a straight line (linear regression). For example, a regression method finds a linear relation between rainfall data and streamflow based on observations of rain and streamflow in a stream segment.

Mechanistic models focus on simulating detailed processes (e.g. biological or physical) that explicitly describe system behaviour in a more advanced way, meaning a detailed understanding of the system is required. Many hydrological models are mechanistic models (or at least partly so), as they require a high degree of system understanding about the physical processes of, for example, rainfall, evaporation, flow over the stream bed and flow through the subsurface.

Deterministic models use an (empirical or mechanistic) relationship, an equation that is assumed to describe how the system works, to produce an output. This assumption is accepted as valid for all other predictions for similar systems. By contrast, **stochastic models** run many versions of deterministic models, each of which is slightly different in its input or equations, leading to a possible (probabilistic) range of outputs.

Empirical, mechanistic**,** deterministic and stochastic models are often classed as numerical models: They require many mathematical computations over several time or iteration steps, usually being data hungry and computationally demanding.

[40] For a description of the different model types, see also chapter two in PCE (2018).

Conceptual models work on the basis that one can hypothesise how processes should work. That hypothesis is then often used as an initial estimate or applied as a set of conditions to design further models. Conceptual models can be complex in hypotheses, but they will not be computationally intensive. The explanation of a water budget in stocks and flows for New Zealand, as previously described in this chapter, is a conceptual model. As conceptual models generally do not require much computing, they are therefore not classed as numerical models, but they can be used to set up a numerical model.

Models can be a combination of all the above to include more holistic understandings. **Integrated catchment models** can consist of various linked model types, each representing a different environmental domain (e.g. river, lake, soil, groundwater) and may also incorporate social, cultural and economic parameters.[41] **Māori models** connect all ecosystems and include spiritual, socio-cultural, economic and other relational parameters, including required engagement between mana whenua and the catchment manager. Māori models will be discussed in more depth in chapter four.

Uncertainty and sensitivity

"Models, of course, are never true, but fortunately it is only necessary that they be useful."

– George Box[42]

A model without uncertainty does not exist. The outputs of models are inherently uncertain because they are based on observations that are often sparse, and through a series of assumptions and simplifications that cannot maintain the inherent variability of natural and human-made systems. Another source of uncertainty is the errors and limitations in the observations that models are based on. It is essential that modellers therefore identify, quantify and communicate the uncertainties associated with their models, otherwise false impressions of their veracity can develop and propagate in the decision-making process.

If misunderstood, uncertainty can have negative connotations in the minds of decision makers who find themselves associating uncertainty with incomplete or poor outputs. Leaving out information about uncertainty renders a model output less transparent and increases the risk of erroneous decision making (see Box 1.2).

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41 For example, see Dymond et al. (2010).

42 Box, 1979, p.2.

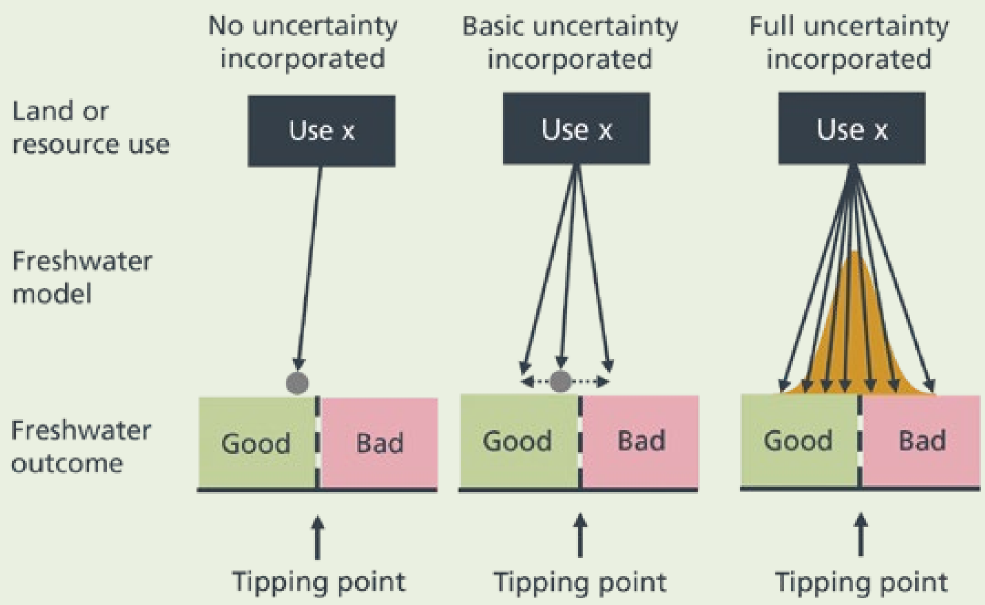
Box 1.2: An example of use of uncertainty in water models and decision making

Quantifying the effect of land or water use on a freshwater resource is associated with high uncertainties.[43] Multiple water abstractions from one stream will have a significant effect on the water level in the surrounding area. Water models are generally used to link some form of land or resource use to an impact on freshwater (e.g. a tipping point). However, modelling the effects of water takes on downstream flows and the groundwater level is a complex process, where results will likely have a large associated uncertainty.

A model output might misleadingly show the model result as being 100% certain (Figure 1.7, left). A decision based on that result will be that the tipping point has not been reached and water take can continue without any issues. However, if uncertainty of that same model result is taken into account (e.g. the model standard deviation; Figure 1.7, middle), there is a possibility that the water take will result in an outcome that is just over the tipping point.

The decision might still be in favour of the water take but is likely to be taken with more caution. If the same model presents results as probabilities – by using the appropriate model uncertainties (Figure 1.7, right) – it will show that in some cases there is a probability that the tipping point will be exceeded (i.e. that the fish species will disappear).

A risk-averse stance (and a precautionary approach) would be to reduce water take until no model probabilities cross the tipping point. The same model is used, but showing the results with an estimation of their uncertainty is likely to lead to more environmentally robust decisions.



Source: PCE

Figure 1.7: Model output with and without uncertainty information. Water models are generally used to link some form of land or resource use to an impact on freshwater, e.g. a tipping point. (Left) output from a model without uncertainty information; (middle) output from a model with basic uncertainty information, e.g. standard deviation; (right) output from a model with full uncertainty information, e.g. as a normal distribution of possible model outputs.

[43] Doherty and Moore, 2020; Larned et al., 2022.

Model sensitivity relates to the model's response to changes in the input data. Sensitivity analysis identifies the influence of each input data source and assesses its relationship to model outputs. Knowing which data are making the model change most helps provide an understanding of model outcomes and associated uncertainties. It also helps to understand how much a model can be simplified. For example, if sensitivity analyses shows that a model output is only sensitive to one of its multiple inputs, then it might make sense to simplify the model to focus on that one input.

Model calibration is the process by which model equations are iteratively adjusted until a best fit is obtained between model output and observations. **Model validation** refers to the comparison of the model outputs with observations or other information for substantiating model use. Validation should not use data that were used for calibration.

Hymenophyllum dilatatum

2 Water models everywhere

A large number of models exist

This report identified that at least **75 biophysical freshwater models** are used by regional councils and unitary authorities in a regulatory context to assist with better water resource management, including managing contaminant discharges and water takes. (See Appendix 1 for a full list of the 75 models and their brief descriptions.[1]) This number is likely an underestimate, as not all models will have been captured during this investigation. Further, it does not include models that are currently under development by various organisations but have not yet been used by regional councils and unitary authorities in a regulatory context.

In addition to the 75 biophysical models, the report commissioned on freshwater models developed by, or in close collaboration with, mana whenua and Māori entities, describes a further 33 models.[2] Some of these Māori models are discussed in chapter four. This proliferation of models results in the use of different model assumptions, algorithms and input data sources. Rather than adding value, it confronts regulators with the quandary of having to choose the 'best' model and then defend that choice. That is not an easy task.

Many models overlap and diverge

The 'top 24' models – a subset of the 75 models – that have been used by at least three councils (Table 2.1) were analysed in more detail for this report. These models were categorised as to whether they addressed water quality, water quantity, or both, and clustered by the primary environmental domains they were designed for. It is important to note that some models cover several environmental domains (e.g. CLUES, eWater Source, SWAT).

This analysis reveals that many models are being used in the same environmental domain, sometimes for the same purpose. As different models use different assumptions, equations and data sources, when multiple models are used for the same purpose within the same domain, they can produce divergent results. However, in some cases, it makes sense to use more than one model to perform a complex task as different models can provide complementary information. In such cases, models must be able to work and join well together, which is not always possible.

[1] This report generally refers to the name of the model software and not the full modelling process of how it was applied at any specific location. That is because the models generally go by their specific name (e.g. MODFLOW, CLUES, SPASMO).

[2] See Taylor (2023).

Table 2.1: Summary of the 'top 24' models that have been used by at least three councils.

Model name	Summary description
MODFLOW	Globally, the most widely used groundwater flow modelling software. Contains many sub-models that cover most of the water cycle, including groundwater contaminant transport. Often used in conjunction with the Model-Independent Parameter Estimation and Uncertainty Analysis (PEST) software to infer statistics on stochastic model runs.
SPASMO	The Soil Plant Atmosphere System Model (SPASMO) simulates the transport of water, microbes and solutes through soils, integrating variables such as climate, soil, water uptake by plants in relation to farm and orchard practices, and any other factors affecting environmental processes and plant production.
CLUES	The Catchment Land Use and Environmental Sustainability (CLUES) model is a self-labelled 'super model' that combines multiple catchment-scale models (Overseer, SPASMO, SPARROW) in a simplified form to evaluate current loads and perform rapid scenario testing for nutrients, *Escherichia coli* (*E. coli*) and sediment.
REC-based regression	Statistical (regression) models, based on a set of regression methods, built on relations and attributes of the digital representation of the national river network, which is used to map the River Environment Classification (REC) dataset with river monitoring data of nutrients, streamflow or other properties.
SedNetNZ	A sediment erosion model that predicts the generation and transport of sediment through river networks, based on a simple representation of soil, hillslope and channel processes. It provides estimates of sediment load generated by erosion processes (landslides, gullies, earthflows, surface, and bank erosion) and sediment deposition on floodplains.
Overseer	A model that supports farmers and growers to understand nutrient flows on their farms, improve performance and reduce losses to the environment through better use of nutrients.
IrriCalc	A soil water balance model used to estimate, for example, irrigation demand and groundwater recharge. Software is not open, but a free web-based irrigation calculator exists.

SEFA-RHYHABSIM	System for Environmental Flow Analysis (SEFA, superseding River Hydraulic HABi-tat SIMulation (RHYHABSIM)) implements the Instream Flow Incremental Methodology (IFIM), a methodology to assess fish habitat suitability with different environmental and flow regimes in rivers and streams, established from nationwide field-observed data. SEFA contains water allocation scenarios, habitat hydraulics analysis, water temperature modelling, sediment transport analysis, dissolved oxygen modelling, riparian modelling, hydrologic and habitat time series analysis, and more.
TopNet	A hydrological catchment-based model designed for dynamic catchment-scale to nationwide streamflow prediction, including flood forecasting.
Bespoke water balance/budgets	A range of methods to assess water flows in and out of a catchment. Based on steady-state estimates of water cycle (e.g. rainfall, evaporation, streamflow, groundwater flow). Often developed in a spreadsheet. Six different bespoke water balance models have been identified in this investigation and for the purposes of this assessment they have been grouped together.
eWater Source	A software framework that can flexibly link and apply hydrologic models through model coupling interfaces. Embeds an internal suite of surface water models and a simple groundwater model. The agreed model for water accounting in the cross-boundary Murray–Darling Basin, Australia. It can also be used for catchment-based modelling studies.
SWAT	The Soil & Water Assessment Tool (SWAT) covers a range of simulations in quantity and quality of surface water and groundwater, and at a range of scales (e.g. small watershed to river basin). It predicts the environmental impact of land use, land management practices and climate change, and assesses soil erosion prevention and control, non-point source pollution control and regional management in catchments.
Hunt/Theis stream depletion tools	A collection of groundwater tools and resources developed and/or compiled by Environment Canterbury. It is available online and contains a well interference assessment tool, a drawdown tool, stream depletion tools, two aquifer system tools and other tools developed by Dr Bruce Hunt (University of Canterbury).
MIKE suite	A suite that contains a variety of surface water models for a range of purposes covering all hydrological surface water catchment processes: MIKE11 (river modelling), MIKE3FM (hydrodynamic module), MIKE-SHE (integrated hydrological model including groundwater, surface water, recharge and evapotranspiration), and MIKE21 (hydrodynamics, waves, sediment dynamics, water quality and ecology).

FEFLOW	A numerical finite element groundwater flow model for porous and fractured media, including mass transfer and heat transfer. Used as an alternative to MODFLOW.
SCAMP/CASM	Simplified Contaminant Allocation Model Platform (SCAMP) is a spreadsheet-based method to assess effects of land use and contaminant (diffuse and point) discharge on water quality. It assesses loads at various points (e.g. outlets of catchments). It is simplified in that councils can simulate scenarios in a reasonably short time, yet advanced enough that the pre-developed macros in the spreadsheet cover the necessary important processes. Previously known as the Contaminant Allocation & Simulation Model (CASM).
EFSAP	Environmental Flows Strategic Allocation Platform (EFSAP) is a water planning and management tool designed to help set regional or large-(spatial) scale water resource use limits for rivers. The tool predicts how limits on water take and minimum residual river flows affect, or can be designed to optimise, reliability of water use and effects on in-stream environments. Examples of out-of-stream use include domestic water and irrigation. In-stream environmental values include physical habitat for fish.
NZ River Maps	Not a model *per se*, but a collation of data and model outputs available through a web interface. A wide range of biophysical variables is available (e.g. sediment, hydrology, fish habitat).
Estuary Trophic Index	The Estuary Trophic Index provides a nationally consistent approach to the assessment and prediction of estuary eutrophication for 443 New Zealand estuaries. The tool has three sub-components: susceptibility assessment, an estuary health score based on measured data, and an estuary health score based on a Bayesian belief network.
Our Land and Water (OLW) typologies	A model output, rather than a model, produced as datasets of landscape characteristics (typologies) that can be used to estimate nutrient loss from soils to the rest of the catchment. Developed by Our Land and Water National Science Challenge.
Bespoke nutrient balance (leaching) budgets	A range of methods to assess catchment-scale water and nutrient budgets and mass balance methods to infer nutrients entering a lake, river, stream or catchment outlet. Often developed in a spreadsheet. Three different bespoke nutrient balance budgets have been identified in this investigation and for the purposes of this assessment they have been grouped together.

DYRESM-ELCOM-CAEDYM	A chain of models often coupled for simulation of lake water quality. The DYnamic REservoir Simulation Model (DYRESM) is a one-dimensional hydrodynamic model resolving the vertical distribution of temperature, salinity and density in lakes and reservoirs. The Estuary, Lake and Coastal Ocean Model (ELCOM) is a three-dimensional substitute of DYRESM. The Computational Aquatic Ecosystem DYnamics Model (CAEDYM) is an aquatic ecological model that simulates time-varying fluxes of biogeochemical variables (e.g. nutrient species, phytoplankton biomass). These can be coupled and are often used with DYRESM for lakes (one-dimensional, DYRESM-CAEDYM), or ELCOM for lakes, estuaries and coastal areas (three-dimensional, ELCOM-CAEDYM).[3]
CHES	Cumulative Hydrological Effects Simulator (CHES) predicts how water flows in a catchment will change with multiple water uses (e.g. direct abstractions or storage reservoirs), and what the consequences will be to in-stream ecosystems and reliability of water take.
WAIORA	Water Allocation Impacts on River Attributes (WAIORA) is a Microsoft Windows based decision support system designed in the early 2000s to provide guidance on whether a flow change could have adverse impacts on the following environmental parameters: dissolved oxygen, total ammonia, water temperature, habitat for aquatic life.

Sediment models

Experts largely agree on the difficulty of modelling sediment loads in rivers, streams and estuaries. Given this complexity, it is reasonable to assume that using more than one sediment model could be beneficial. However, the stocktake counted a total of 13 models that are designed to assess sediment in rivers and streams, which suggests an unnecessarily large overlap in their application (Table 2.2 and Figure 2.1).

Councils used seven different models to estimate sediment loads in rivers and streams and to explore options to reduce sediment loss. Six additional models were used in other environmental domains but were also able to model sediment in rivers and streams.

The outputs of these sediment models diverge significantly and so will decisions based on them. For example, different models used to estimate sediment yield in and around the Manawatū provided orders of magnitude differences when compared to observations.[4] Similarly, large differences were reported in local studies in Southland,[5] Waikato, Auckland and Northland.[6]

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3 McBride et al., 2019.
4 Dymond et al., 2016.
5 Plew, 2020.
6 Hicks et al., 2019.

Source: Peter Scott

Figure 2.1: Heavy rainfall can lead to mass landslides and erosion on exposed hillsides, as seen here on this farmland in Hawke's Bay. As well as being a costly loss of productive soil, landslides can add significant amounts of sediment and phosphorus into water bodies. The stocktake assembled for this investigation counted a total of 13 models that are designed to assess sediment in rivers and streams. The outputs of these sediment models diverge significantly and so will decisions based on them.

Table 2.2: Sediment models for estimating sediment in rivers and streams and their use by councils. See Appendix 1 for model descriptions and full names.

Model	Used by	Comment
Sediment models used to estimate sediment loads in rivers and streams		
SedNetNZ	BOPRC, ES, GWRC, HBRC, HRC, NRC, ORC, TRC, WRC	
FWMT	AC, NRC	Embeds LSPC as engine for sediment modelling.[7]
NZEEM	GWRC, WRC	
WAIORA	AC, WRC	
Physiographic models	ES, NRC	

[7] Auckland Council, 2021.

NZSYE	NRC	Embeds NZEEM as an engine for sediment modelling.
RUSLE	GWRC	
Models used in other environmental domains but also able to model sediment in rivers and streams		
CLUES	ES is the only regional council using CLUES for sediment modelling. BOPRC, ECAN, GWRC, HRC, NRC, ORC, TRC and WRC use it for other environmental domains but not for sediment modelling.	Embeds SPARROW as the engine for sediment modelling and is considering integrating NZSYE as a sub-model.
eWater Source	AC, BOPRC, GDC, GWRC and HBRC use it for other environmental domains but not for sediment modelling.	Embeds Australian-developed erosion model, also called SedNet,[8] as the engine for sediment modelling.
MIKE suite	AC, BOPRC, ECAN, GWRC and MDC use it for other environmental domains but not for sediment modelling.	
SWAT	GWRC, HBRC, MDC, ORC and WRC use it for other environmental domains but not for sediment modelling.	
SPARROW	Used as sub-model in CLUES but could be used as an independent model.	
Delft3D-FLOW/ DELWAQ	BOPRC used it for Estuary Trophic Index modelling, but it could also be used for in-stream modelling of sediment.	

List of councils:

AC = Auckland Council

BOPRC = Bay of Plenty Regional Council

ECAN = Environment Canterbury

ES = Environment Southland

GDC = Gisborne District Council

GWRC = Greater Wellington Regional Council

HBRC = Hawke's Bay Regional Council

HRC = Horizons Regional Council

MDC = Marlborough District Council

NCC = Nelson City Council (does not use models)

NRC = Northland Regional Council

ORC = Otago Regional Council

TDC = Tasman District Council

TRC = Taranaki Regional Council

WCRC = West Coast Regional Council

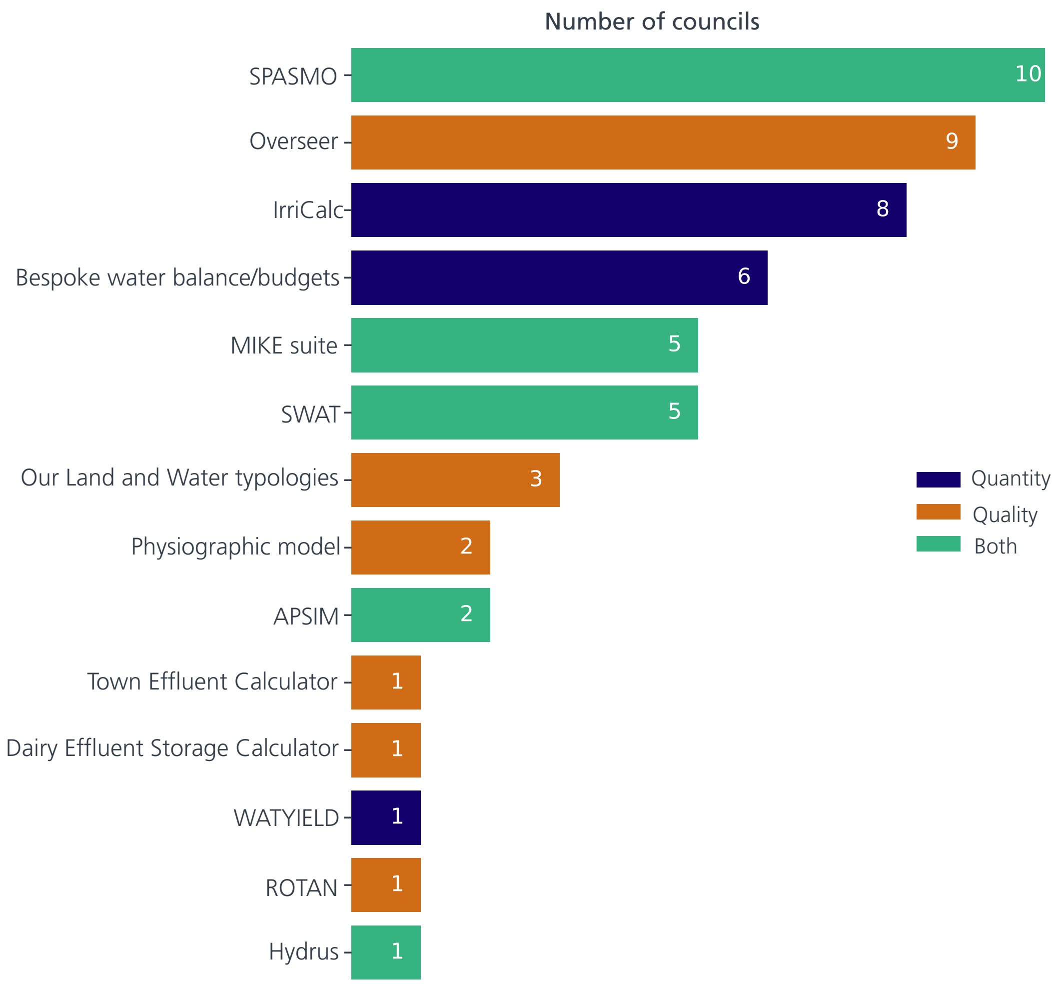
WRC = Waikato Regional Council

[8] The Australian SedNet model inspired the SedNetNZ model, but they should be considered as two separate models.

River and soil water quality models

Further overlap can be found with river and soil water quality models.

Nineteen models are in use for soil water estimation (Figure 2.2).[9] Nine of these models are soil nutrient loss models that are designed to predict nitrogen and phosphorus loss from soil.[10] These are used by 13 of the 16 councils in a wide variety of applications and combinations (Table 2.3).[11]



Source: PCE

Figure 2.2: Models designed to model soil water, covering soil water quantity, quality, or both. As some models cover multiple environmental domains, the number in the bar denotes the number of councils that have reported the use of that model for any environmental domain. Six bespoke water balance models have been grouped into one line item.

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9 In Figure 2.2, six bespoke water balance models have been grouped together.

10 SPASMO, Overseer, MIKE suite, SWAT, OLW typologies, APSIM, Hydrus, physiographic models, ROTAN.

11 Taranaki Regional Council, West Coast Regional Council and Nelson City Council do not use this type of model.

Source: mikeccross, Flickr

Figure 2.3: The area of irrigated agricultural land increased by 91% (nearly doubled) between 2002 and 2019, particularly in the Canterbury Plains, as shown here.[12] IrriCalc is a soil water balance model used by regional councils to estimate irrigation demand and groundwater recharge.

[12] Stats NZ, 2021.

Table 2.3: Soil nutrient loss models and their use by councils. See Appendix 1 for model descriptions and full names.

Model	Used by	Comment
SPASMO	AC, BOPRC, ECAN, GDC, HBRC, HRC, MDC, NRC, TDC, WRC	Only used for water quantity (SPASMO-IR) by NRC, HRC, BOPRC.
Overseer	AC, BOPRC, ECAN, ES, GWRC, HBRC, HRC, ORC, WRC	
OLW typologies	HRC, ORC, TDC	
APSIM	BOPRC, GWRC	
Physiographic models	ES, NRC	Only used for informing policy, i.e. understanding of system.
ROTAN	BOPRC	
MIKE suite	AC, BOPRC, ECAN, GWRC, MDC	
SWAT	GWRC, HBRC, MDC, ORC, WRC	
HYDRUS	BOPRC	Only used for water quantity.

List of councils:

AC = Auckland Council
BOPRC = Bay of Plenty Regional Council
ECAN = Environment Canterbury
ES = Environment Southland
GDC = Gisborne District Council
GWRC = Greater Wellington Regional Council
HBRC = Hawke's Bay Regional Council
HRC = Horizons Regional Council
MDC = Marlborough District Council
NCC = Nelson City Council (does not use models)
NRC = Northland Regional Council
ORC = Otago Regional Council
TDC = Tasman District Council
TRC = Taranaki Regional Council
WCRC = West Coast Regional Council
WRC = Waikato Regional Council

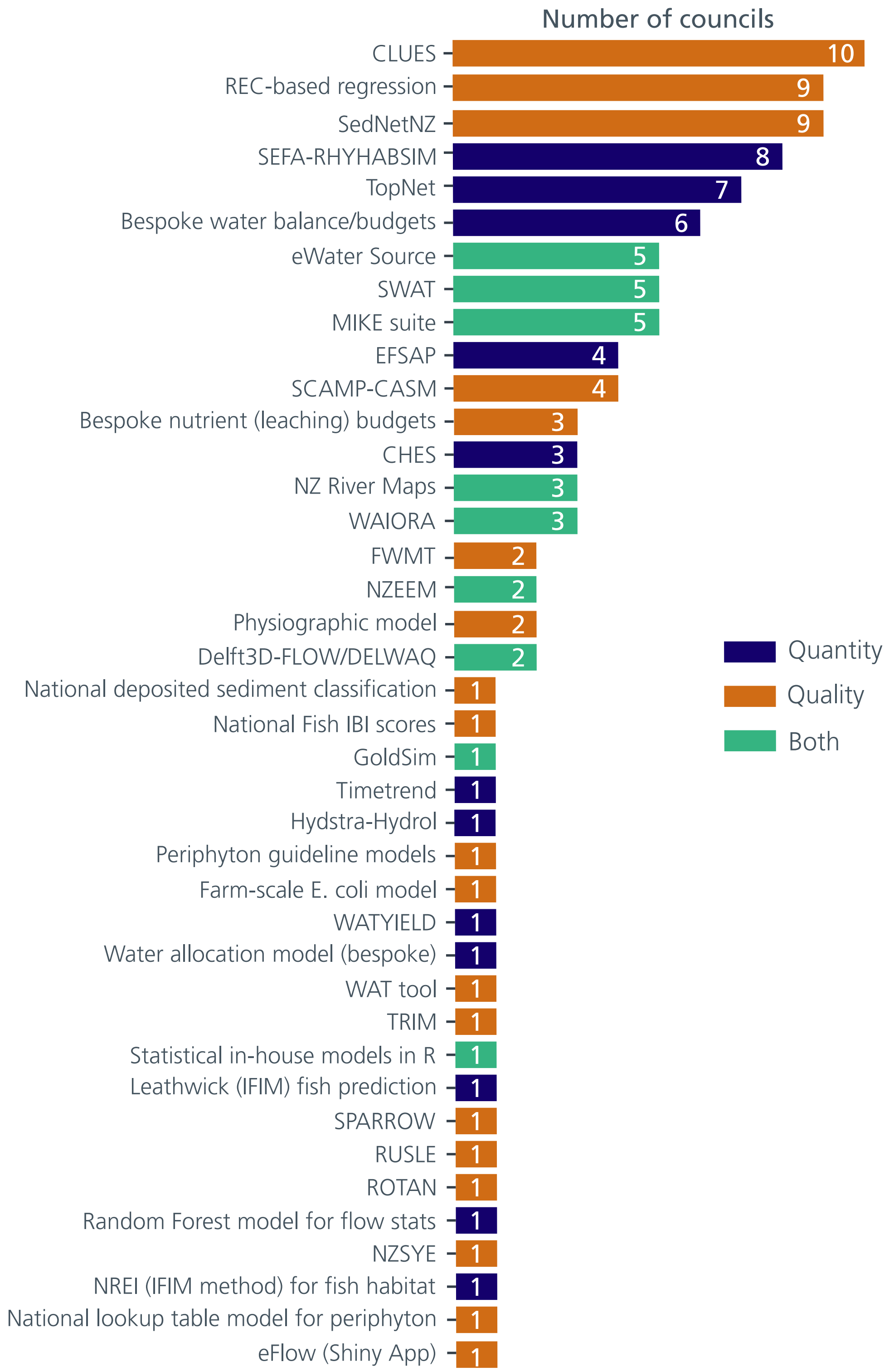
Forty-seven models are specifically designed to model in the environmental domain of rivers and streams, covering river water quantity, quality, or both (Figure 2.4).[13] Nineteen river water quality models are designed to model nutrient loads in rivers and streams.[14] This number excludes three urban models,[15] and four sediment models.[16]

[13] In Figure 2.3, six bespoke water balance models have been grouped together as have three bespoke nutrient (leaching) budgets.

[14] CLUES, REC-based regression, eWater Source, MIKE suite, SCAMP-CASM, NZ River Maps, SWAT, FWMT, WAIORA, Delft3D-FLOW/DELWAQ, eFlows Explorer, GoldSim, HYPE, look-up table periphyton, ROTAN, SPARROW, TRIM, two bespoke nutrient leaching budgets.

[15] CLM, MUSIC, SUSTAIN.

[16] SedNetNZ, NZEEM, RUSLE, NZSYE.



Source: PCE

Figure 2.4: Models specifically designed to model in the environmental domain of rivers and streams, covering river water quantity, quality, or both. As some models cover multiple environmental domains, the number in the bar denotes the number of councils that have reported the use of that model for any environmental domain. Six bespoke water balance models have been grouped in one line item; as have three bespoke nutrient (leaching) budgets.

Catchment water quality models

While it will sometimes make sense to use complementary models to undertake complex tasks (for example, addressing the various regulatory requirements or landscapes found across New Zealand), the use of too many models in regulation can lead to confusing and even conflicting conclusions.

Box 2.1 provides an example of model divergence and explores interoperability among several models used in New Zealand (River Environment Classification (REC)-based regression models, SCAMP, CLUES).

Box 2.1: Model divergence: Joining statistical models with process-based models for contaminant predictions

REC-based regression models are generally preferred by councils for predicting current or historical contaminants at the whole-of-catchment scale because such statistical models are largely driven by observations. However, the application of REC-based regression models to develop 'what-if' scenarios is challenging. Currently, councils prefer process-based models to predict catchment contaminant loads for different scenarios of changes in management practices or land use.

In New Zealand, the CLUES and SCAMP models provide the sort of quick and simple process-based results that can be used to predict contaminant loads under different scenarios at the whole-of-catchment scale. But for models like these to work well in tandem with a REC-based regression model, there needs to have been an element of co-development to optimise complementarity. The SCAMP model is well-linked to REC-based regressions and yields comparable estimates of nutrient loads and concentrations. Conversely, CLUES and REC-based regression models are much less congruent and interoperable than they could be. This is a problem because CLUES is widely used by 10 of the 16 councils.

At the national scale, recent predictions of total nitrogen loads based on CLUES and REC-based regression models diverge. The most recent REC-based regression model estimates a total nitrogen load ranging from 157 to 190 kilotonnes per year. In contrast, the CLUES model generates an estimate of 236 kilotonnes per year, without uncertainty provided (Table 2.4).

At the regional scale, these models also diverge, with CLUES and REC-based regression outputs differing –20% and +130% for total nitrogen and total phosphorus, respectively.[17] It has been suggested that REC-based regression outputs be used to calibrate outputs from CLUES.[18] That has not been done to date, leaving CLUES results unnecessarily incongruent with REC-based regression models. An additional problem with CLUES arises from the fact that it combines other model applications as sub-models.[19] But these are mostly adjusted, simplified or old model versions,[20] with some using proprietary software that lacks transparency. Updating CLUES to address the above issues would be complex and would require a degree of collaboration that currently does not exist.

[17] Plew, 2020.

[18] Snelder et al., 2018.

[19] SPARROW, NZSYE, Overseer, SPASMO.

[20] Semadeni-Davies et al., 2019.

Table 2.4: Current total nitrogen load: Results from REC-based regressions and CLUES at the national scale.

Source	Model	Current total nitrogen load for New Zealand (kilotonnes per year)
Snelder et al., 2018	REC-based regression	187
MfE, 2019	REC-based regression	186
MfE, 2020b	CLUES	236
Snelder et al., 2020	REC-based regression	169 (range 148–196)
Snelder, Smith et al., 2023	REC-based regression	172 (range 157–190)

Hydrologic rainfall-runoff models

A certain richness in model variety is needed for water quantity predictions in water bodies to address multiple topics such as flow generation and loss, habitat suitability with low flow and water allocation. However, at least nine models contain different hydrologic rainfall-runoff prediction methods,[21] which are hard to compare or combine because most of these models are proprietary.

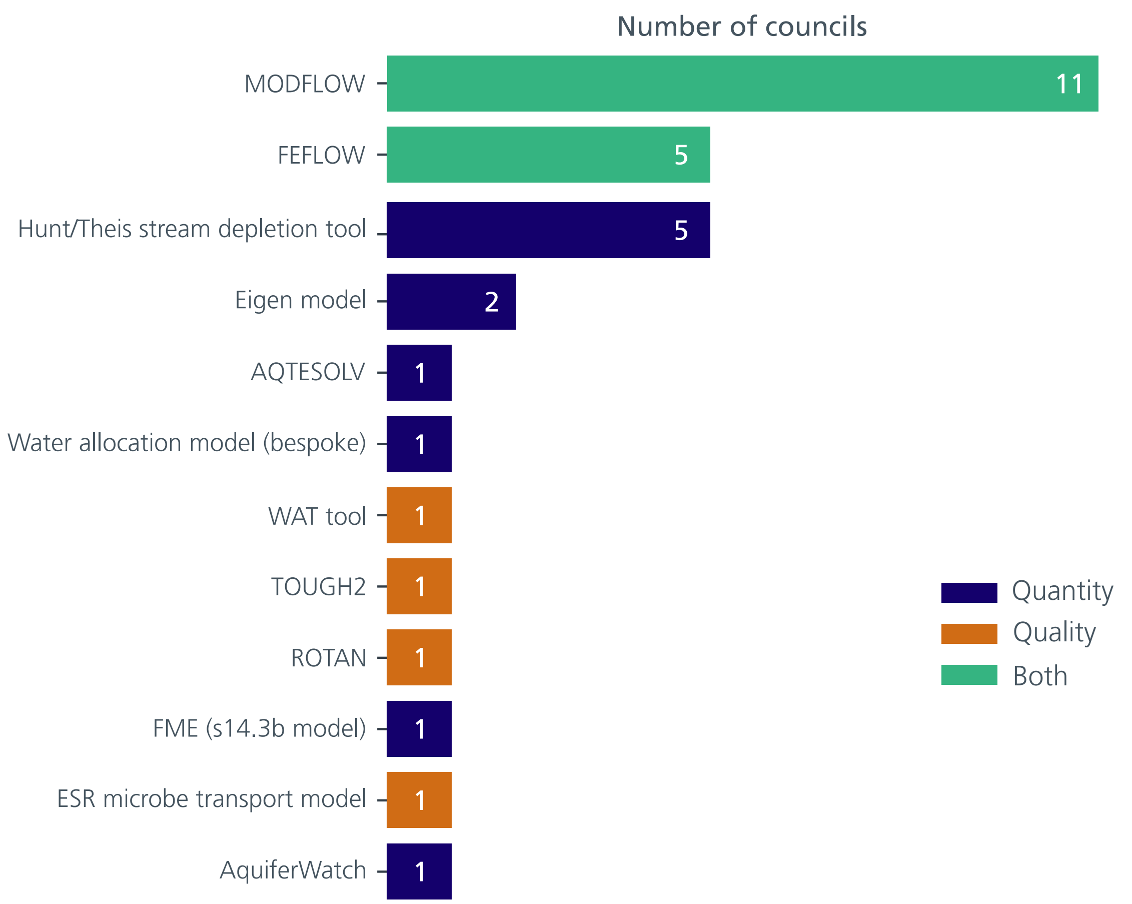
There are even more divergent rainfall-runoff prediction methods used in models for other applications. For example:

- Sediment and nutrient models might embed rainfall-runoff estimates based on either model equations or data, each of them potentially different due to different data, model assumptions or time periods used.
- Groundwater flow models often use their own estimates of groundwater discharging as baseflow into rivers and of rainfall runoff.[22]
- Flood forecasting models (not a key focus of this investigation) used within the operational departments of a council might also embed different hydrologic streamflow predictors, which could be used for water resource studies.

Groundwater models

Groundwater models are a class apart. Many councils and model experts agree that groundwater is ‘the child left behind’, even though it represents three-quarters of all ‘young’ freshwater stocks. While 47 models in the stocktake target rivers and streams (Figure 2.4), only 12 models target groundwater (Figure 2.5), many of which embed overly simplified model assumptions. One of the exceptions is MODFLOW, which is the most widely used freshwater model by councils of all models in the stocktake. This could be because, despite its complexity, it is fully transparent, free, and the accepted industry standard for both groundwater quantity and quality research.

[21] TopNet, eWater Source, MIKE suite, SWAT, FWMT, Delft3D-FLOW, GoldSim, HYPE, Hydstra-hydrol.
[22] For example, MODFLOW, FEFLOW.



Source: PCE

Figure 2.5: Models specifically designed to model groundwater, covering groundwater quantity, quality, or both. As some models cover multiple environmental domains, the number in the bar denotes the number of councils that have reported the use of that model for any environmental domain.

Models are not systematically evaluated

Given that many water resource models are used in a regulatory context, it is critical that they are fit for their intended purpose.

However, their fitness for purpose is currently hard to judge, as models are not systematically evaluated. This makes it hard to determine which model is best for use in any particular circumstances. The duplication and experimentation described in this and the next chapter are the results of this.

A certain richness of models can stimulate innovation. Having multiple models available can be beneficial if their differences can be assessed. A 'multi-model' or 'multi-evidence' platform could shed light on these differences and help identify which models should be preferred. This is common practice in other areas of modelling that are more advanced, such as weather forecasting (Figure 1.4). For similar advances to be made in New Zealand's freshwater modelling, all water resource models need to be evaluated. And for that, they need to be robust and transparent enough to enable them to be usefully compared.

Criteria for model evaluation exist, and include a set provided by the United States Environmental Protection Agency (US EPA) and the checklist provided in the New Zealand guidance by the Ministry for the Environment (MfE) on environmental models.[23] Guided by these publications and criteria, technical evaluations of the 'top 24' models were performed. Figure 2.6 shows an assessment of the complexity and transparency of these models. All outputs of the technical model evaluation, including a description of the criteria used, are described in more detail in Appendix 2.

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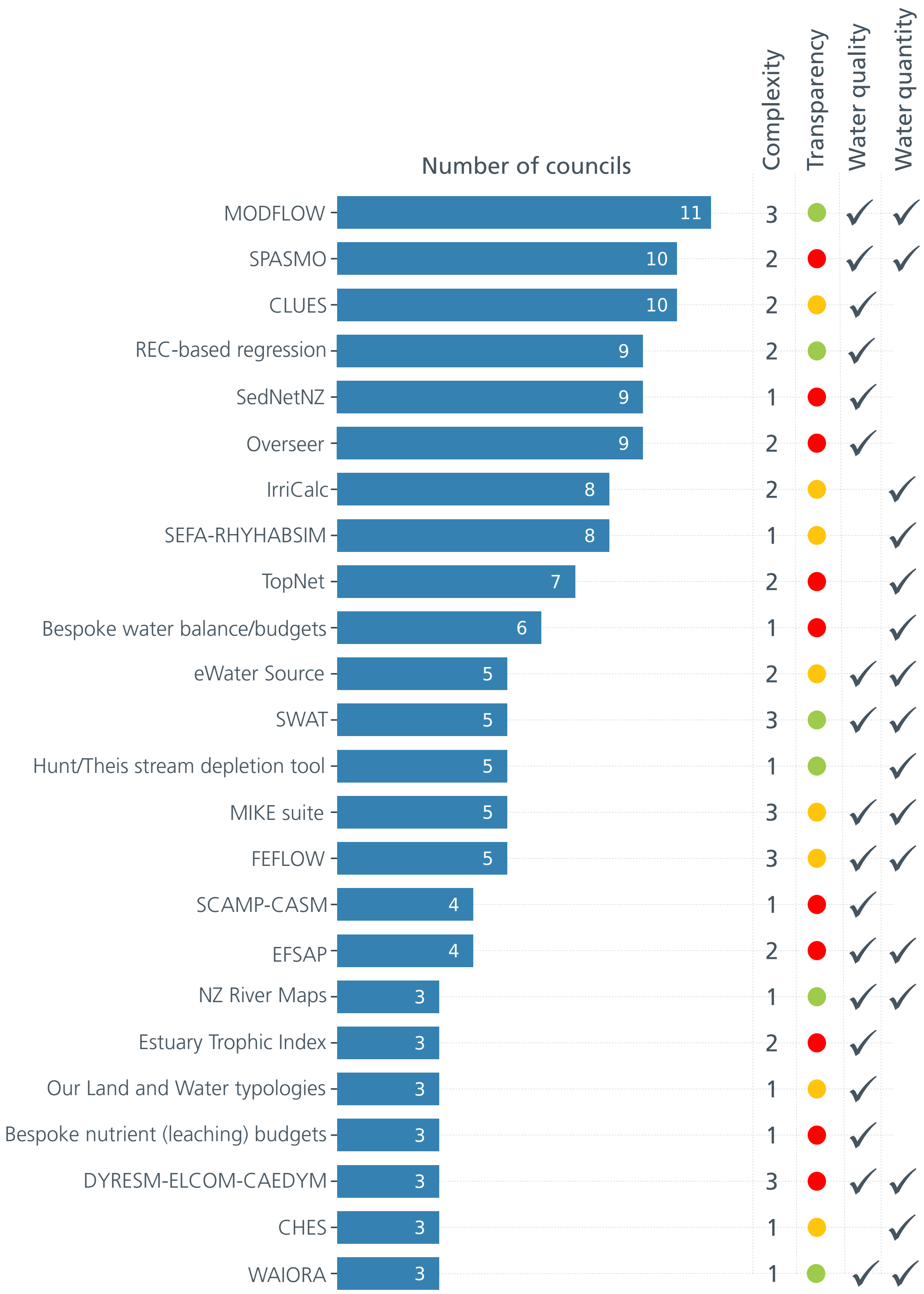
[23] See US EPA (2009) and MfE (2023b).



Source: PCE

Figure 2.6: Assessment of the 24 models that have been used by three councils or more. Note that for the purposes of this evaluation, six bespoke water balance models have been grouped together, as have three bespoke nutrient (leaching) budgets. The number in the bar denotes the number of councils that have reported the use of any specific model. Complexity is categorised as 1 = simple; 2 = moderately complex; 3 = very complex. Transparency is categorised as fully transparent (green); moderately transparent (amber); not transparent (red). In addition, models are categorised as those that are focused on water quantity, water quality, or both. More detailed explanations can be found in Appendix 2.

The technical model evaluation found that most models have a good scientific basis (model structure, algorithms, peer review and validation). However, it also found many shortcomings with respect to transparency, uncertainty and computational infrastructure. Each of these weaknesses stands in the way of the comparability and interoperability of models, including the potential to reuse them when needed, or assess their effectiveness at a later stage.

Across the evaluated models, the **scientific basis** is generally strong. Model algorithms are mostly appropriate, with the exception that sub-models still have known limitations. For example, underlying assumptions in CLUES and Our Land and Water (OLW) typologies rely on unverifiable farm-scale information derived from Overseer and/or SPASMO estimates. Similarly, bespoke water and nutrient budget assumptions used by councils are not easily available and may contain weak or flawed assumptions. However, model equations and model structure in many cases tackle the variable of interest appropriately, and model structures appear to be efficient.[24]

Transparency varies significantly across the evaluated models, with most being deficient.

- Thirteen models are proprietary.[25] Some of these models are not made available to anyone except the model developer,[26] and only the results of the studies are delivered to the client. Software manuals exist for six of these models,[27] which provide an acceptable level of documentation for those wanting to apply the model. However, this documentation is generally not used by third parties because most of these model applications are undertaken directly by the developers of those models with the outputs supplied to clients, including council staff. Most model applications, whether with or without manuals, describe their model assumptions in client reports. In these cases, model details are often omitted, or left as a reference to another study, leaving it to the client to know whether or how to explore detailed information. In some cases, scientific papers have restricted access, making it even harder for the users of modelling outputs to evaluate those models.
- Six models are open access, which means that the results, or an interface to use the model without access to the model code, are freely available.
- Five models are open source. Two of these are highly advanced models that come with extensive documentation (MODFLOW and SWAT). The other two provide limited guidance. The Hunt/Theis stream depletion tools has some limited documentation, but it is a simple tool and relatively easy to use. By contrast, the model source code of REC-based regressions is completely open, yet its advanced algorithms and the code itself might be perceived as complicated by new users.

Despite recent improvements in the robustness and transparency of Overseer,[28] its code is still not open, and its data sits behind proprietary doors. It has been shown that results from models like this cannot be easily verified when applied at the catchment scale by councils.

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[24] This does not mean that use of the model software is well-described; this falls under transparency.

[25] A limited version of eWater Source comes with a free-for-research licence; full access to CLUES is available for research purposes, but not for commercial use.

[26] SPASMO, IrriCalc, SedNetNZ, and TopNet, although simple versions exist on a website (e.g. SPASMO, IrriCalc). The National Institute of Water and Atmospheric Research (NIWA) has recently made a website available where one can run a TopNet model. However, this is still experimental.

[27] CLUES, eWater Source, SCAMP, SEFA, MIKE suite, and FEFLOW.

[28] MPI, 2023.

The situation is similar for SPASMO. Its assumptions are described in published papers, yet there is no manual for SPASMO, which is a significant drawback. Further, it is a heavily proprietary software that has been developed in isolation. Its development is solely paid for by industry, and the data it uses are mostly not open.

Despite these drawbacks, the stocktake shows that councils are still heavily relying on Overseer and SPASMO. The simple reason given by both councils and model experts is that there are no obvious alternatives for use at the property scale. In theory, alternative and open software (APSIM and SWAT) could handle most, if not all, of the functionality of both Overseer and SPASMO.[29] However, these models would start on the backfoot as they would need to be tailored to model specific locations and catchments. Further, they cannot immediately make use of the rich industry-owned data that Overseer and SPASMO use. In addition, these models are advanced and complex in nature and would require additional skills and resources to embed them in council processes.

The ability of a model to generate an **uncertainty** estimate of its prediction increases its transparency. Uncertainty estimates can also help explain some of the differences between models and facilitate comparison. Of the top 24 models being used by councils, only eight provide uncertainty as a standard output parameter.[30] This may be by estimating a value for each catchment as x (value) ± y (uncertainty) – for example, a mean flow at the bottom of a catchment of three plus or minus one cubic metre per second. Alternatively, a model can be run many times in a stochastic way to deliver a distribution of possible model outcomes – for example, a nitrogen load for the catchment of between two and five kilotonnes per year.

Both approaches can be rigorously implemented by parameter estimation tools such as PEST. The fact that these models are equipped to be used in this way does not mean that this has happened in all instances where regional councils have applied them. For example, out of the 11 usages of the MODFLOW groundwater modelling suite, the use of PEST was only mentioned five times.

Model calibration against observations is another important criterion. Calibration leads to modelling outputs that are likely to be closer to the observations to which the model has been calibrated for. However, calibrating a model falls well short of providing an uncertainty estimate for the model. Since model calibration is a measure of a model fit to the observation dataset, an uncertainty estimate cannot be reliably given for catchments without observations.

Many model applications include some form of validation when their applications are described in technical journals. However, while validation might be done nationally or for few catchments around the country, validation is often lacking when councils use models to inform policies in their catchments. Such applications do not commonly predict the uncertainty associated with given estimates, and if they do, it is possibly erroneous since it was based on validation data from somewhere else.

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[29] APSIM is an open source, highly advanced platform for modelling and simulation of agricultural systems. APSIM initiative members are from Australia, the United States and New Zealand (AgResearch and Plant & Food Research). APSIM is used by two councils. For more information, see Appendices 1 and 2.

[30] MODFLOW, REC-based regressions, eWater Source, MIKE suite, FEFLOW, SCAMP-CASM, SWAT and DYRESM-CAEDYM.

A commonly agreed **computational infrastructure** for models might pave the way towards greater consensus on model use, model presentation, uncertainty incorporation and the sharing of model data.[31] More consensus on computational infrastructure would benefit transparency. Initial efforts to develop a shared model infrastructure as part of Our Land and Water Science Challenge explored the potential of interoperable tools.[32] This work revealed many barriers, which included the lack of resources available to freshwater modellers and computer scientists, and the amount of work that would be needed to harmonise many diverging models. Mirroring the daily experience of freshwater modellers in New Zealand, the interoperable models project ended up (re)describing the problem but could not finish or successfully operationalise the concept.[33]

Models are not used to their full potential

During the model stocktake and assessment, it became clear that councils are often opting to develop their own models from scratch, rather than modifying existing (or established) models to suit their local circumstances.

Of the 75 models presented in the stocktake (see Appendix 1), 45 (60%) have been developed for use by a specific council, often for a specific application in a specific location (Figure 2.7). These models have not been used by other councils. Furthermore, even within councils, these **single-use models** are rarely reused to evaluate progress and plan effectiveness or for similar applications in other parts of the region – for example, in subsequent regional plans (or plan changes).

While specificity of local conditions may, in some cases, indicate the need for single-use model development, most of the more widely used models are sophisticated and sufficiently flexible to be used in a wide variety of settings and most catchments. However, only three models (MODFLOW, SPASMO and CLUES) have been used by ten councils or more (Figure 2.7).

This finding indicates that many models are not being used to their full potential.

Council staff reported that many modelling approaches were trialled and abandoned because the models were found to be too complex or costly, or that re-running models took too long. When initial modelling was unsuccessful, council staff were then under time pressure to find a replacement and often opted for simpler models that could be deployed more quickly.

As a small country, New Zealand cannot afford to waste scarce modelling resources on multiple forays into expensive model developments, especially when suitable tools already exist. Freshwater modelling experts acknowledge this and are calling for the reuse of existing open-source models for multiple projects.[34]

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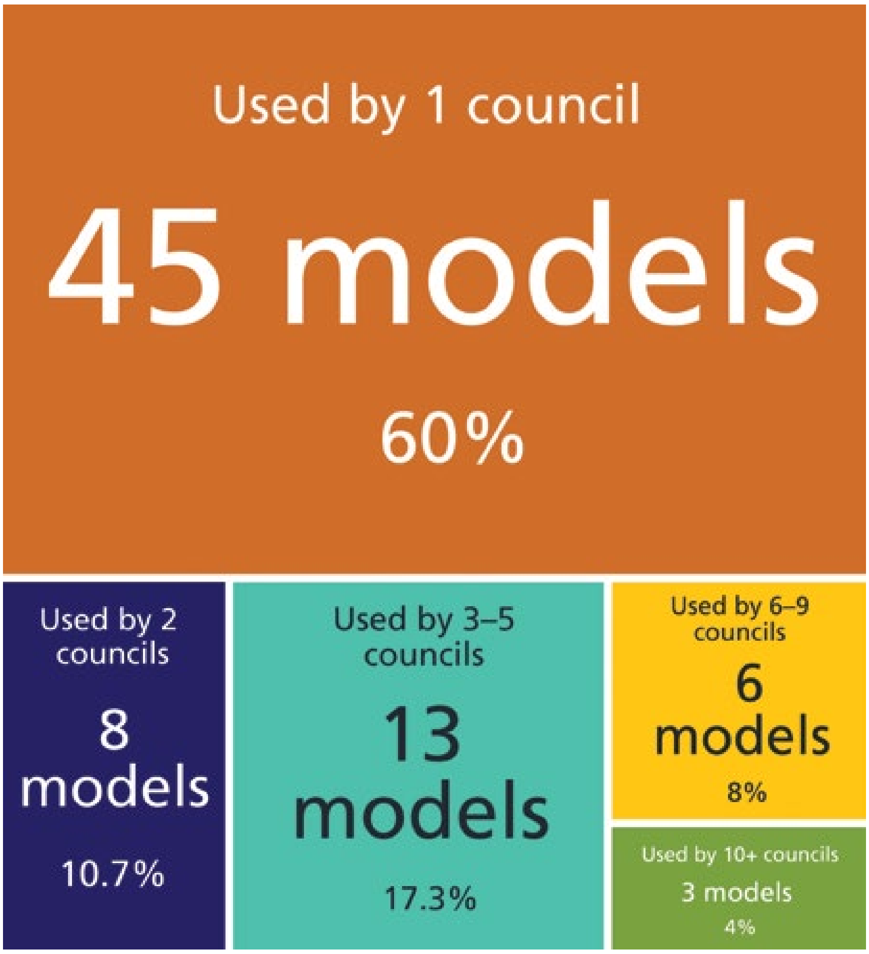
[31] Computational infrastructure means model software and hardware. Assessing computational infrastructure includes such considerations as the programming software used, whether high performance computers are required or not, whether these are implemented well, and how simple a model is to run. For more detail, see Appendix 2.

[32] Our Land and Water National Science Challenge, 2020.

[33] Elliot et al., 2020.

[34] Larned and Snelder, 2023.



Source: PCE

Figure 2.7: Shared model use across councils. A heavy share of 'single-use' models (45 models out of 75) indicates that many models are not being used to their full potential, as these models are not shared or reused across councils. By contrast, only three models are used by more than ten councils.

Tmesipteris sigmatifolia

3 How models are used

The legislative framework governing water resource management

The legislative framework governing the management of water in New Zealand is a complex one. Under the current framework, different types of water – freshwater, coastal water, flood water, drinking water, wastewater, stormwater – are managed under different regulatory instruments. However, nature does not have artificial boundaries. The different types of water are interlinked, so, for example, the management of freshwater affects drinking water and vice versa.

While requirements for freshwater are spread over many different regulatory instruments, the principal act governing water is the Resource Management Act (RMA) 1991, under which four successive versions of national policy guidance and regulation have been elaborated – the most recent iteration being the National Policy Statement for Freshwater Management (NPS-FM) 2020. An extended summary can be found in Appendix 4 for those unfamiliar with the regulatory framework.

In very brief terms, the NPS-FM 2020 required regional councils to maintain and improve freshwater quality and ecosystems and to achieve or better the national bottom-line limits for specific attributes and contaminants. To do so, the National Objectives Framework (NOF) in the NPS-FM 2020 required councils to set visions, objectives and targets for specific freshwater attributes and contaminants and set rules, limits and methods for achieving those visions, objectives and targets. Modelling can help with all of these.

The NPS-FM 2020 also erected the concept Te Mana o te Wai as a fundamental concept that imposed a hierarchy of obligations on those implementing freshwater policy.[1] However, the future use of the concept, and indeed the entire state of national direction on freshwater, is now in question given the Government's announcement in December 2023 that it intends to replace the NPS-FM 2020.[2] Notwithstanding that, it is likely that any legal framework for water management will rely on the use of tools such as modelling to support its systematic implementation.

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1 The hierarchy of obligations is (1) the health and wellbeing of water bodies and freshwater ecosystems, (2) the health needs of people (such as drinking water), and (3) the ability of people and communities to provide for their social, economic and cultural wellbeing, now and in the future. For details, see NPS-FM 2020, clause 1.3.

2 McClay et al., 2023.

The current freshwater regulatory framework forms an intricate web of policies and rules that interact with each other.[3] It is a complex system that presents challenges to both regulators and water users. No discussion of modelling can take place that is divorced from the ambitions and requirements of the legal framework currently in force. While the discussion that follows on the role of models in the policy framework is based on the legal requirements at the time of writing, it is likely to be useful in any successor setting.

The role of models in the policy framework

Given the ambitious nature of the legislation, including the NPS-FM 2020, successful implementation requires robust evidence and appropriate management tools.

The NPS-FM 2020 – the key national direction instrument on the management of freshwater – sets out ambitious requirements but does not prescribe any specific models or modelling requirements for use.

Instead, it requires the "best information available" to be used to support its implementation.[4] Clause 1.6 explicitly states: "In giving effect to this National Policy Statement, local authorities must use the best information available at the time, which means, if practicable, using complete and scientifically robust data."

It goes on to clarify that in the absence of "complete and scientifically robust data", best information can include information obtained from modelling, partial data and local knowledge. When using data, local authorities must prioritise those that have the greatest level of certainty and take all steps to reduce uncertainty.

The wording implies a hierarchy of information sources, where modelling is not as robust as data. However, models can, if used appropriately, be as robust a source of evidence as monitoring data. Modelling and observations (monitoring) are interdependent. The use of multiple lines of evidence can increase rigour and analytical strength. These points are discussed further in chapter five.

Models support a range of regulatory requirements

Given that the NPS-FM 2020 requires the "best information available" to be used to support its implementation, it is useful to examine where models can assist in providing information that plausibly meets this standard. The term 'best information' is not entirely helpful. In practical terms, most practitioners would regard the 'best' information as being the most *robust* information available.

In a number of regulatory settings models are likely to provide the most robust information on which the process for meeting a specific requirement in a consistent way can rely. In those instances, the use of models is considered best practice. The term 'best practice' is not intended to imply that models are legally required to be used; rather, it is used to denote where models are likely to provide robust evidence needed to meet a particular regulatory requirement.

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[3] In addition to the RMA and the NPS-FM requirements, at the time of writing, there are also requirements stemming from the National Environmental Standards for Freshwater 2020 (NES-F); Measurement and Reporting of Water Takes Regulations 2010 (amended in 2020); Stock Exclusion Regulations 2020; Freshwater Farm Plans Regulations 2023; National Environmental Standards for Sources of Human Drinking Water 2007 (NES-DW); New Zealand Coastal Policy Statement 2010 (NZ-CPS); and the National Policy Statement for Highly Productive Land 2022 (NPS-HPL).

[4] NPS-FM 2020, clause 1.6.

In other contexts, the use of models may be considered *useful*. Fulfilling a regulatory requirement could benefit from the use of models, but other tools and information (e.g. monitoring data, expert opinion) might be sufficient.

It is worth noting that one of the factors influencing the choice of models or other types of information is the degree of pressure on the resource. For example, where a water body is under pressure and close to a tipping point, models may provide the most robust information to test the impact of policy choices on that tipping point and assess confidence levels surrounding any predictions. However, where there is low resource pressure – for example, abundant water – other sources of information and other approaches may be considered sufficient. Where models are considered to provide the most robust information but current models are not up to the task, the case for model development becomes pressing.

The following sections analyse various regulatory requirements through the lens of how models can assist in enabling the requirements to be met, and the associated challenges.

Where water models can provide the most robust information to support regulatory requirements

Using the description above, models are considered to provide the most robust information for several regulatory requirements. These include the requirement to **identify and set limits on resource use** (as land-use controls, input controls or output controls) that will achieve target attribute states, and for any nutrient outcomes needed to achieve target attribute states.[5]

The essence of limit setting can be boiled down to predicting levels of resource use that ensure that desired environmental outcomes are achieved or that impacts on environmental outcomes are avoided or minimised. Some experts argue that "causal, predictive relationships that link levels of resource use (the causes) to responses in values (the effects)" are critical tools for this task.[6] Yet, the same experts point out that "predicting freshwater responses to resource use across the 'causal chains' that link human activities on land to freshwater ecosystems" is a significant challenge.[7]

Models are well-suited to this task as they are able to fill gaps in existing measurements and gain insights into biophysical processes. These can include identifying and accounting for the role of spatial and temporal variability ('hotspots and hot moments') in physical processes. In this way they can improve the quality of critical predictions and also identify where more data or information may be required to improve those predictions over time.

Models play an important role in limit-setting processes by allowing the repeatable, quantitative and measurable exploration of options or scenarios to contribute to informed decisions about the environmental, economic and social impacts of any limits. This is a contribution that can significantly enhance the value of expert opinions. For example, if a contaminant needs to be reduced to meet a target attribute state, models are the engine behind exploring 'what-if' scenarios that can help identify the best way to achieve that reduction.

5 NPS-FM 2020, clauses 3.12 and 3.14.

6 Larned et al., 2022, p.141.

7 Larned et al., 2022, p.141.

Source: denisbin, Flickr

Figure 3.1: Models are considered to provide the most robust information for several regulatory requirements, including identifying and setting limits on resource use. Several models were used in the catchment of Lake Rotorua (pictured here) to create a regulatory framework with nitrogen discharge limits.

Providing future outlooks and predicting future states in the absence of modelling would not be far from pure guess work. When setting resource limits, councils are required to have regard to the **foreseeable impacts of climate change**.[8] Climate change effects are broad and include not only rainfall inputs but also temperatures and river flows, which then change water demand and the types of crops able to be grown. In turn, changed water demand affects recharge (especially from irrigation). On top of those effects, sea level rise affects near-coastal water allocation as well. Only models – whether conceptual or computer-generated – can include numerous factors and their climate change impact projections in robust and evidence-based ways to help assess how future climate is likely to affect freshwater attributes or limits.

[8] NPS-FM 2020, clause 3.14(2).

Models can also provide the most robust information for **setting environmental flows and levels** and **identifying take limits**.[9] Determining water levels and flow rates that achieve desired environmental outcomes (and have certain impacts on freshwater ecosystems, species and habitat) requires a combination of monitoring data and modelling to assess impacts at different flows. Modelling can provide the most robust information to set informed water take limits as volume of take, rate of take, or both. As with the limits on resource use, predictive models can assess causal links between the amount of water allocated, taken and used and the effects on the water body and surrounding ecosystems.[10]

Assessing trends is a statistics problem and therefore almost by definition demands the use of statistical models.[11] Determining whether water quality is improving or deteriorating, investigating the causes and considering the likelihood of any deterioration continuing, its magnitude and the risk of adverse environmental effects all require the identification of trends and therefore models.

Modelling can also provide the most robust information for **freshwater quality and freshwater quantity accounting systems** that are required by the NPS-FM 2020.[12] As stated in the NPS-FM, the purpose of accounting systems is to provide baseline information (measured, modelled or estimated) to:

- set target attribute states, environmental flows and levels, and limits
- assess whether a freshwater management unit (FMU) is, or is expected to be, over-allocated[13]
- track over time the cumulative effects of activities (such as increases in discharges and changes in land use).

In particular, models can:

- estimate and track the cumulative effects of activities
- estimate the proportion of contaminant load that has been allocated
- estimate the amount of each contaminant attributable to each source
- determine whether a catchment is over-allocated (based on any particular threshold).

Further, regional councils may need to demonstrate whether **naturally occurring processes** are preventing national bottom lines from being achieved.[14] Determining the effect of naturally occurring processes requires an analysis of causes and effects. Monitoring and field observations alone will rarely be sufficient to arrive at a conclusion. Models allow repeatable scenarios and semi-quantitative approaches to be used to untangle multiple stressors and separate natural from human-induced states.

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[9] NPS-FM 2020, clauses 3.16 and 3.17.

[10] Note that the amount of water allocated is not the same as the amount actually taken at any point in time.

[11] NPS-FM 2020, clause 3.19.

[12] NPS-FM 2020, clause 3.29.

[13] An FMU is defined as any part of a water body or water bodies, and their related catchments. It is up to councils to set FMUs in their regions. FMUs are to some extent a creation of convenience, whereas a catchment is more clearly defined by hydrology.

[14] NPS-FM 2020, clause 3.32.

Another task where models can provide the most robust information is in **quantifying current contaminant loads** in a catchment, and any changes in these loads as a result of activities (including farm practice changes and land use changes).[15] Determining contaminant loads relies on modelling, since it needs to accurately integrate complex data and concepts such as the dynamics of contaminant transport and attenuation properties of the subsurface. Models also do a good job of estimating concentrations of contaminants in receiving environments when monitoring data or monitoring stations are missing. Predicting the likely effects of specific activities in terms of loads and concentrations calls for predictive tools such as models.

Table 3.1 summarises, with accompanying rationales, the regulatory requirements where the use of models is considered to provide policymakers and regulators with the most robust information.

Table 3.1: Specific water management requirements where models are considered to provide the most robust information. In this context, models are considered to offer a more robust methodology and provide robust evidence to understand the natural world, to ensure that regulatory requirements are adequately met. In other words, doing it without models is considered suboptimal and not best practice.

Regulatory requirement	Why models are considered to provide the best information
Setting limits on resource use **(NPS-FM 2020, clause 3.14) – output controls; FMUs/water bodies**	Models link resource use at sub-catchment, catchment and water body scale with environmental impacts.
Setting limits on resource use **(NPS-FM 2020, clause 3.14) – output controls; property-scale**	Models link resource use at property scale with environmental impacts.
Having regard to the foreseeable impacts of climate change **(NPS-FM 2020, clause 3.14(2)) in providing future outlooks**	Only models can include projections of climate change impacts to help provide an outlook for how future climate will affect freshwater.
Setting special provisions for attributes affected by nutrients **(NPS-FM 2020, clause 3.13)**	Models act as proxies needed to work out abundance of attributes affected by nutrients (e.g. periphyton) at any given concentration of nutrients (e.g. nitrogen and phosphorus).
Setting environmental flows and levels **(NPS-FM 2020, clause 3.16)**	Models are needed to set informed water flows and levels based on values of water bodies and ecosystems.

[15] Temporary standards for agricultural intensification and intensive winter grazing (regulations 24 and 30 in the NES-F 2020) essentially require this. The NES-F 2020 states that consenting authorities need to be satisfied that granting a consent will not result in an increase in either:

- contaminant loads in the catchment, compared with the loads as at the close of 2 September 2020, or
- concentrations of contaminants in freshwater or other receiving environments (including the coastal marine area and geothermal water), compared with the concentrations as at the close of 2 September 2020.

Note that temporary standards are scheduled to expire on 1 January 2025.

Identifying water take limits **(NPS-FM 2020, clause 3.17) – FMUs**	Models are needed to estimate the amount of water available in a water body, how much is available for use and resulting effects on water body values, including to freshwater species and ecosystems after water is taken for human use.
Identifying water take limits **(NPS-FM 2020, clause 3.17) – property-scale (resource consent conditions)**	Models are needed to estimate the amount of water available in a water body, how much is available for use by all and each of the individual takes, and resulting effects on water body values, including to freshwater species and ecosystems after water is taken for human use.
Assessing trends **(NPS-FM 2020, clause 3.19)**	Trends are defined by statistical models.
Maintaining freshwater accounting systems **(NPS-FM 2020, clause 3.29)**	Models are needed to assess whether a catchment is over-allocated (based on any particular threshold) and to estimate and track cumulative effects of activities, including water takes and land uses.
Assessing whether processes are naturally occurring **(NPS-FM 2020, clause 3.32)**	Models can separate natural versus human-induced states.
Allocating water quantity **(RMA 1991, section 30(1)(fa), and NPS-FM 2020, clause 3.28)**	Models are needed to establish how much water is available in different locations and at different times, and how much has already been allocated.
Allocating contaminant discharge capacity **(RMA 1991, section 30(1)(fa))**	Models are needed to establish the ability of a receiving environment to diffuse or absorb contaminant discharges and how much of this capacity can still be allocated (or re-allocated).
Safeguarding the coastal environment and sustaining its ecosystems **(NZ-CPS 2010, objective 1)**	Models are needed to mimic natural processes to determine cause–effect relationships and links between activities and freshwater and downstream coastal environments. This includes determining assimilative capacity of the receiving environment and practical ways to restore water quality.
Quantifying catchment contaminant loads and any changes **(NES-F 2020, regulations 24 and 30)**	Models are needed to estimate the quantum of contaminants in a catchment, including spatial variability and any changes over time.

Where water models can provide useful information to support regulatory requirements

The NPS-FM 2020 requires councils to **determine baseline water quality states** for a specified range of attributes.[16] A baseline state is interpreted as a reference point in the past (e.g. the state of an attribute on a particular date).

While requiring that the best information available at the time must be used, the NPS-FM 2020 gives preference to observed data drawn from monitoring over models.[17] The Ministry for the Environment's (MfE) 2023 *Guidance on the National Objectives Framework of the National Policy Statement for Freshwater Management* explicitly states that the "baseline state should be determined as close as possible to the location where current or future monitoring sites will be located."[18] In practice this may not always be possible, given the patchiness of monitoring stations around the country and the inherent difficulty of anticipating where future monitoring stations may be located. When monitoring data are insufficient to ascertain an attribute's baseline state, information from other sources, including local knowledge and modelling, is needed. Models can also help locate potential problem areas (e.g. hotspots), where additional monitoring stations can then be installed at strategic locations.

Setting target attribute states and identifying the site or sites to which the target attribute state applies is another regulatory requirement.[19] Target attribute states are envisaged to be stepping stones towards desired environmental outcomes and long-term visions.

The 2023 MfE guidance explicitly states that target attribute states:

> "must be set at or above the relevant baseline state … for all or part of the FMU or catchment where it has been set. It should always be set at or above the national bottom line (unless exceptions apply, see clause 3.11)."[20]

These targets can be set subjectively based on community aspirations. Models are not strictly needed for that. However, to set realistic target states, the characteristics of land use, landscape and climate parameters of an FMU need to be combined. To do this, a model is needed.

Models can help set targets based on the predicted environmental impacts of activities, assess how far towards desired environmental outcomes targets will get us, and help determine whether additional stepping-stone targets are needed. Given the issues surrounding monitoring sites, it may not be possible to arrive at targets for every identified attribute relying purely on monitoring data. In the absence of monitoring, modelling can help fill gaps to facilitate an informed target-setting process.

Target states may vary within an FMU depending on the catchment's characteristics. MfE guidance explicitly states:

> "The scale for setting [target attribute states] and limits does not have to be synched with whole FMUs. [Target attribute states] and limits can apply to part of an FMU, or the same [target attribute state] or limit may be set for multiple FMUs."[21]

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[16] NPS-FM 2020, clause 3.10.
[17] NPS-FM 2020, clause 1.6.
[18] MfE, 2023c, p.59.
[19] NPS-FM 2020, clause 3.11.
[20] MfE, 2023c, p.62.
[21] MfE, 2023c, p.53.

To illustrate the point, the guidance provides an example of a tributary that has a different ecosystem and land use from other tributaries and the mainstem of a river system, and as a result, might have different requirements for a target attribute state.[22] It would be ideal, but it is unlikely, that all tributaries in a catchment have monitoring data. Therefore, models are useful to fill in gaps at sub-catchment scale where (often) no monitoring exists.

Models are also considered useful for scenario exploration and options analyses that are needed to inform section 32 (of the RMA 1991) evaluation reports. Models (in particular, economic models) are used to quantify benefits and costs of anticipated effects on desired values (including environmental ones). In addition, models are useful for the evaluation and comparison of options, including assessing the efficiency and effectiveness of options in achieving objectives.

Table 3.2 summarises, with accompanying rationales, those regulatory requirements where models can provide useful information to assist in meeting the requirement.

Table 3.2: Specific water management requirements where models can provide useful information, meaning that fulfilling the requirement could benefit from the use of models, but other tools and sources of information (e.g. monitoring data, expert opinion) might also be sufficient.

Regulatory requirement	Why water models are considered to provide useful information
Sustainable management of resources while avoiding, remedying or mitigating any adverse effects of activities on the environment **(RMA 1991, section 5)**	Models can help assess potential adverse effects and their causes, magnitude and distribution, and can be used to test the effectiveness of management options.
Preparing evaluation reports **(RMA 1991, section 32)**	Models are used to quantify the benefits and costs of anticipated effects (including environmental). They are useful for evaluating and comparing options, including how effective the options will be.
Implementing Te Mana o te Wai **(NPS-FM 2020, clause 2.1)**	Models that support the hierarchy can help determine water quantity and quality available at various locations and under different management regimes.
Determining baseline water quality states **(NPS-FM 2020, clause 3.10)**	Models can fill gaps in monitoring data and networks, and back cast to a specific date (baseline date).
Setting target attribute states **(NPS-FM 2020, clause 3.11) – FMUs/sites**	Models help set targets based on predicted environmental impacts of activities, and on analysis of measured attribute data.
Preparing action plans **(NPS-FM 2020, clause 3.15) – FMUs**	Models can help determine the effectiveness of various management interventions in achieving desired outcomes and target states.

[22] MfE, 2023c, p.53.

Assessing whether target attribute states and environmental outcomes are being achieved and, if not, whether and when they are likely to be **(NPS-FM 2020, clause 3.30)**	Models can help assess whether an outcome or target has been met, especially via proxy indicators in the absence of direct monitoring data.
Specific water conservation order requirements that include allowed flows, contaminant loadings, temperature, pressure **(RMA 1991, sections 199–217)**	Models can help with setting informed flows, contaminant loadings, temperature and pressure.
Assessing interactions between freshwater management, urban development and land-based primary production and supporting activities **(NPS-HPL 2022, policy 2)**	Models can help assess links between water and land use.
Integrated management of freshwater, including considering land use and development effects on receiving environments **(NPS-FM 2020, policy 3)**	Models can help in building an integrated picture and evaluating effects of scenarios on desired values, targets and outcomes.
Promoting community wellbeing **(Local Government Act 2002, section 3)**	Models are useful for generating public alerts and providing an early warning system (including for physical wellbeing as a public health and safety matter). In the freshwater context, this could include providing warnings associated with swimming at popular locations.

Models can be useful at different stages of the planning cycle

In addition to meeting specific legal requirements, models can help councils to meet their general environmental management responsibilities. Regional councils are required to develop and review regional planning instruments, including objectives, policies and methods. Models play a useful role at many stages of the planning cycle, including:

- informing the development of planning instruments, including regional plans
- informing consenting
- informing compliance
- informing enforcement
- assessing plan effectiveness.

Models can also be useful for initiatives that are carried out outside of the formal planning framework and planning instruments. They can help to educate and empower people to make their own decisions.

How models have been used in a regulatory context

Use of models for different regulatory requirements

Models have been used in the context of managing both water quantity (water takes) and water quality (contaminant discharges) since the inception of the RMA in 1991 and in the context of successive versions of the NPS-FM. Table 3.3 captures model use to date and relates it to regulatory requirements that are not limited to the NPS-FM 2020.

Table 3.3: Model use for regulatory requirements by regional councils. This table captures past and current model use as well as the modelling being developed to support implementation of the NPS-FM 2020. Regulatory requirements are not limited to those from the NPS-FM 2020; they also include requirements from the RMA 1991 and other legislative instruments.

Regulatory requirement	Councils that use or have used models	Total number of councils
Implementing Te Mana o te Wai	For discussion on Te Mana o te Wai implementation and the use of models, see chapter four. For discussion of current freshwater models developed by, or in close collaboration with, mana whenua to manage freshwater, also see chapter four of this report and a separate report prepared by Taylor (2023).	–
Setting limits on resource use to manage water quality (output controls; catchment/water bodies)	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, ORC, TDC, WRC	11
Setting limits on resource use to manage water quality (output controls; property-scale)	BOPRC, ECAN, HBRC, HRC, ORC, WRC	6
Having regard to the foreseeable impacts of climate change in providing future outlooks	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Setting special provisions for attributes affected by nutrients	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, NRC, ORC, WCRC, WRC	12
Setting environmental flows and levels	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, NRC, ORC, TDC, TRC, WRC	13
Identifying water take limits (catchments)	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, WRC	13

Identifying water take limits (property-scale, resource consent conditions)	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, WRC	13
Assessing trends	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Maintaining freshwater accounting systems	AC, HRC, NRC, ORC, WRC	5
Assessing whether processes are naturally occurring	ECAN, GWRC, ORC, TRC	4
Allocating water quantity	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, WRC	13
Allocating contaminant discharge capacity	BOPRC, ECAN, ES, HBRC, HRC, WRC	6
Determining links between human activities and coastal water quality, natural conditions and states that support the ecosystem and natural habitat	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Quantifying catchment contaminant loads and any changes	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WRC	14
Establishing cause–effect relationships	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WRC	14
Exploring scenarios	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WRC	14
Preparing evaluation reports	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, NRC, ORC, TDC, TRC, WRC	13
Sustainable management of resources while avoiding, remedying or mitigating any adverse effects of activities on the environment	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Determining baseline water quality states	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, NRC, ORC, TDC, TRC, WCRC, WRC	14
Setting target attribute states (under the NPS-FM 2020 and earlier requirements)	BOPRC, ECAN, ES, GDC, GWRC, HRC, NRC, ORC, TRC, WRC	10

Preparing action plans (including under the NPS-FM 2020 and earlier requirements)	BOPRC, ECAN, GDC, NRC, ORC, TRC, WRC	7
Assessing whether target attribute states and desired environmental outcomes are being achieved and, if not, whether and when they are likely to be	ECAN, HRC, ORC	3
Specific water conservation order requirements that include allowed flows, contaminant loadings, temperature, and pressure	ECAN, HBRC Note that there are no water bodies with water conservation orders in Northland, Auckland, Waikato, Marlborough.	2
Assessing interaction between freshwater management and land-based primary production and supporting activities at a catchment level	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Integrated management of freshwater, including considering land use and development effects on receiving environments	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Promoting community wellbeing	AC, NRC	2

List of councils:

AC = Auckland Council

BOPRC = Bay of Plenty Regional Council

ECAN = Environment Canterbury

ES = Environment Southland

GDC = Gisborne District Council

GWRC = Greater Wellington Regional Council

HBRC = Hawke's Bay Regional Council

HRC = Horizons Regional Council

MDC = Marlborough District Council

NCC = Nelson City Council (does not use models)

NRC = Northland Regional Council

ORC = Otago Regional Council

TDC = Tasman District Council

TRC = Taranaki Regional Council

WCRC = West Coast Regional Council

WRC = Waikato Regional Council

The majority of the councils are using models (or have recently used them) to support water quantity management (i.e. to set environmental flows and levels or identify water take limits at catchment and property scale). Likewise, most councils are using models to establish cause–effect relationships, assess trends, and explore options or scenarios and prepare evaluation reports with those options.

More than two thirds of councils are using models to set limits to better manage water quality (i.e. to quantify catchment contaminant loads and any changes required, or to model available options to set limits on contaminants at the scale of the whole catchment). However, fewer than half of the councils reported using models to set property-scale limits on contaminants.

It is interesting to examine model use to date to support implementation of a few specific NPS-FM 2020 requirements. Of the sixteen councils, all but Nelson City Council and Marlborough District Council are using models (often alongside monitoring data) to determine baseline water quality states for some of the NPS-FM 2020 attributes. Twelve councils have reported using models to set special provisions for attributes affected by nutrients, including using national-level periphyton look-up tables.

Only five councils have reported using models as part of the requirement to maintain freshwater accounting systems. While this requirement was in place in the earlier versions of the NPS-FM, the present low use of models possibly reflects, in part, the high bar placed on the current models for robust use in accounting. Likewise, only four councils reported using models to assess whether processes are naturally occurring. Lower use of models in this case possibly reflects the novelty of this requirement.

Model use also varies among councils. While Bay of Plenty Regional Council, Environment Canterbury, Hawke's Bay Regional Council, Horizons Regional Council and Waikato Regional Council often use models in a regulatory context, West Coast Regional Council is only using a very limited number of models, and Nelson City Council has not used any freshwater models at all. This is likely a reflection of the budget of these councils and the scale and complexity of issues that require models, including the level of pressure on the resource. Further, model use may reflect the level of familiarity and experience in limit setting at regional councils. If councils have prepared previous land and water regional plans with limits on water takes and contaminant discharges, they will have experience of using models in a regulatory context and be more prepared to address any challenges that may arise. Further, at the time of writing, all regional councils and unitary authorities are working to implement the NPS-FM 2020. As many of the regulatory requirements identified in Table 3.3 come from the NPS-FM 2020, the deadline for policy implementation is likely to have influenced the use of models to date and any of the modelling work currently in progress to support regulatory requirements.

Source: Keith Murray, Flickr

Figure 3.2: Whataroa River, West Coast. The choice of models – or whether to use them at all – is determined by a range of factors, including the specific questions that need to be answered, available resourcing and expertise, confidence in using models, and previous experiences with models and other sources of evidence. For example, West Coast Regional Council is only using a very limited number of freshwater models.

Looking at model use for a small number of specific regulatory requirements (determining baseline water quality, identifying water take limits or set flows and levels, and setting limits on water quality; Table 3.4) confirms that numerous models are in use among councils. The table also confirms the high number of custom-built models that are being used by a single council.[23] The table also shows that councils are using multiple models (often overlapping or duplicating) to address the same regulatory requirement. This points to experimentation by councils in the search for a model that works best. As a result, many individual models are not used to their full potential.

[23] A significant proportion of models used for the three regulatory tasks were only used by one council: determining baseline water quality (62%, or 18 of 29 models), identifying water take limits or set flows and levels (41%, or 11 of 27 models) and setting limits on water quality (62%, or 13 of 21 models).

There may sometimes be good reasons to use a variety of models for the same task. For example, determining baseline water quality states for a range of attributes listed in the NPS-FM 2020 cannot currently be done with a single model, as different existing models are better suited for modelling specific attributes or contaminants (e.g. nitrogen, phosphorus, *Escherichia coli* (*E. coli*), etc.). Yet, at least 15 models are being used to predict nitrogen losses and movement from soil to water.[24] Similarly, in identifying water take limits, at least eight different models are being used to estimate the soil water balance – that is, to estimate how much water evaporates and how much drains down to recharge groundwater.[25] One is left wondering whether this represents the most efficient deployment of what are expensive models to operate.

Table 3.4: Models used by councils for three different regulatory requirements (see Appendix 1 for model descriptions and full names).

Requirement/ council	Estimating baseline water quality	Identifying water take limits or setting flows and levels	Setting limits on water quality, including calculating catchment loads and any reductions required
Auckland Council	• FWMT (rivers, not lakes, only for some attributes) • REC-based regression (RF models for visual clarity in rivers) • Investigating use of Safeswim for primary contact sites	• MODFLOW/FEFLOW and other water balance models to set groundwater quantity take limits • EFSAP and WAIORA to set surface water quantity limits (minimum flow and take limits) • FME (s.14.3b) model to better support surface water allocation	• FWMT to estimate relative load reductions required across various river attributes that can be modelled. • Still investigating possible use of national-scale 'look-up tables' for 'nutrient criteria'
Bay of Plenty Regional Council	• eWater Source • APSIM (as plugin to eWater Source) • CLUES • DYRESM-CAEDYM (lakes) • Lakewatch (lakes) • Bespoke water balance • ROTAN	• EFSAP • Hydrus • IrriCalc • SPASMO-IR • MODFLOW (+PEST)	• CLUES • Overseer

[24] Physiographic models, FWMT, eWater Source, APSIM, CLUES, ROTAN, SPASMO, TRIM, Overseer, SWAT, SCAMP, OLW typologies, Hydrus, MIKE suite, and REC-based regressions. This list does not include lake models.

[25] SPASMO-IR, IrriCalc, Hydrus, HYPE, SWAT, eWater Source, WATYIELD, and bespoke soil moisture balance models. The number of models could be higher, but more specific information was not given on whether other models (e.g. MODFLOW, FEFLOW, TopNet, MIKE3FM) were also used for the soil water component.

Environment Canterbury	• MODFLOW • Bespoke (spreadsheet/ geographic information system (GIS), empirical) • ELCOM-CAEDYM	• MODFLOW • Eigen • Spreadsheet • MIKE-SHE	• MODFLOW • CLUES • Overseer • Bespoke (spreadsheet/ GIS)
Environment Southland	• REC-based regressions • SedNetNZ • Estuary Trophic Index	• Hydrogeological stats • MODFLOW • NREI • AQTESOLV	• Overseer • REC-based regression • SCAMP-CASM • CLUES (estuaries and lakes) • Vollenweider lake model
Gisborne District Council	• SPASMO • REC-based regression • Periphyton guideline model	• SEFA/RHYHABSIM • IrriCalc (crop water requirements) • EFlow • NZ River Maps • FEFLOW • Conceptual water budgets • eWater Source	• eWater Source • Farm-scale *E. coli* model
Greater Wellington Regional Council	• eWater Source • SedNetNZ • Overseer • REC-based regression • CLUES • DYRESM-CAEDYM • APSIM • CLM • NZEEM	• MODFLOW • IrriCalc • TopNet • eWater Source • MIKE suite • EFSAP • SEFA • WAIORA	• CLM • MUSIC • RUSLE • eWater Source • SedNetNZ
Hawke's Bay Regional Council	• TRIM • SPASMO • Overseer • SWAT	• MODFLOW • SWAT (recharge + runoff) • eWater Source (recharge + runoff + streamflow) • TopNet (runoff + streamflow) • IrriCalc (recharge)	• TRIM • SPASMO • Overseer • Bayesian model

Horizons Regional Council	• Statistical models (REC-based RF) • Hydstra-hydrol	• SEFA/RHYHABSIM • SPASMO • Hydstra-hydrol	• SCAMP (nitrogen, phosphorus) • CLUES (*E. coli*) • SedNetNZ (sediment) (NPS-FM) • Updated REC-based national periphyton model • Overseer
Marlborough District Council	• No models used	• IrriCalc • MODFLOW	• No models used
Nelson City Council	• No models used	• No models used	• No models used
Northland Regional Council	• REC-based regression Random forest (RF) model to inform base line water quality in unmonitored reaches • Physiographic models to enhance understanding of water quality processes considering landscape and land use characteristics (e.g. high-phosphorus and volcanic geology)	• WAT (accounting) • MODFLOW • FEFLOW • EFSAP • Hunt/Theis stream depletion tools • CHES • SPASMO-IR • SEFA/RHYHABSIM • RF model for flow stats in unmonitored reaches	• CLUES to predict future state (% reduction in contaminant load under different mitigation scenarios) using REC-based RF baseline state as input dataset
Otago Regional Council	• OLW typologies • REC-based regression (RF)	• SEFA/RHYHABSIM • IrriCalc • TopNet • SWAT • CHES • GoldSim • MODFLOW • Bespoke soil water balance	• OLW typologies • REC-based regression
Taranaki Regional Council	• REC-based regression • SedNetNZ • SCAMP • CLUES	• SEFA/RHYHABSIM • NZ River Maps	• SCAMP (nitrogen, phosphorus) • CLUES (*E. coli*) • REC-based regression (*E. coli*) • SedNetNZ (sediment)

Tasman District Council	• Cawthron benthic community index model • SPASMO • REC-based regression • Ecological modelling in-house • OLW typologies	• Leathwick • IrriCalc • MODFLOW • Eigen model • WATYIELD • Bespoke water allocation model	• Eigen model
Waikato Regional Council	• CLUES • NZEEM • Overseer	• MODFLOW • FEFLOW • SPASMO • IrriCalc • SEFA • Hunt/Theis stream depletion tools • SWAT • WAIORA • Conceptual models • Soil moisture balance models	• MODFLOW • FEFLOW • SPASMO • SedNetNZ • NZEEM • CLUES • Overseer • SCAMP-CASM • SWAT
West Coast Regional Council	• REC-based regressions • National Fish IBI scores • Fine sediment calculator	• CHES • Conceptual • TopNet	• No models used

The use of models at different stages of the planning cycle

Looking at the aptness and use of models at different stages of the planning cycle provides an insight into the variability of their usage across the 16 councils. While models play a useful role at many stages of the planning process, they have predominantly been used to inform the development of regional plans and other planning instruments (Table 3.5). All councils, except for Nelson City Council, have used (and are using) models at this stage of the planning process.

Models are also used as part of the consenting process – for example, to determine activity status or specific conditions attached to a resource consent. Twelve regional councils have reported using models for consenting purposes.

Six councils have reported using models as part of a compliance package, to establish the effects basis for intervention. For example, the Lake Rotorua Nutrient Management rules in the Bay of Plenty have a compliance platform, of which model outputs is one matter to be considered. Resource consents contain actions to deliver modelled outputs, and it is these specific and measurable actions that compliance/enforcement relates to.

No councils have reported using models for direct enforcement such as breaches of resource consent conditions. Due to the need for a higher confidence threshold, enforcement is generally undertaken on the basis of actions and activities.

There are very few cases where models have been re-run to assess the effectiveness of non-regulatory programmes or to assess specific plan provisions as part of the development of new plans.[26] No councils have reported using models to formally assess plan effectiveness under the monitoring requirements or the duty to review policy statements and plans.[27] This could be explained by the fact that regional plans have not reached the end of their 10-year operative life by which time a review is required, or it could indicate that carrying out plan effectiveness reviews has been a lower priority for regional councils compared with preparing new plans.

Reusing a model as part of the assessment of plan effectiveness could provide confidence about the robustness of the plan, including specific rules, and whether desired outcomes are being achieved. Instead, staff from several councils report that many models are left to die on the shelf, never to be used again.

Table 3.5: Use of models at different stages of the planning cycle.

Stages of the planning cycle	Councils that use or have used models at that stage	Total number of councils
Development of planning instruments	AC, BOPRC, ECAN, ES, GDC, GWRC, HBRC, HRC, MDC, NRC, ORC, TDC, TRC, WCRC, WRC	15
Consenting	AC, BOPRC, ECAN, ES, GDC, HBRC, HRC, MDC, NRC, ORC, TDC, WRC	12
Compliance	BOPRC, ECAN, HBRC, HRC, NRC, WRC	6
Enforcement	None	0
Assessment of plan effectiveness	None	0

List of councils:

AC = Auckland Council

BOPRC = Bay of Plenty Regional Council

ECAN = Environment Canterbury

ES = Environment Southland

GDC = Gisborne District Council

GWRC = Greater Wellington Regional Council

HBRC = Hawke’s Bay Regional Council

HRC = Horizons Regional Council

MDC = Marlborough District Council

NCC = Nelson City Council (does not use models)

NRC = Northland Regional Council

ORC = Otago Regional Council

TDC = Tasman District Council

TRC = Taranaki Regional Council

WCRC = West Coast Regional Council

WRC = Waikato Regional Council

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26 For example, effectiveness of the Sustainable Land Use Initiative, also known as SLUI, was assessed in the Manawatū-Whanganui region.

27 For details of monitoring requirements or the duty to review plans, see s 35(2) and s 79 of the RMA 1991.

Use of models across the simplicity–complexity spectrum

Models used by councils cover the entire spectrum of complexity, from very simple models (e.g. a spreadsheet with volumes or flows of water and/or nutrients) to advanced complex numerical models that can estimate near-real-time temporal changes.

This is in principle good: Councils need access to a suite of models that cover different levels of complexity. Sometimes a simple model is sufficient, and its use may save time and money. More advanced models (and more data) might be needed to simulate a particular system behaviour not described by the simpler model, or where more difficult tasks are required or complex policies need to be considered.

Many councils are yet to find the ideal level of model complexity for their needs. Council experts indicated that most of the models in use are too simple and agree that advanced models generally offer more. However, some reported moving back to simpler models after finding that very complex models proved to be beyond what they could realistically operate. This observation is based on a snapshot in time: council perceptions of complexity are always evolving, and they are currently deeply engaged in various phases of modelling and regional planning as part of the implementation of the NPS-FM 2020 requirements. Box 3.1 illustrates the range of experiences across councils, and Figure 3.4 captures a snapshot of perceived model complexity.

Box 3.1: Council experiences across the model simplicity–complexity spectrum

Waikato Regional Council has used multiple models in the development of regional plan changes for Lake Taupō (Variation 5) and Waikato-Waipa (Plan Change 1). While the Lake Taupō plan change started with a set of relatively simple models, in Waikato-Waipa, the council used a range of models of varying complexity. The council acknowledges the need for simpler models (because they are often faster to run and easier to communicate) yet also sees the drawback that simple models oversimplify reality. By comparison, more complex models attempt to simulate processes with a greater degree of detail, often including temporal variation. Importantly, the council acknowledges the need to clearly identify, quantify and present uncertainties in an understandable fashion in all cases.

Waikato Regional Council reported a strong desire to use many models. Council scientists are comfortable using a range of models in freshwater management, with continued use of models not bound by plan change time frames. This includes the use of more complex models to better understand complex processes such as the interaction between ground water and surface water in predicting nitrate concentrations. Aiming to better assess past model use in search of better models, Waikato Regional Council is promoting a multi-evidence platform where model performance and uncertainties can be compared.

Source: Dougal Townsend, GNS Science

Figure 3.3: Lake Taupō is valued for its scenery, clean water and internationally renowned trout fishing. Concerns about increasing nitrogen loading in the lake, particularly from intensive farming nearby, led Waikato Regional Council to impose a nitrogen cap for land users in the catchment. A set of relatively simple models, including Overseer, were used to calculate nitrogen loads and targets. The cap was complemented by a nitrogen trading scheme and the establishment of a fund to help buy properties in the catchment and retire them from pastoral farming.

Greater Wellington Regional Council is an example of a council that moved from a complex modelling approach to a simpler one. The Ruamāhanga Whaitua process trialled an integrated advanced modelling approach to join several models across environmental domains.[28] However, a lack of data and technology coupled with a lack of transparency for several of the models undermined confidence in the process, which was too complex and time-consuming for the task at hand. Interdependency of the models contributed to the time-consuming nature of the process. Tight deadlines for other Whaitua processes, a loss of confidence in the first modelling approach, and a diminishing marginal information value of complex modelling saw the remaining modelling efforts default to simpler model combinations and expert panels coupled with insights from the previous work.

Environment Canterbury has used a whole spectrum of models, from very complex to more simple ones. Early attempts to use advanced integrated models for Plan Change 2 (Hinds, MIKE-SHE model) proved difficult to complete in the required time frames, and simpler bespoke models were resorted to for the plan change recommendations. Complex modelling (stochastic MODFLOW model) was used for the Waimakariri catchment Plan Change 7, where effects on drinking water in the neighbouring zone (Christchurch) were in question, and time frames were extended to complete the modelling. At the same time, simpler modelling approaches (nutrient and water budget spreadsheets) were applied in other catchments (Ōrāri-Temuka-Ōpihi-Pareora) for Plan Change 7.

[28] This included TopNet, IrriCalc, Overseer, Farmax, APSIM, MODFLOW (incl. MT3D sub-model), eWater Source and DYRESM-CAEDYM. For more information, see GWRC (2018).

The use of complex numerical models ended up causing substantial stress for council staff. Problems encountered included a lack of capacity, tight deadlines, political pressures on nutrient limit caps, and overly complex model applications. Simpler models, including nutrient and water budget spreadsheets, often proved as effective within the context of explaining possible outcomes and trade-offs to the community, and came at a much lower cost to ratepayers. Staff use the term 'horses for courses' to explain their approach to model use – that is, using a model which can best tackle the questions that need to be addressed given the time and resourcing available.

Hawke's Bay Regional Council has moved from relatively simple and opaque to advanced and fully transparent modelling. In the Tukituki catchment for Plan Change 6 (2013–2015) a relatively simple, bespoke, opaque and non-collaborative model (TRIM) was used. The shortcomings of this model, along with the adversarial nature of cross-examination of experts in a Board of Inquiry process, led the council to adopt a different approach.

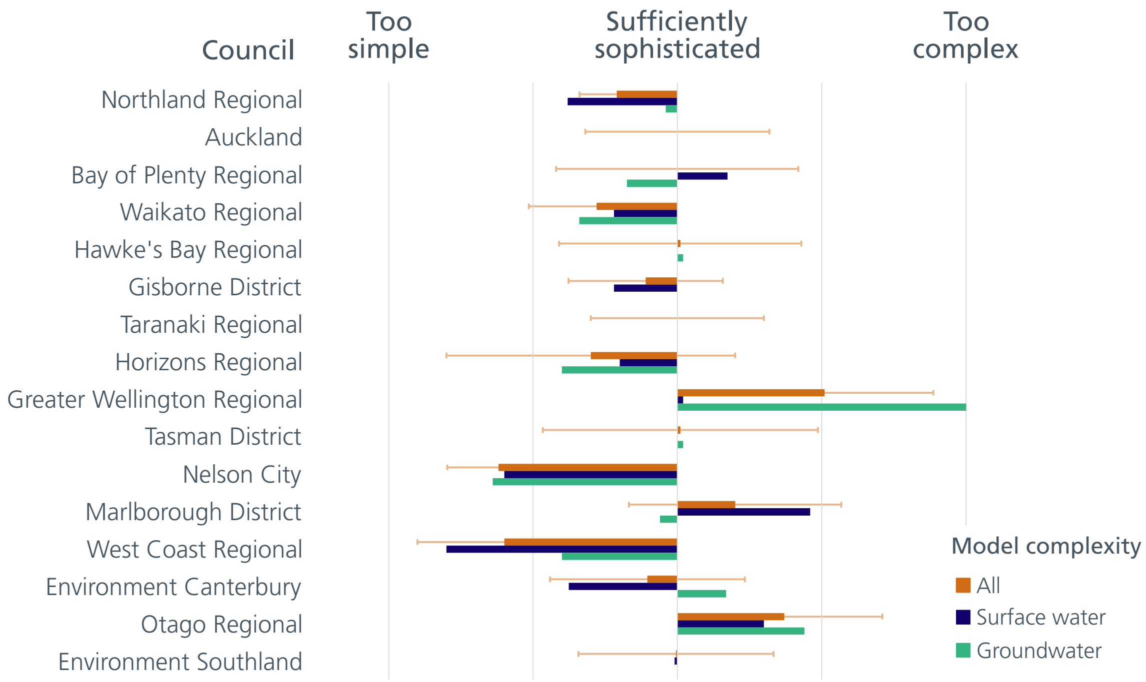
In the Tūtaekurī, Ahuriri, Ngaruroro and Karamū (TANK) catchments, Plan Change 9 was notified in 2020 and involved managing water quality and quantity. In the TANK process, Hawke's Bay Regional Council has fully committed to transparent modelling. This includes the use of advanced open-source SWAT and MODFLOW models that can simulate relevant processes and system characteristics.

There are two clear advantages to the council's open-source approach. Technically, the two models give Hawke's Bay Regional Council the means to include uncertainty and surface water and groundwater connection in their models. Socially, the use of advanced open-source models has given the council the ability to engage with the community early. Modelling 'with an open bonnet' also helped with facilitating greater acceptance of model outputs and lowering the risk of model results being challenged. However, at the time of writing, Plan Change 9 remains before the Environment Court, with 16 appeals lodged.[29]

Auckland Council is currently developing complex model approaches for both planning and operational purposes. The Freshwater Management Tool (FWMT) and Safeswim (used for swimmability warnings on beaches) are highly complex models, but, at least so far, there have not been any adverse results that have tempered enthusiasm for the models. Questions have been raised, however, regarding whether the costs of the models are justified.

West Coast Regional Council and **Nelson City Council** reported (almost) no model applications. A lack of resourcing and a lack of budget (due to the small ratepayer bases) pose challenges.

[29] Several iwi are among the appellants. See Taylor (2023) for further details on the engagement with mana whenua in the TANK catchments.



Source: PCE

Figure 3.4: Results of a survey of perceived model complexity across councils. Deviation from the ideal 'sufficiently complex' data point. Information was compiled using input of both surface water and groundwater experts. Error bars indicate uncertainty and show estimated standard deviation. The questions included "In general, do you think current applications of surface water models within the council are too simple or too complex?" Respondents could choose a value on a slider between 'too simple', 'sufficiently sophisticated' and 'too complex'. A follow-up question gave the option for elaboration with "Do you have any thoughts on how to get to a desired state of 'sufficiently sophisticated' models?"

Challenges associated with model use in a regulatory context

Regional councils are grappling with new requirements and the use of modelling to support them

The NPS-FM 2020 requires that the best available information is used but does not prescribe any specific models or modelling requirements for use. As a result, debates are taking place about what represents the best information given the outcomes that are being sought. In many cases, council staff are leaning towards using a mix of monitoring data and modelling outputs, with the use of models dependent on the requirements at hand. Any changes to the NPS-FM 2020 will no doubt prolong these debates. However, it is worth emphasising that robust models and data will be needed *regardless* of the policy framework. While models cannot make decisions for decision makers, they can assist the exploration of options and associated consequences, and illustrate the possible implications of any regulatory interventions.

The choice of models – or whether to use them at all – is determined by a range of factors, including the specific questions that need to be answered, available resourcing and expertise, confidence in using models, and previous experiences with models and other sources of evidence.

Source: Anna Hooper, PCE

Figure 3.5: Rangitīkei River flows through the Manawatū-Whanganui region. Horizons Regional Council is one of the councils that often uses models in a regulatory context.

As discussed previously, for some regulatory requirements models will be likely to provide the best information to support a robust and consistent process to ensure that a specific requirement is met. An example is limit setting. This involves defining the capacity of the environment to assimilate contaminant loss and water use and then establishing limits to ensure that capacity is not overwhelmed. Robust models will be an important component of this type of policy implementation.

The NPS-FM 2020 places a higher information requirement on science than its predecessors and the integration of other sources of information needed to support its successful implementation.[30] This includes better data, better models and better integration of models than currently exist.

Modelling at multiple scales presents its challenges. At present, the ingestion of property-scale information into catchment-scale models can be computationally challenging and is further hampered by data availability and accessibility.

While many models currently exist, huge uncertainty remains in predicting freshwater responses from resource use at the property scale all the way down to water bodies at the bottom of the catchment. That is mostly because a robust 'causal chain' of multiple models, which is needed to simulate effects from properties to receiving aquatic ecosystems, is lacking.[31] Models that are available to estimate parts of these causal chains lack transparency – for example, Overseer and SPASMO, which attempt to estimate the impact of resource use at property scale.

Further, a lack of agreed models capable of being coupled for use in this causal chain modelling risks inconsistency of model outputs (e.g. Box 2.1 explained the challenge between joining up statistical models that estimate current water quality and models that explore scenarios as part of the limit-setting process). Joining up these models, or their outputs, is not a straightforward task.[32]

Several freshwater modelling experts summarised it well when, in the context of the NPS-FM 2020, they concluded that while environmental modelling is challenging and some tools may be outdated, these tools are needed to implement policy, and scientists and modellers need to up their game.[33]

Thin resourcing risks the sustainability of individual models

Given that New Zealand is a small country, it is perhaps not surprising to encounter a concern among council staff about resourcing. When surveyed, staff from all councils signalled a shortage of freshwater scientists and a significant lack of inhouse technical modelling skills.[34]

Faced with a lack of inhouse skills, councils are often forced to subcontract much of their modelling work to external providers. But not all councils have the financial resources to do so. In these cases, councils tend to make decisions based on the observations and data at their disposal. If these data are sparse, and they often are, the resulting decisions can lead to suboptimal outcomes – be that for those who are regulated, or for the environment.

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[30] Mātauranga Māori is also needed to implement Te Mana o te Wai.

[31] Larned et al., 2022.

[32] For example, the Our Land and Water National Science Challenge project 'Interoperable Models' highlighted many challenges, including both technical issues and practical constraints. See Elliot et al. (2020).

[33] Larned et al., 2022; Larned and Snelder, 2023. This was also reaffirmed in conversations with regional council experts and modellers across the sectors undertaken for this investigation.

[34] Members of the regional sector's two special interest groups – Groundwater Forum and Surface Water Integrated Management – were asked to indicate how many surface water and groundwater scientists and modellers they thought were available at their councils.

The overall shortage of skills means that model development and application is often left to one staff member within a council. Similarly, if the work is subcontracted out, it will often be undertaken by a consultant whose model is only developed or maintained by a single person.

Reliance on a single person – whether a researcher, consultant or council staff – poses challenges.

- Solo model development means that only one person has comprehensive knowledge of the model's workings and limitations arising, for example, from the way scientific hypotheses and assumptions are coded. This can be exacerbated by a lack of documentation and poor access to the software by third parties.[35] It can be challenging for one person to detect their own errors and may result in model software quickly becoming outdated. At a minimum, a succession plan is needed to ensure model longevity, but such plans are rarely in place in models reliant on a single person.
- Model application has similar challenges. Much is at stake if only one person is familiar with the model, its inputs, the scenarios that have been explored, the assumptions and limitations that have been applied, and its particular application. Should that person leave the job, there are serious challenges for any newcomers seeking to use or reuse the model.

These challenges are key factors behind the low reuse of models, including their reuse to assess whether policies, plans and on-the-ground actions are on track to achieve desired environmental outcomes. Limited resourcing makes the need for more collaboration urgent. Models developed in collaboration have the added advantage of usually being more transparent, since the partners are working in the same environment.

Collaboration is key, but barriers still exist

During the engagement undertaken for this investigation, model experts have overwhelmingly reported that current model development is siloed and fragmented. It is not a problem if models are developed by different developers (e.g. Crown Research Institutes (CRIs), consultants, universities or regional councils) as long as this is done in a collaborative atmosphere.

A collaborative effort in comparing and combining the model equations could help reduce the number of models being used. For example, the developers of REC-based regressions and SCAMP models provide a good example of collaboration. By using each other's approaches and data, they ensure congruent results between model applications.

However, collaboration efforts are hindered by the fact that model development often takes place in isolation inside different institutions, and there is often a strong reluctance to share model codes. In the case of CRIs, an explanation for this behaviour suggests itself. The statements of core purpose, which spell out each CRI's individual scope of operation, make it clear that all seven CRIs contribute to freshwater management, and all can legitimately claim leadership of specific areas of science and research that (partly or fully) cover the freshwater domain (Table 3.6). This in itself is not surprising, and the overlaps justify a collaborative approach.

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[35] The SPASMO model is a case in point.

However, in practice, collaboration has suffered at the hands of a competitive desire to 'own' an environmental domain. The result has been the development of competitive models. For example:

- The National Institute of Water and Atmospheric Research (NIWA) and Manaaki Whenua – Landcare Research (MWLR) have developed competing sediment models.[36]
- NIWA, MWLR, GNS Science and Plant & Food Research have each developed different models for the same process of soil drainage.[37]
- Besides GNS Science and the Institute of Environmental Science and Research (ESR), NIWA has also recently started to develop groundwater flow models.[38]

In my view this is not primarily the fault of CRIs. Rather, it is a direct consequence of the way the Government makes its research investments. As the principal funder of public good science, the Government is in a position to influence the level of collaboration and model duplication. However, it has been myopically focused on competition for resources. While it would be foolhardy to dismiss the value of innovation through competition, when public money is being spent to maintain and extend something in the nature of a public good such as modelling capability, the Government should be prepared to exercise better oversight to ensure that scarce resources are used to best effect. It should require collaborative engagement in modelling as a condition of funding. Modelling experts interviewed for this review frequently remarked that better collaboration between modellers would be desirable, and the idea of a national 'pool of modellers' was floated.[39]

Whatever the relative contribution of these problems, it is clear that the current approach to model development is not leading to well-supported, collaborative modelling work or leading to more transparent models. This contrasts with the international modelling experience, including in the Netherlands, the USA and Australia (see Appendix 3 for details).

[36] NIWA developed NZSYE. MWLR developed NZEEM and SedNetNZ.

[37] NIWA developed TopNet. MWLR developed WATYIELD. GNS Science developed a water balance model and the National Groundwater Recharge Model. Plant & Food Research developed SPASMO.

[38] NIWA has recently started developing several models, including a streamflow depletion model that aims to simulate streamflow depletion due to both surface and groundwater abstractions, and TopNet for groundwater (TopNet-GW). For more information about the models, see NIWA (2023), Griffiths (2023) and Yang (2023).

[39] The idea came from engagement and workshops with modelling experts undertaken for this investigation.

Table 3.6: Extracts from the statements of core purpose for each CRI, including outcomes and scope of operation (i.e. research areas) relevant to freshwater.[40]

CRI	Relevant outcomes	Primary research area (CRI is the lead)	Secondary research area (CRI is a contributor)
AgResearch	Position New Zealand as a global leader in the development of environmentally sustainable, safe and ethical pastoral production systems and products; increase the capacity of rural communities and enterprises to adapt to changing farming conditions in ways that balance economic, environment, social and cultural imperatives.	Pasture-based animal production systems; integrated social and biophysical research to support pastoral sector development	Freshwater management
ESR	Improve the safety of freshwater and groundwater resources for human use and the safer use of biowastes.	Impacts of the environment on human health, including groundwater, fresh and drinking water quality and safe biowaste use; integrated social and biophysical research to support decision making in the environmental, public health and justice sectors	Freshwater management
GNS Science	Improve the sustainable management of and increase economic returns from groundwater resources.	Groundwater processes and quality	Freshwater management
MWLR	Achieve the sustainable use of land resources and their ecosystem services across catchments and sectors.	Catchment-level ecosystems (including wetlands) and related ecosystem services; land cover, land-use capability and effects, and spatial land information that integrates across sectors and scales; soil characterisation, processes and services	Freshwater management

[40] New Zealand Government, 2010a, b, c, d, e, f, g. Statements of core purpose, released by the Research, Science and Technology Minister in November 2010, set the roles of each CRI. Mapp, 2010.

NIWA	Increase economic growth through the sustainable management and use of aquatic resources; enhance the stewardship of New Zealand's freshwater ecosystems and biodiversity.	Aquatic resources and environments (with a focus on surface freshwaters and coastal environments)	Freshwater management
Plant & Food Research	Sustain growth in New Zealand's horticultural and arable sectors driving ongoing efficiency gains with the development of environmentally resilient production systems.	Sustainable production and processing systems for the horticultural and arable industries	Freshwater management
Scion	Enhance New Zealand's opportunity to benefit from forestry-based ecosystem services to improve both the global market position of industry and the environmental sustainability of forestry production in New Zealand.	Sustainable forest management and tree improvement; forestry and forestry-based ecosystem services to inform land-use decision making	Freshwater management

Data shortcomings affect models

Models are an extension of data, so any shortcomings with data are carried over into models. Robust data, like models, should be openly (or at least easily) accessible and up to date, and be supported by appropriate documentation, information on provenance and in a format for efficient incorporation into models. However, known data shortcomings include data paucity and data accessibility.

Data paucity limits the robustness of models

A shortage of data affects models. Without robust data there will be no robust models.

Experts within councils generally agree that there is a shortage of data in the form needed for freshwater policy and planning purposes (Figure 3.6). The view is that, despite some recent improvements, databases within councils are still piecemeal and disconnected. Explanations include the following.

- Connections between individual consent records, catchment-scale allocated volumes and those applying freshwater models are poor.
- Regional councils are struggling either to keep a record of land use data over time, or to access their own consenting databases (or those of district councils) for use in modelling.
- A lack of common data standards is making incorporation of these data into models prone to error, despite an improvement in water metering data recording to better estimate actual water use (rather than allocated amounts).
- There is a lack of transparent, property-scale data on contaminant inputs. In the absence of any alternatives, councils continue to use Overseer and SPASMO, which use underlying data that are often neither accessible nor verifiable.

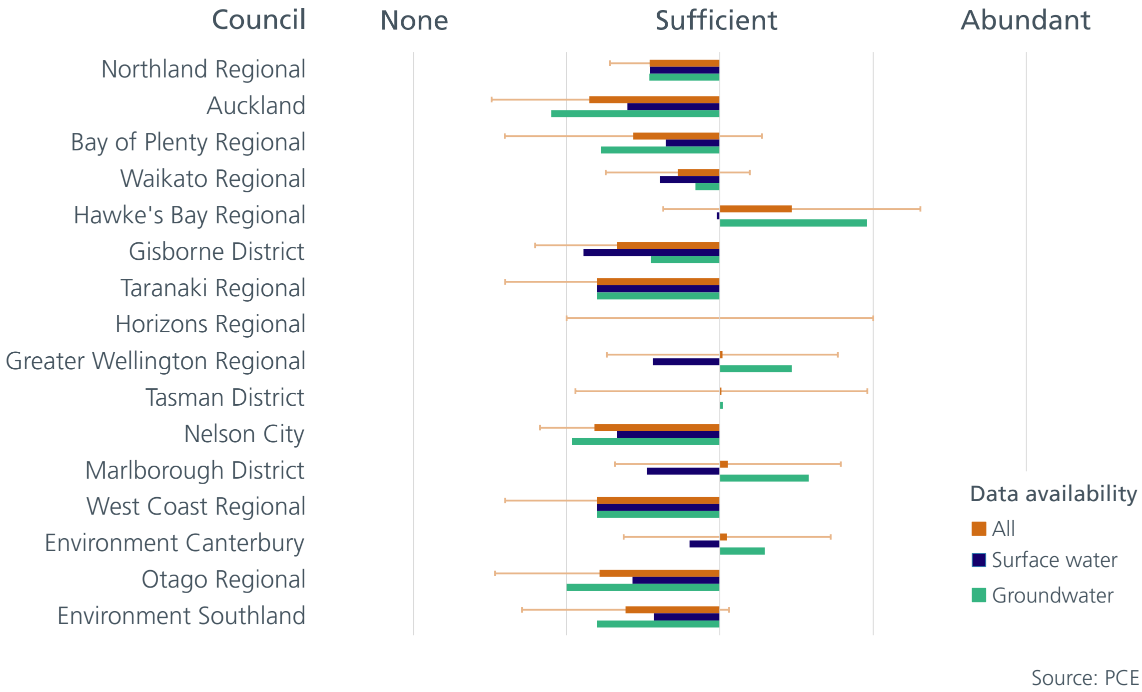

Figure 3.6: Freshwater data availability across councils. Deviation from the ideal 'sufficient' data point. Information was compiled using input of both surface water and groundwater experts, mostly through questions in an online survey and council meetings. Error bars indicate the uncertainty and show estimated standard deviation.

Data that exist are often difficult to access, hindering transparency

Another known shortcoming is limited data accessibility, which is hindering transparency.

Earlier reports have already outlined that much of New Zealand's environmental data are not openly accessible or have limited accessibility.[41] For example, much data on farm management and many estimates of nutrient loss to our water are owned by the farming industry. Data on soil, flow and climate are not shared with regional councils in a forthcoming way by CRIs. Regional councils do not routinely share information between one another. Further, different types of data (including freshwater data) are not stored consistently in databases. As a result, retrieving and formatting data for modelling requires far more effort than it should.

Data that sit behind models suffer from being not accessible, not synchronised across models or not easily updateable. With limited data available, modellers have to work with whatever is at hand. As a result, there is a risk that data from different time periods with different degrees of uncertainty relating to different digital river networks are scrambled together without a proper awareness of the congruence of the various datasets being assembled. If the data being used are incongruent, there is an increased risk of model incongruence.

[41] PCE, 2019, 2020, 2022.

An example is the River Environment Classification (REC), which can be described as a 'catchment typology' – that is, a categorisation of a catchment into general descriptors (e.g. terrain, climate, soil, geology, land use and streamflow). The latest version of REC data (v2.5) is openly available and is used frequently in models. Predictions of hydrology for REC catchment typologies use streamflow data that are based on the average calculated over the 1960–2001 period.[42] Land cover is based on LCDB5 (data from summer 2018/2019). Soil and geology are from a 2000 land resources inventory. And climate data are drawn from a 2011 assessment. Models that use REC to derive nutrient loads from a period around the early 2000s could expect errors from the slightly different periods from which these are drawn.[43] Recent studies using more up-to-date nutrient concentration observations may also experience a skew due to misalignment of input data timeseries, as older data were used as the basis for establishing a relationship between nutrients and REC attributes.

More up-to-date data are available – for example, geological data from QMAP.[44] However, up-to-date soil data and recent climate data are held by CRIs and are usually only available on request. Recent streamflow data from TopNet are also not publicly available (again, sometimes on request) and have been developed using a digital river network that is different from the REC2.5 network.

Many councils are not satisfied with either national digital river network, and are hiring consultants to develop better digital networks for their regions. While this illustrates dissatisfaction with the quality of data, it is also linked to data accessibility. While specific data of higher quality may not be consistently available nationally, it may be available for one region and accessible to a specific consultant developing a better digital river network. However, a multiplicity of digital river networks makes any study based on REC subject to an unknown yet possibly large uncertainty.

Typologies describing variation in land use and land 'type' that are linked to estimates of contaminant losses are also used on smaller scales (e.g. farms) to describe land characteristics across the nation. Categories in these typologies include land uses (e.g. dairying, native forest or urban), climate (e.g. wet, dry), and topography (e.g. steep, flat). However, these typologies are inconsistent, mainly because their underpinning data varies. A 2023 study showed that three recently developed farm typologies led to substantial differences in nutrient loss prediction estimates in catchments, with differences of at least 33% for nitrogen and 66% for phosphorus.[45]

Sporadic attempts to improve access to environmental data have been made over the years. In 2014, the Land, Air, Water Aotearoa (LAWA) initiative was launched to provide more consistency on data provision across councils. This has resulted in an attractive web interface for the public to interact with some regional environmental data. However, it falls well short of what is needed. LAWA was never designed to provide councils with a place to store or share data, and it is therefore not a comprehensive database, although it might appear as such. Neither does it provide councils with tools or guidance to make databases across councils more consistent. Had LAWA been designed to include these capabilities, it could have been a much more useful and serious tool for councils.

[42] Woods et al., 2006; Snelder et al., 2018.

[43] Snelder et al., 2018.

[44] The quarter million mapping programme run by GNS Science. For details, see GNS Science (no date).

[45] Snelder, Cox et al., 2023.

Generally, councils hold their own data in their own databases and on websites to inform the public about water in their regions. While most councils use LAWA, not all of the locally held data are on LAWA.[46]

Additional tools are used by some councils. For example, Auckland Council uses the Safeswim website, which uses models to provide beachgoers in the Auckland Region with more up-to-date information on swimmability, including risks and hazards.[47] Another website that aims to display groundwater wells data (physical bore log data) across different regions is Wells Aotearoa New Zealand. However, at the time of writing, the website is only displaying data for two regions.[48] Given the experience with LAWA, the custodians of Wells Aotearoa New Zealand need to make a more convincing case to councils on the benefits of consistent data visualisation and sharing across the country.

Other valuable freshwater data are available in maintained and long-term national databases such as the National Groundwater Monitoring Programme and the National River Water Quality Network. Prioritisation of these programmes falls under the umbrella of two CRIs. This is advantageous since it has resulted in long-standing datasets that are consistent across the country. These data are therefore often used for a variety of purposes, such as state and trend of environment assessments and research.

However, current arrangements have their drawbacks. Funding to platforms in charge of such datasets comes from the Ministry of Business, Innovation and Employment's (MBIE) Strategic Science Investment Fund, which has largely remained static over many years. In the case of the National River Water Quality Network, as a result of this financial strain and in agreement with MBIE and local government agencies, NIWA has reduced the number of sites it operates. NIWA now operates 42 of the original 77 sites established in 1989 and is about to discontinue or transfer to regional councils another 30 monitoring sites, keeping charge of just 12 sites. The corollary is that regional councils will be asked to fund locally a greater share of a network that has national benefits. Relying on regional authorities may place the long-term funding of the network at risk and may increase data inconsistency across the country. If anything, the resources of the regional councils are even more stretched than CRIs'.[49]

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[46] PCE, 2019; Moreau, 2023.

[47] For details, see https://www.safeswim.org.nz.

[48] At the time of writing, the website is displaying data for Waikato and Otago. Two other councils (Auckland Council and Environment Canterbury) are currently working on data integration. For details, see https://wellsnz.teurukahika.nz.

[49] PCE, 2019, 2022.

Source: Charlotte Lee-Smith, PCE

Figure 3.7: One of the current 42 National River Water Quality Network sites for monitoring water quality is on the Hutt River Te Awakairangi.

Asplenium polyodon

4

Māori models

Models that illustrate a te ao Māori view

A model developed from a te ao Māori view will look very different to one developed from another worldview. They are more holistic, going beyond biophysical parameters to encapsulate social, cultural, economic and relational parameters; the physical and spiritual realms; and socio-political parameters like kaitiakitanga and rangatiratanga.

Models are used widely by Māori. They are based on extensive observations and made the predictions necessary for safe trans-Pacific navigation possible, as well adaptation to the new environment that was Aotearoa.

Whakapapa is the basis for te ao Māori models. Whakapapa makes sense of the connections between all things and how they interact, thus allowing experts to predict an outcome based on the understanding of those interactions. For example, for some iwi, in simple terms Te Ihorangi is an atua of rain and ancestor of īnanga. This connection is made because we know that when the heavy rain season occurs, īnanga start migrating to estuarine environments to spawn.

The maramataka (Māori calendar) is a model. The observation of stars, the moon and sun during the year help Māori predict when certain species are active and thus able to be hunted, when plants should be planted or harvested, and what weather conditions might follow in the new year or seasons, to prepare for or avoid hazards. The maramataka also goes beyond the physical into the spiritual connection between celestial bodies, people and taonga species.[1]

Observations of certain tohu (indicators) were also used in a predictive way. For example, there is a saying that when the kōwhai is in bloom, the kina are fat, and so, it is time to go diving for them.

1 Harris et al., 2013; Clarke and Harris, 2017.

Although founded on the same principles, Māori models are highly variable across the nation. Many hapū and iwi have developed tools using current biophysical models. Others have noted that these models are unable to incorporate all of what is known of the world from a te ao Māori perspective. More all-encompassing models have been developed to illustrate the holistic way in which the world is viewed – for example, through whakapapa and the responsibility of care that people have with water. Many are reclaiming their mātauranga Māori that was lost due to colonisation. Tools that were used to make predictions are being revitalised or reshaped in light of an inherent need to reconnect with the taiao and reawaken their kaitiakitanga. An added benefit is that these tools can also be used to respond to new pressures and regulatory requirements.

Models are being developed as a useful decision-support tool with relevant inputs to assist hapū and iwi in decision making. To be relevant for Māori, models need to illustrate the way the world is observed and encapsulate everything that is important to them. Biophysical data will be an important input, but a cultural lens will rearrange what is important and to whom. The use of Māori models requires a good working relationship between mana whenua and regulators and cannot be used independently of this relationship.[2] Ontologies like te ao Māori define the creation of a model, its inputs, and ultimately how the model represents a certain reality.

Implementing Te Mana o te Wai and the use of models

The National Policy Statement for Freshwater Management (NPS-FM) 2020 is ambitious as it tightly links resource use to the mauri of freshwater (Box 4.1). It also incorporates Te Mana o te Wai as the fundamental concept. In December 2023, the Government signalled that it will replace the NPS-FM 2020.[3] This may include changes to the Te Mana o te Wai provisions, including the hierarchy of obligations. The discussion that follows proceeds on the basis that the concept will continue to play a key role.

Put simply, Te Mana o te Wai re-deals the cards in favour of the environment, as it outlines the following hierarchy of obligations:

- first, the health and wellbeing of water bodies and freshwater ecosystems
- second, the health needs of people (such as drinking water)
- third, the ability of people and communities to provide for their social, economic and cultural wellbeing, now and in the future.

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[2] Taylor, 2023.

[3] McClay et al., 2023.

In its literal sense Te Mana o te Wai means the authority or sovereignty of the water. It is about the protection of mauri and restoring and preserving the balance between water, the wider environment and the community. Given the imbalances that are evident everywhere – beaches and rivers that are not swimmable, water that cannot support diverse life forms – it is hard to see how any national policy statement for freshwater management could not seek to rebalance things in favour of te mana o te wai. Certainly, from the point of view of Māori, the health of our water goes to the heart of article 2 of the Treaty of Waitangi, and no future management regime will be able to disregard this.

A mātauranga Māori expert group has explained that "Te Mana o Te Wai represents a paradigm shift":[4] The health of the environment needs to be provided for first, human health second and social, economic, and cultural wellbeing third. As the implementation of Te Mana o te Wai is relatively new for both regulators and Māori, it poses some practical challenges, like deciding how and when to use science and mātauranga Māori together or separately; and where models might fit. Implementation will require data sourced from te ao Māori and the continued involvement of mana whenua, who hold these data.

Box 4.1: Mauri

Even though the use of a concept like Te Mana o te Wai is relatively new, the use of mauri as a measure is not.

Mauri (life essence or life force) is a fundamental concept in te ao Māori and is included in the description of Te Mana o te Wai. It is a flow between all things: people, the environment, and the metaphysical. It tells us the quality of that flow based on the component parts' interactions. If the mauri is strong, then all things connected to it will flourish. If it is degraded or weak, then it requires a rebalancing to restore that connection.[5] When mauri is diminished, the mana of the connected components is diminished (Figure 4.1).

Mana and mauri coexist; hence mauri plays a definitive role in the concept of Te Mana o te Wai in the NPS-FM 2020. Models being used to support the NPS-FM 2020 therefore need the ability to include the state of mauri and how it relates to the mana of the wai.[6]

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4 Poipoia, 2022a, p.10.

5 Taylor, 2023.

6 Taylor, 2023, pp.16–20.

Source: Sebastian We, Flickr

Figure 4.1: Mauri (life essence or life force) is a fundamental concept in te ao Māori. If the mauri is strong, then all things connected to it will flourish. Te Puna Waiora o Te Waikoropupū Springs, pictured here, are considered to have strong mauri, as the springs contain some of the clearest water in the country and were traditionally used for healing and ceremonial blessings. They are a taonga and wāhi tapu to Māori. A water conservation order was put in place in 2023 to protect the springs.

Te Ao Māori models and Te Mana o te Wai

A report on Māori models and Te Mana o te Wai commissioned for this investigation found that many whānau, hapū, iwi and Māori groups are already using a combination of traditional and contemporary tools and models to assist them in influencing water management in their rohe. A stocktake of Māori models identified 33 models that had either been developed by Māori or in collaboration with Māori.[7]

As yet, none are in use by councils to support the full implementation of the NPS-FM 2020, and most have not progressed past the pilot stage. This is due to the relative novelty of NPS-FM 2020 requirements, and a lack of understanding by councils of the obligation to involve tangata whenua (to the extent they wish to be involved) in various aspects of freshwater management (including decision-making processes). In cases where support from councils has been re-prioritised, some Māori groups have picked up the responsibility for water modelling themselves.[8]

[7] Taylor, 2023, pp.26–38.

[8] For example, in the Mōhaka and Waihua catchments. For details, see Box 4.2 of this report and Taylor (2023, pp.66–78).

Some of the models are, however, in use at different stages of the planning cycle. For example, the Kaitiaki Flows model developed by Ngāti Rangiwewehi (Box 4.2) is in use for resource consenting purposes but has yet to inform policies and rules as part of the National Objectives Framework (NOF) implementation.[9] While conceptual models have been developed and used by numerous Māori practitioners and kaitiaki to better understand and articulate the nature of a water body, local mātauranga and ways the water may be impacted, there continues to be a disconnect between the models and the influence of tangata whenua on freshwater management.[10]

Although councils are not currently using Māori models to implement the NPS-FM 2020, existing Māori models are adaptable and could be used for this purpose. For this reason, the stocktake included an analysis of whether these models could be used for implementing the NPS-FM 2020.[11] The criteria used to assess these models were:

- the hierarchy of obligations underpinning Te Mana o te Wai
- the six Te Mana o te Wai principles
- the five requirements for regional councils when implementing Te Mana o te Wai.[12]

These criteria were used as part of a traffic-light system where green suggests that the model aligns well with the criteria, while red indicates that the model does not. The stocktake also included information on spatial scale, model type (quality, quantity or both), stage of development and key drivers.[13]

Eight models were considered 'good' or 'green' but only three of these were in use. Two in this category were specifically focused on Te Mana o te Wai and seemed to be relatively sophisticated, although they were in development. One example is the Ōtākaro Digital Twin model, which uses diverse data inputs like ecological parameters, infrastructure, mahinga kai and climate change. It then incorporates the principles of Te Mana o te Wai and scenario simulation into its decision-making processes.[14]

Five models were classified as average to poor. This was due to a lack of involvement of mana whenua in the development and application of the models.[15] In addition, in some cases, when the development of the models was Māori-led, there was limited consideration of how model governance would be implemented by councils, the wider community, or stakeholders, which resulted in very limited model use.[16]

Nineteen models, where mana whenua were involved in model development to some extent, were assessed as average. As most of these models were developed before the hierarchy of obligations was introduced, they did not meet this criterion.[17]

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9 See Box 4.2 of this report and Taylor (2023, pp.51–65).

10 Taylor, 2023.

11 Taylor, 2023, pp.26–38.

12 NPS-FM 2020, clauses 1.3(5), 1.3(4) and 3.2(2).

13 See the full stocktake prepared by Lara Taylor, available on the PCE website.

14 Rokohouia Digital Twin model was the second example. For more details, see Taylor (2023, pp.27–32).

15 Taylor, 2023, p.27.

16 Taylor, 2023. p.27–29.

17 Taylor, 2023, p.27.

Three case studies provided more in-depth information about the Māori-centric models and illustrated the complexity of model development with mana whenua, as well as identified best practice (see Box 4.2).[18]

All mana whenua developed freshwater models identified in the research included mauri as an underpinning principle. If contemporary biophysical models are used, it needs to be clear which biophysical component is being used, what environmental aspect or process it is trying to simulate, and how it aids in the assessment of mauri.

Further work is needed to improve the use of these models and best practice in developing them between councils and tangata whenua. Māori models that were not specifically developed for Te Mana o te Wai need additional work to meet this requirement, and other models need work to improve their usability when implementing Te Mana o te Wai in close and early engagement with tangata whenua.[19]

Box 4.2: Freshwater models developed by mana whenua

The case studies profiled here are examples of where mātauranga Māori can (potentially) successfully contribute to regulatory processes. These examples were chosen from a much longer list of 33 mana whenua developed freshwater models.[20]

The approaches taken by mana whenua are diverse and specific to their unique relationship with landscapes and with those who live within and manage the catchment in their rohe. However, it is only through true partnership where mana whenua are able to express their tino rangatiratanga and kaitiakitanga that model development can effectively produce a tool that works for them.

Kaipara Moana Remediation

The Kaipara Moana Remediation programme is centred around the remediation of sedimentation from land use in the large catchments that drain into the Kaipara Harbour. A strategic partnership arrangement between Kaipara Uri hapū and iwi entities, Auckland Council and Northland Regional Council established the programme in response to the declining health of Kaipara Moana.

The programme has been designed to make better environmental management decisions by developing models. It draws on several information sources, including mātauranga Māori, science, and landowner knowledge to identify solutions that will be needed to implement the NPS-FM. Three models are being developed as independent tools but are interrelated and inform each other. Although not specifically developed for the implementation of the NPS-FM 2020, with some modifications they could be used in this way. These models are Tātaki Wai, Kōrero Tuku Iho and Mātai Onekura.

[18] For more details, see Taylor (2023).

[19] Taylor, 2023, pp.85–110.

[20] For more details on the three case studies, see Taylor (2023, pp.39–83).

Tātaki Wai is a model based on water quality management science across the whole catchment. Tātaki Wai came from an open-source model but went through an assessment by an independent expert panel to confirm that it could be used for decision making in the Kaipara. Its main purpose is to identify where to prioritise efforts to reduce sediment and erosion across the whole catchment.

The Kōrero Tuku Iho model captures narratives on the health and wellbeing of Kaipara Moana to develop Kaipara Uri understanding of Te Mana o te Wai and create values and attributes as part of the NOF requirements.

Mātai Onekura is an on-farm planning model that produces remedial action plans that can feed into Tātaki Wai to identify the best solution to reduce sediment in each river system. Sharing the insights from this programme might benefit other iwi trying to set up similar large-scale environmental restoration programmes using different knowledge systems and demonstrates a tangible example of how a good process could work.

As each tool is dependent on the others, they all need to be functional and financially resourced. This allows for all tools to be improved together, ensuring their use for certain regulatory settings is appropriate. The next step in the development of these models will be to ensure that kaitiaki on the ground are included in their future development and use.

Kaitiaki Flows

Ngāti Rangiwewehi are kaitiaki and have mana over Awahou River in Rotorua, to which they whakapapa and have physical and spiritual connections. A long history of grievance disconnected the iwi from the awa. An Environment Court decision to restore their cultural connection to their taonga and the return of land surrounding Te Waro Uri (from which the Rotorua municipal water supply is sourced) was the precursor to the development of the Kaitiaki Flows model by Ngāti Rangiwewehi.

With Te Mana o te Wai (from previous versions of the NPS-FM) in mind, the model was redefined from a previous tool now being used for a resource consent condition for the Ngongotahā municipal water supply. It is the only model in use nationally that uses mātauranga Māori and Western science to assess appropriate water takes for municipal water supply.

Mātauranga-ā-Rangiwewehi underpinned the development of the model. The use of pūrākau (narratives) set the theoretical and methodological frameworks to appropriately use this mātauranga within the model. For example, the awa is said to hold a kaitiaki, Pekehaua, so that when you swim in the awa you are cleansed by that kaitiaki. Pekehaua is also said to have used underwater channels to travel. "This graphic imagery, and its attendant metaphorical implications, is apt in discussing a uniquely Rangiwewehi way of framing knowledge and the processes we employ to gather, assimilate and engage with our tribal mātauranga (knowledge)."[21] Western science and mātauranga is then interpreted through an iwi–science engagement framework that was applied in the co-development and validation of the model with GNS Science.

[21] Taylor, 2023, p.52.

The model uses flow monitoring to determine the naturalised flow of the awa and the effects of extraction of water for drinking. Using this statistical model, the kaitiaki flow is determined – that is, the flow a waterway needs to retain to protect its health and wellbeing, and that of the ecosystem it supports. It is more specifically defined as the flow for a particular water body that exceeds the flow consistent with the local values of tangata whenua (e.g. amenity, environment and spirituality). These values are identified through iwi-based assessment processes. In the Awahou Stream, the kaitiaki flow was determined to be the moving minimum mainstem flow that is 90% of daily mean naturalised flow.

Importantly, this model recognises that the integrity of the respective water body must be protected first and foremost. It then also provides space to consider sustainable socio-economic use and development by and for the iwi.

Wide participation by Ngāti Rangiwewehi in the process of defining the kaitiaki flow regime underlined the importance of kaitiakitanga and co-management roles for the deployment of this model. The process showed how traditional Māori knowledge can be transferred into policy and could provide a guideline to iwi engagement in other iwi–science water projects. The only concern is whether the regional council will enable the scaling up of this model in both policy and practice, which is what Ngāti Rangiwewehi and other iwi would like to see.

The model gives expression to Te Mana o te Wai, recognises its hierarchy and uses mātauranga Māori and science in its application, yet also links to the biophysical component of baseflow volumes. Ngāti Rangiwewehi view the inclusion of two knowledge systems as a powerful tool that ensures Te Mana o te Wai is given effect to and its hierarchy of obligations met. Although specifically developed for drinking water purposes, the model could be used in other freshwater planning rules that are related to the implementation of the NPS-FM.

Further, this model, and the process to develop it, provides a very good example of how the principles underpinning the NPS-FM 2020 were successfully met:

- **Mana whakahaere/governance:** The co-governance partnership between Ngāti Rangiwewehi and Rotorua Lakes Council that was the catalyst for the creation of the model was awarded a 2022 Local Government New Zealand Excellence Award in the Environmental Wellbeing section. It is considered to be a genuine partnership, with iwi producing outcomes that benefit all.
- **Kaitiakitanga/stewardship:** The model is an expression of Te Mana o te Wai and the hierarchy that is consistent with Ngāti Rangiwewehi tikanga and kaitiakitanga. The development process was rigorous and ensured that kaitiaki understood and were involved throughout the whole process, with their tikanga at the centre of the model. The model is also scientifically robust for resource consenting processes.
- **Manaakitanga/care and respect:** Ngāti Rangiwewehi believe that this model is not only significant for them but for all iwi across Aotearoa, should they wish to use it. It is a tool that can be used to protect the health of the water as a resource and as a taonga for all who depend on it.

Mōhaka

Mana whenua of the Mōhaka and Waihua catchments were assisted by Hawke's Bay Regional Council in developing the Mōhaka me Waihua freshwater plan to respond to the implementation of the NPS-FM. The Mōhaka and Waihua awa are significant for mahinga kai, rongoā and recreation. But there has been growing concern about water quality, particularly due to dairy farming that is increasing nitrogen concentrations in the awa.

Due to Cyclone Gabrielle, Hawke's Bay Regional Council's budget was re-prioritised, resulting in reduced delivery and budget for the Mōhaka me Waihua freshwater plan and implementation. Ngā mana whenua o Mōhaka (the project team) thus decided to commission the development of its own models to predict the state of water quality and ecology of significant river sites. Ngā mana whenua o Mōhaka used national-level information and datasets that were presented to tangata whenua in the attempt to develop attributes, targets and limits for their catchment. This work is still in development.

There is a diversity of expertise involved in the development of these models, including tangata whenua experts in science and policy, independent experts who do not whakapapa to the awa, a project manager, administration support and kaitiaki. This is to ensure data can be interpreted and aligned to te ao Māori values and are able to be disseminated and discussed with whānau through wānanga to ultimately develop limits.

The process has been long, and not without challenges. Namely:

- Funding from regional councils was only committed for the plan development stage, not implementation.
- Governance and decision-making opportunities did not adequately take into account Te Tiriti and NPS-FM compliance.
- Community groups, including mana whenua, were not included at the right time in the process, undermining progress.

Despite these issues, mana whenua are continuing to develop the model and other information sources on their own. After losing external support, they have taken on the responsibility of applying the model for freshwater decision-making purposes. The group has also identified the need to develop a process of inclusion to involve community, kaitiaki, scientists and experts in mātauranga.

Source: Ngāti Pāhauwera

Figure 4.2: For mana whenua, Mōhaka awa (pictured) and Waihua awa are a source of identity and pride. The awa are significant for mahinga kai and kōhatu (river stones for hāngi, weaponry, etc) and are home to important kaitiaki (taniwha). But there has been growing concern about water quality, particularly due to dairy farming that is increasing nitrogen concentrations in the awa. Mana whenua in the catchments were assisted by Hawke's Bay Regional Council in developing the Mōhaka me Waihua freshwater plan to respond to the implementation of the NPS-FM.

Challenges

The NPS-FM 2020 requires regional councils to engage with communities and tangata whenua to determine how Te Mana o te Wai applies to water bodies and freshwater ecosystems in the region. This has a cascading effect on values-setting and the limit-setting process outlined in the National Objectives Framework (NOF) part of the NPS-FM 2020. Councils are familiar with the limit-setting requirements, as this was required by the previous versions of the NPS-FM. The challenge raised by the 2020 version of the NPS-FM was to find a way to ensure that the limit-setting process outlined in the NOF was aligned with the Te Mana o te Wai hierarchy, as the objective of the NPS-FM 2020. The Government's signalled replacement of the NPS-FM 2020 will create more uncertainty and complicate the debate. What follows is a discussion of additional challenges raised by the 2020 policy statement.

Historically, mana whenua have not been included in regulatory processes to the extent that they wished to be. The marginalisation of mātauranga Māori resulting from the vast privileging of Western science has resulted in an assumption that the former is less robust or certain than the latter.[22] This poses challenges for the assessment of models that have been developed by Māori. This task needs to be undertaken by those who whakapapa to the awa and the whenua. The challenge is to ensure that models created within te ao Māori are improved, critiqued and assessed within that same worldview. Similarly, it is up to tangata whenua to determine whether specific biophysical models work for them and support the vision for that rohe.

Biophysical models might not be able to provide a full picture of whether the NPS-FM 2020 is fully achieved if those models are unable to support the achievement of the hierarchy of obligations and the mauri of the wai. It may be that models developed by Māori within a te ao Māori worldview are better suited for that task. The outputs from biophysical models, however, might fit well as inputs into models developed by mana whenua. Conversely, biophysical models might be able to be joined up with the mana whenua developed models, or tailored to specific values – for example, to model īnanga or tuna as a valued mahinga kai species when led by mana whenua.[23] Whatever the case, it is likely that communities and iwi will be calling for the use of both types of models.

As discussed earlier, developing 'causal chains' of multiple biophysical models is complicated. Models developed using mauri may provide users with a more simplified version of a causal link model, where the quality of mauri shows what the relationship and mana of each component is. Either way, the necessity to understand mauri, and how that might be used as a measure within Māori models, is an innovative area that should be further explored.

However, as noted earlier, to date no mana whenua developed models have been used to support the implementation of the NPS-FM 2020 all the way through the NOF process. To decide which models to use, more consultation needs to take place between councils and tangata whenua to identify what other information sources or models are needed.

[22] Taylor, 2023, pp.9, 15, 103–105.

[23] Mahinga kai is one of the compulsory values in the NPS-FM 2020. See NPS-FM 2020, Appendix 1A.

Process is as important as the model itself

The process to develop and implement models based on mātauranga Māori is as important to tangata whenua as the model itself. The NPS-FM 2020 is process and principles heavy and requires councils to engage with tangata whenua, facilitating their active engagement. This requirement is designed to overcome the historical experience of tangata whenua who have either been involved too late in the decision-making process or completely left out.

This past practice meant that the values tangata whenua placed on water, beyond its use as a resource, were never well understood, let alone protected in the management process. Effective engagement will help redress this and can also help councils to redeploy resourcing that may have been earmarked for a model that is not a good fit with mātauranga from tangata whenua. Councils will need to work closely with mana whenua to identify what model development may be required to inform their decision-making process. Councils will need to help empower tangata whenua and be responsive to how tangata whenua would like to be involved.

Two documents produced as part of the Our Land and Water National Science Challenge provide good guidance on where and how tangata whenua should be involved in the implementation of the NPS-FM 2020, but could also be used to identify involvement specific to model development for freshwater management.[24] Councils must be flexible in their priorities, strategies and budgets to build the capability and capacity of tangata whenua in the development of models, should they wish to be involved.[25] Further, councils should ensure tangata whenua are aware of all potential opportunities to be involved so they have an opportunity to shape the process of model development.

At the time of writing this report, many councils recognised that the involvement of tangata whenua is an essential part of the process. The engagement of office of the Parliamentary Commissioner for the Environment (PCE) staff for this investigation did not specifically focus on issues of how mana whenua developed models would fit into existing catchment modelling, or how mana whenua developed models might be used in preparing new regional plans. This was the reason for commissioning the consultant's report on the use of mana whenua developed models to date.[26] Regardless, some direction could come from Māori models being used for resource consenting purposes. The Kaitiaki Flows model developed by Ngāti Rangiwewehi is a good example of this.[27]

The challenges that arise from close and early engagement with Māori and the use of Māori models in regulation are not council specific but include a broader issue of the lack of guidance from central government and resourcing for Māori to fill knowledge gaps. A review conducted for the Ministry of Business, Innovation and Employment by Martin Jenkins in 2023 noted the small percentage of central research funding that resourced Māori and kaupapa Māori research across four themes important to Māori.[28] Taiao was one theme in which freshwater would sit.

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[24] Poipoia, 2022a, b.
[25] Taylor, 2023, pp.103, 106–108.
[26] Taylor, 2023.
[27] For details see Box 4.2 in this report and Taylor (2023, pp.51–65).
[28] MartinJenkins, 2023.

While the analysis only focused on funding for the years 2018, 2019 and 2020 (i.e. before the introduction of the NPS-FM 2020), this study provides a snapshot of the limited amount of resourcing allocated to Māori from central government to support the development of mātauranga Māori, which could include the development of Māori models. Within the stocktake and case study analysis done by Taylor (2023), funding and support were seen as a big barrier to producing these models and using them within the freshwater regulatory system.[29]

In summary, Māori use models as tools to understand the growing pressures on freshwater and to manage freshwater in a way that encapsulates their values. Biophysical models for many Māori have a place, but they are just one tool in the toolbox. The key to any model that might be used for the purposes of Te Mana o te Wai is that it needs to reflect the intent of Te Mana o te Wai: It needs to help people make decisions on protecting the mauri of the wai while the hierarchy of obligations is adhered to. Bringing two systems together requires expertise on both sides, but this cannot be done without engaging with mana whenua.

[29] Taylor, 2023, pp.85–110.

5

Polystichum oculatum

Guidance on environmental models and modelling

Existing guidance

This chapter examines key New Zealand guidance documents that focus on aspects of freshwater policy, environmental modelling and associated uncertainty. It also discusses the challenges posed by this guidance.

Guidance on environmental models

Prior to 2023, New Zealand lacked widely applicable guidance on what good practice looked like for those developing and using environmental models in a regulatory context. This absence was noted in *Overseer and regulatory oversight: Models, uncertainty and cleaning up our waterways*,[1] which recommended that such guidance be developed.

Since then, guidance for developing, adapting and applying environmental models in a regulatory context in New Zealand has been produced.[2]

Guidance published by the Ministry for the Environment (MfE) in June 2023 aims to be applicable to all environmental models that are used in a regulatory context. This guidance emphasises the importance of both monitoring data and modelling, as well as the importance of transparency in respect of both models and their underlying data.[3]

The guidance lists procedural and project management steps for developing, applying and adapting environmental models.[4] Many of the procedural steps touch on aspects of good modelling practice.

1 PCE, 2018.

2 MfE, 2023b.

3 MfE, 2023b, pp.5, 18.

4 The steps are establishing whether modelling is appropriate to the context; confirming the scope and nature of application; adopting robust project management and oversight arrangements; assessing uncertainty and sensitivity; determining the level of scrutiny required; choosing the right model, or models, for the job; training and calibrating the model, and corroborating its predictions; preparing the model for deployment; maintaining commitment to continual improvement; establishing appropriate arrangements for ongoing stewardship; and actively managing the implications of model evolution. For details, see MfE (2023b, pp.19–30).

The guidance also specifies that 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
- be scientifically credible and deliver an adequate level of certainty or trust
- operate within the practical constraints of the context.[5]

The list is not limited to the technical robustness of a model. It also includes practical feasibility and constraints surrounding the model's use and development.

The guidance goes on to state that respect for Te Tiriti o Waitangi and te ao Māori should be one of the core components of environmental models. Further, there's an obligation for participants to give effect to Te Mana o te Wai in freshwater management and find space for all knowledge systems (including Māori and 'Western' biophysical science) to inform decision making.[6]

The guidance contains a checklist for model evaluation, which draws heavily on the set of assessment criteria developed by the United States Environmental Protection Agency (US EPA) specifically for models used to inform regulatory decisions. The New Zealand and US EPA checklists are compared in Table 5.1.

Table 5.1: Comparison of New Zealand and US EPA criteria for evaluation of environmental models.[7]

The New Zealand criteria for model evaluation	The US EPA criteria for model evaluation
• Conceptual basis • Respect for Te Tiriti o Waitangi • Range of perspectives • Scientific and technical rigour • Trust and confidence • Computational infrastructure • Assumptions and limitations • Data availability and quality • Test cases • Validation and corroboration • Sensitivity and uncertainty analysis • Model resolution capabilities	• Scientific basis • Computational infrastructure • Assumptions and limitations • Peer review • Quality assurance and quality control • Data availability and quality • Test cases • Sensitivity and uncertainty analysis • Corroboration of model results with observations • Benchmarking against other models • Model resolution • Transparency

5 MfE, 2023b, p.11.
6 MfE, 2023b, pp.14–16.
7 US EPA, 2009; MfE, 2023b.

The US EPA's guidance reflects the legal and constitutional context in which the US EPA operates. While elements of it may reflect the particularly litigious culture that exists in the USA and cannot provide any help with unique elements of water management such as Te Mana o te Wai, it remains a robust and useful starting point, especially for assessing the technical robustness of models.

Overall, the publication of New Zealand guidance is a positive step, as it provides a useful start for improving modelling relating to our environment. It fulfils the Parliamentary Commissioner for the Environment's 2018 recommendation to develop such guidance. While some of the guidance may seem general, this is due to its broad scope since it is intended to extend to *all* environmental models and is not limited to freshwater modelling.

Beyond MfE's 2023 guidance, several publications on the fitness for purpose of models exist in academic literature and other publications. For example, Hamilton and co-authors explore fit-for-purpose modelling as the intersection of usability, reliability and feasibility.[8]

In addition to MfE's guidance on environmental models, several other government documents contain guidance on the use of models in freshwater management. One such publication is MfE's 2024 guide for councils on the use of Overseer in a regulatory context.[9] Publication of this guide fulfils another 2018 PCE recommendation.[10] While the scope of this document is limited to one model, it provides commentary and guidelines on the use of Overseer for a range of regulatory tasks and processes.

Guidance on policy

As mentioned in chapter three, the **National Policy Statement for Freshwater Management (NPS-FM) 2020** – the key national direction instrument on the management of freshwater – does not prescribe any specific models or modelling requirements for use.

Some guidance on the standards that models should meet to ensure quality outputs is provided in the **2023 National Objectives Framework (NOF) guidance document**. This guidance document is aimed at clarifying the policy intent and expectations of the NPS-FM 2020. These standards include "identifying sources of uncertainty (such as through global sensitivity analysis) and taking action to reduce these" and "ensuring all parts of the model, including all assumptions and uncertainties, are clearly set out and transparently reported."[11]

8 Hamilton et al., 2022.

9 MfE, 2024. Overseer is a property-scale model used by several councils across the country to estimate and help manage nutrient losses from farms.

10 PCE, 2018, recommendation 7.

11 MfE, 2023c, p.31.

The NPS-FM 2020 also contains a clause titled 'Best information'.[12] It explicitly requires local authorities to "use the best information available at the time, which means, if practicable, using complete and scientifically robust data."[13] The point about using the best available information at any particular point in time is sensible, but the section goes further to say that:

> "In the absence of complete and scientifically robust data, the best information may include information obtained from modelling, as well as partial data, local knowledge, and information obtained from other sources, but in this case local authorities must:
>
> (a) prefer sources of information that provide the greatest level of certainty; and
>
> (b) take all practicable steps to reduce uncertainty (such as through improvements to monitoring or the validation of models used)."[14]

The phrasing of this requirement in the NPS-FM 2020 is unfortunate. It lends itself to the inference that there is some ideal state of complete and robust scientific data. There isn't. All information – whether obtained from modelling, local knowledge, or datasets – will be incomplete. That does not automatically render it 'not scientifically robust' or imply the existence of some hierarchy of information sources. Models, if appropriately used, can be as robust a source of evidence as monitoring data, and as stated earlier, modelling and observations (monitoring) are interdependent. Further, the use of multiple lines of evidence can increase rigour and analytical strength.[15]

The wording also implies that local knowledge is inferior in the hierarchy of information, and this may pose challenges when attempting to use mātauranga Māori to support decision making. It is somewhat at odds with another NPS-FM 2020 requirement, which requires every regional council to enable the application of a diversity of knowledge and its systems, including mātauranga Māori, when giving effect to Te Mana o te Wai.[16] The use of mātauranga Māori as an important evidence base has been discussed in a previous report on New Zealand's environmental reporting system.[17] Knowledge that was gained through careful and often subtle observations of very specific locations over many generations can be used to develop models to better manage freshwater.[18]

Regarding the hierarchy of information sources, the 2023 NOF guidance document emphasises:

> "Where possible, use real data, rather than modelled. However, models will be required to identify and understand relationships between values and attributes, and to calculate catchment-scale interactions. Only use modelled data where other types are not available."[19]

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[12] NPS-FM 2020, clause 1.6.

[13] NPS-FM 2020, clause 1.6(1).

[14] NPS-FM 2020, clause 1.6(2).

[15] PCE, 2023.

[16] NPS-FM 2020, clause 3.2(2)(d).

[17] PCE, 2019.

[18] As many current models using mātauranga Māori are relatively new, further thinking needs to be conducted about what assumptions and uncertainties are held within these models and how best to use these models with other decision-making tools. Recent guidance published by MfE on mahinga kai as one of the compulsory values of the NOF is a good starting point. See Ruru et al. (2022).

[19] MfE, 2023c, p.31. It is worth contrasting this advice with advice in another piece of guidance on developing, adapting and applying environmental models in a regulatory context: See MfE (2023b, p.5).

Use of the term ‘real data’ is another poor choice of wording. *All* data come with a degree of uncertainty. Most environmental data measured from gauge, sensor or laboratory analysis are *de facto* relying on a model of some sort, whether it be a proxy, or the coding of an electronic device. Further, monitoring data are the product of the sampling and analysis methodology, so any limitations in that methodology will be carried over into the monitoring results. Treating observations as some sort of ‘gold standard’ in the belief that they avoid uncertainty is a flawed assumption.[20]

Beyond that, field measurements and observations are often sparse in both time and location: A monthly sample will hardly capture the effect of more dynamic events such as peak flows and floods. Understanding the effects of such events often requires a combination of observations and models. Sounder guidance would recommend the use of models *in addition to* measurements with an explicit, scientifically credible uncertainty estimate. After all, models are built on measurements.

Guidance documents on implementing clause 3.13 of the NPS-FM are a further point of reference to the use of models in freshwater management.[21] One of the documents provides guidance on the interpretation and use of look-up tables of in-stream nutrient concentrations and exceedance criteria for achieving periphyton target attribute states. This guidance states that the look-up tables (which are outputs from statistical modelling) “are intended to be starting points for defining nutrient concentration criteria, not as a mandated method for setting *nutrient criteria*”.[22]

Another of the guidance documents in this package outlines four strategies for implementing clause 3.13 of the NPS-FM 2020, and lists all available methods (including statistical models, i.e. regression models). However, it does not specify a recommended method or methods. It states that “tools are not covered in any detail, nor is one tool advocated over another. Instead, some general guidelines are provided to help you select the most appropriate tools in light of constraints and intended use.”[23] The guidance does “not recommend one set of published [instream concentration thresholds] over another. There is currently no consensus on which of these … will be most effective and efficient for managing nutrient inputs to New Zealand’s rivers.”[24]

Instead of recommending specific statistical models, the guidance includes some general rules for good practice in regression modelling that can be applied to any specific regression approach selected, including documenting the modelling approach and outputs, checking the model fit and analysing uncertainties.

While informative, this guidance on implementing clause 3.13 of the NPS-FM 2020 leaves it up to the councils to decide which method or methods are best to use. More often than not, making an informed decision requires time and expertise, which are in short supply when resourcing is thin.

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[20] Westerhoff, 2015.

[21] MfE, 2022a, b, 2023a.

[22] MfE, 2022a, p.29.

[23] MfE, 2022b, p.73.

[24] MfE, 2022b, p.78.

Guidance on uncertainty

While numerous international publications on uncertainty exist, in the New Zealand context there are a few guidance documents that are worth mentioning.[25]

Key messages from **MfE's 2018 guide to communicating and managing uncertainty** include the need to:

- estimate uncertainty as accurately as possible
- communicate it in a straightforward way
- include uncertainty in decision making, especially when the environmental consequences could be irreversible.[26]

While the 48-page guidance is helpful in explaining some aspects of uncertainty and practical lessons on how to communicate it, it lacks important insights from experts on uncertainty, such as those involved in groundwater modelling and uncertainty estimation software. As the main focus of the guidance is not on modelling best practice, it is perhaps unsurprising that the guidance adopts a cautious approach to using models.[27]

By contrast the **Environment Court of New Zealand** provides more succinct guidance on uncertainty. The court's *Practice Note 2023* outlines a code of conduct for expert witnesses who, in giving evidence, must:

"ix. identify the nature and extent of uncertainties in any scientific information and analyses relied on and the potential implications of any uncertainty;

x. if relying on a mathematical model, include appropriate or generally accepted sensitivity and uncertainty analyses for that model; and,

xi. apply any technical terminology as used in this clause (including uncertainty, sensitivity, confidence and likelihood) or as used in their evidence according to its generally accepted meaning among experts in the witness's field of expertise."[28]

This clear and concise wording more explicitly acknowledges that both field observations and models suffer from uncertainty, which must be appropriately communicated. Further, uncertainty should not be used as an excuse to do nothing, nor should it be ignored.

The **NPS-FM 2020** is clear in this regard, as it states that local authorities:

"(a) must not delay making decisions solely because of uncertainty about the quality or quantity of the information available; and

(b) if the information is uncertain, must interpret it in the way that will best give effect to this National Policy Statement".[29]

In summary, there are several guidance documents in New Zealand that focus on aspects of freshwater policy, environmental modelling and associated uncertainty. However, multiple guidance documents create their own challenges.

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[25] For example, see Marchau et al. (2019) and Bhatt et al. (2020).

[26] MfE, 2018.

[27] Further, the 2009 US EPA guidance already provided good explanation of uncertainty and practical tips for communicating it. See US EPA (2009).

[28] Environment Court of New Zealand, 2023, s 9.3(a).

[29] NPS-FM 2020, clause 1.6(3).

Source: Phillip Capper, Flickr

Figure 5.1: A range of models is currently used to help manage contaminant discharges and water takes across the country, including in the catchment of Te Waihora Lake Ellesmere (pictured). However, current guidance on model use in a regulatory context falls short of what is useful.

Councils need more help than the existing guidance documents provide

The combined effect of the multiple guidance documents reviewed above could actually discourage the use of models, particularly the suggestion that modelling is not as robust as data from measurements and observations. Anyone seeking guidance on environmental modelling needs to consult several documents, including (but not limited to) the guidance on developing, adapting and applying environmental models in a regulatory context. The totality of the guidance provided needs to be reviewed and improved.

Shortfalls in the existing guidance on environmental modelling

Firstly, given other guidance documents, the strength of MfE's stand-alone specific guidance on developing, adapting and applying environmental models in a regulatory context is somewhat diminished. From the perspective of providing clarity on modelling, this guidance would work better if positioned as the 'master guidance on environmental modelling' to which the other documents could refer.

Secondly, awareness of this guidance on environmental models among model developers and model users seems to be low. This is in part because the guidance is reasonably new, but several workshops and events planned at the time of publication did not happen, leading to a very quiet launch. The guidance is at risk of being ignored and not adhered to if more is not done to promote it. Simply publishing the guidance does not substitute or guarantee its implementation.

Thirdly, while transparency is described in detail in the guidance document, when it comes to the checklist for model evaluation, transparency is tucked under a broader and more process-driven criterion called 'trust and confidence' and does not appear in any other part of model evaluation. That might be a small oversight (and amenable to a quick fix) but with potentially large implications, because model transparency is by far the most important criterion in determining whether transparent decisions can be made using any specific model. By contrast, the US EPA has transparency as an explicit assessment criterion.

Fourthly, the guidance has little to say about the current suite of freshwater models. That is partly because of its broader scope that aims to cover all environmental models. In addition, the guidance focuses on process and lists several procedural and project management steps for developing, applying and adapting environmental models. However, it does not provide any technical assessments of the existing models and is silent on whether models in New Zealand actually meet the evaluation steps and the good practice process of model application as described by the guidance.[30]

Selecting a 'fit-for-purpose' model requires guidance on managing trade-offs and practical constraints

MfE's 2023 guidance on environmental models specifies that 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
- be scientifically credible and deliver an adequate level of certainty or trust
- operate within the practical constraints of the context.[31]

In other words, the components of a fit-for-purpose environmental model listed in the guidance include both the technical robustness of a model (scientific credibility) and the practical feasibility and constraints surrounding the model's use and development. The two are not easily resolved. By contrast, the US EPA guidance on environmental models focuses on technical model robustness only.

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[30] By contrast, chapter two and Appendix 2 of this report contain key findings and a detailed technical evaluation of the most widely used 24 models. This evaluation used mostly existing technical criteria from previously mentioned work by US EPA (2009), PCE (2018) and MfE (2023b).

[31] MfE, 2023b, p.11.

Trade-offs between usability, reliability and feasibility are inevitable.[32] Decision making needs to be transparent and its consequences clear. For example, practical constraints (e.g. limited expertise or resources during the development phase of a model) have direct implications for the type and complexity of the model that is developed. While the guidance emphasises that the modelling needs to be fit for purpose, it does not offer any direction on balancing the trade-offs. It is worth noting that two expert modellers have recently emphasised that transparency of environmental modelling should not be subject to trade-offs.[33]

Engagement with council staff revealed many instances of councils trialling and abandoning a model after establishing that it was not best suited to the task at hand. In some cases, the models were found to be too complex for the available data. Following guidance from the US EPA or MfE on how to select a model that is fit for purpose would limit the possibility of that situation arising.

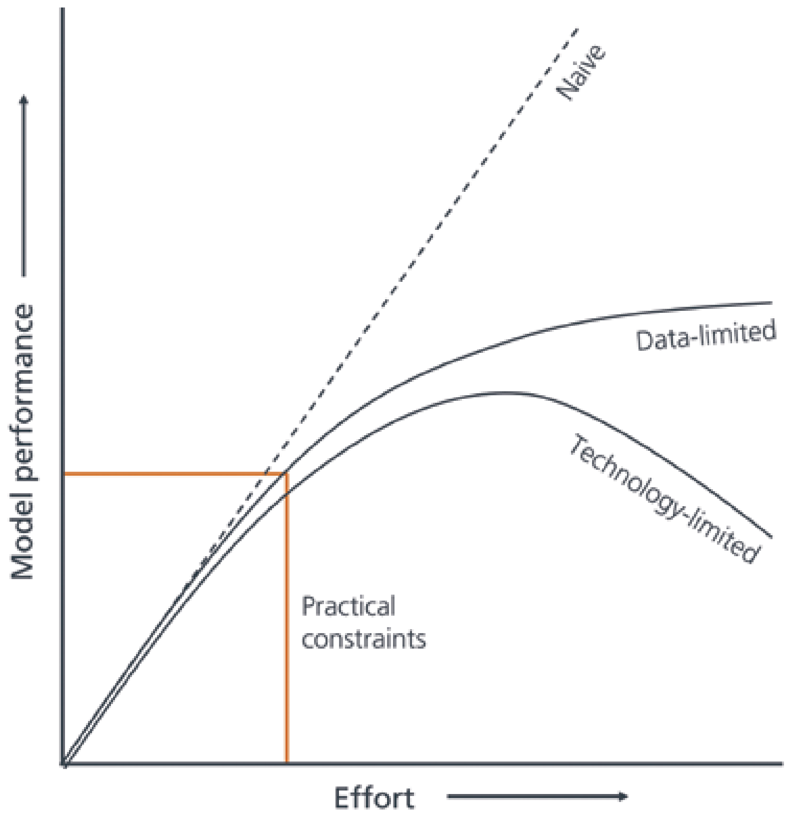
Some councils mentioned that a lack of inhouse skills or resources in modelling, political pressure and tight time frames had influenced the type and complexity of the model chosen. These factors can compromise modelling quality, and in some situations, have led to councils choosing a simpler model over a more complex alternative. Unwillingness to sustain investment in modelling capabilities can also weigh in favour of such a choice.

While it may seem expedient for councils to make such a decision based on short-term and non-technical considerations, a price could be paid if the model doesn't adequately answer the questions and fulfil the purpose it is expected to. This further supports the need for long-term investment in modelling for policy and management regardless of current time pressures from policy.

Simple models are not always the most appropriate tool and may provide less robust results. Figure 5.2 provides a schematic visualisation of the impact of practical constraints. When looking at model performance, limitations in both data and technology lead to declining marginal returns on investment (or effort). However, practical constraints have the potential to more severely affect model performance, as they limit the effort spent on developing and tailoring a model, thus putting a hard ceiling on the model performance that is able to be achieved.

32 For example, Hamilton et al. (2022) explored the intersection of usability, reliability and feasibility in the context of fit-for-purpose environmental models.

33 Larned and Snelder, 2023.



Source: Adapted from Jeremy White, Intera, pers. comm., 19 May 2023

Figure 5.2: Factors that influence model performance. There are declining marginal returns on investment (or effort) in model performance. The 'naive' assumption that model performance is linear in relation to the effort put into its development has long been understood to be 'data-limited', i.e. limited by the amount of good data that is available for the model.[34] Limitations of technology (e.g. skills, human resources, computer resources) can further limit or even negatively affect model performance. Given the inadequate guidance on modelling, there are many other decision and planning forces at play in modelling that could inhibit efforts and thus model performance. These are often referred to as 'practical constraints', e.g. time pressure of planning, willingness to change, funding and expertise (in orange).

More comprehensive guidance on how to assess and select models that are fit for purpose and on how to use those in a regulatory setting would help councils avoid costly mistakes from choosing a model that is too simple or not suited to the task at hand. It would also help councils overcome some of the practical constraints of inadequate resourcing and lack of inhouse technical expertise.

[34] Grayson and Blöschl, 2001.

Current guidance needs to be followed up with practical support

Engagement with council staff in the course of this project found that staff are looking for help to support on-the-ground freshwater management.

Yet, the guidance documents produced by MfE, including the one on environmental models, do not provide that. Publication of guidance to clarify policy intent or provide additional explanation does not guarantee its implementation.

Councils need further assistance to help them implement guidance. Practical help with implementation and application of the guidance on environmental models should include assistance with choosing the appropriate model and associated technical evaluations.

If councils use the guidance as it stands, they may continue to make decisions on model development and use that favour practical considerations without realising the long-term consequences. Such consequences could include poor environmental decisions and a shortfall in scientific capacity that could hinder councils at subsequent planning stages. Another risk is that the use of less robust models, alongside the absence of agreement on optimal model choice and use, exposes councils to legal challenges.

During engagement undertaken for this investigation, all councils mentioned the need for greater collaboration, including sharing modelling resources and model code. While regional sector special interest groups facilitate improved communication channels, they are voluntary. These groups are often driven by the enthusiasm of their members and lack formal support. Voluntary special interest groups are not sufficient to promote serious coordination and alignment and establish a more efficient, collaborative modelling environment.

Overall, council staff are looking to MfE for greater support on freshwater management. In particular, councils with a smaller ratepayer base are asking for centrally supplied and maintained models that can be applied in any part of the country by being tailored to different locations, taking into account local specificity. Providing a preferred suite of models would provide greater consistency and efficiency, as long as they could be tailored to local characteristics to produce robust results.

If current guidance is not properly implemented, councils will continue to be left to their own devices in developing or selecting models to meet freshwater management requirements in their regions. Appendix 3 provides a few international examples of consensus-based model suite development.

Fearing the risk of legal challenge

During engagement undertaken for this investigation, 'litigation phobia' was often mentioned by council staff as a concern when using models for regulatory purposes. This fear can be described as an ongoing concern from council staff about the potential for legal challenge to the use of models and the outputs from models. This was often due to prior litigation outcomes where model results were contested or other models were used to contest a council's models and decisions (see Box 5.1). Over time, concerns about model use and the fear of litigation risk could dissuade councils from using appropriate, fit-for-purpose models, potentially resulting in poor environmental outcomes.

Box 5.1: Contesting rules based on model outputs through litigation

Modelling inevitably comes with uncertainties, yet compliance with specific rules necessitates precision in the approach and robust justification. Quantification of uncertainty is critical for enabling robust and informed decision making, as any single modelling output without a confidence interval could be easily challenged.

For example, for the Selwyn Waihora catchment, Environment Canterbury used Excel and geographic information system (GIS) based bespoke nutrient models to inform plan development and estimate a nitrogen load of 902 tonnes per year for the catchment, assuming attenuation factors based on measured concentrations.

Central Plains Water Ltd made a submission challenging the proposed nitrogen load for the catchment, citing a lack of confidence in Environment Canterbury's model. The irrigation company undertook their own eWater Source modelling with additional inputs and presented an alternative catchment load of 979 tonnes per year. This was accepted by the hearing commissioners, and as a result, the load for the catchment was increased by 77 tonnes per year.[35] It is worth observing that in this case the difference in the two modelled loads was only 8%, but the error on measured loads can exceed this figure.

Responding to legal challenge is also expensive. For example, the direct legal costs incurred in litigation flowing from the Bay of Plenty Regional Council's Plan Change 10 (which was underpinned by model outputs and the use of Overseer at a property level) were around $500,000. However, the total estimated cost of PC10 from start to finish is estimated to have been $4 million.[36] The duration of the plan preparation process and the expertise required at all stages of the process (including expert witnesses for a range of subject matter areas) weighed heavily on the overall costs.

[35] Sheppard et al., 2015.

[36] BOPRC, pers. comm., 15 September 2023.

The risk of legal challenge arises for councils in their application of models due to several compounding factors described earlier in this report:

- A large number of water models are used. Many of them are opaque and have overlapping functions.
- The strengths, weaknesses and suitability of models for their intended purpose are not systematically evaluated, making it difficult to determine which models are best in any particular circumstances.
- Guidance on model use (including judging if a model is fit for purpose) falls short of what is useful.
- There is inadequate resourcing and a shortage of expertise among model developers and model users.

If models are not systematically evaluated and their fitness for purpose is questionable, it is highly unlikely that they will withstand challenge. Legal challenge in relation to model use would be less likely, and more difficult to sustain, if an agreed suite of transparent models equipped to quantify uncertainty were available, together with access to appropriately equipped modellers.

Lack of transparency increases the risk of models not being legally defensible. While the courts are not best placed to comment on the technical strengths and weaknesses of models, in some cases their decisions have provided clear direction on the use of a model in particular policy settings. This is discussed further in Box 5.2.

Box 5.2: What the courts have said about the use of water modelling

The use of modelling, in relation to water quality and quantity, has been the subject of assessment by the courts. While the advantages of modelling are acknowledged, commentary has largely focused on the limitations of models, particularly when applied in a regulatory context. Judicial comment on the limitations of models may support the adoption of a cautious approach by local and regional authorities in the application of water modelling.

In *Lindis Catchment Group Incorporated v Otago Regional Council*, the advantages of models were recognised by the court.[37] However, this was subject to standard qualifications on the use of models, including:

- the need to scrutinise the quality of input data
- the need to identify all assumptions (e.g. as to rating curves to convert river level data to river flow) and inputs
- the need for models to be calibrated
- the desirability of re-running tests independently
- the need for transparency about 'patch-ups' (e.g. amendments of rating curves)
- the need for careful explanation of statements of 'statistical significance' and *p*-values.[38]

[37] *Lindis Catchment Group Incorporated v Otago Regional Council* [2019] NZEnvC 166.

[38] *Lindis Catchment Group Incorporated v Otago Regional Council* [2019] NZEnvC 166, at [236].

The use of models in regulatory processes gives rise to procedural and substantive risks, as noted by the court in *Federated Farmers of New Zealand Incorporated v Bay of Plenty Regional Council*.[39] The existence of these risks, and the acknowledgement of them by the court, increases the potential for legal challenge. The court identified a range of specific requirements that need to be met when using the model Overseer in a regulatory context, which expands on the qualifications outlined in *Lindis Catchment Group Incorporated v Otago Regional Council*. These requirements include:

a) A consistent approach to model input data and maximising the accuracy of that data;

b) The use of best management practices appropriate for local environmental conditions, such as soil types and weather patterns;

c) Using the model to predict trends and relative changes in farm management systems, rather than absolute values;

d) Calibrating model outputs with field measurements for environments where conditions differ significantly from those where an acceptable level of calibration has been achieved;

e) Using only appropriately qualified and experienced experts to run the model for compliance purposes;

f) Establishing a clear, efficient and reliable process to review and update model outputs and management practices at appropriate intervals;

g) Appropriate on-site verification that modelled inputs and outputs are being complied with, in addition to independent peer review of performance; and

h) A compliance mechanism that is certain, reasonable, practical and legally enforceable.[40]

More recently it has been acknowledged in *Aratiatia Livestock Limited v Southland Regional Council* that models may be useful where there is a lack of monitoring data, particularly when applied to achieve an overview of water quality and ecological state at a regional or sub-regional scale. However, this comes with large uncertainties where the model is applied beyond its limits.[41]

This case highlighted the importance of identifying the landscape scale that the model is applied to, as the local or river reach scale was not appropriate for the model used. *Director General of Conservation v Northland Regional Council* also considered scale relevant to the potential modelling limits but found that the model used in that case was robust when applied at the aquifer scale.[42] A creative solution was adopted in this case to manage the limitation of assumptions in the model by applying a review condition to the consent to be undertaken at each stage of model updates to ensure that assumptions were verified and remained predictive.

[39] *Federated Farmers of New Zealand Incorporated v Bay of Plenty Regional Council* [2019] NZEnvC 136.

[40] *Federated Farmers of New Zealand Incorporated v Bay of Plenty Regional Council* [2019] NZEnvC 136, at [117].

[41] *Aratiatia Livestock Limited v Southland Regional Council* [2022] NZEnvC 265, at [48].

[42] *Director General of Conservation v Northland Regional Council* [2022] NZEnvC 170.

6

Gleichenia alpina

Key findings and recommendations

Summary of key findings

This investigation has revealed major shortcomings in how models have been developed and used in freshwater management. They can be summarised as follows.

- A large number of water models exist. Many of them are opaque and have overlapping functions. Rather than adding value, the proliferation of models confronts regulators with the quandary of having to choose the 'best' model and then defend that choice, which is not an easy task.
- Data underpinning models are frequently non-transparent or inaccessible.
- Model development is siloed and fragmented, hindering collaboration efforts.
- The strengths, weaknesses and suitability of models for their intended purpose are not systematically evaluated, making it hard to judge which models are best for any particular circumstances.
- Experimentation in model use and a failure to share or reuse models between or even within councils leads to a large number of expensive 'single-use' models that represent a poor use of scarce resources.
- Resourcing is thin and expertise is in short supply among model developers and model users.
- Guidance on model use (including judging if a model is fit for purpose) falls short of what is useful. Practical implementation support is lacking.
- There is a lack of commitment to and investment in mana whenua developed models and associated processes to involve mana whenua in the development and application of freshwater models.

The shortcomings identified in this review, including weak leadership and lack of coordination and collaboration, are in no small part a consequence of New Zealand's highly devolved approach to environmental regulation, where each council has responsibility for managing freshwater in its regions and using models to do that. Understandably, decisions are best made at the catchment or rohe scale due to the different ways communities relate to their catchments, the different ways tangata whenua whakapapa to their awa, and the variability of environments in each catchment. However, this has come at the price of an inefficient and siloed modelling environment. Looked at nationally, New Zealand's modelling resource is dispersed and unevenly spread amongst regional councils, publicly funded research institutions and some businesses.

Another consequence of the current shortcomings is an elevated risk of legal challenge to council decisions based on modelling outputs. Councils are looking to central government for help, but the guidance currently available is generalised and not specific to the challenges that are raised by the use of freshwater models. Further, there is a lack of practical implementation support to turn any guidance into practice and ensure a much more robust and confident use of fit-for-purpose models. In short, on a national scale, freshwater modelling is not organised in a way that can best support the regulation and management of freshwater in New Zealand.

Recommendations: Towards transparent and defensible models and their use

Overall, these shortcomings highlight the all-encompassing need for better national-level coordination and support for freshwater modelling if it is to be used effectively and robustly to support water regulation and management. New Zealand cannot afford to waste scarce modelling resources on forays into multiple, expensive, and often ineffective model developments and applications.

The overarching need for better coordination and support can be broken down into the five steps that need to be taken:

1. Further develop national guidance on the use of models in a regulatory context.
2. Establish a rōpū of experts to support the development and implementation of Māori freshwater models.
3. Ensure an evaluation of existing freshwater models is undertaken.
4. Select or develop a preferred suite of models adaptable to local circumstances.
5. Establish a national freshwater modelling support centre.

The first four steps can be progressed without any organisational drama. They are designed to bring about lasting improvements in modelling that should be able to support any regulatory framework. As models assist in understanding the implications of regulatory interventions, steps for immediate improvement focus on the technical components that are needed regardless of the exact shape of the policy and regulation. They also extend to the expertise, skills and research needed to ensure that models are robust and can be confidently used at the science–policy interface.

While these four steps can be progressed immediately, they would benefit from the establishment of a national freshwater modelling support centre, which in my view is the most effective and efficient way of carrying the desired improvements into the future. This is the focus of my fifth recommendation.

Guidance on the use of models in a regulatory context

Recommendation 1: The Ministry for the Environment (MfE) should further develop national guidance on the use of models in a regulatory context to support freshwater management across the country.

Stronger and improved national guidance on the use of models in a regulatory context to support freshwater management across the country is required. Revised existing guidance combined with practical implementation support will provide a useful start. This will assist both model developers and users to follow an overall agreed approach to modelling and in turn drive improvement in model development and use over time.

The improved guidance should:

- be specific to freshwater modelling in a regulatory context
- be elevated to an umbrella document connecting the diverse existing guidance pieces that mention the use of models
- clearly place modelled outputs and monitoring data on the same hierarchical level, as all data come with a degree of uncertainty, and the use of multiple lines of evidence can increase rigour and analytical strength
- clearly spell out all key components that are required to make freshwater models technically robust – this should explicitly include such technical aspects of models as their strengths, weaknesses, and transparency in evaluation checklists
- be followed up with practical implementation support.

Freshwater models are only one tool in freshwater management and will not provide us with all that is needed to achieve desired outcomes. Guidance needs to reflect the sometimes limited and specific role of models in a process that enables decision making at the local level. But whatever role models may play, guidance should be clear that the scientific robustness required for their development and use should not be compromised.

Support for the development of Māori models

Recommendation 2: MfE should establish a rōpū of experts to support the development and implementation of Māori freshwater models.

MfE should establish a rōpū of experts that can provide guidance, coordination and support for the development and use of Māori models. The guidance from this rōpū should assist councils and tangata whenua on best process and the use of models to implement Te Mana o te Wai.

Best process guidance (complementing the guidance called for in Recommendation 1) is needed to enable councils to engage with tangata whenua on the development and application of freshwater models. Engagement criteria in the NPS-FM 2020 should be further refined as they relate to freshwater modelling.[1]

[1] Recommendations in Taylor (2023) provide further refinements and suggestions to prompt and support appropriate modelling. See Taylor (2023, pp.106–110).

The use of models developed by Māori for freshwater management is nascent and there has been little resource available to assist mana whenua. Councils often commit to implement mātauranga Māori tools but are unsure of how they align with regulatory requirements. A rōpū of experts could help tangata whenua and councils to bridge the gap between Māori models and the regulatory system. It could also provide advice on the best use of mātauranga Māori in enabling interaction between biophysical models and mana whenua developed freshwater models.

Lastly, a rōpū of experts could provide coordination and support to tangata whenua wishing to develop and apply freshwater models.

Evaluation of freshwater models against the guidance

Recommendation 3: MfE should ensure an evaluation of existing freshwater models against guidance on the use of models in a regulatory context is undertaken.

Evaluation of existing freshwater models against a set of criteria in the national guidance is required. Currently the strengths, weaknesses and suitability of models for their intended purpose are not systematically evaluated, making it hard to judge which models are best for any particular circumstances.

While one-off model evaluation will shed light on existing models and will provide a starting point, regular evaluation will lead to more efficient and transparent model (re-) use and accelerate the selection or development of a preferred suite of models. Regular evaluation will also aid in efficiently solving existing issues of model incongruence.[2]

MfE should advise on the best way to undertake the evaluation. But in my view, the evaluation should be undertaken by an advisory group comprising people with expertise in biophysical science and mātauranga Māori. The advisory group needs to operate at arm's length from competitive pressures and take a consistent approach.

While criteria for model evaluation exist, the following ones are key:

- transparency and accessibility of models and underpinning data
- the ability of models to be connected with other models
- model strengths and weaknesses
- model assumptions and limitations, including ability to generate uncertainties
- the suitability of a model for its intended purpose.

[2] For example, there is an opportunity to make the CLUES and REC-based regression models more congruent for contaminant predictions, as outlined in chapter two of this report.

A preferred suite of models adaptable to local circumstances

Recommendation 4: MfE should lead the selection or development of a preferred suite of models adaptable to local circumstances.

A preferred suite of models adaptable to local circumstances is required, as New Zealand would benefit from a clearer consensus on model use. That does not mean a one-size-fits-all approach. Models need to address different levels of complexity and different domains of application (e.g. groundwater, lakes, river reaches; contaminants, water quantity, etc).

While models must be able to incorporate locally specific conditions, councils should not have to start from scratch. They need access to a suite of robust and transparent models that can handle the range of tasks in a range of settings.

A preferred suite of fit-for-purpose models that can be used and reused in the regulatory context for general as well as specific requirements would make model application across councils more comparable and consistent. This would enable councils to learn from each other's experiences. It would also streamline processes associated with the use of models in a regulatory context. It would avoid councils' resources being wasted building customised models that reinvent the wheel and are often used only once.

Overseas experience provides some confidence that having a preferred suite of models can work. Details of international experience, including in the Netherlands, the USA and Australia, can be found in Appendix 3. It seems extraordinary that a small country like New Zealand should press on with a fragmented system when much better resourced and sophisticated economies have pooled resources to ensure a critical mass of skills, transparency and efficient use of scarce resources.

It makes sense to select a preferred suite of models on the basis of model evaluation. That will improve the legal defensibility of model use and increase transparency of the decision-making process. Regulators and regulated alike want to be in a situation where only scrutinised models are used for regulatory use.

Technically, a preferred suite of models should include models that operate at different scales to enable assessment of pathways of water or contaminants from the mountains to the sea, ki uta ki tai. There are plenty of models available that can be run for almost all New Zealand's catchments, with a few changes to the input data and minor tweaking of the model. From a technical perspective, there is nothing standing in the way of a more nationally coordinated approach to biophysical model applications across catchments for regulatory purposes.

While the use of a preferred model suite should be strongly encouraged, it does not need to be mandatory. There may be instances when new models using scientific advances and innovative techniques need to be developed. But the advantages of being able to rely on a core preferred suite include:

- easier engagement with mana whenua and communities based on more transparent approaches
- easier explanation across sectors, councils and experts in the field of what these models can and cannot do, including their uncertainties, leading to greater transparency of decisions on environmental outcomes
- a reduced risk of litigation.

Councils are calling for national leadership of freshwater modelling, better guidance, and greater collaboration and model sharing. A preferred suite of biophysical models capable of being customised to meet local conditions would help answer those needs.

A national freshwater modelling support centre

Recommendation 5: The Minister for the Environment should establish a national freshwater modelling support centre with a mandate to support regional councils, unitary authorities and mana whenua. The Secretary for the Environment should prepare a report advising the Minister for the Environment on where and how such a centre could fit into existing institutional arrangements.

This final recommendation proposes a vehicle to carry the preceding recommendations into the future. In my view a national freshwater modelling support centre would be the most effective and efficient way to streamline the system, fix the identified shortcomings, and ensure a much more robust and confident use of fit-for-purpose models to inform the regulation and management of water in New Zealand.

Establishing a support centre is not about creating a new agency. Indeed, the extent to which it needs to be physical or virtual needs consideration. But it would make sense for the Government to ensure that there is a small unit dedicated to improving our overall game in modelling. A suitable 'home' would likely be a national-level agency or ministry (e.g. Environmental Protection Authority, MfE) that has the appropriate mandate, oversight, incentives, and funding to address many of the issues identified in this report. It would make less sense to locate a centre regionally or within a Crown Research Institute, since it is the *national* coordination of modelling efforts that is needed.

I am not suggesting changes to our devolved regulatory policy setting. After all, decisions need to be made at the regional level and follow from engagement with communities and mana whenua. But national-level collaboration and coordination of expertise on how models might work together and best fit into the policy framework could greatly strengthen that devolved system. This should extend to both the development of models and their use and application. Practical support with implementation should include assistance with choosing appropriate models and associated technical evaluations.

I have deliberately not spent time thinking about the governance of such a centre. The Government has first to decide whether it wants to improve the way we direct resources towards water modelling. But assuming that it does, any national centre should be able to draw on personalities who understand how water regulation works, how research is prioritised and how mātauranga and Māori expertise in relation to water can be engaged.

7

Pellaea calidirupium

Appendices

Appendix 1: Stocktake of biophysical freshwater models

The findings of this biophysical freshwater model stocktake were based on meetings with 16 regional councils and unitary authorities, followed by information requests on past and current model use in a regulatory freshwater management context. It covers water resource models dealing with both water quantity and quality in all water bodies that have been used by regional councils and unitary authorities to support a range of regulatory freshwater management requirements, including implementation of the National Policy Statement for Freshwater Management.

Table A1.1 covers a total of **75** models. This includes 66 individual models, plus six bespoke water balance models and three bespoke nutrient balance spreadsheets. In this table, the six bespoke water balance models have been grouped together in one row, as have the three bespoke nutrient (leaching) budgets.

Table A1.1: Biophysical models and their descriptions.

Model name	Number of councils that use this model	Developer/ New Zealand contact	Model description	Link
APSIM	2	Consortium, current members from Australia, USA and New Zealand	The Agricultural Production Systems SIMulator (APSIM) is a platform for modelling and simulation of agricultural systems. It contains a suite of modules that enable the simulation of systems for a diverse range of plant, animal, soil, climate and management interactions.	https://www.apsim.info/
AQTESOLV	1	Hydrosolve Inc	This is Windows software for modelling subsurface hydraulic properties during aquifer testing – for example, in a well or newly drilled borehole.	http://www.aqtesolv.com/default.htm
Aquifer-Watch	1	Thomas Wöhling	AquiferWatch is a bespoke model used by Marlborough District Council in the Upper Wairau Plains. It is based on a specific application of an Eigen model approach.	https://ui.adsabs.harvard.edu/abs/2020EGUGA..22.4568W/abstract
Bayesian model for estuarine areas	1	NIWA	Bayesian modelling is used to model multiple stressors on six Hawke's Bay estuarine ecosystems.	https://docs.niwa.co.nz/library/public/HBRCp5478.pdf
Bespoke nutrient (leaching) budgets	3	Various	Councils have developed a range of methods to assess catchment-scale water and nutrient budgets and mass balance methods to infer nutrients entering a lake, river, stream, or catchment outlet. These bespoke models are often developed in a spreadsheet. Three different nutrient leaching budgets were discovered in this investigation.	https://atlas.boprc.govt.nz/api/v1/edms/document/A4309998/content

Bespoke water balance/ budgets	6	Various	A range of methods have been developed by councils to assess water flows in and out of a catchment or water body based on steady-state estimates of the water cycle (e.g. rainfall, evaporation, streamflow, groundwater flow). These bespoke models are often developed in a spreadsheet. Six different water balance models were discovered in this investigation.	n/a
CHES	3	NIWA	The Cumulative Hydrological Effects Simulator (CHES) predicts how water flows in a catchment will change with multiple water uses (e.g. direct abstractions or storage reservoirs) and what the consequences will be to in-stream ecosystems and the reliability of water take.	https://niwa.co.nz/freshwater/ches-smarter-use-new-zealands-river-waters

CLM/C-CALM	2	NIWA	The Contaminant Load Model (CLM) is an urban water quality model with a geographic information system (GIS) platform that estimates the annual loads of total suspended solids and zinc and copper (total, dissolved and particulate) generated by different land covers at the stormwater catchment scale. It is based on the Auckland Council spreadsheet CLM model. The Catchment Contaminant Annual Loads Model (C-CALM) is a spatial decision support system for planning applications. It estimates annual contaminant loads at the neighbourhood to stormwater management unit (sub-catchment) scale, from diffuse sources, for total suspended solids, small particles and dissolved zinc and copper. The estimated load is then adjusted for water treatment.	https://niwa.co.nz/c-calm
CLUES	10	NIWA	The Catchment Land Use and Environmental Sustainability (CLUES) model is a self-labelled ‘super model’ that combines multiple catchment-scale models (Overseer, SPASMO, SPARROW) in a simplified form to evaluate current loads and perform rapid scenario testing for nutrients, Escherichia coli (*E. coli*) and sediment.	https://niwa.co.nz/freshwater/clues-catchment-land-use-environmental-sustainability-model

CREST	1	No info found	The Coastal Receiving Environment Scenario Tool (CREST) system was developed to evaluate whether modelled load reductions in a catchment will translate to improved coastal water quality.	n/a
Delft3D-FLOW/ DELWAQ	2	Deltares	This model suite contains a flow model (Delft3D-FLOW), two water quality models (e.g. DELWAQ), an ecological modelling model and sediment transport model. Only sub-components are further discussed in this table.	https://oss.deltares.nl/web/delft3d
DESC	1	DairyNZ	The Dairy Effluent Storage Calculator (DESC) helps determine dairy effluent storage requirements for dairy farms. The calculator uses measurements from farms, including farm management and milking practices, to determine the volume of storage required for the farm dairy effluent system. It runs a daily soil water balance using over more than 30 years of daily climate data. The soil water balance allows it to determine soil moisture levels and, depending on soil characteristics, it determines when irrigation could have occurred.	https://www.dairynzdesc.co.nz/Home/About

DYRESM-ELCOM-CAEDYM	3	University of Western Australia	This is a chain of models often coupled for simulation of lake water quality. The DYnamic REservoir Simulation Model (DYRESM) is a 1D hydrodynamic model resolving the vertical distribution of temperature, salinity and density in lakes and reservoirs. The Estuary, Lake and Coastal Ocean Model (ELCOM) is a 3D substitute of DYRESM. The Computational Aquatic Ecosystem DYnamics Model (CAEDYM) is an aquatic ecological model that simulates time-varying fluxes of biogeochemical variables (e.g. nutrient species, phytoplankton biomass). These can be coupled and are often used with DYRESM for lakes (1D, DYRESM-CAEDYM) or ELCOM for lakes, estuaries and coastal areas (3D, ELCOM-CAEDYM).	https://ref.coastalrestorationtrust.org.nz/site/assets/files/8291/2012_11_hamilton_waituna_lagoon_modelling_developing_quantitative_assessments_to_assist_with_lagoon_management.pdf
eFlows Explorer (Shiny App)	1	NIWA	This is not a model *per se*, but a collation of data and model outputs available through a web interface. Model statistics on environmental flows are available.	https://shiny.niwa.co.nz/eflowsexplorer/

EFSAP	4	NIWA	The Environmental Flows Strategic Allocation Platform (EFSAP) is a water planning and management tool designed to help set regional or large-scale water resource use limits for rivers. The tool predicts how limits on water take and minimum residual river flows affect, or can be designed to optimise, the reliability of water use and effects on in-stream environments. Examples of out-of-stream use include domestic water and irrigation. In-stream environmental values include physical habitat for fish.	https://niwa.co.nz/freshwater/environmental-flows-strategic-allocation-platform-efsap
Eigen model	2	Environmental Science and Research (ESR); Aqual-inc Research Limited	Eigen functions and values are mathematical functions that describe the dependencies between variables. The model has been used in a wide range of theoretical and practical applications. For many of these applications the Eigen values quantify the dependencies among a set of variables, and these dependencies can be ranked in order of importance according to some measure. For groundwater levels, Eigen models have been developed that link groundwater levels to groundwater recharge.	https://doi.org/10.13140/RG.2.2.19317.65761
ESR microbe transport model	1	ESR	This groundwater microbe transport model was developed to assess bacterial removal in soils and groundwater.	https://envirolink.govt.nz/assets/Envirolink/48-Mldc3-AssessingBacterial-RemovalInSoils.pdf

Estuary Trophic Index	3	NIWA	The Estuary Trophic Index provides a nationally consistent approach to the assessment and prediction of estuary eutrophication for 443 New Zealand estuaries. The tool has three sub-components: susceptibility assessment, an estuary health score based on measured data, and an estuary health score based on a Bayesian belief network.	https://niwa.co.nz/freshwater/new-zealand-estuary-trophic-index
eWater Source	5	eWater CRC (AUS)	This is a software framework that can flexibly link and apply hydrological models through model coupling interfaces. It embeds an internal suite of surface water models and a simple groundwater model. It is the agreed model for water accounting in the cross-boundary Murray–Darling Basin, Australia. It can also be used for catchment-based modelling studies.	https://ewater.org.au/products/ewater-source/
Farm-scale *E. coli* model	1	Richard Muirhead and Graeme Doole	This spreadsheet model was developed for Gisborne District Council to model the effectiveness and cost-effectiveness of mitigations to reduce *E. coli* losses from sheep and beef farms.	n/a
FEFLOW	5	DHI	This is a numerical finite element groundwater flow model maintained for porous and fractured media, including mass transfer and heat transfer. It is used as an alternative to MODFLOW.	https://www.mikepoweredbydhi.com/products/feflow

FME (s.14.3b) model	1	Auckland Council	This Auckland Council specific model was built with the Feature Manipulation Engine (FME) within ArcGIS. It contains Auckland Council's bespoke 's.14.3(b)' model for estimating unconsented groundwater, as permitted by section 14(3)(b) of the Resource Management Act 1991. It was used to help inform resource consent allocation decisions.	https://knowledgeauckland.org.nz/publications/water-management-report-auckland-council-section-14-3-b-groundwater-takes/
FWMT	2	Auckland Council; Morphum Environmental; Paradigm Environmental	The Freshwater Management Tool (FWMT) is a freshwater accounting and decision-making tool based on United States Environmental Protection Agency (US EPA) models Loading Simulation Program in C++ (LSPC) and System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN). It is used by Auckland Council and Northland Regional Council.	https://www.knowledgeauckland.org.nz/search/?query=fwmt https://www.morphum.com/projects/fwmt
Generalised habitat models	1	Environment Southland	This fish habitat model is used where NREI is not available online. It was custom built for Environment Southland.	n/a
GoldSim	1	GoldSim	GoldSim allows users to create models of water supply, water resource and hydrological systems to carry out risk analyses, evaluate potential environmental impacts, support strategic planning, and make better resource management decisions. GoldSim has powerful probabilistic simulation capabilities for representing the inherently uncertain and stochastic nature of all real-world systems.	https://www.goldsim.com/Web/Applications/Areas/EnvironmentalSystems/WaterResources/

Hunt/Theis stream depletion tools	5	Environment Canterbury	This is a collection of groundwater tools and resources developed and/ or compiled by Environment Canterbury. It is available online and contains a well interference assessment tool, a drawdown tool, stream depletion tools, two aquifer system tools and other tools developed by Dr Bruce Hunt (University of Canterbury).	https://www.ecan.govt.nz/your-region/your-environment/water/tools-and-resources/
HYDRUS	1	PC Progress	HYDRUS is a Microsoft Windows based model that uses meteorological data, soil type, vegetation type, soil temperature, solute concentration and root distribution input data to simulate the movement of water, heat and multiple solutes in variably saturated porous media (and viruses, colloids and bacteria).	https://www.pc-progress.com/en/Default.aspx?hydrus
Hydstra-hydrol	1	Kisters	A rainfall-runoff hydrological model that uses a modified Australian Water Balance Model that is calibrated to the catchment characteristics of the region.	https://www.kisters.com.au/hydstra/
IrriCalc	8	Aqualinc Research Limited	This is a soil water balance model used to estimate irrigation demand and groundwater recharge. The software is not open, but a free web-based irrigation calculator exists.	https://www.irrigationnz.co.nz/PracticalResources/IrrigationDevelopment/AllocationCalculator
Lakewatch	1	Bay of Plenty Regional Council	Lakewatch software is a useful tool for monitoring observations and trends in a lake's chemical and physical state and for the computation of the Trophic Level Index.	https://www.boprc.govt.nz/media/33541/Report-100203-Env0912RotoruaLakesWaterQualityReport2009.pdf

Leathwick	1	John Leathwick	A River Environment Classification (REC)-based statistical method to classify and rank biodiversity and occurrence of freshwater fish species.	https://doi.org/10.1071/MF11067
MIKE suite	5	Dansk Hydraulisk Institut (DHI)	This suite, developed by consultancy DHI, contains a variety of models for a range of purposes covering all hydrological surface water catchment processes: MIKE11 (river modelling), MIKE3FM (hydrodynamic module), MIKE-SHE (integrated hydrological model, including groundwater, surface water, recharge and evapotranspiration) and MIKE21 (hydrodynamics, waves, sediment dynamics, water quality and ecology).	https://www.mikepoweredbydhi.com/products
MODFLOW	12	United States Geological Survey (USGS)	MODFLOW is the most accepted groundwater flow modelling software in the scientific community. It contains many sub-models that cover most of the water cycle, including groundwater contaminant transport. It is often used in conjunction with the statistical software PEST to infer statistics on stochastic model runs.	https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs

MUSIC	1	eWater	The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) can model a wide range of treatment devices to identify the best way to capture and reuse stormwater runoff, remove its contaminants and reduce runoff frequency. With MUSIC you can evaluate these treatment devices to achieve water-sensitive urban design and integrated water cycle management goals.	https://ewater.org.au/products/music/
National deposited sediment classification	1	Cawthron Institute	This national dataset is used for regression classification of deposited fine sediment. It uses the REC as well as the New Zealand Freshwater Fish Database (NZFFD) and councils' monitoring networks. It should therefore be treated as different from the REC-based regression model mentioned above.	https://environment.govt.nz/assets/publications/CawRpt_2994_Deposited_sediment_classification_for_NZ_streams.pdf
National Fish IBI scores	1	Ministry for the Environment (MfE)	The Fish Index of Biotic Integrity (Fish IBI) calculator uses compiled data per river reach across New Zealand.	https://environment.govt.nz/acts-and-regulations/freshwater-implementation-guidance/nof/values-and-attributes/fish-index-of-biotic-integrity/ https://mfenz.shinyapps.io/fish-ibi-calculator/

National look-up tables for periphyton	1	MfE	Not a model *per se*, but a set of periphyton look-up tables to derive setting nutrient targets for periphyton in the NPS-FM. It is based on a regression model and is used to assist regional authorities to define defendable dissolved macronutrient concentrations (phosphorus and nitrogen) and instream plant abundance as water quality standards for a broad range of river types and hydrological regimes.	https://environment.govt.nz/publications/guidance-on-look-up-tables-for-setting-nutrient-targets-for-periphyton-second-edition/
NREI (IFIM method) for fish habitat	1	John Leathwick	This advanced IFIM-based model (see SEFA) makes spatially explicit predictions of net rate energy intake (NREI).	https://niwa.co.nz/sites/default/files/a_guide_to_instream_habitat_survey_methods_and_analysis.pdf
NZ River Maps	3	NIWA	Not a model *per se*, but a collation of data and model outputs available through a web interface. A wide range of biophysical variables is available and includes sediment, hydrology and fish habitat.	https://shiny.niwa.co.nz/nzrivermaps/
NZEEM	2	MWLR	The New Zealand Empirical Erosion Model (NZEEM) is one of the erosion models for evaluating regional land-use scenarios. The model can be used to predict mean sediment discharge in response to land-cover/land-use scenarios in a GIS.	https://doi.org/10.1016/j.envsoft.2009.09.011
NZSYE	1	NIWA	The New Zealand Sediment Yield Estimator (NZSYE) is a statistical model that has been calibrated nationally against measured sediment loads determined for water quality sites across New Zealand.	https://environment.govt.nz/assets/publications/freshwater-policy/Sediment-ME1663-Final-1.9-V2.docx

Our Land and Water (OLW) typologies	3	Our Land and Water National Science Challenge	This is a model output, rather than a model, produced as datasets of landscape characteristics (typologies) developed in the Our Land and Water National Science Challenge. It could be used to estimate nutrient loss from soils to the rest of the catchment.	https://doi.org/10.1080/00288233.2020.1713822 https://doi.org/10.1080/00288233.2021.1936572 https://doi.org/10.1080/00288233.2021.1876741 https://doi.org/10.1080/00288233.2020.1844763
Overseer	9	Ministry for Primary Industries (MPI); AgResearch; Fertiliser Association of New Zealand	Overseer describes nutrient flows on farms. It takes nutrients that are present or introduced to the farm, models how they are used by plants and animals on the farm, and then estimates how they leave the farm and in what form. The model supports farmers and growers to improve performance and reduce losses to the environment through better use of nutrients.	https://www.overseer.org.nz/
Physio-graphic models	2	Land and Water Science	This is a set of statistical methods and spatial data to infer factors controlling landscape susceptibility to loss of contaminants.	https://ourlandandwater.nz/news/how-northland-regional-council-is-using-physiographic-science/
Random forest (RF) model by NIWA for flow stats	1	NIWA	The river flow stats were developed with flow gauge data, REC modelling and the random forest model. Since it is focused on flow stats, and not on water quality, it should be treated as separate to the REC-based regression model.	https://www.nrc.govt.nz/media/mh0h443i/reportonassessmentofwateravailableforallocationfinal.pdf

REC-based regression	9	Land Water People (LWP)	REC is a database of catchment spatial attributes, summarised for every segment in New Zealand's network of rivers. The attributes were compiled for the purposes of river classification, while the river network description has been used to underpin models. REC-based regression models are statistical regression models built on relations between attributes in the REC dataset and monitoring data of nutrients, streamflow or other properties.	https://niwa.co.nz/freshwater/management-tools/environmental-flow-tools/river-environment-classification https://landwaterpeople.co.nz/
Regional Cawthron MCI model	1	Cawthron Institute	The Macroinvertebrate Community Index (MCI) model was developed by the Cawthron Institute. It is not really a model, but more the results of a model output.	https://environment.govt.nz/assets/Publications/Files/mci-user-guide-may07.pdf
ROTAN	1	NIWA	The ROtorua and TAupo Nitrogen (ROTAN) model is based on the Scandinavian HBV-N model, to route nitrogen losses from soil through catchment, which includes attenuation. It is a GIS-based rainfall-runoff-groundwater model that can predict the water flows and nitrogen concentrations in streams on a daily or weekly time scale. It can also account for the time lags between nitrogen leaching and delivery to the lakes. It does not model phosphorus.	http://tools.envirolink.govt.nz/assets/Uploads/predicting-nitrogen-inputs-to-lake-rotorua-using-rotan-annual-october-2016.pdf

RUSLE	1	USDA; AgResearch for NZ model	The Revised Universal Soil Loss Equation (RUSLE) and its predecessor, the Universal Soil Loss Equation (USLE), predict mean annual soil loss from surface erosion based on a set of equations derived from empirical measurements of soil losses from agricultural plots.	https://doi.org/10.1016/j.envsoft.2021.105228
Safeswim	2	Auckland Council; Northland Regional Council; Watercare; Surf Lifesaving; Auckland Regional Public Health Service. Developed by DHI.	This web-based GIS provides real-time information on water quality and swimming conditions at several of New Zealand's beaches and swimming spots. It is not really a model, but more a geospatial interface developed using models of urban wastewater overflow into coastal water.	https://www.safeswim.org.nz/
SCAMP/ CASM	4	RMA Science	The Simplified Contaminant Allocation Model Platform (SCAMP) is a spreadsheet-based method to assess effects of land use and contaminant (diffuse and point) discharge on water quality. It assesses loads at various point and is simplified in that councils can simulate scenarios in a reasonably short time. It was previously known as the Contaminant Allocation & Simulation Model (CASM).	https://rmascience.co.nz/index.php/water-modelling/#CASM-Begin

SedNetNZ	9	Manaaki Whenua – Landcare Research (MWLR)	This sediment erosion model predicts the generation and transport of sediment through river networks based on a simple representation of soil, hillslope and channel processes, providing estimates of sediment load generated by erosion processes (landslides, gullies, earthflows, surface, and bank erosion) and sediment deposition on floodplains.	https://www.sciencedirect.com/science/article/abs/pii/S0169555X15302415
SEFA-RHYHABSIM	8	Jowett Consulting	System for Environmental Flow Analysis (SEFA, superseding River Hydraulic HABi-tat SIMulation (RHYHABSIM)) implements the Instream Flow Incremental Methodology (IFIM), a methodology to assess fish habitat suitability with different environmental and flow regimes in rivers and streams. It was established from nationwide field-observed data. SEFA contains water allocation scenarios, habitat hydraulics analysis, water temperature modelling, sediment transport analysis, dissolved oxygen modelling, riparian modelling, hydrologic and habitat time series analysis, and more.	http://sefa.co.nz/

SPARROW	1	USGS	The SPAtially Referenced Regression On Watershed (SPARROW) model is used to estimate long-term average values of water characteristics, such as the amount of a contaminant that is delivered downstream. It uses existing monitoring data, location and strength of contaminant sources, and characteristics of the landscape. It is an open-source model with no commercial or intellectual property constraints and is included in CLUES.	https://www.usgs.gov/mission-areas/water-resources/science/sparrow-modeling-estimating-nutrient-sediment-and-dissolved
SPASMO	10	Plant & Food Research	The Soil Plant Atmosphere System Model (SPASMO) simulates the transport of water, microbes and solutes through soils, integrating variables such as climate, soil, water uptake by plants in relation to farm and orchard practices, and any other factors affecting environmental process and plant production. SPASMO-IR is the SPASMO module dedicated to water quantity that used by councils to model the effect of irrigation.	https://flrc.massey.ac.nz/workshops/17/Manuscripts/Paper_Clothier_2017.pdf
Statistical inhouse models in R	1	Bay of Plenty Regional Council	These are bespoke models coded in the R programming language to derive trends.	n/a

SUSTAIN	1	US EPA	System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN) is a decision support system that assists stormwater management professionals with developing and implementing plans for flow and pollution control measures to protect source waters and meet water quality goals. SUSTAIN allows watershed and stormwater practitioners to develop, evaluate, and select optimal best management practice (BMP) combinations at various watershed scales based on cost and effectiveness.	https://www.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain
SWAT	5	United States Department of Agriculture (USDA); Texas Water Resources Institute	The Soil & Water Assessment Tool (SWAT) covers a range of simulations in quantity and quality of surface water and groundwater at a range of scales (e.g. small watershed to river basin scale). It predicts the environmental impact of land use, land management practices and climate change, and assesses soil erosion prevention and control, non-point source pollution control and regional management in watersheds.	https://swat.tamu.edu/
Timetrend (statistical)	1	Jowett Consulting	This free statistical analysis is used for trend and equivalence analyses of environmental timeseries in a Windows interface.	https://www.jowettconsulting.co.nz/home/time-1
TopNet	7	NIWA	This is a hydrological catchment-based model designed for dynamic catchment-scale to nationwide streamflow prediction, including flood forecasting.	https://www.sciencedirect.com/science/article/abs/pii/S0309170808001012

TOUGH2	1	Berkeley Lab, USA	Transport Of Unsaturated Groundwater and Heat (TOUGH2) is a numerical simulator for non-isothermal flows of multicomponent, multiphase fluids in one, two, and three-dimensional porous and fractured media. The chief applications for which TOUGH2 is designed are in geothermal reservoir engineering, nuclear waste disposal, environmental assessment and remediation, and unsaturated and saturated zone hydrology.	https://tough.lbl.gov/licensing-download/
Town Effluent Calculator	1	Unknown	A tool used by Horizons Regional Council. No further information was found.	n/a
TRIM	1	NIWA	TRIM_CATCHMENT is a simplified version of ROTAN and includes both nitrogen and phosphorus together with groundwater and streams. It is different from CLUES, which is a conceptual, data-based model that is widely used to estimate annual nitrogen and phosphorus loads in streams but does not include groundwater.	https://www.hbrc.govt.nz/assets/Document-Library/RWSS-Final-RMA-Reports/Modelling-Reports/RWSS-M3-Stream-Modelling-Trim-2-Calibration-NIWA-May-2013a.pdf https://www.epa.govt.nz/assets/FileAPI/proposal/NSP000028/Evidence/fb0104e42c/22-Kit-Rutherford-Evidence.pdf

Vollenweider lake models	1	N/A	This model examines phosphorus loads in lakes. A statistical relationship between areal annual phosphorus loading to a lake normalized by mean depth and hydraulic residence time, to predict lake phosphorus concentration.	Vollenweider, R.A., 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Memorie dell' Istituto Italiano di Idrobiologia, 33: 53-83
WAIORA	2	NIWA	Water Allocation Impacts on River Attributes (WAIORA) is a decision support system designed to provide guidance on whether a flow change could have adverse impacts on the following environmental parameters: dissolved oxygen, total ammonia, water temperature and habitat for aquatic life. It embeds the New Zealand Empirical Erosion Model (NZEEM) for sediment.	https://niwa.co.nz/freshwater/our-services/catchment-modelling/water-allocation-impacts-on-river-attributes-waiora
WAT (capture zone tool)	1	Northland Regional Council	The Water Allocation Tool is a custom-built GIS tool from Northland Regional Council.	https://ndhadeliver.natlib. govt.nz/delivery/DeliveryManagerServlet? dps_pid=IE37647182 See page 66
Water allocation model (bespoke)	1	Tasman District Council	This is a custom-built water allocation model used by Tasman District Council.	n/a
WATYIELD	1	MWLR	WATYIELD is a water balance model based on inputs of rainfall and estimates of evapotranspiration and soil properties. It is used to calculate the flow out of a catchment and crop water requirements. It is often used to look at the effects of land use change on water yield.	https://icm.landcareresearch.co.nz/knowledgebase/publications/public/Watyield_Users_guide.pdf

Table A1.2: Sub-models used in the MODFLOW model.

Sub-models of MODFLOW	Number of councils that use this sub-model	Developer/ New Zealand contact	Sub-model description	Link
PEST	5	John Doherty	Model-Independent Parameter Estimation and Uncertainty Analysis (PEST) is a software package used for automated calibration and calibration-constrained uncertainty analysis of any numerical model.	https://pesthomepage.org/pest
MT3D	3	USGS	This is a sub-package for contaminant transport.	https://www.usgs.gov/software/mt3d-usgs-groundwater-solute-transport-simulator-modflow

Appendix 2: Technical evaluations of 24 freshwater models

While model evaluation guidance exists both nationally and internationally, models within New Zealand are not currently systematically evaluated. To fill this gap, the office of the Parliamentary Commissioner for the Environment (PCE) has analysed the most commonly used freshwater models, taken from the stocktake of biophysical models (Appendix 1), against a set of criteria. These 24 models are either in use or have recently been used by at least three regional councils or unitary authorities to support a range of regulatory freshwater management requirements.

This evaluation is intended as a starting point for later fine-tuning. It provides a concise overview of the strengths and weaknesses of commonly used models.

The evaluation criteria are based on previous work of the US EPA, findings from the PCE report on Overseer, and MfE 2023 guidance.[1] The criteria are described below. The results of this evaluation are summarised in two tables below (Table A2.1 and Table A2.2).

It is important to note that this evaluation is mostly at the technical model/software level. It provides a visual overview of models' technical strengths and weaknesses.

The question of whether a model is fit for its intended purpose depends on its specific application. Such an assessment of a model's fitness for purpose should be undertaken on a case-by-case basis given the intended purpose of the model and include specific circumstances and questions that need to be answered.

Criteria

A. Scientific basis

Description of the scientific concept on which this model is based.

- Is the scientific concept sound and consistent with current science?
- Is the algorithm appropriate?
- Has mātauranga Māori been included in the model?
- Have other concepts, i.e. alternative approaches or other models, been explored?
- Is the model structure scientifically sound:
  - Does it compute the variables needed, or only proxies thereof?
  - Are there any model dependencies or sub-models doing the same thing?
  - Is every sub-component using the same data source?

[1] US EPA, 2009; PCE, 2018; MfE, 2023b.

B. Transparency

- Is the model open source?
- Is the model open access?
- Is model use for research free?
- Is commercial model use free?
- Is the model currently maintained?
- Is there a good description and explanation of the model? For example, does the model have clear user instructions and a detailed description of how it operates?
- Have the model results been made publicly accessible? (Assessed depending on specific application.)
- Can the model results be linked back to the source model equations?
- Have the model and the model results been communicated appropriately with all stakeholders in the regulatory process? (Assessed depending on specific application.)

C. Computational infrastructure and maintenance

- Is the computational infrastructure such that a model can be applied flexibly? For example, does the model require high performance computing systems to run? If so, what is the availability of that high performance computing system?
- How much expertise is required to run the model? (Rated from simple (1) to complicated (3).)
- Is the model software, including its versioning methods, up to date?
- Can the model be easily run again with new data – i.e. how updateable is the model?
- How interoperable is the model – i.e. can the model be joined with other models, and is there evidence of that being done in the past?
- Are there any processes in place for quality control? For example, is there a regular assessment of data quality? Are alerts generated when data are missing or results are out of bounds? Are there other issues with comparison or correlation with observed or other known data?

D. Assumptions and limitations

- What are the assumptions in the model that affect model performance?
- What are model limitations (such as statements where it cannot be applied)?
- Are these assumptions and limitations explained clearly and openly?

E. Peer review

- Has the model undergone a review by at least two reviewers who are experts in that field of modelling?

F. Sensitivity and uncertainty analysis

- What is the technical capability of the model to generate an estimate of uncertainty and/or an estimate of probabilities?
- What is the influence of each model input on model outputs? Which model input is making the model change most? (Assessed depending on specific application.)

G. Validation

- How many data are available for use of the model and for validation of the model? (Assessed depending on specific application.)
- How have model results been validated against an independent set of observations (i.e. not the observations that the model was developed with)? (Assessed depending on specific application.)
- What are the results of studies where the model has been compared or benchmarked to other models? This could include descriptions of model incongruence, if any. (Assessed depending on specific application.)

H. Temporal and spatial scale and resolution

- This is a description of the spatial and temporal resolution of the model. It should include a description of whether a model is technically limited to steady-state results, or capable of generating dynamic outputs.

Tables A2.1 and A2.2 below provide a traffic-light assessment of the 24 commonly used freshwater models, providing a visual overview of models' technical strengths and weaknesses. The table is ordered based on the number of regional councils that have reported the use of any specific model. Note that for the purposes of this evaluation, six bespoke water balance models have been grouped together in one column, as have the three bespoke nutrient budgets. For future model evaluations, this could be elaborated on to include a concise description of the model, capturing what it can and cannot do to identify its strengths and weaknesses.

Table A2.1: Preliminary evaluation of the first 12 of 24 models against set criteria (part 1). Note that in this table, six bespoke water balance models have been grouped together in one column. Y = yes; N= no; M = maybe (i.e. not by default but might be possible).

Criteria	Specific questions	Models											
		MODFLOW	SPASMO	CLUES	REC-based regression	SedNetNZ	Overseer	IrriCalc	SEFA-RHYHABSIM	TopNet	Bespoke water balance budgets	eWater Source	SWAT
Scientific basis	Does the model algorithm estimate variable of interest directly (Y) or does it estimate a proxy (N)?	Y	Y	M	Y	Y	M	Y	M	M	M	Y	Y
Scientific basis	Is the algorithm valid?	Y	Y	M	Y	Y	Y	Y	Y	Y	M	Y	Y
Scientific basis	Is the model structure efficient (Y) or are there any inconsistencies in, for example, sub-models or algorithms (N)?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Transparency	Is the model open source?	Y	N	N	Y	N	N	N	N	N	M	N	Y
Transparency	Is the model open access?	Y	N	Y	Y	N	N	Y	N	N	M	N	Y
Transparency	Is model use for research free?	Y	N	Y	Y	N	N	N	N	N	M	M	Y
Transparency	Is model use for commercial use free?	Y	N	N	Y	N	N	N	N	N	M	N	Y
Transparency	Are the model structure and software sufficiently explained?	Y	Y	Y	Y	Y	M	Y	Y	Y	N	Y	Y
Computational infrastructure and maintenance	How much expertise is required to run the model? (rated from simple (1) to complicated (3))	3	2	2	3	1	2	2	1	3	1	2	3
Computational infrastructure and maintenance	Is the model software (versioning), including its versioning methods, up to date?	Y	N	Y	N	N	M	N	Y	Y	N	Y	Y
Computational infrastructure and maintenance	Can the model be easily run again with new data – i.e. how updateable is the model?	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y
Computational infrastructure and maintenance	How interoperable is the model – i.e. can the model be joined with other models, and is there evidence of that being done in the past?	Y	N	Y	Y	N	M	N	N	N	N	Y	Y

Computational infrastructure and maintenance	Are there any processes in place for quality control (e.g. regular assessment of data, checks for missing data)?	Y	M	N	Y	M	N	M	Y	Y	N	Y	Y
Assumptions and limitations	Have model assumptions and limitations been defined clearly (e.g. assumptions of parameters, or what the model cannot be used for)?	Y	N	Y	Y	Y	M	N	Y	N	M	Y	M
Peer review	Has the model undergone a peer review (and was it acceptable) by at least two peers who are experts in the field of modelling?	Y	Y	Y	Y	Y	M	Y	Y	Y	M	Y	Y
Sensitivity and uncertainty analysis	Has the model code been equipped to incorporate sensitivity analyses?	Y	M	M	Y	N	N	N	N	Y	N	M	Y
Sensitivity and uncertainty analysis	Is the model code equipped to incorporate uncertainty analyses?	Y	N	M	Y	N	N	N	N	N	N	Y	Y
Validation	Is there evidence in the form of case studies?	Y	Y	Y	Y	Y	M	Y	Y	Y	M	Y	Y
Validation	Has the model algorithm been compared to an independent set of observations?	Y	N	N	Y	Y	Y	Y	Y	Y	M	Y	Y
Validation	Has the model been benchmarked to other models?	Y	M	Y	Y	Y	N	Y	Y	Y	M	Y	Y
Temporal and spatial scale and resolution	Is the model steady state (SS) or dynamic (D), or can it be used for both (B)?	B	B	SS	SS	SS	SS	B	SS	B	SS	B	B
Temporal and spatial scale and resolution	If dynamic: What is the typical time step? (weekly (W), daily (D), or not applicable (NA))	W	D	NA	NA	NA	NA	D	NA	D	NA	D	D
Temporal and spatial scale and resolution	What is the typical spatial resolution of the model? (property (1), sub-catchment (2), catchment (3), region (4), nation (5))	1	1	2	2	1	1	1	2	2	2–3	2–3	2
Temporal and spatial scale and resolution	What is the typical spatial coverage of the model? (paddock/farm (1), sub-catchment (2), catchment (3), region (4), nation (5))	2	3–5	3–5	3–5	3–4	3–4	1–5	2	3–5	3	3–4	3

Table A2.2: Preliminary evaluation of the second 12 of 24 models against set criteria (part 2). Note that in the table, three bespoke nutrient budgets have been grouped together in one column. Y = yes; N= no; M = maybe (i.e. not by default but might be possible).

Criteria	Specific questions	Models											
		Hunt/Theis stream depletion tools	MIKE suite	FEFLOW	SCAMP-CASM	EFSAP	Estuary Trophic Index	OLW typologies	Bespoke nutrient budgets	DYRESM-ELCOM-CAEDYM	CHES	NZ River Maps	WAIORA
Scientific basis	Does the model algorithm estimate variable of interest directly (Y) or does it estimate a proxy (N)?	Y	Y	Y	Y	M	Y	Y	M	Y	M	Y	M
Scientific basis	Is the algorithm valid?	Y	Y	Y	Y	Y	Y	M	M	Y	Y	Y	Y
Scientific basis	Is the model structure efficient (Y) or are there any inconsistencies in, for example, sub-models or algorithms (N)?	Y	Y	Y	Y	Y	M	N	Y	Y	Y	Y	M
Transparency	Is the model open source?	M	N	N	N	N	N	N	M	N	N	N	N
Transparency	Is the model open access?	Y	N	N	N	N	Y	Y	M	N	N	Y	Y
Transparency	Is model use for research free?	Y	N	N	N	N	Y	Y	M	N	N	Y	Y
Transparency	Is model use for commercial use free?	Y	N	N	N	N	M	Y	M	N	N	Y	Y
Transparency	Are the model structure and software sufficiently explained?	N	Y	Y	M	M	Y	Y	N	Y	Y	Y	Y
Computational infrastructure and maintenance	How much expertise is required to run the model? (rated from simple (1) to complicated (3))	1	3	3	1	2	2	1	1	3	1	1	1
Computational infrastructure and maintenance	Is the model software (versioning), including its versioning methods, up to date?	M	Y	Y	N	N	N	M	N	N	M	Y	N
Computational infrastructure and maintenance	Can the model be easily run again with new data – i.e. how updateable is the model?	Y	Y	Y	Y	Y	N	N	N	M	Y	N	Y
Computational infrastructure and maintenance	How interoperable is the model – i.e. can the model be joined with other models, and is there evidence of that being done in the past?	N	Y	Y	M	N	M	M	N	Y	N	Y	N
Computational infrastructure and maintenance	Are there any processes in place for quality control (e.g. regular assessment of data, checks for missing data)?	N	Y	Y	Y	N	M	N	N	M	M	Y	M

Assumptions and limitations	Have model assumptions and limitations been defined clearly (e.g. assumptions of parameters, or what the model cannot be used for)?	N	Y	Y	Y	M	Y	M	M	M	M	M	Y
Peer review	Has the model undergone a peer review (and was it acceptable) by at least two peers who are experts in the field of modelling?	Y	Y	Y	Y	N	Y	Y	M	N	M	M	Y
Sensitivity and uncertainty analysis	Has the model code been equipped to incorporate sensitivity analyses?	N	Y	Y	M	N	N	N	N	M	M	M	N
Sensitivity and uncertainty analysis	Is the model code equipped to incorporate uncertainty analyses?	N	Y	Y	Y	N	N	M	N	M	Y	M	N
Validation	Is there evidence in the form of case studies?	Y	Y	Y	M	Y	Y	Y	M	Y	Y	M	Y
Validation	Has the model algorithm been compared to an independent set of observations?	N	Y	Y	Y	N	Y	Y	M	Y	Y	Y	Y
Validation	Has the model been benchmarked to other models?	Y	Y	Y	N	N	N	Y	M	Y	Y	M	N
Temporal and spatial scale and resolution	Is the model steady state (SS) or dynamic (D), or can it be used for both (B)?	SS	B	B	SS	SS	SS	SS	SS	B	B	SS	SS
Temporal and spatial scale and resolution	If dynamic: what is the typical time step? (weekly (W), daily (D), or not applicable (NA))	NA	D	W	NA	NA	NA	NA	NA	D	D	NA	NA
Temporal and spatial scale and resolution	What is the typical spatial resolution of the model? (property (1), sub-catchment (2), catchment (3), region (4), nation (5))	1	2	3	2–3	2	3	2	2–3	2	3	2	2
Temporal and spatial scale and resolution	What is the typical spatial coverage of the model? (paddock/farm (1), sub-catchment (2), catchment (3), region (4), nation (5))	1	3	3	3	3–4	3–5	3–5	3	2	3	3–5	2

Appendix 3: International examples of what can be achieved

Open-source model software development in the United States

The use of open data and software in government practice likely originated in the 1950s in the USA.[2] Much of the open software available was developed by US government institutions but is now well used outside of the USA.

MODFLOW

MODFLOW was developed by the United States Geological Survey (USGS) in the early 1980s to replace the extremely incongruent groundwater flow model suites within the USGS.[3] It is currently the most-used software for groundwater flow modelling in the world. Its popularity stems from several factors:

- flexibility of the software, platform, add-ons
- well-documented guidance
- legal defensibility, i.e. it has been successfully used in many court cases
- agreed governance across the whole of the USGS.[4]

A small, dedicated group of USGS scientists is funded to develop and maintain the software. Since MODFLOW is flexible and modular, a much larger group of scientists from across the world are writing applications that wrap around, or use instances of, MODFLOW software.

SWAT

The **Soil Water Assessment Tool (SWAT)** was developed in the early 1990s by merging models of soil water quantity and quality and river flow in a geographic information system (GIS) framework. The model has been continuously improved ever since. It is available as open-source software and maintained by Texas A&M University. Next to MODFLOW, it is one of the most widely used hydrological models for processes that include soil, water, land surface runoff, nutrient loss and water quality prediction. Similar to MODFLOW, SWAT models can be linked flexibly to other hydrological models.

LSPC and SUSTAIN

The US EPA supported the development of the watershed modelling system **Loading Simulation Program in C++ (LSPC)**, which simulates hydrology, sediment and general water quality on land, and contains a simplified stream transport model. LSPC uses a Microsoft Access database to manage model data and weather text files to drive the simulation. The system contains modules to assist in calculations of contaminant load and source allocations. LSPC can be considered an update of the hugely popular yet much older predecessor model software Hydrological Simulation Program – Fortran (HSPF, developed throughout the 1960 and 1970s), as it is more compatible with Microsoft Windows software.[5]

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[2] Batarseh et al., 2020.
[3] McDonald et al., 2003.
[4] USGS, 1997.
[5] Shen et al., 2005.

System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN) is a decision support system that assists stormwater management professionals to develop and implement plans for flow and pollution control measures to protect source waters and meet water quality goals.[6] The SUSTAIN model is no longer maintained by the US EPA. The latest version stems from 2014 and there are no plans for updated versions.

LSPC and SUSTAIN are relatively outdated; however, they form the core of the Freshwater Management Tool (FWMT) developed by Auckland Council with two consultancies – Morphum Environmental and Paradigm Environmental. While LSPC and SUSTAIN are open, some of the tailored improvements in FWMT are proprietary.

Australian catchment accounting and the eWater Source tool

A nationally agreed platform for water allocation and accounting modelling

The **eWater Source** tool (often called just 'Source') is a model platform developed in Australia and now used in New Zealand.

Source is a software framework that can flexibly link and apply hydrologic models through modern model coupling interfaces. An internal suite of surface water models for both water quality and quantity are also embedded within the framework.

Source has been formalised as the Australian National Hydrology Modelling Platform for use in water resource assessments. It received that status mostly because it was developed to be used for water resource management in the Murray–Darling Basin, which covers five of the eight states and territories in Australia. The Murray–Darling Basin Authority, an independent statutory agency in the Australian Government, has a rigorous accreditation process for developing water resource plans. That process includes many regulatory and cultural aspects, but also prescribes use of the Source model. Hence, Source will remain the Australian 'go-to' tool for water allocation and accounting for the foreseeable future.

Source can be used for catchment-scale studies, particularly those involving wider hydrological processes, including water quality. However, this use of the tool does not have the same governance status as the water allocation and accounting models in Source. For this reason, catchment-scale model approaches still vary widely in Australia.

An advantage of Source is that it provides good modelling guidelines and has documentation and instructional videos available online for free. However, use of the software is not free. Source comes with a free-for-research licence, but this is very limited in its use.

Source includes a simple groundwater model. In theory, a MODFLOW model can be loosely coupled to Source; however, it is unclear if this provides a computationally efficient solution for groundwater driven studies.

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6 For more information on SUSTAIN, see US EPA (no date).

Netherlands Hydrological Instrument

A consensus-based model suite for water management

The **Netherlands Hydrological Instrument (NHI)** is a model framework that integrates the most commonly used groundwater, soil water and surface water models. Models used both nationally and regionally within the Netherlands include open-source models of MODFLOW (groundwater), metaSWAP (unsaturated zone), and RIBASIM (hydrological river basin) at the national scale, and a range of other models for activities like irrigation and water allocation, which vary across different regional applications.

Development of the NHI started in 2005.[7] After repeatedly being confronted with incongruence of models from different ministries, the national water management body – Rijkswaterstaat – and national research institutes initiated the development of a better, more collective and harmonised approach to freshwater resource modelling.[8] In 2013, a consensus-based NHI was achieved, thanks to the cooperation of most national and regional water management organisations. These organisations now collaboratively fund the NHI model.

The NHI is governed by national and regional steering groups with representation from the three types of funders: central government, regional water authorities and water service entities. The steering groups decide on development priorities and are guided by scientific advisory boards.

The NHI is the first and most developed of three water modelling platforms in a wider national water model. The other platforms deal with water quality (nutrients) and water safety (dike strength and flood hazard).

The NHI models have been used for several regulatory applications: to analyse catchment-scale effects of climate change, for national guidance on implementation of the EU Water Framework Directive, and to coordinate water resource management, such as the distribution of water between catchments, in times of drought. Regional NHI models are used to calculate the effects and feasibility of regional plans, the maintenance of sub-catchment-scale waterways, and smaller-scale tile drainages and weirs.

As an open-source model framework, the NHI is a widely used and accepted set of models for freshwater resource management in the Netherlands, where both national and regional-scale model applications are developed, maintained and regularly updated. Improvements in the national model can be used to improve regional models. In return, regional-scale results and data feed their way back into updated versions of the national model. Use of the NHI is not enshrined in Dutch law but is considered common practice since it is updated, standardised, easily available and generally accepted by hydrologists, regulators, and the legal system.

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7 van der Giessen, 2005.

8 Rijkswaterstaat (RWS) is the operational branch of the Dutch Ministry of Water and Infrastructure. RWS is and has been hugely impactful in large infrastructural and water development works in the Netherlands, such as the Delta Works (the primary defence infrastructures (dikes, dams and barriers) against the sea) and the Room for the River Works (the widening and depoldering of river systems at 34 locations to reduce flood impacts).

Appendix 4: Legislative framework governing water resource management in New Zealand

The legislative framework governing the management of water in New Zealand is complex, with different types of water managed under different regulatory instruments. However, water is, by its very nature, connected – freshwater will affect drinking water and stormwater can affect freshwater – so specific regulations can affect other types of water.

Resource Management Act 1991

At the time of writing, the management of freshwater is primarily governed by the **Resource Management Act 1991 (RMA)** (and associated national direction instruments).

The purpose of the RMA is to promote the sustainable management of natural and physical resources, recognising that "safeguarding the life-supporting capacity of air, water, soil, and ecosystems" is an important part of sustainable management.[9] In achieving the purpose of the RMA, matters of national importance must be recognised and provided for. These include "the preservation of the natural character of the coastal environment (including the coastal marine area), wetlands, and lakes and rivers and their margins" and "the relationship of Māori and their culture and traditions with their ancestral lands, water, sites, waahi tapu, and other taonga".[10] The concept of adverse effects on the environment is one of the key concepts in the RMA. Broadly speaking, the RMA provides an integrated framework for regulating both environmental management and land use planning. It aims to achieve sustainable management of natural and physical resources while avoiding, remedying or mitigating any adverse effects of activities on the environment.

The RMA contains several specific water management provisions, including restrictions on water use and discharges of contaminants to the environment, water shortage directions, provisions for water conservation orders, and freshwater farm plans.[11] Their implementation and practical elaboration are devolved to regional councils and unitary authorities.

Specifically, the RMA tasks regional councils with controlling the use of land, and the use of water and contaminant discharges in their regions.[12] The use of water is specified to include taking, using, damming and diverting water, and control of the quantity, level and flow of water in a water body. This includes setting any maximum or minimum levels or flows of water, and controlling the range, or rate of change, of levels or flows of water.[13]

While management of water use and discharges of contaminants sit solely with regional councils, both regional councils and territorial authorities have been tasked with the management of land use.[14]

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[9] RMA 1991, s 5(2)(b).

[10] RMA 1991, s 6(a) and (e).

[11] RMA 1991, ss 14, 15, 69, 70, 80A, 199–217, 217A–217Q, 329.

[12] RMA 1991, s 30.

[13] RMA 1991, s 30(1).

[14] RMA 1991, ss 30(1)(c) and 31(1)(b).

The implementation of the legal framework for water created under the RMA 1991 falls on regional councils and unitary authorities. In exercising their functions and powers they should have regard to kaitiakitanga, and other specified matters, and must take into account the principles of Te Tiriti o Waitangi.[15]

National Policy Statement for Freshwater Management

In the first two decades of the resource management system, from 1991 to 2011, central government provided limited guidance to regional councils, who were left to make most water-related policy decisions. Intensifying land use in some rural areas and urban expansion in others saw freshwater deteriorate in many places. This resulted, in 2011, in national policy direction for freshwater being issued in the form of a **National Policy Statement for Freshwater Management (NPS-FM)**, one of the national direction instruments prepared under the RMA. Progressively more ambitious revisions followed in 2014, 2017 and 2020. This regulatory approach to water is still relatively new and rapidly evolving.

The current, 2020 version of the NPS-FM, and additional national direction instruments, were the result of the Government's 2019 Essential Freshwater policy package, which aimed to improve the quality of freshwater. The Essential Freshwater policy package had three objectives:

- stop further degradation of our freshwater
- start making immediate improvements so water quality improves within five years
- reverse past damage to bring our waterways and ecosystems to a healthy state within a generation.[16]

Of particular importance was the introduction into regulation of the concept of **Te Mana o te Wai**.[17] Regional councils are required to give effect to Te Mana o te Wai by applying a hierarchy of obligations and following the principles encompassed by the concept (see Box A4.1).

The NPS-FM 2020 contains four compulsory values – ecosystem health, human contact, mahinga kai and threatened species – and requires regional councils to prepare new or revised regional freshwater plans. At the time of writing, an extension has been granted by the Government, and these plans now need to be notified by the end of 2027.

The **National Objectives Framework (NOF)**, which is an integral part of the NPS-FM 2020, requires regional councils to set visions, objectives and targets for specific freshwater attributes and contaminants to ensure the hierarchy of obligations and local definitions of Te Mana o te Wai are met.[18] This is done by setting rules, limits and methods for achieving those visions, objectives and targets – all through engagement with tangata whenua and communities.[19]

Regional councils are required to maintain and improve freshwater quality and ecosystems and achieve or better the national bottom-line limits for specific attributes and contaminants.

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[15] RMA 1991, ss 7 and 8.

[16] MfE, 2020a, p.1.

[17] However, the future use of the concept, and indeed the entire state of national direction on freshwater, is now in question given the Government's announcement in December 2023 that it intends to replace the NPS-FM 2020. See McClay et al. (2023).

[18] Poipoia, 2022a.

[19] The NOF contains 22 attribute tables, 10 of which require limits on resource use, and the remaining 12 require action plans. See NPS-FM 2020, appendices 2A and 2B.

Box A4.1: Te Mana o te Wai

Te Mana o te Wai is a fundamental concept outlining a hierarchy of obligations that have been enshrined in the objective of the NPS-FM 2020. They must be applied in all freshwater management.[20] The hierarchy of obligations is:

- first, the health and wellbeing of water bodies and freshwater ecosystems
- second, the health needs of people (such as drinking water)
- third, the ability of people and communities to provide for their social, economic and cultural wellbeing, now and in the future.

Put simply, Te Mana o te Wai re-deals the cards in favour of the environment. In its literal sense Te Mana o te Wai means the authority or sovereignty of the water. It is about the protection of mauri and restoring and preserving the balance between water, the wider environment and the community.[21]

Te Mana o te Wai also encompasses six principles relating to the roles of tangata whenua and other New Zealanders in the management of freshwater. These principles, which inform the implementation of the NPS-FM 2020, are as follows.

- **Mana whakahaere:** the power, authority and obligations of tangata whenua to make decisions that maintain, protect and sustain the health and wellbeing of, and their relationship with, freshwater.
- **Kaitiakitanga:** the obligations of tangata whenua to preserve, restore, enhance and sustainably use freshwater for the benefit of present and future generations.
- **Manaakitanga:** the process by which tangata whenua show respect, generosity and care for freshwater and for others.
- **Governance:** the responsibility of those with authority for making decisions about freshwater to do so in a way that prioritises the health and wellbeing of freshwater now and into the future.
- **Stewardship:** the obligations of all New Zealanders to manage freshwater in a way that ensures it sustains present and future generations.
- **Care and respect:** the responsibility of all New Zealanders to care for freshwater in providing for the health of the nation.

[20] In addition to clauses 1.3 and 2.1 in the NPS-FM 2020, Te Mana o te Wai is part of Policy 1 (clause 2.2) and clause 3.2 of the NPS-FM 2020.

[21] The concept of Te Mana o Te Wai has become a central pillar of environmental policy: It has been incorporated into the NPS-FM 2020; Taumata Arowai–the Water Services Regulator Act 2020; and the Water Services Act 2021. The concept of Te Mana o te Wai is also mentioned in the recently repealed Water Services Entities Act 2022 and Water Services Economic Efficiency and Consumer Protection Act 2023.

As well as applying the hierarchy of obligations at every step of the NOF implementation, implementing Te Mana o te Wai requires:

- engaging with communities and tangata whenua to determine how Te Mana o te Wai applies to water bodies and freshwater ecosystems
- active involvement of tangata whenua in freshwater management (including decision-making processes) to the extent they wish to be involved – this includes identifying local approaches to giving effect to Te Mana o te Wai
- engaging with communities and tangata whenua to identify long-term visions, environmental outcomes, and other elements of the NOF
- enabling the application of a diversity of systems of values and knowledge, such as mātauranga Māori, to the management of freshwater
- adopting an integrated approach, ki uta ki tai, to the management of freshwater.[22]

Other relevant environmental legislation

In addition to the NPS-FM 2020, several other national direction instruments prepared under the RMA are directly relevant to the management of freshwater.

- The **National Environmental Standards for Freshwater 2020 (NES-F)** aim to stop further degradation of water quality through specific rules and requirements that limit further intensification of some land uses, restrict further loss of natural inland wetlands, control high-risk practices like intensive winter grazing, and set a cap on the maximum amount of synthetic nitrogen fertiliser that can be applied to pastoral land.[23]
- The **Measurement and Reporting of Water Takes Regulations 2010** were amended in 2020, and now require improved recording and reporting of water takes.
- The **Stock Exclusion Regulations 2020** aim to prohibit the access of cattle, pigs and deer to wetlands, lakes and rivers.
- The **Freshwater Farm Plans Regulations 2023** set out further obligations for the preparation, certification, audit and enforcement of freshwater farm plans.
- The **National Environmental Standards for Sources of Human Drinking Water 2007 (NES-DW)** set out requirements for the protection of human drinking water sources from contamination. These standards sit at the interface of freshwater and drinking water, as they aim to manage drinking water in the context of its source – rivers, lakes or aquifers.

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[22] For details, see NPS-FM 2020, clauses 3.2 and 3.4.

[23] Note that the NES-F contain several temporary standards regarding agricultural intensification, which are scheduled to expire on 1 January 2025.

Requirements for freshwater are spread over many different regulatory instruments. They form an intricate web of policies and rules that interact with each other. Managing this complexity presents challenges both for regulators and water users.

Given that activities on the land have an impact on water, other national direction instruments that aim to manage land for specific purposes are also indirectly relevant to water management, further complicating the regulatory landscape.[24]

The management of *coastal water* largely falls under the **New Zealand Coastal Policy Statement 2010 (NZ-CPS)**. Its objectives and policies seek to safeguard the coastal environment and its ecosystems, including marine and intertidal areas, estuaries, dunes and land.

Two policies specifically relate to the enhancement of water quality and discharge of contaminants.[25] While the policies require particular regard to be directed to issues (e.g. sensitivity of the receiving environment or the capacity of the receiving environment to assimilate the contaminants), the NZ-CPS, unlike the NPS-FM 2020, lacks bottom lines or explicit requirements to set limits.

Some of the complexity arising from different types of water being managed under different legislation or national direction instruments may be mitigated through robust implementation.

However, the management of *drinking water, wastewater* and *stormwater* largely falls under different *primary* legislation – the **Local Government Act 2002** and the recent **water services reform legislation**.[26] Separate legislation cannot, however, undo the fact that the management of freshwater affects drinking water and vice versa.

Te Tiriti o Waitangi sections in the legislation above are relevant here in terms of engagement with whānau, hapū and iwi and the treatment of water as a taonga that must be protected under article 2. Finally, most Te Tiriti o Waitangi settlement arrangements provide for the way in which the Crown and its agencies are required to include Māori in the management of the different aspects of water within the settlement area.

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24 These include national policy statements for highly productivity land (2022), indigenous biodiversity (2023) and urban development (2020), and national environmental standards for plantation forestry (2017).

25 NZ-CPS 2010, policies 21 and 23.

26 At the time of writing, the water services legislation included the Taumata Arowai–the Water Services Regulator Act 2020 and the Water Services Act 2021. The Water Services Entities Act 2022, the Water Legislation Act 2023, and the Water Services Economic Efficiency and Consumer Protection Act 2023 have been repealed and the responsibility for water services delivery has been returned to local authorities.

Hymenophyllum minimum

References

Auckland Council, 2021. Freshwater management tool: Report 2. Baseline configuration and performance. Prepared by the Auckland Council Healthy Waters Department, Paradigm Environmental, and Morphum Environmental Ltd. for Auckland Council. Auckland: Auckland Council.

Batarseh, F.A., Kumar, A. and Eisenberg, S., 2020. The history and future prospects of open data and open source software. In: F. A. Batarseh and R. Yang (eds), Data Democracy: At the Nexus of Artificial Intelligence, Software Development, and Knowledge Engineering. Academic Press: 29–43.

Beauséjour, M. and Mac-Thiong, J.-M., 2020. Building models for prediction: are we good at it? Spinal Cord 58(11): 1147–1149.

Bhatt, U., Antorán, J., Zhang, Y., Liao, Q.V., Sattigeri, P., Fogliato, R., Melançon, G.G., Krishnan, R., Stanley, J., Tickoo, O., Nachman, L., Chunara, R., Srikumar, M., Weller, A. and Xiang, A., 2020. Uncertainty as a Form of Transparency: Measuring, Communicating, and Using Uncertainty. Proceedings of the 2021 AAAI/ACM Conference on AI, Ethics, and Society, 2021. https://arxiv.org/abs/2011.07586 [accessed 11 March 2024].

Booker, D.J. and Snelder, T.H., 2023. Climate change and local anthropogenic activities have altered river flow regimes across Canterbury, New Zealand. Water Resources Management 37(6–7): 2657–2674.

Box, G.E.P., 1979. Some problems of statistics and everyday life. Journal of the American Statistical Association 74(365): 1–4.

Clarke, L. and Harris, P., 2017. Maramataka. In: H. Whaanga, T. T. Keegan and M. Apperley (eds), He Whare Hangarau Māori — Language, culture & technology: 129–135. Hamilton: University of Waikato.

Doherty, J. and Moore, C., 2020. Decision support modeling: Data assimilation, uncertainty quantification, and strategic abstraction. Groundwater 58(3): 327–337.

Dorigo, W., Dietrich, S., Aires, F., Brocca, L., Carter, S., Cretaux, J.-F., Dunkerley, D., Enomoto, H., Forsberg, R., Güntner, A., Hegglin, M.I., Hollmann, R., Hurst, D.F., Johannessen, J.A., Kummerow, C., Lee, T., Luojus, K., Looser, U., Miralles, D.G., Pellet, V., Recknagel, T., Vargas, C.R., Schneider, U., Schoeneich, P., Schröder, M., Tapper, N., Vuglinsky, V., Wagner, W., Yu, L., Zappa, L., Zemp, M. and Aich, V., 2021. Closing the water cycle from observations across scales: Where do we stand? Bulletin of the American Meteorological Society, 102(10): 1897–1935.

Dymond, J.R., Davie, T.J.A., Fenemor, A.D., Ekanayake, J.C., Knight, B.R., Cole, A.O., de Oca Munguia, O.M., Allen, W.J., Young, R.G., Basher, L.R., Dresser, M. and Batstone, C.J., 2010. Integrating environmental and socio-economic indicators of a linked catchment–coastal system using variable environmental intensity. Environmental Management, 46(3): 484–493.

Dymond, J.R., Herzig, A., Basher, L., Betts, H.D., Marden, M., Phillips, C.J., Ausseil, A.-G.E., Palmer, D.J., Clark, M. and Roygard, J., 2016. Development of a New Zealand SedNet model for assessment of catchment-wide soil-conservation works. Geomorphology 257: 85–93.

Elliot, S., Evans, T., Cichota, R., Djanibekov, U., Herzig, A., Jackson, B., Sandoval, D.L., McDonald, S., Monge, J., Semadeni-Davies, A., Taves, M., Thiange, C., Vibart, R., Wakelin, S., Yalden, S., Yang, J. and Yoswara, H., 2020. Land-Water Interoperable Models: Project Summary. Prepared for Our Land and Water. Hamilton: National Institute of Water and Atmospheric Research.

Environment Court of New Zealand, 2023. Practice Note 2023. Wellington: Environment Court of New Zealand.

Fenemor, A., 2022. Themes from the modelling for management workshop. NZHS E-Current newsletter 61: 17–20.

Fenemor, A., Green, S. and Price, R., 2023. Modelling of nitrate losses and impacts from Waimea Plains rural land uses. Contract Report LC4215 prepared for Tasman District Council under Envirolink Grant 2212-TSDC180. Landcare Research New Zealand Ltd and Tasman District Council.

Gleeson, T., Befus, K.M., Jasechko, S., Luijendijk, E. and Cardenas, M.B., 2016. The global volume and distribution of modern groundwater. Nature Geoscience 9(2): 161–167.

GNS Science, no date. Digital QMAP (Geological Maps at 1:250,000). https://www.gns.cri.nz/data-and-resources/digital-qmap-geological-maps-at-1250000/ [accessed 11 March 2024].

Grayson, R. and Blöschl, G. (eds), 2001. Spatial patterns in catchment hydrology: Observations and modelling. Cambridge, UK: Cambridge University Press.

Greater Wellington Regional Council, 2018. Ruamāhanga Whaitua. https://www.gw.govt.nz/environment/freshwater/protecting-the-waters-of-your-area/ruamahanga-whaitua/ [accessed 11 March 2024].

Griffiths, J.; Yang, J.; Woods, R.; Zammit, C.; Porhemmat, R.; Shankar, U.; Rajanayaka, C.; Ren, J.; Howden, N., 2023. Parameterization of a national groundwater model for New Zealand. Sustainability 15(17): 13280.

Hamilton, S.H., ElSawah, S., Guillaume, J.H.A., Jakeman, A.J. and Pierce, S.A., 2015. Integrated assessment and modelling: Overview and synthesis of salient dimensions. Environmental Modelling & Software 64: 215–229.

Hamilton, S.H., Pollino, C.A., Stratford, D.S., Fu, B. and Jakeman, A.J., 2022. Fit-for-purpose environmental modeling: Targeting the intersection of usability, reliability and feasibility. Environmental Modelling & Software 148: 1–12.

Harris, P., Matamua, R., Smith, T., Kerr, H. and Waaka, T., 2013. A review of Māori astronomy in Aotearoa-New Zealand. Journal of Astronomical History and Heritage 16(3): 325–336.

Hawke's Bay Regional Council, 2024. Hawke's Bay 3D Aquifer Mapping: A three-dimensional view into the region's groundwater resources using SkyTEM technology. ArcGIS Storymap. https://storymaps.arcgis.com/stories/7455b027ae0540d8a3457de98635ac84 [accessed 11 March 2024].

Hicks, M., Semadeni-Davies, A., Haddadchi, A., Shankar, U. and Plew, D., 2019. Updated sediment load estimator for New Zealand. NIWA Client Report 2018341CH prepared for Ministry for the Environment. Christchurch: National Institute of Water and Atmospheric Research.

Larned, S.T., Howard-Williams, C., Taylor, K. and Scarsbrook, M., 2022. Freshwater science–policy interactions in Aotearoa-New Zealand: Lessons from the past and recommendations for the future. Australasian Journal of Water Resources 26(1): 131–152.

Larned, S.T. and Snelder, T.H., 2023. Meeting the growing need for land-water system modelling to assess land management actions. Environmental Management 73: 1–18.

Mapp, W. Statements chart clear path for CRIs. Press release, 17 November 2010. https://www.beehive.govt.nz/release/statements-chart-clear-path-cris [accessed 11 March 2024].

Marchau, V.A.W.J., Walker, W.E., Bloemen, P.J.T.M. and Popper, S.W. (eds), 2019. Decision making under deep uncertainty: From theory to practice. Cham: Springer Nature.

MartinJenkins, 2023. Exploring the use of government RSI funding for Māori. Report prepared for MBIE. Martin, Jenkins & Associates Ltd.

McBride, C.G., Allan, M.G. and Hamilton, D.P., 2019. Assessing the effects of nutrient load reductions to Lake Rotorua: Model simulations for 2001–2015. ERI report 124 prepared for Bay of Plenty Regional Council. Hamilton: Environmental Research Institute, University of Waikato.

McClay, T., Simmonds, P. and Hoggard, A., 2023. Government takes first steps towards pragmatic and sensible freshwater rules. Press release, 14 December 2023. https://www.beehive.govt.nz/release/government-takes-first-steps-towards-pragmatic-and-sensible-freshwater-rules [accessed 11 March 2024].

McDonald, M.G., Harbaugh, A.W. and the original authors of MODFLOW, 2003. The history of MODFLOW. Ground Water 41(2): 280–283.

McDowell, R.W., Monaghan, R.M., Smith, C., Manderson, A., Basher, L., Burger, D.F., Laurenson, S., Pletnyakov, P., Spiekermann, R. and Depree, C., 2021. Quantifying contaminant losses to water from pastoral land uses in New Zealand III. What could be achieved by 2035? New Zealand Journal of Agricultural Research 64(3): 390–410.

McDowell, R.W., Snelder, T.H., Cox, N., Booker, D.J. and Wilcock, R.J., 2013. Establishment of reference or baseline conditions of chemical indicators in New Zealand streams and rivers relative to present conditions. Marine and Freshwater Research 64(5): 387–400.

Merriam-Webster, no date. "model". https://www.merriam-webster.com/dictionary/model [accessed 11 March 2024].

Meteoblue, 2023. MultiModel Ensemble forecast for Wellington. https://www.meteoblue.com/en/weather/forecast/multimodelensemble/wellington_new-zealand_2179537 [accessed 2 November 2023].

Ministry for the Environment (MfE), 2018. A guide to communicating and managing uncertainty when implementing the National Policy Statement for Freshwater Management 2014. Wellington: MfE.

Ministry for the Environment (MfE), 2019. Essential freshwater: Impact of existing periphyton and proposed dissolved inorganic nitrogen bottom lines. Wellington: MfE.

Ministry for the Environment (MfE), 2020a. Essential freshwater: Overview factsheet. Wellington: MfE.

Ministry for the Environment (MfE), 2020b. Summary of modelling to inform environmental impact assessment of nutrient proposals. Wellington: MfE.

Ministry for the Environment (MfE), 2022a. Guidance on look-up tables for setting nutrient targets for periphyton. 2nd ed. Wellington: MfE.

Ministry for the Environment (MfE), 2022b. Setting instream nutrient concentration thresholds for nutrient-affected attributes in rivers: Guidance on implementing clause 3.13 of the NPS-FM. Wellington: MfE.

Ministry for the Environment (MfE), 2023a. A guide to implementing clause 3.13 of the NPS-FM 2020. Wellington: MfE.

Ministry for the Environment (MfE), 2023b. Developing, adapting and applying environmental models in a regulatory context in New Zealand: Guidance document. Wellington: MfE.

Ministry for the Environment (MfE), 2023c. Guidance on the National Objectives Framework of the NPS-FM. Wellington: MfE.

Ministry for the Environment (MfE), 2024. Responding to the Overseer model redevelopment review: A guide for councils. Wellington: MfE.

Ministry for the Environment (MfE) and Stats NZ, 2020. New Zealand's environmental reporting series: Our freshwater 2020. Wellington: MfE and Stats NZ.

Ministry for the Environment (MfE) and Stats NZ, 2022. New Zealand's environmental reporting series: Environment Aotearoa 2022. Wellington: MfE and Stats NZ.

Ministry for the Environment (MfE) and Stats NZ, 2023. New Zealand's environmental reporting series: Our freshwater 2023. Wellington: MfE and Stats NZ.

Ministry for Primary Industries (MPI), 2023. Overseer redevelopment programme report. Technical Paper No: 2023/12. Wellington: MPI.

Monaghan, R., Manderson, A., Basher, L., Spiekermann, R., Dymond, J., Smith, C., Muirhead, R., Burger, D. and McDowell, R., 2021. Quantifying contaminant losses to water from pastoral landuses in New Zealand II. The effects of some farm mitigation actions over the past two decades. New Zealand Journal of Agricultural Research 64(3): 365–389.

Moreau, M., 2023. Technical review of the 2020 groundwater quality indicator to support methodological improvements. Consultancy Report 2023/19. Wairakei: GNS Science.

Moreau, M. and Bekele, M., 2017. Groundwater component of the water physical stock account (WPSA). GNS Science Consultancy Report 2014/290 – Revised September 2017. Lower Hutt: GNS Science.

Mourot, F.M., Westerhoff, R.S., White, P.A. and Cameron, S.G., 2022. Climate change and New Zealand's groundwater resources: A methodology to support adaptation. Journal of Hydrology: Regional Studies 40: 1–25.

New Zealand Government, 2010a. AgResearch: Statement of core purpose.

New Zealand Government, 2010b. GNS Science: Statement of core purpose.

New Zealand Government, 2010c. Institute of Environmental Science and Research: Statement of core purpose.

New Zealand Government, 2010d. Landcare Research: Statement of core purpose.

New Zealand Government, 2010e. National Institute of Water and Atmospheric Research: Statement of core purpose.

New Zealand Government, 2010f. Plant & Food Research: Statement of core purpose.

New Zealand Government, 2010g. Scion: Statement of core purpose.

Nisbet, E.G., Dlugokencky, E.J. and Bousquet, P., 2014. Methane on the rise—Again. Science, 343(6170): 493–495.

National Institute of Water and Atmospheric Research (NIWA), 2023. New Zealand streamflow depletion model: A tool for sustainable water resource. https://niwa.co.nz/lakes/freshwater-update/freshwater-update-90-april-2023/new-zealand-streamflow-depletion-model-tool-sustainable-water-resource [accessed 11 March 2024]

Our Land and Water National Science Challenge, 2020. Interoperable Modelling. https://ourlandandwater.nz/project/interoperable-modelling/ [accessed 11 March 2024].

Oxford Learner's Dictionaries, no date. "model". https://www.oxfordlearnersdictionaries.com/definition/english/model_1?q=model [accessed 11 March 2024].

Parliamentary Commissioner for the Environment (PCE), 2018. Overseer and regulatory oversight: Models, uncertainty and cleaning up our waterways. Wellington: PCE.

Parliamentary Commissioner for the Environment (PCE), 2019. Focusing Aotearoa New Zealand's environmental reporting system. Wellington: PCE.

Parliamentary Commissioner for the Environment (PCE), 2020. A review of the funding and prioritisation of environmental research in New Zealand. Wellington: PCE.

Parliamentary Commissioner for the Environment (PCE), 2022. Environmental reporting, research and investment: Do we know if we're making a difference? Wellington: PCE.

Parliamentary Commissioner for the Environment (PCE), 2023. Submission on the Natural and Built Environment Bill and the Spatial Planning Bill. Wellington: PCE. https://pce.parliament.nz/media/ffeevjzy/pce-submission-on-nbe-and-sp-bills.pdf [accessed 11 March 2024].

Phillips, C., 2020. Wai puna: An indigenous model of Māori water safety and health in Aotearoa, New Zealand. International Journal of Aquatic Research and Education 12(3): 1–21.

Plew, D., 2020. Models for evaluating impacts of nutrient and sediment loads to Southland estuaries: To inform the Southland Regional Forum process. NIWA Client Report 2020216CH prepared for Environment Southland. Christchurch: National Institute of Water and Atmospheric Research.

Poipoia, 2022a. Te Mana o te Wai: Guidelines for Mana Whenua: National Policy Statement for Freshwater Management 2020. Our Land and Water National Science Challenge.

Poipoia, 2022b. Te Mana o te Wai: Training Programme: Council focus. Our Land and Water National Science Challenge.

Reid, J., 2021. Adopting Māori wellbeing ethics to improve Treasury budgeting processes. https://pce.parliament.nz/media/2h3h1a3t/reid-adopting-ma-ori-wellbeing-ethics-to-improve-treasury-budgeting-processes-pdf-12mb.pdf [accessed 11 March 2024].

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 Regional Council.

Rosen, M.R. and White, P.A. (eds), 2001. Groundwaters of New Zealand. Wellington: New Zealand Hydrological Society Inc.

Ruru, I., Kanz, W., Afoa, E., Clarke, C., Nutsford, D., Lowe, M., Jelicich, A. and Shivnan, S., 2022. Implementing mahinga kai as a Māori freshwater value: A kete for implementing mahinga kai in the context of the National Policy Statement for Freshwater Management 2020. Prepared for the Ministry for the Environment by Maumahara Consultancy Services Ltd, Awamoana Ltd, Morphum Environmental Ltd, and Tektus Consultants Ltd. Wellington: Ministry for the Environment.

Semadeni-Davies, A.F., Jones-Todd, C.M., Srinivasan, M.S., Muirhead, R.W., Elliott, A.H., Shankar, U. and Tanner, C.C., 2019. CLUES model calibration: Residual analysis to investigate potential sources of model error. New Zealand Journal of Agricultural Research 64(3): 320–343.

Shen, J., Parker, A. and Riverson, J., 2005. A new approach for a Windows-based watershed modeling system based on a database-supporting architecture. Environmental Modelling & Software 20(9): 1127–1138.

Sheppard, D.F., Solomon, R. and van Voorthuysen, R., 2015. In the matter of proposed Variation 1 to the proposed Canterbury Land and Water Regional Plan. Report and recommendations of the hearing commissioners. Adopted by council at its decision on 23 April 2015. Christchurch: Environment Canterbury.

Singh, S.K., Pahlow, M., Booker, D.J., Shankar, U. and Chamorro, A., 2019. Towards baseflow index characterisation at national scale in New Zealand. Journal of Hydrology 568: 646–657.

Skipper, A.S., 2020. Ko Te Kawa Tūpanapana i ngā Hau Tūpua a Tāwhiri-mātea: The validation, revitalisation and enhancement of Māori environment knowledge of weather and climate (PhD). Hamilton: The University of Waikato.

Snelder, T., Cox, T., Fraser, C., Elliot, A. and Kerr, T., 2023. Quantifying catchment nutrient modelling parameters: An analysis using the available New Zealand data. LWP Client Report Number: 2023-03. Lyttelton: Land Water People (LWP) Ltd.

Snelder, T., Kilroy, C. and Booker, D., 2022. Derivation of nutrient criteria for periphyton biomass objectives using regional council monitoring data. LWP Client Report Number: 2021-13. Lyttelton: Land Water People (LWP) Ltd.

Snelder, T., Smith, H., Plew, D. and Fraser, C., 2023. Nitrogen, phosphorus, sediment and Escherichia coli in New Zealand's aquatic receiving environments: Comparison of current state to national bottom lines. LWP Client Report Number: 2023-06. Lyttelton: Land Water People (LWP) Ltd.

Snelder, T.H., Larned, S.T., Fraser, C. and De Malmanche, S., 2021. Effect of climate variability on water quality trends in New Zealand rivers. Marine and Freshwater Research 73(1): 20–34.

Snelder, T.H., Larned, S.T. and McDowell, R.W., 2018. Anthropogenic increases of catchment nitrogen and phosphorus loads in New Zealand. New Zealand Journal of Marine and Freshwater Research 52(3): 336–361.

Snelder T.H., Whitehead A.L., Fraser C., Larned S.T. and Schallenberg M., 2020. Nitrogen loads to New Zealand aquatic receiving environments: comparison with regulatory criteria. New Zealand Journal of Marine and Freshwater Research 54(3): 527-550.

Stats NZ, 2021. Irrigated land. https://www.stats.govt.nz/indicators/irrigated-land [accessed 11 March 2024].

Stats NZ, 2022. Environmental-economic accounts: Water physical stocks, year ended June 1995–2020. https://www.stats.govt.nz/information-releases/environmental-economic-accounts-water-physical-stocks-year-ended-june-1995-2020 [accessed 11 March 2024].

Tait, A., Henderson, R., Turner, R. and Zheng, X., 2006. Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. International Journal of Climatology 26(14): 2097–2115.

Taylor, L., 2023. Te Mana o te Wai, Te Oranga o ngā Tāngata. Prepared for the Parliamentary Commissioner for the Environment. Auckland: E Oho! Awakening Aotearoa.

Taylor, L.B., Fenemor, A., Mihinui, R., Sayers, T.A., Porou, T., Hikuroa, D., Harcourt, N., White, P. and O'Connor, M., 2020. Ngā Puna Aroha: Towards an indigenous-centred freshwater allocation framework for Aotearoa New Zealand. Australasian Journal of Water Resources: 1–13.

Toebes, C., 1972. The water balance of New Zealand. Journal of Hydrology (NZ) 11(2): 127–139.

United States Environmental Protection Agency (US EPA), no date. System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN). Tool for Selecting Best Management Practices to Protect Water Quality. https://www.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain [accessed 14 March 2024].

United States Environmental Protection Agency (US EPA), 2009. Guidance on the development, evaluation, and application of environmental models. Washington, DC: United States Environmental Protection Agency.

United States Geological Survey (USGS), 1997. Modelling ground-water flow with MODFLOW and related programs. USGS Fact Sheet FS-121-97. Denver: United States Geological Survey.

United States Geological Survey (USGS), 2022. The water cycle. https://www.usgs.gov/special-topics/water-science-school/science/water-cycle [accessed 14 March 2024].

van der Giessen, A. (ed), 2005. Naar een gezamenlijk nationaal hydrologisch modelinstrumentarium [Towards a collective national hydrological model instrument]. Eindrapport van de werkgroep Consensus Hydrologie (WUR/Alterra; RIVM/MNP; RWS/RIZA). Bilthoven, Netherlands.

Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A. and Ramu, P., 2016. Modelling with stakeholders – Next generation. Environmental Modelling & Software 77: 196–220.

Weir, J., Thomas, J. and Fenemor, A., 2023. Groundwater modelling to test reversal of river drying – Waimea Plains, Nelson. In: New Zealand Hydrological Society Conference, Auckland 28 November – 1 December 2023, Auckland, New Zealand: Oral Abstracts, 125–126. Wellington: New Zealand Hydrological Society.

Westerhoff, R.S., 2015. Using uncertainty of Penman and Penman–Monteith methods in combined satellite and ground-based evapotranspiration estimates. Remote Sensing of Environment 169: 102–112.

Westerhoff, R., Rawlinson, Z.J. and Kerr, T., 2019. Nationwide estimates of renewable and non-renewable groundwater volumes in New Zealand. In: New Zealand Hydrological Society Conference, Rotorua 3–6 December 2019, Rotorua, New Zealand: Oral Abstracts, 176–177. Wellington: New Zealand Hydrological Society.

Woods, R., Hendrikx, J., Henderson, R. and Tait, A., 2006. Estimating mean flow of New Zealand rivers. Journal of Hydrology (New Zealand) 45(2): 95–110.

Yang J., Rajanayaka C., Daughney C.J., Booker D., Morris R., Thompson M., 2023. Metamodelling of naturalised groundwater levels at a regional level in New Zealand. Sustainability 15(18): 13393.

Zhang, Y., Kong, D., Gan, R., Chiew, F.H.S., McVicar, T.R., Zhang, Q. and Yang, Y., 2019. Coupled estimation of 500 m and 8-day resolution global evapotranspiration and gross primary production in 2002–2017. Remote Sensing of Environment 222: 165–182.

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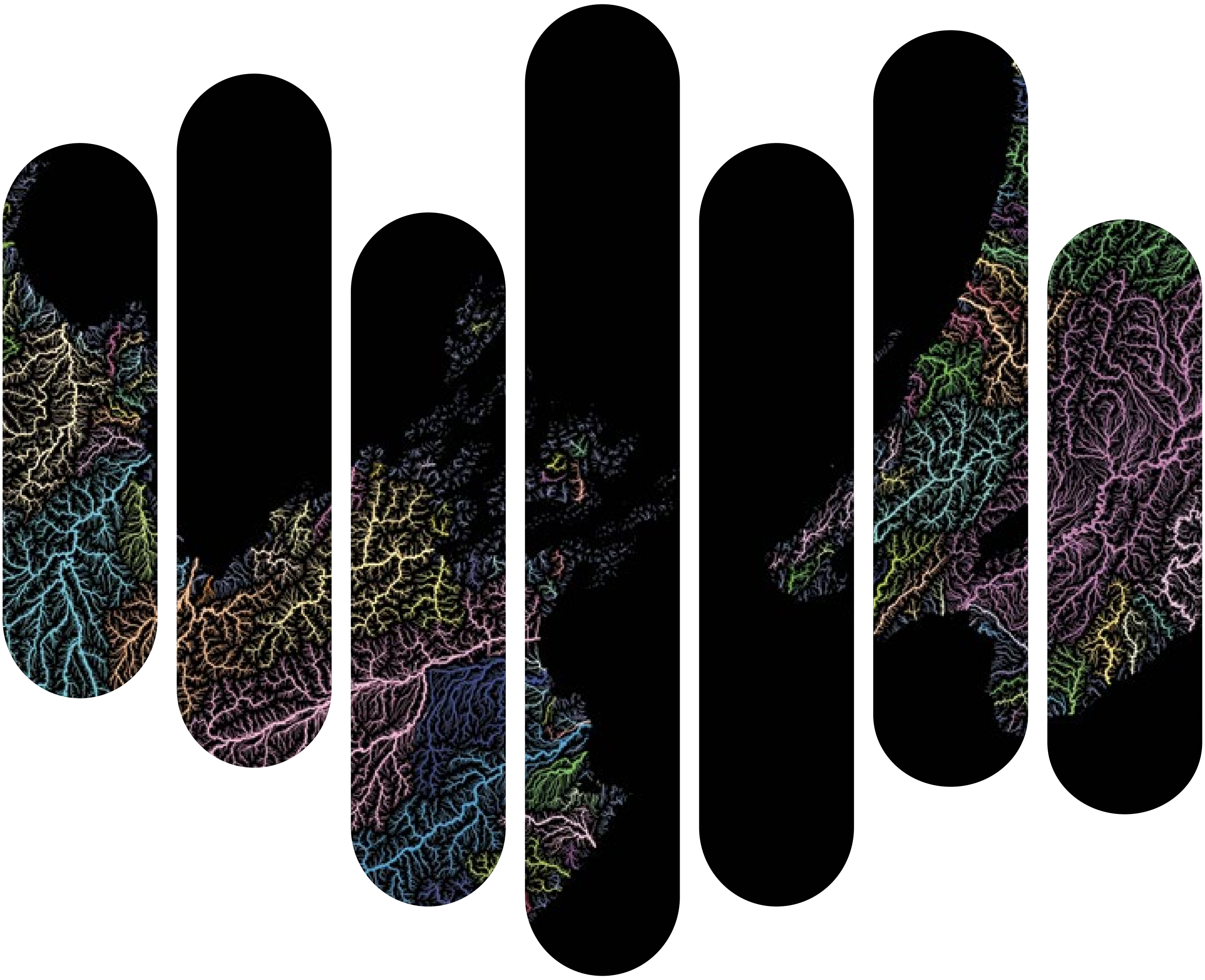
June 2024

ISBN
978-0-947517-46-5 (print)
978-0-947517-47-2 (electronic)



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