Understanding the Practice of Water Quality Modelling

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Abstract

"Models are a summary of the science." They combine a range of existing knowledge to provide insight into complex systems and situations. As creators of models, scientists accept their use without requiring much explanation. However, to those outside the scientific community models can seem like black boxes, and the variety of available models can cause confusion.

This report discusses the use of water-quality modelling for an audience that is unfamiliar with this practice. It focuses on modelling that addresses the loss of nitrogen and phosphorus from rural properties and their loads and concentrations in waterways. We provide brief descriptions of some of the key water-quality models that are relevant in a New Zealand context, and discuss the key differences among them.

Keywords
Catchment, model, nutrient loads, nutrient transport, on-farm, water quality

Contents

1. Introduction

"Models are a summary of the science" (Mark Shepherd & David Wheeler). They combine a range of existing knowledge to provide a simplified representation of reality. By encapsulating the key agents, elements, processes, and decisions, models provide insight into complex systems and situations.

"All models are wrong, but some models are useful" (George E. P. Box). Although no model provides a perfect representation of reality, we often need models to represent the world, because direct measurement is usually impossible, and intuition or using simple proxies can only account for some of the complexity.

Scientists and engineers are often the creators of models. Hence, their use in the scientific community is well established and accepted without requiring much explanation. However, to many outside the scientific community, the practice of modelling is difficult to understand. Furthermore, the variety of available models, their appropriate uses and the level of confidence that should be placed in their results often results in confusion.

This report discusses the practice and value of water-quality modelling for an audience that is unfamiliar with it. It focuses on modelling that addresses the loss of nutrients (nitrogen and phosphorus) from rural land and the resulting loads in local waterways. We provide brief descriptions of some of the key water-quality models that are relevant in a New Zealand context, and discuss the key differences among them.

Models are used to understand water quality patterns because the processes that determine nutrient loss, transportation, and concentration are complex. This complexity arises from spatial variability of soil, topography and land use; and temporal variability of climate, land management practices and nutrient transport beneath the ground. Models provide an effective way to understand and investigate these phenomena.

In the face of such complexity, models can be very valuable. Although expert intuition and the use of proxies are sometimes suggested as alternatives to modelling, these are in fact simplistic informal models. Formal scientific modelling, with its processes of documentation, validation and review provides a consistent and transparent approach to understanding the factors that affect water quality.

Models are often superior to relying solely on measurement. Measurements provide values for a specific context or situation, but models enable us to understand the systems that we are measuring, and to generalize our results to other situations. Both measurements and models contain uncertainty. Good modelling practice includes accounting for this uncertainty and ensuring that the model results are consistent with observed measurements.

Models are used because they merge the results of many separate scientific studies. They are constructed from the existing scientific knowledge and, where weaknesses in the existing science are identified, new knowledge is often created to inform the model.

Models inform the direction of research, provide tools to answer research questions, and express the results of research in a way that others can understand. They are an important part of doing good science. In general, the quality of a model and the robustness of its results are tested within the scientific community before model results are made available to the wider society. This helps ensure that modelling, and scientific activity in general, upholds the standards of rigor that are expected by the scientific community.

Models provide a valuable tool to support the design of policy. Councils, industry and other stakeholders use models to identify the drivers of an issue, their magnitudes, and the extent of intervention necessary to meet their goals. Where intervention is desired, models enable councils to experiment (virtually) with different designs of policy and to observe the types of outcomes that are likely to result under different policies.

It is important to acknowledge that all the models we consider in this report focus on the presence of nutrients in waterways. Nitrogen and phosphorus are key determinants of water quality and ecosystem health for many New Zealand waterways. However, the translation from nutrient concentrations and loads to water quality and ecosystem health is complex, varies between locations and is not yet fully understood. Hence we do not discuss it further in this report.

Water-quality models can be classified as either farm level models or catchment-scale transport models. There is a variety of models in each category because different models are required to answer different questions, to model different situations, to work at different levels of detail, or to make use of different sources of data. When used appropriately, the variety of available models should be seen as a strength rather than as a weakness.

The remainder of this report is set out as follows. The first four sections answer the questions "what is a model?", "why are models used?", "how are models developed" and "how are models used?" respectively. The last three sections provide an overview of some of the current water-quality models in New Zealand, answer the question "why are there different models?", and give our conclusions.

2. What is a model?

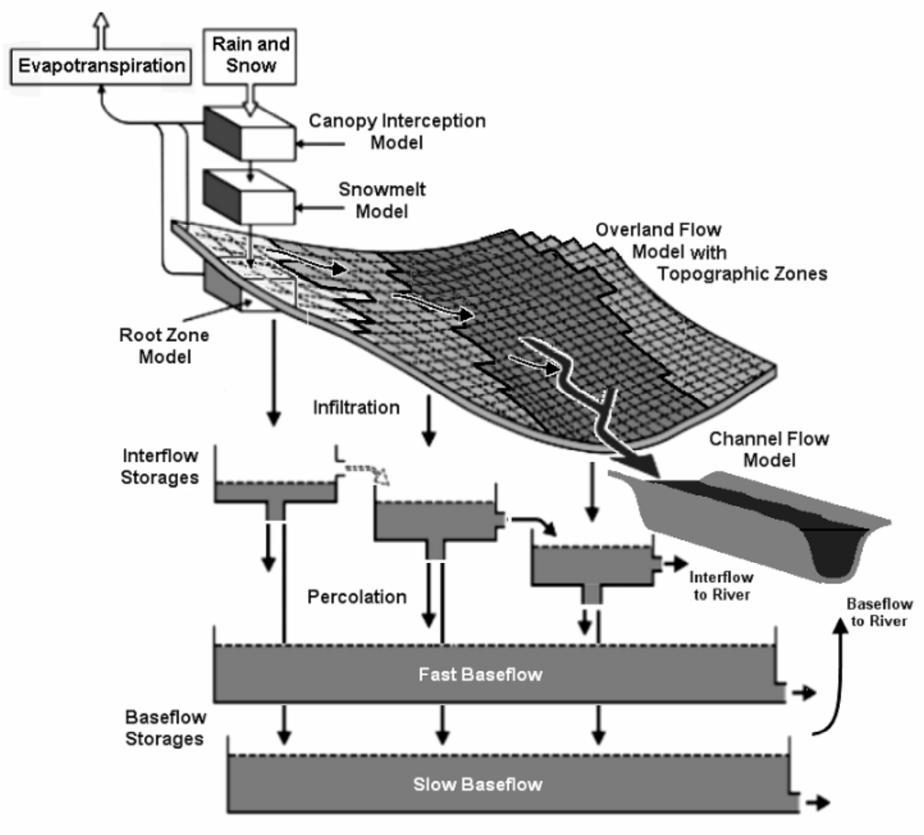
A model is a simplified representation of reality that focuses on the key agents, elements, components, processes, flows, decisions, inputs and outputs of a system. Models describe how these parts relate, and which parts have causal impacts on other parts.

Constructing a model formalizes scientific endeavours by requiring scientists to specify their assumptions, identify the phenomena they are concerned with, and explain their methodology. This benefits scientists by holding them to a standard of rigour, making their work more accessible, and removing the need to measure and monitor every parameter. It also benefits the users of the research who can better understand how any research question has been framed, and the context in which a study has been conducted.

We think of models in two broad categories: Theoretical or conceptual models provide representations of reality that emphasize the key components and their interactions without seeking to quantify the magnitude of any component or interaction (they are not quantitative). Examples of theoretical or conceptual models include systems of algebraic equations and flow diagrams (see for example Figure 1). These types of models are often used in situations where numeric data are unavailable, yet to be collected, or not of interest. For example, when investigating a new catchment a scientist specifies the phenomena that are likely to be key to determining water-quality before attempting to quantify any of these phenomena.

Numerical or computer models provide representations of reality that both describe how the different parts of the model interact and quantify the magnitude of the different interactions. Conceptual models inform the design of numerical models and provide a context for their results to be interpreted. Weather forecasts and economic forecasts are outputs from numerical computer models. All the models we discuss in section 6 are numerical computer models. These types of models are almost always informed by other research activities that have collected and analysed data. In this respect models summarize and embody existing science.

Figure 1: Example of conceptual model (from Graham and Butts, 2005)



3. Why are models used to understand water quality?

Models are used to understand water quality because the processes that determine water quality are more complex than can be represented in any single experimental study. While a single study might identify or quantify a specific component of reality, a model often combines the results of many studies with each study informing a sub-part of the model. For example, given a general understanding of water flow and nutrient transport (arising from a legacy of scientific research), data of river and spring flows might be combined with knowledge of farming practice and soil nutrient levels to inform a numeric model of local nutrient loads, which is then tested against studies of lake water quality. Constructing a model in this way often involves some simplification of the results reported by each constituent study.

Many complex phenomena determine water quality. These include the conversion of nutrients to different forms within the farm system, the movement of nutrients around the farm, the uptake of nutrients by plants, the leaching of nutrients from the soil, the loss of nutrients through erosion, the transport of nutrients via surface water streams, and the transport of nutrients via slow groundwater flows. Models provide an effective and transparent way to think about and communicate how we understand these phenomena.

Models are used not because they are perfectly accurate, but because in many situations they are superior to the alternatives. Three alternatives to using formal models to understand water quality are 1) measurement, 2) intuition and 3) proxies. We consider each of these in turn.

1) Measurement is sometimes proposed as an alternative to the use of models. For example, we could attempt to measure nutrient loss from a farm. Unfortunately, this is not technically feasible, and our best attempts come at very high cost: Consider a simple farm with two different soil types and five cropping rotations. This farm would require water samples from each crop and soil type every time it rained enough to cause nutrient leaching. These measures should be taken in triplicate, so if there were ten rainfall events each year, measuring nutrient loss from such a farm would require upwards of 300 samples. Water analysis costs upwards of $40 per sample so costs for this farm would exceed $12,000 per year (this excludes the costs of taking and storing the samples which would exceed the cost of water analyses), and would still result in very high uncertainty on the amount of nutrients loss (Vogeler and Snow, 2012). For pastoral farms, installing lysimeters (devices that record drainage and enable us to calculate evaporation and plant transpiration) is estimated to cost $10,000 for each 50cm diameter lysimeter (Lilburne et al., 2012). Given that a minimum of three lysimeters are required to measure nitrogen on a single paddock, and more than 20 may be required to provide sufficient accuracy, the cost of measurement with lysimeters is prohibitively high.

Measurements are location, time and context specific. Different locations, times or contexts imply the need for additional measurements. This is seldom ideal as we often wish to consider how outcomes might vary, for example with changes in rainfall or stock management practices. In contrast, modelling is informed by strategically chosen measurements that enable scientists to identify and quantify key relationships. This enables models to investigating how results might differ in different contexts and regions.

While models are sometimes critiqued as containing errors, it is important to recognise that measurements also contain error. These errors can be very large (Lilburne et al., 2012) and are inherited by models. Just as good scientific practice includes taking measurements and accounting for the error in the measurements, so also it includes developing models and accounting for the uncertainty any errors introduce to the results.

2) "Expert knowledge" or intuition is sometimes considered an alternative (or as an adjunct) to the use of modelling. Consider an expert who approaches a situation where there is

poor water quality (possibly due to high nutrient losses) and claims to know, intuitively, what the problem is and how to fix it. In effect, this is the use of an implicit or informal model: The expert's intuition is based on a simplified version of how reality works (a model).

While simple informal models can capture complexities that more formal models ignore, there are significant advantages to a formal modelling approach. There can only be confidence in the results from intuition through confidence in the expert. In contrast, when a model is specified and written down, the model and its results becomes visible to, and subject to critique from, scientists and other experts. This transparency enables the quality of the model to be tested and helps ensure that its results are robust (Overseer and CLUES are examples of water-quality models in New Zealand that have been tested, and improved, as a result of scientific critique).

3) Proxies are sometimes considered an alternative to the use of scientific modelling. Rather than draw on all the available scientific knowledge, a single indicator is chosen as a proxy for nutrient loss. For example, animal density is used as a proxy for nutrient loss in regulation in Europe and the USA (Saam et al., 2005).

This approach attempts to provide a halfway point between using intuition and developing models. In effect it creates a simplistic model that ignores the other details and complexities of the situation. Given that nutrient loss is determined by a diverse number of factors, models that consider a range of factors, and the interactions between them, are often preferable to the use of proxies.

When considering issues relating to water quality, local councils frequently work in the context of the Resource Management Act (1991). Under section 30 of this Act, Councils are required to evaluate the effectiveness and appropriateness of any plans they propose under the Act. This evaluation requires them to consider the benefits and costs of their proposal, alternatives to their proposal, and the risks of acting and of not acting according to their proposal.

Models provide a valuable tool to support the design of policy in this context. Councils use models to identify the causes of an issue, their magnitudes, and the extent of intervention necessary to meet social goals. Where intervention is desired, models enable councils to experiment (virtually) with different designs of policy and to observe the types of outcomes that are likely to result under different policies. For example, ROTAN has been used to identify the key sources of nitrogen in Lake Rotorua and to identify how the nitrogen load to the lake might vary under different mitigation and land use change scenarios (Rutherford et al., 2009). In addition, models can be used to help assess compliance with regulation (Overseer has been used for this purpose) and to assess the likely effectiveness of policies. It follows that models are powerful tools for informing and empowering decision makers.

4. How are models developed?

Models are developed as part of the scientific process of conducting research. They may be developed to guide the initial direction of research, to address research questions, or as the intended outcome from research. In general, the development of a model occurs according to the following process:

1. The purpose of the model is defined.
2. The existing scientific knowledge is examined. This stage includes conducting reviews of the published literature and consulting with recognised experts in the field. The goal of this examination is to identify the key factors and relationships that are of interest.
3. The scope of the model is defined, specifying what factors and relationships will be included in the model and in how much detail. For example: Does the model need to consider the sources of nitrogen leaching on farms, or just their transport to the local lake? Are we interested in phosphorus loads on an annual, monthly, daily or hourly time frame? Is the focus national, regional or individual catchment water quality? The answers to these questions are driven by the intended purpose of the model.
4. The data that is needed for the model is collected. This may entail taking measurements as part of collecting new data. As part of this stage, the reliability of the data is assessed (considering the nature and magnitude of any errors with the data).
5. Supporting and constituent research is completed. If the model cannot be constructed from existing scientific knowledge, new research is necessary. This research may require the development of sub-models that act as inputs to the original model.
6. The model is realized as a computer program. This computer program is often talked about as “the model” and is frequently given its own name.
7. The model is documented. This documentation describes the scope of the model, how it has been constructed, the datasets that it draws on and the uses it can be put to. In addition, the documentation describes the assumptions that were necessary

during the construction of the model, why they were made and their likely impact on the model results.

8. The model is tested by the scientists involved in its development. The focus of this in-house testing is often checking the model results for consistency with observations and intuition. This may lead to models being calibrated to help ensure that they better match reality.
9. Where possible the model is validated. Sometimes referred to as "ground truthing", this process involves comparing the model results against data that has not been used to build or calibrate the model. This process helps quantify any uncertainty associated with the model.
10. The model, along with its documentation and validation, is exposed to the wider scientific community who have opportunity to comment and critique (most often this occurs in the context of journal articles, working papers and conferences). This process is often called "peer review" and encompasses not just the model results, but also its methodology and underlying assumptions. This is a standard part of the scientific process, having the goal to enhance and clarify the new work. Where critical issues are identified with the model the developing scientists may return to stages 3 and 4.
11. The model is made available for applications for stakeholders and those outside the scientific community who have an interest in it. The model results are assessed by stakeholders outside the scientific community.

Further discussion of good practice for developing models is given by Scholten et al. (2000) and James (2003). Some examples of model calibration and validation for water quality are given by Cichota and Snow (2009), Cichota et al. (2010), Cichota et al. (2012) and Mackay et al. (2012).

While we have presented these stages sequentially, it is important to acknowledge that often these stages overlap. Furthermore, scientists may return to earlier stages during the development of a model in order complete the later stages. For larger and more complex models these stages may be followed for different sub-parts (or sub-models) of the model.

The peer review process imposes upon scientists a requirement for rigor. Rigor gives credibility to models, their results, and the conclusions that are drawn from them. While situations arise where an organization funding the application of a model applies pressure to bias the results, such results are unlikely to pass scrutiny by the rest of the science community. Users and funders of models can therefore have confidence in models and results that have undergone peer review, and should request it of those models and results that have not.

It should also be recognized that a completed model is not static. Models are never perfect because scientific understanding is never perfect. Developing and maintaining models is an ongoing and iterative process. As models are critiqued and as scientific knowledge increases, components of the model may be enhanced or require revision. For example, the Overseer model was critiqued as not being calibrated to Canterbury's soils and dry climate. In response to this feedback further research was conducted that led to Overseer being refined to better respond to Canterbury's soils and climate (Trevor Webb, Landcare Research, pers. comm.).

To those outside the scientific community, the process by which models are improved has, on occasion, been misinterpreted as an indication that models are unreliable. However, improvements to models, whether in response to feedback or to take account of new science, almost always take place near the limits of a model's capabilities. In this way the capability and applicability of a model is extended. The foundation of any model is seldom critiqued.

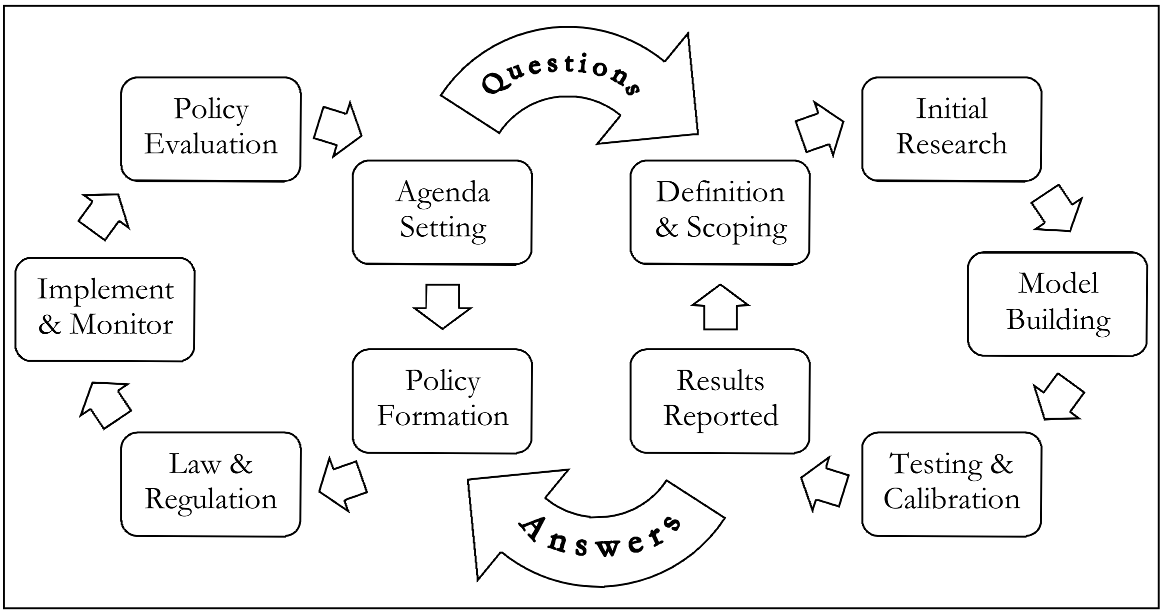
5. How are models used?

Water-quality models are used for research, farm-level consulting, to inform policy design and as a compliance tool. We discuss the first two uses in brief, before focusing on the use of models for informing policy.

Research models are used for quantifying outcomes of interest (such as nutrient loss), forecasting future nutrient concentrations or loads, and identifying areas of further interest (whether there are key technologies that can decrease nutrient loss) or concern (the waterways enriched with nutrients). Farm-level consulting models are used for quantifying outcomes of interest (such as nutrient loss) and for informing farm management decisions (such as how fertilizer or dairy shed effluent could be applied more effectively, or when is it optimal to irrigate).

The use of models is often requested to inform the development of policy. Once an issue has been identified, models could be used to identify its magnitude, the key causes and a range of possible responses. Figure 2 shows this interaction between the modelling cycle and the policy cycle.

Figure 2: Interaction between policy and modelling cycles



In addition to informing the design of policy, models can also be used in the implementation and evaluation of policies. In the Lake Taupo catchment, the use of Overseer (version 5.4.3) is required by the regional plan (Environment Waikato, 2010) to determine farms' nitrogen losses and required holdings of discharge allowances. Models are yet to be used for evaluating water-quality policy after it has been implemented, but have been used for assessing the impact of councils' efforts to reduce erosion (Dymond et al., 2010), in New Zealand.

The use of models for informing policy design has its challenges. These often arise at the interface between policy and science. Differences in timescales between policy demands and modelling capabilities can impose pressure on scientists to use models and provide results that have not undergone sufficient review. Although model results are themselves subject to review and critique, the interpretation of model results for use in policy is not always reviewed by the scientists who are responsible for them. Despite these challenges, modelling is still a valuable tool for informing policy; addressing these challenges would enhance its value further.

The use of models with legislation has even greater challenges. These arise because the rigor that is required for legislation is different from the rigor that is required for science. Scientists use models to generate insights, and scientific rigor helps ensure that these insights are robust. Legislation uses models to quantify limits and to measure performance (for example, ROTAN has been used to help inform the maximum acceptable nitrogen load to Lake Rotorua; and farm nitrogen losses to Lake Taupo are being calculated using Overseer). Rigor is required to ensure that these numbers are accurate. Models can generate insights and inform policy design even with moderate levels of uncertainty, such as plus-or-minus 30 percent – in fact, such errors are very satisfactory for many models. However, lower levels of uncertainty are desired for legislation. When using a model for legislative purposes, decision makers need to account for uncertainty in the model and, where this uncertainty is too great, allocate sufficient resources to its improvement (Shepherd et al., 2009; Chris Arbuckle, Aspiring Environmentalist, pers. comm.).

6. What are the key water-quality models?

In this section we provide a short list of some of the key models used for investigating nutrient losses, concentrations and loads in waterways. Our focus in providing this list is to highlight the differences between each model, their relative strengths, and when / why you would use a particular model.

A wide range of water-quality models exists. For example, models have been developed for nutrients, pesticide, sediment loss, erosion and bacteria; for informing land management practices including stocking rates and the application of fertilizer and irrigation; and for both urban and rural contexts. We limit the scope of this list to models currently in use for modelling nitrogen and phosphorus loss from rural land (these are the nutrients of interest in most situations) and the concentrations and loads in freshwater. Other studies and websites have compiled lists with different scopes and also illustrate the interactions between models. An interested reader might investigate: Samarasinghe and Greenhalgh (2012), Cichota and Snow (2009), Bryant and Snow (2008), Garraway et al. (2011), Arbuckle (2013), https://teamwork.niwa.co.nz/display/IFM, and http://tools.envirolink.govt.nz/.

We divide the models into two categories: Farm scale nutrient models that provide estimates of nutrient loss, and catchment scale transport models that consider how nutrients travel across catchments and larger areas to local water bodies. In each category we list the models alphabetically.

6.1. Farm scale nutrient models

Farm scale models consider nutrient loss in response to land management decisions on a farm, paddock or plot scale. Sometimes called "root zone" models, these models calculate the amount of nutrients that are lost from the top-most soil layers instead of being absorbed by plant roots.

Figure 3: Classification of farm scale models

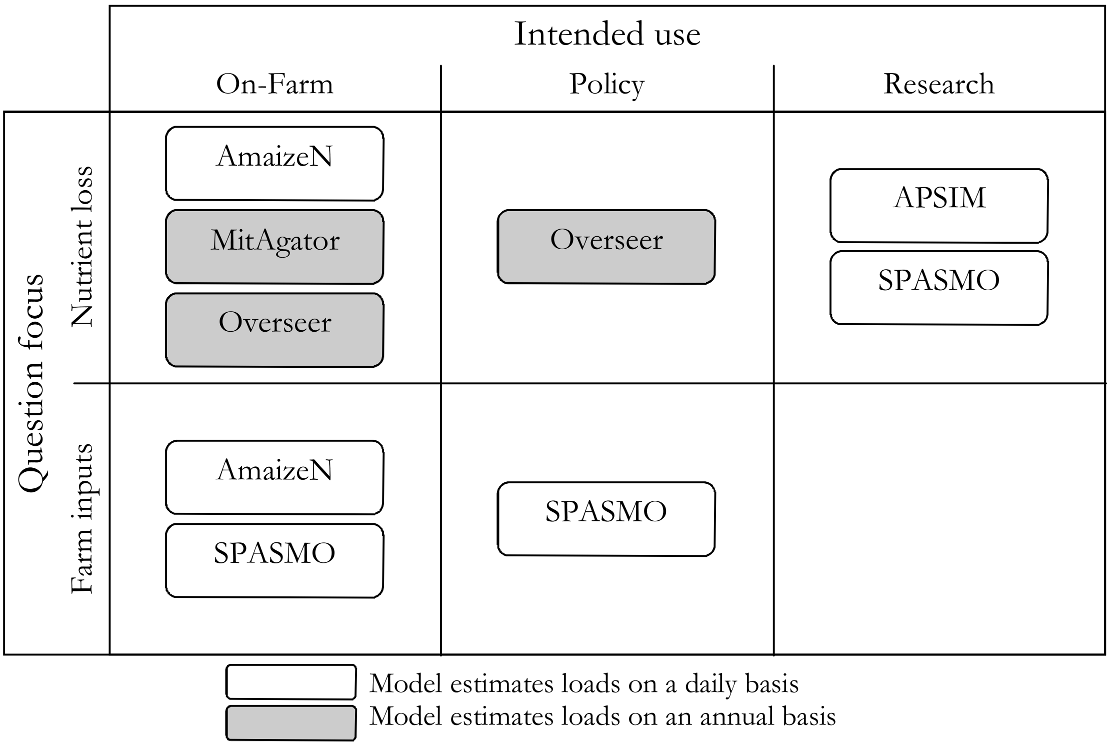


Figure 3 classifies these models based on their current uses and level of detail. Following the description of each model, we give examples of questions that the model is designed to answer.

AmaizeN

AmaizeN Lite is a management tool developed to help growers of maize maximize the yield of their crops and minimise the residual nitrogen in their soil. It produces suggested effective fertilizer application rates, expected yields, and estimates of nitrogen leaching. The model inputs include region, climate, crop and soil data, in addition to results from soil samples (Roger Williams, Foundation of Arable Research, pers. comm.).

AmaizeN has been developed by the Foundation for Arable Research for use in New Zealand. It is intended for on-farm decision making and it has been designed with a simple user interface to facilitate its use by farmers (Foundation for Arable Research, 2013).

AmaizeN addresses questions such as:

- When and how much fertilizer should I apply to my maize crop?
- How will this affect my expected yield and nitrogen loss?

APSIM

APSIM (Agricultural Production System Simulator) is a process-based model of arable, pastoral and forestry activities. It produces paddock or farm level estimates of production, drainage, and nutrient leaching from soil on a daily time step. The model inputs include fine resolution spatial data on climate, slope, soil properties, irrigation, and crop and stock management, and also detailed weather data.

APSIM is a highly advanced model that is used by an international community who continue to collaborate and develop the model. Both AgResearch and Plant and Food Research are part of this community. APSIM is intended to be used as a research tool by scientists, but can be made accessible to farm consultants using simpler user interfaces. It has been used by the Pastoral 21 group, has been linked to the DairyNZ Whole Farm Model, and also used to inform the development of Overseer (Keating et al., 2003; Beukes et al., 2011; Cichota et al., 2010; Cichota et al., 2012; P21 Environment, 2011).

ASPIM addresses questions such as:

- How much nutrients is lost from the land?
- How does nutrient loss vary with weather?
- How often do extremely high levels of nutrient concentrations occur?

MitAgator

MitAgator is a spatially explicit model that extends the results produced by Overseer (see below) to identify where on the farm property nutrient loss is occurring. It produces farm maps of land from which nutrient loss is most significant, and can suggest possible sites for targeted mitigation along with estimates of the cost and effectiveness of different mitigation activities. The model inputs include Overseer reports, farm maps, maps of soil, and a digital elevation model with very fine resolutions.

MitAgator has been recently developed by Ballance Agri-Nutrients under the Primary Growth Partnership. It is currently undergoing an 18 month validation assessment. Once approved, it is intended for use by farmers and their advisers. (Stafford and Peyroux, 2013; Richard McDowell, AgResearch, pers. comm.).

MitAgator addresses questions such as:

- Where on my property are nutrients lost?

- How does nutrient loss vary with management practices, what mitigation strategies will be effective, and where should I target them?

Overseer

Overseer is a farm system model for pastoral, arable, horticultural and forestry activities. It produces estimates of long-term average nutrient losses via drainage and runoff at a farm and farm block level. Overseer also estimates greenhouse gas emissions and aids in planning fertiliser applications. Its inputs include climate and soil data, in addition to land use, animal numbers, production, crop and stock management practices. These inputs are intended to be information that is readily available to the farmer.

Overseer is jointly owned by the Ministry for Primary Industries, the Fertiliser Association of New Zealand, and AgResearch. It is subject to ongoing governance by the owners, input by interested parties (Regional Councils), development and refinement (version 6 is in use at the time of writing). Training is provided for users of the model (for example, all fertiliser company representatives are required to complete a course on Overseer at Massey University). Overseer is intended for use by the farm advisor, and deliberately limits its required inputs to facilitate this. It was designed to encourage the efficient use of nutrients on farms , but has also been incorporated in regulation by the Bay of Plenty (for the Rotorua Lakes), Waikato (for Lake Taupo) and Horizons (the One Plan) regional councils. As part of the "Clean Streams Accord", the dairy industry mandated that every dairy farmer have Overseer run for their property. Overseer is also used on many dry stock, arable and horticultural farms. The Pastoral 21 group has used Overseer for informing and directing research into agricultural productivity. Simplified versions of Overseer have been incorporated into catchment level transport models, for example CLUES. (AgResearch, 2010; McDowell et al., 2005; Wheeler and Shepherd, 2012; Shepherd and Wheeler, 2012; Shepherd et al., 2013; Wheeler and Shepherd, 2013).

Overseer addresses questions such as:

- What are the average annual nutrient losses from my property?
- How do these losses vary with changes in management practices?
- What is the potential impact on nutrient losses of developing my land for agricultural production?

SPASMO

SPASMO (Soil Plant Atmosphere System Model) is a physics based model of plant growth and nitrogen leaching, with some estimation of phosphorus. It focuses on arable and horticultural activities. SPASMO produces estimates of crop production, drainage and nutrient leaching from soil on a daily time step. Its inputs include spatial data on climate, irrigation, soil properties, land use, and crop and stock management.

SPASMO has been developed by Plant and Food Research over 20 years. Over this time it has been used by scientists for a range of projects for Regional Councils, commercial clients and researchers. Its current users include six Regional Councils for the allocation of irrigation water, and consultants for determining irrigation requirements for specific crops given weather history. As part of the development of Horizon's One Plan SPASMO has been compared against Overseer. (Green and Clothier, 1995; Green et al., 2006; Green et al., 2008; Mackay et al., 2012).

SPAMSO addresses questions such as:

- How does irrigation and rainfall affect my expected crop yield and nutrient losses?
- How sensitive are these results to changes in weather or irrigation?
- How often do extremely high levels of nutrient concentrations occur?

6.2. Catchment scale transport models

Nutrients move from the "root zone" into lakes and rivers via deep groundwater (for example aquifers) and surface water (for example streams). Catchment scale transport models consider the speed and distribution of nutrients along one or more of these pathways. While we often use these models to consider diffuse, or non-point, sources of nutrients these models can also account for point sources of nutrients (including urban areas).

Figure 4: Classification of catchment scale transport models

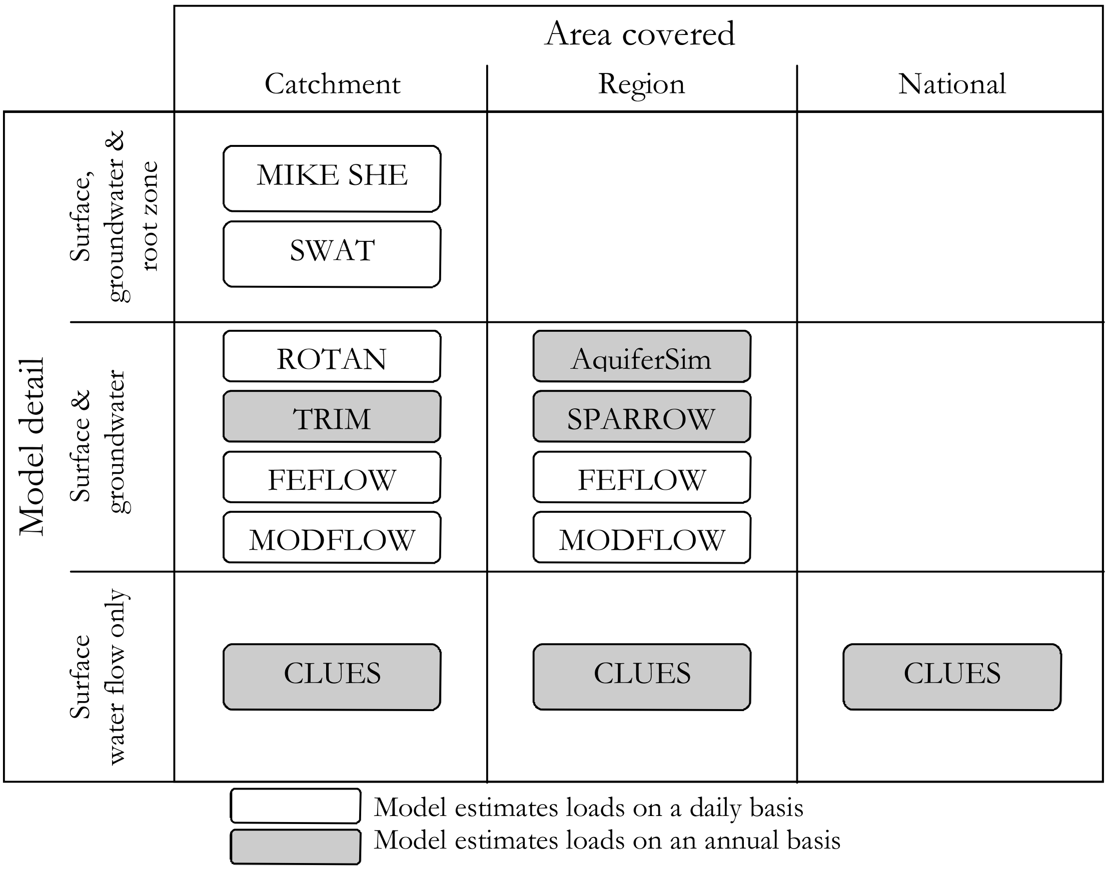


Figure 4 classifies these models based on their complexity and scale. Following the description of each model, we give examples of questions that the model is designed to answer.

AquiferSim

AquiferSim is a region level model of nitrogen transport via groundwater flows. It produces spatial estimates of groundwater discharge to streams, nitrogen in groundwater and concentrations in streams. Its inputs include maps of climate, topography, soil type, groundwater zones, land use and production.

AquiferSim was developed by Lincoln Ventures and Landcare Research as part of the Integrated Research for Aquifer Protection project. It has been used for several case studies in the Hurunui catchment, Mataura valley, and between the Rakaia and Waimakariri rivers. The model is intended for use by scientists and regulators for informing land use and water resources planning. (Bidwell et al., 2005; Lilburne et al., 2006; Bidwell and Good, 2007).

AquiferSim addresses questions such as:

- What are the long-term effects of land-use change on nutrient loads in the groundwater and the levels of groundwater flow?

CLUES

CLUES (Catchment Land Use for Environmental Sustainability) is a large scale water and nutrient transport model. It produces spatial estimates of nutrient loss, loads and concentrations in waterways at a catchment, regional or national level. The model inputs include spatial data of topography, stream reaches, soil, land use and climate.

CLUES was developed for the Ministry of Primary Industries by NIWA in collaboration with the Ministry for the Environment, Lincoln Ventures, Harris Consulting, AgResearch, Plant and Food Research and Landcare Research. The model has been used in Waikato, Manawatu, Canterbury, Southland and the Bay of Plenty as well as at a national level. CLUES makes use of simplified versions of Overseer and SPARROW. It is intended for use by scientists, regional and central government for evaluating different land use scenarios at large scales. (Woods et al., 2004; Woods et al., 2006; Parshotam and Elliott, 2009).

CLUES addresses questions such as:

- How could water quality vary under different land use and farm practice scenarios?
- How could economic outcomes vary under these scenarios?

FEFLOW

FEFLOW (Finite Element Flow) is a model for water flow and contaminant transport via groundwater flows. It produces spatial estimates of nitrogen loads and concentrations along with water flow throughout the groundwater. The model inputs include detailed soil, sub-soil, climate, contaminant, hydrologic and topographic data.

FEFLOW is developed and maintained by DHI, an international research and consulting organisation. It is used by an international community of specialist groundwater modellers and consultants, and has been extensively validated. In New Zealand, FEFLOW has been used in a range of catchments including Auckland, Waikato, Motueka and Canterbury. (Trefry and Muffles, 2007; Diersch, 2009).

FEFLOW addresses questions such as:

- How does climate impact groundwater flows and nitrogen transport?
- How are nitrogen concentrations distributed through streams and groundwater?

MIKE SHE

MIKE SHE is an integrated hydrological cycle model that can consider both stream and groundwater flows of water, as well as atmospheric transportation. It can produce sub-hourly estimates of nutrient concentrations, sediment, and contaminants in rivers and groundwater. Due to the level of detail incorporated into the model it has extensive data input requirements.

MIKE SHE is developed and maintained by DHI, an international research and consulting organisation. The model is intended for engineers, modellers and scientists who want a high level of detail. Environment Canterbury has begun to use this model for its integration of surface water and groundwater. The current focus of their modelling is water quantity but they are intending to use it for water quality soon (Graham and Butts, 2005; Tim Davie, Environment Canterbury Regional Council. pers. comm.).

MIKE SHE addresses questions such as:

- How do surface water and groundwater flows interact with each other, and with the rest of the hydrological cycle?
- What are the consequences on water flow and nutrient concentrations of changes in land use, irrigation and agricultural management practices?
- How often do nutrient concentrations exceed specific thresholds?

MODFLOW

MODFLOW (along with its companion models MODPATH, MT3DMS and RT3D) is a catchment level model for groundwater flow and contaminant transport. It produces spatial estimates of nitrogen concentrations and loads in groundwater and steams. The model inputs include detailed soil, sub-soil, climate, contaminant, topographic and hydrologic data.

MODFLOW was developed by the U.S. Geological Survey. It is used by an extensive international community of specialist modellers, scientists and consultants, and has been extensively validated. MODFLOW is one of the most widely used models in New Zealand for understanding groundwater flows. Applications of MODFLOW in New Zealand have occurred in the Waitaki, Masterton, Lake Taupo, Upper Waikato and Canterbury catchments. (Pollock, 1994; Hadfield, 2007; Clements et al., 1998; Thorley and Scott, 2010; Toews and Gusyev, 2012; Weir and Moore, 2012).

MODFLOW addresses questions such as:

- How do stream and groundwater flows interact with each other, and vary over time?

- How are nitrogen concentrations distributed through streams and groundwater?
- How often do nitrogen concentrations exceed specific thresholds?

ROTAN

ROTAN (Rotorua and Taupo Nitrogen Model) is a catchment hydrology and nitrogen load model. It produces estimates of nitrogen losses from land and lake loads over time. The model inputs include data on climate, stream and groundwater flows, as well as maps of land use, soil type and topography.

ROTAN was developed by NIWA in the context of Lake Rotorua, to account for the complex hydrology underlying the catchment. It was based on the Scandanavian HBV and HBV-N models. The model has been used to inform limit setting in the Lake Taupo and Lake Rotorua catchments, as well as the design of regulation to improve water quality. While the model could be calibrated for alternative catchments there are no further plans for its development. (Rutherford et al., 2008; Rutherford et al., 2009; Rutherford et al., 2011).

ROTAN addresses questions such as:

- What nitrogen loads and concentrations to a lake should we expect given catchment land use, rainfall and mitigation activities?
- How quickly does nitrogen reach the lake along different pathways?

SPARROW

SPARROW (Spatial Regional Regression on Watershed Attributes) was designed to estimate the origin and fate of contaminants (including nutrients) in waterways from a network of monitoring stations. It produces estimates of water flow and nutrient transport. The full model inputs include maps of land use, river reaches, soil drainage and climate, in addition to data on stream flow, overflow rates and groundwater residence times.

SPARROW was developed by the U.S. Geological Survey and has seen extensive use in the US. It has been used for modelling in the Waikato (as part of the WISE model) and a simplified version is incorporated in the CLUES model by NIWA. SPARROW is intended for use by specialist catchment modellers to inform water management. (Woods et al., 2006; Preston et al., 2011a; Preston et al., 2011b).

SPARROW addresses questions such as:

- What nutrient loads should we expect in streams?
- How reliable are these predictions and what variation from them is likely?

SWAT

SWAT (Soil and Water Assessment Tool) is a catchment level hydrology, soil and water-quality model. It produces daily estimates of stream and groundwater flow, nutrient transport and soil moisture. The model inputs include maps of topography, soil, land use and rainfall, time series of rainfall and climate are also required. Due to the level of detail incorporated into the model it has extensive data input requirements.

SWAT is maintained by the United States Department of Agriculture but is used by an international community of researchers. In New Zealand, the model has been applied to the Motueka catchment. SWAT is intended for use by specialist catchment modellers to inform water management. (Waidler et al., 2009; Arnold et al., 2011; Neitsch et al., 2011).

SWAT addresses questions such as:

- What are the long term impacts of land management practices on nutrient concentrations?
- How does the day to day pattern of water flow vary with changes in catchment land use?

TRIM

TRIM (Tukituki River Model) is a river hydrology and water-quality model. It produces estimates of daily average nutrient concentrations and impacts on aquatic biomass in the Tukituki river in response to land-use change (such as those associated with the proposed Ruataniwha Water Storage Scheme) and point source discharges (including from waterwater treatment plants).

TRIM has been developed by NIWA with contributions from Hawkes Bay Regional Council, Cawthron and GNS-Science. The model has been developed in stages, with the initial modelling limited to the Ruataniwha Basin, before being extended to consider the Tukituki river more generally. (Rutherford, 2013a; Rutherford, 2013b).

TRIM addresses questions such as:

- What are the links between rural and urban nutrient losses, water flow and water quality?
- How does aquatic plant growth respond to nutrient concentrations?

7. Why are there different models?

The range of models used in New Zealand is a response to the range of questions that models are expected to answer, and the range of contexts in which models are used. This helps ensure that the model processes and results are relevant to the end users of each specific model.

Different models are required for different intended users. For example: Overseer is intended for use by farmers and farm consultants (among others), and hence the model inputs have been chosen to be information that farmers often have on hand; MIKE SHE is intended for use by scientists (within both research organisations and local government), and hence the model is complex to enable a variety of questions to be investigated in detail; ROTAN is intended for informing nitrate policy in the Lake Rotorua catchment, and hence it focuses on only the key elements of the Rotorua catchment that policy might need to account for. It is important that the choice or design of a model matches its intended uses, and it is critical that users understand how their chosen model is intended to be used.

Different models are required to model different geophysical situations. For example: ROTAN and TRIM both model the transport of nitrogen from land into waterways. However, neither model can act as a substitute for the other. ROTAN models flows of nitrogen to a lake and is calibrated for Lake Rotorua, while TRIM models flows of both nitrogen and phosphorus to and in a river and is calibrated to the Tukituki catchment. Although any model can be calibrated for different catchments, these models have been designed for their specific geographic locations. In addition, each model makes use of science that is particular to its specific water-body.

Different models are required to answer different questions, and the nature of a model user's question will determine which model is most appropriate for their needs. For example: APSIM, Overseer and SPASMO can all estimate nitrogen loss from farm properties, however Overseer has been developed to estimate long-term annual average farm level nitrogen and phosphorus balances (including losses), while APSIM and SPASMO estimate nitrogen loss at a finer time scale and can consider the variability of these losses across time. Although, for many questions, APSIM and SPASMO can substitute for each other APSIM (by nature of its many developers and users) has a more general focus, while SPASMO has a greater emphasis on perennial horticulture and irrigation.

Different models are required to work at different levels of detail and scope. These details may be on a spatial or temporal scale. With respect to spatial detail consider AquiferSim and CLUES: Both models have both been used to investigate nitrogen transport across a range of catchments. However, while AquiferSim provides detailed results for a catchment, CLUES provides less detailed results but can model much larger areas (even producing regional or national results).

It is important to recognize that less detailed models are not inferior to more detailed models. There are tradeoffs between resolution, scope, data requirements, and computer processing time. For example, models with finer resolutions and models with broader scopes (area or length of time covered) require more data and computer processing time (MIKE SHE and SWAT are examples of detailed models with large data requirements). To reduce the cost of collecting data and to provide timely results, scientists tend to limit the resolution or scope of their models. Furthermore, providing results at a coarser spatial or temporal resolution is appropriate where the existing scientific knowledge and data does not enable more detailed results to be produced with confidence. This represents good scientific practice.

The variety of available models should be viewed as a strength of the research community. The different models represent different areas of ongoing research into water quality and these different areas feed back into each other. So insights and knowledge generated from one model in one context, inform the research and design of future models in many other contexts. For example, leaching calculated by Overseer has been compared against SPASMO (Mackay et al., 2012) and APSIM has been used to improve the leaching sub-model in Overseer (Cichota et al., 2012).

Because different models are required for the many different contexts where models are used there is seldom explicit competition between models. There is some competition between scientists over funding pools but this is relatively minor. Given the nature of New Zealand's scientific community it is much more common for models and scientists to work together. This can been seen in the way a range of models are combined with each other: TRIM makes use of Overseer (Rutherford, 2013b), CLUES makes use of Overseer and SPARROW (Woods et al., 2006), and MitAgator makes use of Overseer. More broadly in the context of other models: SPARROW is incorporated into the Waikato Integrated Scenario Explorer (WISE) (Rutledge et al., 2011), and APSIM is incorporated into the Whole Farm Model (Romera et al., 2012). This combining of models may take the form of one model using another model in its entirety, using key components of another model, or using a simplified version of another model, as well as comparing and validating models against each other (such as using APSIM to inform Overseer).

8. Conclusion

This report has discussed models and the use of models for understanding nutrient loss to waterways. The practice of modelling is well established among scientists as it provides an effective way to think about and understand complex phenomena. Models provide structure to guide new research by combining existing knowledge and identifying areas where new knowledge is needed. In this way, models are a summary of the science and a guide for further science.

Models are used for a range of purposes: research; farm management; on-farm limit setting; policy design and as a compliance tool. The users of these models need to ensure that they choose models that are suitable for their intended uses and interpret model results with care.

Models are developed, used and refined in the context of a wider scientific community. This community both informs the design of models and tests the validity of their results. This is an integral part of the accepted processes by which scientific understanding improves.

In this context, the range of models that are used is a strength of the scientific community. Results from separate models are compared against each other to identify strengths and areas for improvement in the models. The use of different models for different contexts, questions and data helps ensure that the model results are relevant to the end users of their results.

There are always challenges when communicating scientific results to stakeholders outside the scientific community. Scientists are aware of the knowledge and the process of peer review that has informed the model, while stakeholders are often aware only that the conclusions have been generated according to a model. The challenge to scientists is to communicate not just the results of their model, but also to provide stakeholders with a glimpse into the science behind the model as part of emphasizing the credibility of their work. The challenge to stakeholders is to ask for this understanding of how the model has been developed, and to understand the definitions and concepts used by the scientist in order to interpret results appropriately and understand the implications of their limitations.

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