THE 'WATER WHEEL' – A TOOL FOR EXPLORING THE BALANCE BETWEEN ECONOMIC AND ENVIRONMENTAL OUTCOMES

Ton Snelder*, Caroline Fraser, John Bright

Aqualinc Research Limited.
PO Box 20-462, Bishopdale, Christchurch 8543, NZ
**Email: t.snelder@aqualinc.co.nz*

Abstract

The National Policy Statement for Freshwater Management (NPS) requires that clear limits to use of water resources are established for all freshwater bodies in New Zealand. It also requires all land and water users – urban and rural – to collectively operate within these limits. Because of the interrelationship between land and water and the health of people, ecosystems and communities, limits will have consequences across a diverse range of values that broadly include the four well-beings: environmental, social, economic and cultural. This means that difficult trade-offs are often involved in setting limits. In addition, assessment of the impact of limits requires integrated, multi-disciplinary studies that evaluate consequences across the four well beings. These technical assessments tend to produce a large amount of complex information that may be difficult to communicate to stakeholders (MFE, 2007).

A water wheel diagram is a graphic that presents the current state (based on monitoring data), or the expected state (based on scenario analysis) of indicators of economic, social, cultural and environmental well-being. The status of each indicator is normalised with reference to thresholds that define acceptability, for example; excellent, good, fair, and poor. Comparison of sets of Water Wheel diagrams representing different scenarios as part of the limit setting process can help to identify the trade-offs between and within the four well-beings.

A limit simulator has been developed to rapidly and easily derive water wheel diagrams that represent the consequences of limits for environmental and resource use values at any point in New Zealand's river network. The model uses data contained in the Ministry for the Environment's River Environment Classification (REC) system and integrates several national scale empirical models including models describing water quality, hydrology, hydraulic geometry and habitat, and stream bed periphyton (slime).

This paper introduces some key concepts associated with technical assessments made for collaborative decision-making around limits. We then describe water wheel diagrams and a limit simulator, which are technical tools for exploring options for limits. Finally we describe the results of a limit-setting scenario analysis in a case study catchment, to illustrate the types of trade-offs often involved in the setting of water quality and quantity limits.

Introduction

Abundant freshwater resources are one of New Zealand's most significant competitive advantages, providing for both outstanding environmental values and an internationally competitive primary industry sector. However, the management of water resources has become a significant issue in New Zealand where per capita demand for water is two to three times higher than most other OECD countries (MFE, 2007). The greatest demand is for irrigation, which accounts for 78% of the permitted water abstractions in New Zealand (MFE, 2006). In addition, although the quality of New Zealand's fresh water is good by international standards, monitoring shows that it is declining and fails to meet guidelines in many places, particularly in lowland water-bodies (Larned et al., 2004; MFE, 2007).

Concerns about freshwater have triggered significant thinking about its management by government, industry and other stakeholder groups that has led to reforms in the way it is managed. First, the National Policy Statement for Freshwater Management (NPS) requires that clear (i.e. unambiguous and measurable) water resource use limits are established for all freshwater bodies in New Zealand (New Zealand Government, 2011). Second, reports to the government by the Land and Water Forum have called for a fundamental change from expert led and often adversarial decision making to more collaborative approaches to setting and living within water resource limits. These reforms will challenge the way resource management decisions are currently made and resources are managed.

Along with these reforms comes a shift in the role that scientists and science play in water resource management in New Zealand. Rather than driving the decision making process, science should be used to support and inform the decisions. In order to achieve this, scientists must present open and transparent information to stakeholders involved in collaborative processes. In particular, assessments should demonstrate the full spectrum of water resources management scenarios and consequent outcomes that are relevant to the decision making group.

The 'Wheel of Water' research program is a three year government funded multi-agency project that is researching collaborative decision making and water resource management. In this article we discuss the development of some key concepts around establishing limits and describe some technical tools that have been developed to assist limit setting processes including water wheel diagrams and a limit simulator.

Key concepts

Limits

A limit is defined by the NPS as the maximum amount of use of a water resource that can be made while allowing an environmental objective to be met. This definition recognises that water resources are of finite size - that is water bodies have a capacity for use, beyond which further resource use will not maintain environmental values at an acceptable level. Resource use generally refers to the activities that alter the quantity or quality of water but may also extend to those activities that alter physical habitat in freshwater bodies. Key water resource uses for which limits apply are consumptive use of water (e.g. takes for water supply or irrigation), non-consumptive use (e.g. takes for hydro-power generation) and use of assimilative capacity (e.g. by point and non-point sources of contaminants).

The benefits of establishing limits include certainty for environmental protection and future resource use, and a basis for managing cumulative effects. The absence of limits means that water resource management decisions will occur on a consent by consent basis, which creates uncertainty for stakeholders and may lead to over-allocation of the resource (OECD, 2007). Some water resources are already considered to be over-allocated (i.e. limits have already been exceeded) in terms of both water quantity (Aqualinc, 2008) and water quality (Larned et al., 2004). Over-allocation is considered to have had detrimental environmental consequences and to be constraining economic opportunities (ME and MA, 2009).

Indicators

The interrelationship between land and water and the health of people, ecosystems and communities means that water resource use has consequences across a diverse range of values that broadly include the four well-beings: environmental, social, economic and cultural. The relationship between the four well-beings and how these are likely to change with different limits can be represented with indicators. Indicators can be used to quantify and simplify aspects of the systems under consideration (i.e. social, environmental, economic and cultural). Useful indicators are relevant to the issues being assessed, are defensible and transparent in their calculation, have a direct or proxy relationship to the outcomes under consideration and respond to variation of the limits. In addition useful indicators should be relatively few in number, but sufficient to represent the important cause and effect relationships. To have a direct use for decision making, indicators need to reflect changes that are relevant to management and policy.

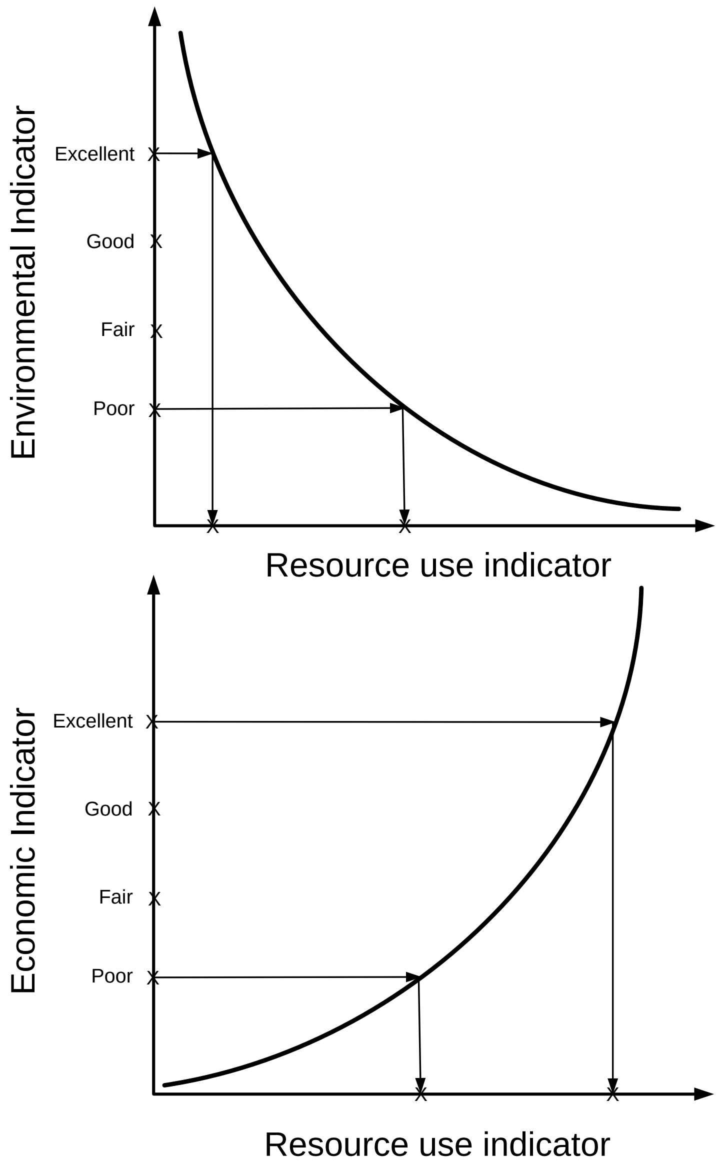
Assessments, technical and socio-political aspects

Assessments of the outcomes across the four well-beings are needed to make informed judgments about where the limits should be set. To be accepted by participants in a collaborative process, water resource use limits must be justifiable and transparent. Justifiability and transparency are facilitated by assessments that describe the consequences of a range of possible limits across all four well-beings and show how these are related.

The top panel in Figure 1 represents a generalised relationship between resource use and an environmental indicator. The relationship indicates that as resource use increases the value of an environmental indicator decreases. The value of the indicator can be subdivided into the categories: excellent, good, fair and poor (Figure 1). The definition of the relationship is technical (i.e. prepared by technical experts such as scientists and economists) but the determination of the acceptability of various levels of indicators, and ultimately the limits, are socio-political decisions.

A collaborative process is unlikely to determine the acceptability of a single indicator in isolation from consideration of other well-beings. For example, the lower panel in Figure 1 represents the relationship between resource use and an economic indicator. The relationship is reverse of that between resource use and the environmental indicator (i.e. the value of the economic indicator increases with increasing resource use). Socio-political judgments concerning the acceptability of the environmental outcome shown on the top panel are likely to be influenced by the consequences for economic indicators shown on the bottom panel. There are also cultural and social outcomes associated with resource use; there are potentially many indicators that are likely to be related to each other in complex ways that need to be considered. The information required to make informed decisions concerning limits is therefore significant and complex.

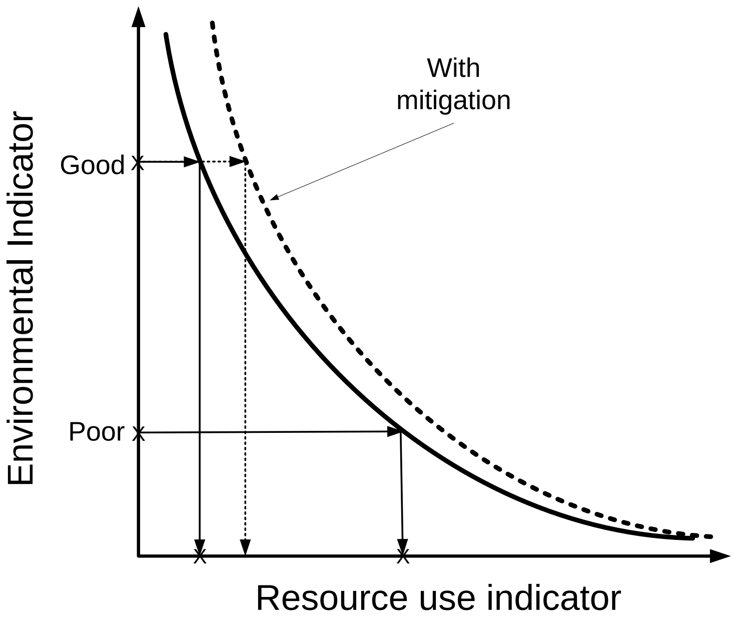
Figure 1: Schematic diagram of the relationship between environmental and economic indicators and resource use. Potential limits to resource use are shown that would achieve excellent, good, fair and poor outcomes for the environmental and economic indicators.



Mitigation

Increased resource use in situations where environmental limits have been reached requires that effects are mitigated. Mitigation measures, for example Good Environmental Practices (GEP) for agriculture, allow continued or increased resource use while staying within limits (Figure 2). The effectiveness of mitigation measures is generally associated with their cost and these economic implications are likely to have consequences for other well-beings. The consequence of potential mitigation measures is therefore likely to be complex and needs to be taken into account in the assessment process.

Figure 2: Schematic diagram of the relationship between an environmental indicator and resource use with and without mitigation. The curve shows that with mitigation, increased resource use can be achieved while meeting the same environmental state.



Scale, uncertainty and effort involved in assessments

There are many factors that potentially influence how assessments can be or should be carried out. For example, assessment approaches need to consider the complexity of the systems involved (both natural and human systems), the level of conflict over resource use (e.g., the degree of over-allocation), the availability of supporting data and knowledge and the availability of relevant expertise.

The legislative framework in New Zealand is inherently risk-based, and requires assessments of environmental effects to be scaled, in terms of detail and effort, according to the magnitude of the resource use and its environmental risk (Rouse and Norton, 2010). Consistent with this are a continuum of approaches to assessment from simple and easily performed to complex and costly. Simple approaches (e.g. based on broad scale empirical relationships) can be used to rapidly explore the consequences of limits in situations with low pressure and/or where environmental and other well-beings are less sensitive. For example, high levels of effort may not be justifiable when developing water resource use limits for jurisdictional regions where water resource use is not high or the hydrological system is not complex. Simple approaches may also be appropriate as a first, low cost, assessment aimed at identifying catchments where there may be future conflicts over resource use.

Situations where environmental and economic values are high require that detailed assessments are made. More complex models that attempt to include a larger number of system components are required in situations where there is significant pressure and conflict. There is likely to be considerable effort involved in assessing the effects of (often localised) mitigation options in order to increase both accuracy and precision in the predicted consequences of alternative water management futures. In these situations, environmental assessments are often made using detailed catchment scale models that are evaluated at high resolution. Similar levels of effort may be associated with economic and other assessments. Detailed assessments are costly and require significant human capital and extensive monitoring data for calibration, but this is justified by the value of the resources or the risks involved.

Information about outcomes - water wheel diagrams

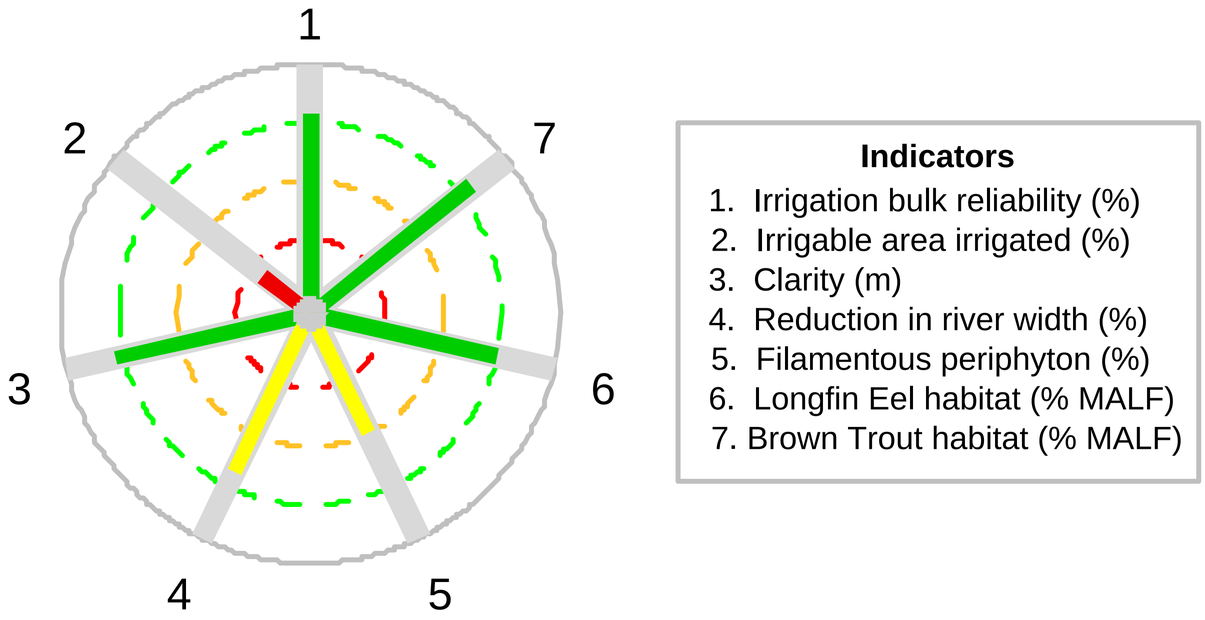
The assessment of the impact of limits on the four well beings requires integrated, multi-disciplinary studies that, as far as possible, describe consequences using a range of indicators that represent the four well beings. Such assessments tend to produce a large amount of complex information that may be difficult to communicate. A water wheel diagram is a graphical tool that is used to display the results of such assessments to stakeholders as part of collaborative processes.

Water wheel diagrams have at least two functions. First, for any specific scenario a diagram shows the assessed state of the indicators on a single plot. The outcomes for each indicator are easily seen from the plot and the acceptability over all indicators is easily appreciated. Second, multiple diagrams can be used to compare outcomes across several scenarios. The advantage is that a considerable amount of information about outcomes across scenarios is presented in a form that can be quickly and easily appreciated.

A water wheel diagram displays the assessed values of several indicators on a single plot (Figure 3). Each spoke of the wheel represents an indicator. The length and colour of the spokes indicate the acceptability of the indicator value on a scale defined by four categories: poor, fair, good and excellent (Figure 3). Long green spokes indicate that the outcome for a particular indicator is excellent. Yellow, orange and red spokes of decreasing length show the indicator is good, fair or poor.

There are two key types of input to constructing a water wheel diagram. First there is the assessment or prediction of indicator values for the scenarios. This is technical information that is produced by experts using models or other approaches. The second input is the determination of the category thresholds for each indicator. The category thresholds are socio-political decisions that reflect the acceptability of certain outcomes. For example, category thresholds may reflect decisions about the acceptability of risk to human health or of levels of water supply reliability. These thresholds are not determined by experts, however experts can provide guidance and help to interpret the meaning of certain levels for an indicator. Because the category thresholds determine the length and colour of the spokes on a water wheel diagram, altering them can alter the appearance of a wheel and therefor the ultimate acceptability of the scenarios. The need to define the category thresholds and the potential sensitivity of the overall conclusions to the thresholds helps to clarify that acceptability is a socio-political decision.

Figure 3 An example water wheel diagram.



Simulation modelling

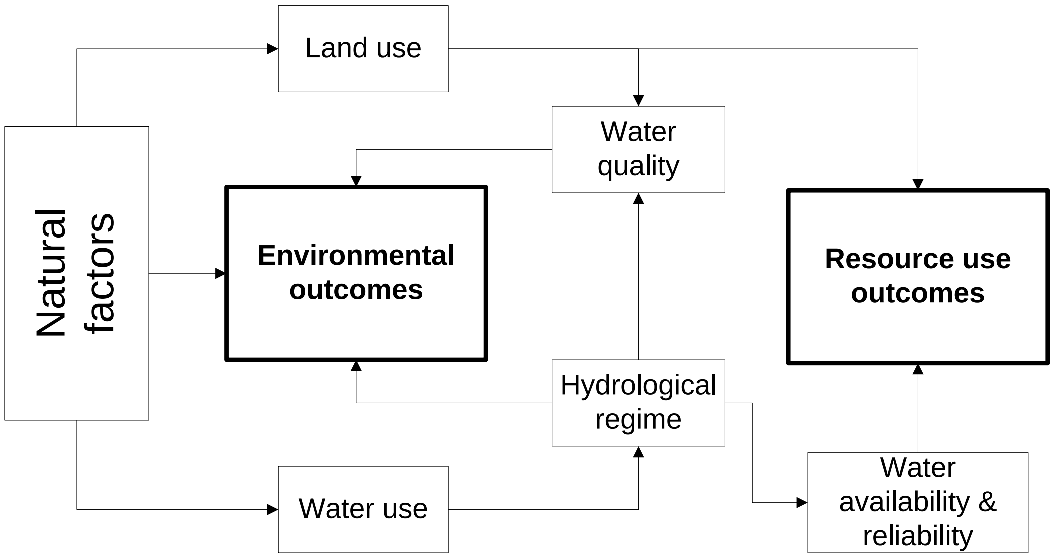
To demonstrate how assessments might be used to generate water wheel diagrams we have developed a limit simulator. The limit simulator is a national scale framework for predicting the consequences of limits on a range of bio-physical and resource use indicators including: water availability and reliability, water quality, hydraulic habitat, and ecological indicators such as maximum periphyton cover.

The limit simulator uses simple empirical models based on national datasets. This constrains the accuracy and flexibility of the model. However, a feature of the limit simulator is the integration of component models to enable the concurrent evaluation of consequences of land and water use for instream values (e.g. habitat, water quality, periphyton) and resource use values (e.g. water reliability and production potential). Another important aspect of the limit simulator that spatial variation in environment such as flow regimes and climate are accounted for. Environmental variation means that the resistance and resilience of environmental systems to the effects of resource use is variable. The variation means that acceptable limits are likely to vary within and between catchments and that the consequences of a specific limit is likely to vary between locations. The simulations account for how a range of resource management options such as minimum flows, total allocation and land use intensity and management interact with natural factors such as the flow regime of rivers to affect outcomes.

The spatial framework for the limit simulator is a digital representation of the New Zealand river network contained within a Geographic Information System (GIS), which was developed as part of the River Environment Classification (REC) (Snelder and Biggs, 2002). The river network was derived from a 30 meter digital elevation model and comprises 560,000 segments with a mean length of ~700m. This means the limit simulator has approximately the same spatial resolution as a 1:50,000 scale map. The river network is associated with a database of environmental variables describing the climate, topography, geology land cover of the catchments of all segments as well as other segment attributes (see Leathwick et al. (2011) for details).

The component models that make up the limit simulator are "generalised" in that they use the REC database to provide predictor data for each segment of the river network. This means that specific data collection to run the analysis is not required and predictions can be made for all river and stream segments of interest that are represented by the REC. The component models account for a range of natural factors, such as differences in stream size and flow regimes, based on information provided by the REC database. The generalised models are used to predict hydrology, water quality and a range of environmental indicators across the study region. In addition, catchment characteristics provided by the REC enable the estimation of potential land use and water demand. Thus, the limit simulator is able to account for land and water use factors and their joint effects on ecological and resource use outcomes (Figure 4). The limit simulator is used to predict the indicator values for a range of scenarios for which limits and resource use intensity vary. These outputs are spatially variable, therefore the results can be presented as maps and also summarised statistically (e.g., histograms showing the distribution of values or catchment averages of the output values).

Figure 4: Schematic representation of the limit simulator framework.



Among the various components of the limit simulator are models that predict hydrological characteristics (river flows). Important hydrological information used by the model includes Flow Duration Curves (FDC), which can be predicted for all REC segments (Booker and Snelder, 2012). FDC can be used to evaluate the consequences of two types of limits that are applied to manage water quantity: total allocation and minimum flows, using methods described by Snelder et al. (2011). In addition, estimates of other hydrological indices are used to evaluate ecological characteristics (Snelder and Booker, In press).

The consequences of minimum flows on habitat of aquatic species are evaluated by the limit simulator using generalised habitat models (Lamouroux and Jowett, 2005). Generalized habitat models are used to estimate the reduction in habitat for specified minimum flows compared to habitat at mean annual low flow (MALF) as an indicator. National estimates of at-station hydraulic geometry parameters (Booker, 2010) are used to provide mean wetted width versus flow relationships and subsequently to compute the reduction in water surface width resulting from specified allocation and minimum flow. The limit simulator uses empirical water quality models (McDowell et al., In press) to assess water quality outcomes.

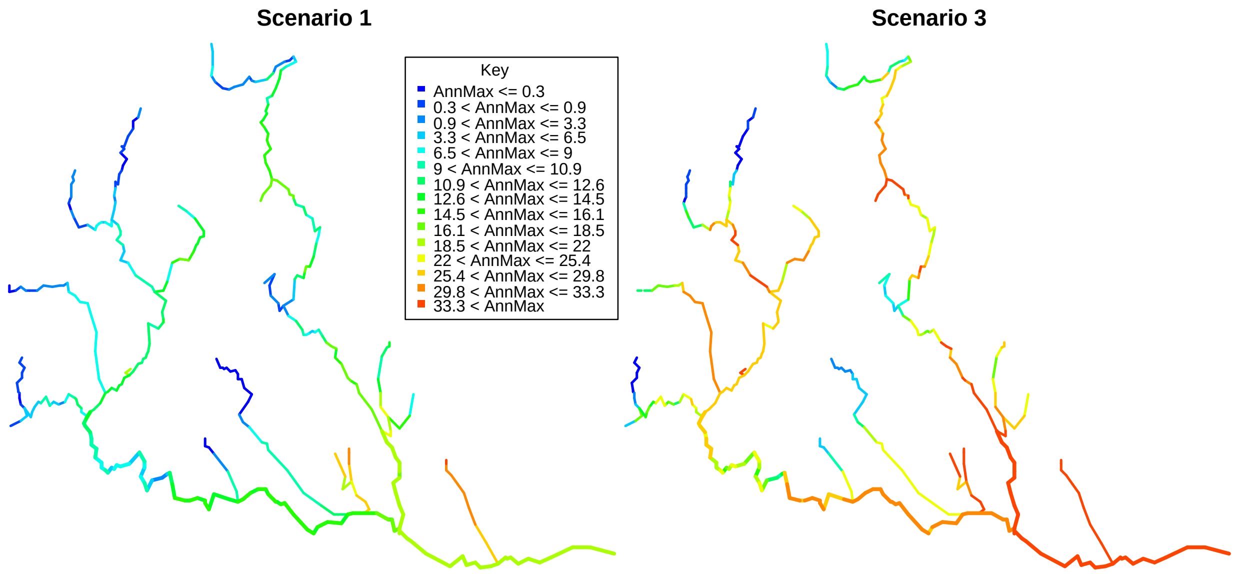
Prediction of periphyton is an example of how the limit simulator integrates several models to assess consequences of both water quality and hydrological changes due to resource use. Periphyton is algae that grows on the bed of rivers and is an important part of the food chain in freshwater. However when nutrient concentrations are high and/or when river flows are artificially reduced, periphyton blooms can have adverse effects for aesthetic, recreation and ecological values (MFE, 2000). The resource uses that can cause periphyton to bloom to unacceptable levels include point and non-point discharges of the nutrients nitrogen and phosphorus and the abstraction of water. Estimates of mean annual maximum periphyton cover (% of the bed) are made based on nutrient concentrations, hydrological indices describing floods and low flows and other natural factors. The limit simulator accounts for the effect of water abstraction on floods and low flows and combines these with predictions of water quality to estimate periphyton cover. Thus, the model is able to assess the consequences of resource use that changes both water quality and quantity, such as land use intensification.

Example application

Results from an application of the limit simulator to a moderate size, hill catchment, with large development potential are presented below. The model was used to simulate the effects of three contrasting sets of limits that range from environmentally conservative limits to more enabling of resource use. The scenarios are labelled Low (Scenario 1), Medium (Scenario 2) and High (Scenario 3) and were defined by varying values of minimum flow, total allocation and land use intensity.

Figure 5 shows predictions for the modelled river network for a periphyton indicator: the mean annual maximum cover by filamentous periphyton. The plots indicate that there is an increase in periphyton cover between Scenario 1 and 3 over much of the catchment. These changes occur because the model predicts that there are increases in nutrient concentration and changes to the flow regime, both of which favour the growth of periphyton.

Figure 5. Predictions of maximum annual filamentous periphyton cover for all segments in a study catchment made using the limit simulator.



The predicted values of seven environmental and resource use indicators are shown on water wheel diagrams for the three scenarios (Figure 6). The indicators examined in this case study are listed in Table 1, along with the (nominal) threshold values for the indicators used to plot the water wheel diagrams.

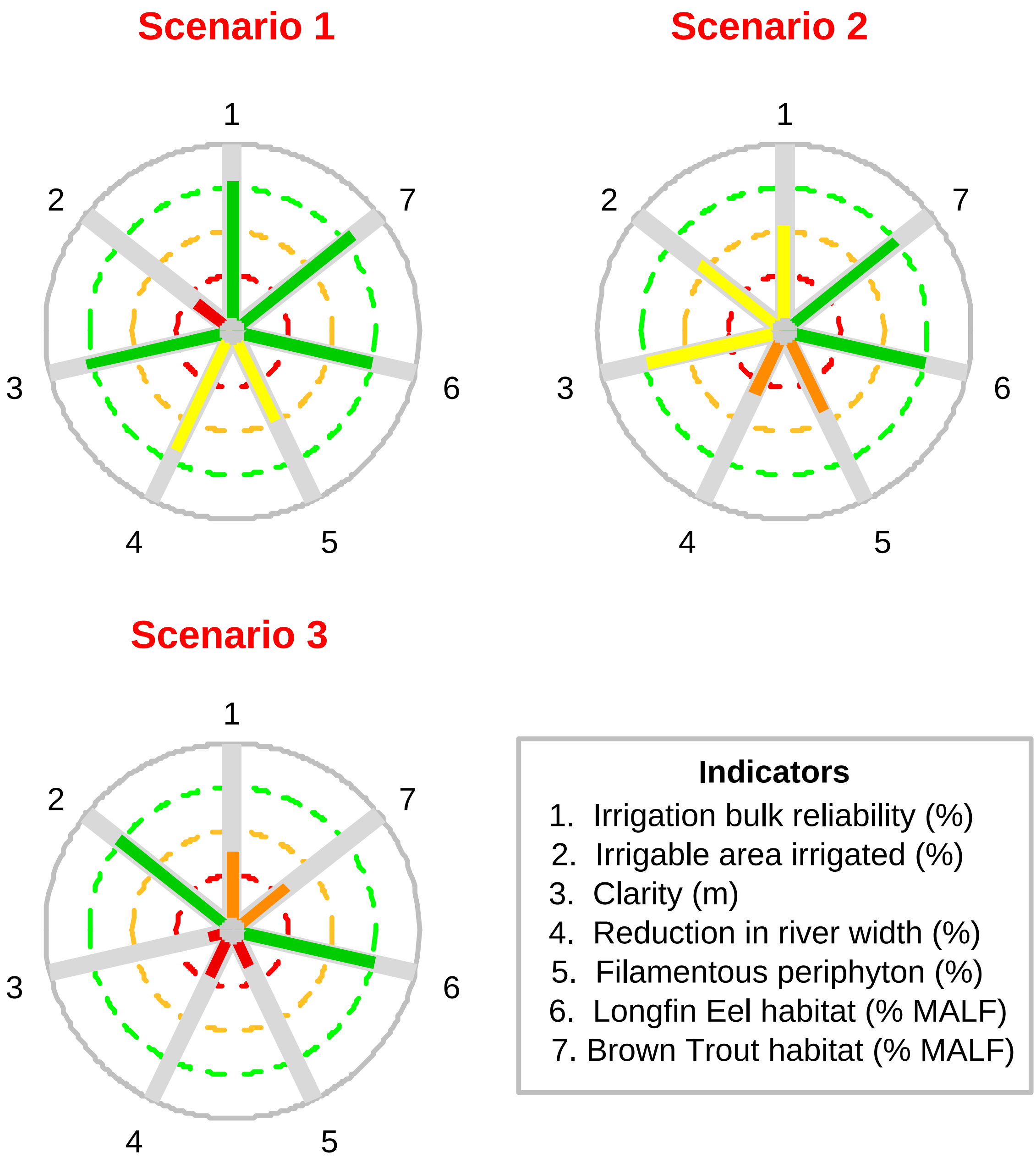
Table 1: Indicators evaluated using the limit simulator and the nominated thresholds. The thresholds are defined in the units shown but are standardised by their range when plotted on the water wheel diagrams.

Indicators	**Poor**	**Fair**	**Good**
Irrigation bulk reliability (% time)	70	80	85
Irrigable area irrigated (%)	10	20	35
Clarity (meters)	1	1.6	2.5
Reduction in river width (%)	-10	-5	-2
Maximum annual filamentous periphyton cover (% of bed)	30	20	10
Long finned eel habitat retained (% of habitat at MALF)	85	95	100
Brown trout habitat retained (% of habitat at MALF)	85	95	100

The water wheel diagrams indicate that no scenario can simultaneously achieve higher than the “good” threshold for all seven indicators (Figure 6). Thus, achieving a higher threshold for any individual indicator requires that a compromise is made for other indicators. Scenario 1 is environmentally conservative and shows that maintaining good or better environmental outcomes requires that irrigated area is not maximised in the catchment. In contrast, Scenario 3 is the most resource enabling, achieving “good” for the irrigable area irrigated indicator, but at the expense of the environmental indicators. Scenario 2 provides a compromise, where none of the indicators exceed the “good” threshold, but nor are any below the “poor” threshold.

This assessment demonstrates that trade-offs are required not only between the resource use and environmental indicators but also within indicators that represent resource use. For example Scenario 3 has higher irrigated area than Scenario 2 but the supply reliability for Scenario 3 is lower than for Scenario 2.

Figure 6: Example water wheel diagrams, showing the seven indicators for the Low (1), Medium (2) and High (3) development scenarios. The values for each indicator were assessed using the limit simulator.



Discussion and Conclusions

The definition of limits for all freshwater bodies has been mandated in New Zealand by the NPS. Setting limits involves balancing different sets of values and ensuring that trade-offs, which are inherent in socio-political decisions, are transparent. It is hoped that collaborative processes that are transparent about how limits are set will help to establish the legitimacy and durability of the resulting management actions and regulations (LAWF 2012). Understanding these trade-offs as part of a collaborative process requires that complex information is effectively communicated to stakeholders. The limit simulator and water wheel diagrams are methods for rapidly quantifying and demonstrating the effects of resource use on both environmental and resource use outcomes.

Setting limits for freshwater resource use is complex because of the strong interrelationship between land and water and the consequences across the four well-beings: environmental, social, economic and cultural. From a technical perspective one of the challenges is integration of scientific disciplines and models. The limit simulator integrates land and water use and produces information about both resource use and environmental outcomes and shows how these interact. The limit simulator is based on a spatial framework that describes New Zealand’s rivers and catchments and simple national-scale empirical models. This means the prediction uncertainties at individual sites can be large and reduces the degree to which simulations can include mitigation measures. However, the model may be appropriate in low risk/pressure situations or as a basis for stratification of risks across broad regions as an initial part of setting water resource limits. In situations where there is greater pressure on water resources more detailed modelling may be justified, for example catchment-scale hydrological models. However, the need to integrate land and water use within the modelling process remains the same.

The effects of water resource use and limits are likely to have implications across all four well-beings and also at multiple scales. Indicators of resource use can currently be transformed into farm scale economic information using production modelling. The Wheel of Water research program is researching how to increase the range of indicators so that the broader scale economic and social consequences of limits can be assessed. The programme is also researching the inclusion of relevant and meaningful cultural indicators so that these can be included in assessments.

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