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A Bayesian Belief Network approach to evaluating complex effects of irrigation-driven agricultural intensification scenarios on future aquatic environmental and economic values in a New Zealand catchment

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Abstract. Agricultural intensification often has complex effects on a wide range of environmental and economic values, presenting planners with challenging decisions for optimising sustainable benefits. Bayesian Belief Networks (BBNs) can be used as a decision-support tool for evaluating the influence of development scenarios across a range of values. A BBN was developed to guide decisions on water abstraction and irrigation-driven land use intensification in the Hurunui River catchment, New Zealand. The BBN examines the combined effects of different irrigation water sources and four land development scenarios, with and without a suite of on-farm mitigations, on ground and surface water quality, key socioeconomic values (i.e. farm earnings and jobs, and contribution to regional gross domestic production (GDP)) and aquatic values (i.e. salmon, birds, waterscape, contact recreation, periphyton and invertebrates). It predicts high farm earnings, jobs and regional GDP with 150% increase in irrigated area, but a range of positive and negative aquatic environmental outcomes, depending on the location of water storage dams and the application of a suite of on-farm mitigations. This BBN synthesis of a complex system enhanced the ability to include aquatic values alongside economic and social values in land-use and water resource planning and decision making, and has influenced objective setting in Hurunui planning processes.

Additional keywords: bathing water quality, braided river, dams, diffuse source pollution, discretisation, groundwater, macroinvertebrates, nitrate, on-farm contaminant mitigation, periphyton, phosphorus, salmon, waterbirds.

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Introduction

The resolution of catchment management issues frequently involves integration of complex interrelationships between socioeconomic, cultural and biophysical attributes and 'values' (i.e. catchment attributes that are important to the human community). This can be assisted greatly by synthesis tools to support stakeholder and decision-maker deliberations to define the problems, examine the consequences of scenarios and develop acceptable approaches (DeFries *et al.* 2004; Jakeman and Letcher 2003; Kragt *et al.* 2011). Irrigated agriculture is the largest consumptive use of freshwater globally (Doll 2002; Postel *et al.* 1996) and associated water infrastructure development and intensification of land use have complex effects on catchment values. In New Zealand, irrigated agriculture typically not only increases economic activity and food production (Doak 2005), but also increases contaminant losses to groundwater and surface water (Wilcock *et al.* 2011) and may also alter stream flow and sediment transport regimes (Young *et al.* 2004).

Agricultural land-use intensification, supported by irrigation, has particular potential to increase economic activity on the relatively dry east coasts of the South and North Islands of New Zealand (Doak 2005). This typically involves change from predominantly dry stock (sheep and beef) grazing to predominantly dairy grazing, which has been associated with degradation of ground and surface water quality (Hamill and McBride 2003). Computer modelling and catchment monitoring studies indicate that these intensification impacts can be mitigated to some extent through the application of on-farm and riparian best management practices (BMPs), and that the costs to the farmers and benefits of different mitigation options vary widely (McDowell *et al.* 2011; Monaghan *et al.* 2009; Quinn *et al.* 2010; Wilcock *et al.* 2009).

Changes to catchment hydrology, sediment transport, materials and biota connectivity and nutrient and pathogen inputs associated with irrigation-driven intensification of agricultural land use can have complex flow-on effects on catchments' biophysical attributes and associated ecosystem services and community values, particularly when the irrigation water is sourced from surface water within the catchment (Allan 2004; Postel and Richter 2003; Wilcock *et al.* 2011). Storage dams and abstraction to supply irrigation water can alter flow and sediment regimes and the movement of organic material and biota within the stream network (Friedl and Wuest 2002; Poff *et al.* 2007; Power *et al.* 1996; Young *et al.* 2004). For example, such changes have potential consequences for instream plant biomass development, channel morphology, fish migration, riparian vegetation, and dilution available to moderate the effects of increased nutrient loads arising from intensification. Understanding such aggregative effects of human activities within a catchment is a major challenge to resource managers (Allan 2004; Bernhardt *et al.* 2006), and even more so to stakeholder groups, who are increasingly being asked to grapple with these issues.

Bayesian Belief Networks (BBNs) are particularly useful for identifying and resolving complex environmental problems because they can incorporate the effects of multiple influences on a wide range of values (economic, social, cultural and ecological) and can include information from a variety of sources, including empirical data, various types of models, literature and expert opinion (Reckhow 2003; Stewart-Koster *et al.* 2010).

The present study developed a BBN of the interactions between selected stakeholder values of an agricultural catchment being considered for irrigation-driven land-use intensification and options for water supply, land development and on-farm and riparian mitigations. An area of 25 000 ha within the Culverden Basin of the Hurunui Catchment has been identified as suitable for further development for irrigated agriculture if water becomes available (Morgan *et al.* 2010), adding substantially to the 16 800 ha area irrigated since the mid 1980s. This expansion of irrigated agriculture raises issues about the potential impacts on catchment and community values (e.g. employment, economic activity, water quality, river health) and the effects on these values of the location and operation of flow abstraction and storage, and the implementation of on-farm and riparian mitigation practices. A series of five stakeholder workshops was held in the catchment during 2010–2011 to attempt to reach a consensus on a 'preferred approach' to addressing the issues and develop recommendations to the Environment Canterbury Commissioners on the development of irrigation within the catchment. The BBN described in the present study draws on information developed as part of that process, evidence presented in earlier Hurunui River Water Conservation Order hearings and general literature. The BBN aimed to provide a tool that presents the complex effects of water resource and land development scenarios on key catchment values as a graphical output that can be used to display the predicted outcomes of different development scenarios to guide deliberations among stakeholders and resource managers on sustainable management in the catchment. The main paper focuses on the scenario modelling results, with a detailed description of the information and assumptions underpinning the model provided in the Supplementary Material.

Materials and methods

Study catchment

The Hurunui River is a gravel bed, alpine-fed river with headwaters in the Southern Alps of the South Island of New Zealand, a mean flow of 68 $m^3 s^{-1}$ at site CH2 (Fig. 1) and a catchment area of 2670 km^2 at its river-mouth. It runs 155 km east through foot hills, across the alluvial Culverden Basin, and through coastal hill lands and plains, before discharging to the Pacific Ocean 85 km north of Christchurch (Fig. 1). The river's barrier-bar estuary is relatively small (1.5 km long thalweg) and dominated by river-flow (the tidal prism is only 5% of mean river flow over a tidal cycle (NZ Estuarine Environment Classification Database (Hume *et al.* 2007)).

One of two main upper tributaries, the North Branch, has natural alpine lakes on its mainstem and consequently has lower bedload transport and flow variability than the South Branch that lacks such lakes (Hicks 2010). The river has two main braided channel reaches: through the plains section across the Culverden Basin; and downstream between State Highway 1 and the sea (Fig. 1). The braided sections have high landscape and biodiversity values, particularly for wading birds (O'Donnell 2004). Elsewhere the river is predominantly single thread in the hill and alpine areas. The river has a self-supporting run of introduced Chinook salmon (*Oncorhynchus tshawytscha*) and the fishery has been ranked as regionally significant (Unwin 2008).

The alpine and foothill areas upstream of the Culverden Basin are relatively undeveloped (1% of area as developed pasture, River Environment Classification (Snelder and Biggs 2002)), whereas downstream Culverden Basin has been developed for mainly sheep and beef agriculture (240 km^2, 33% irrigated), forestry (100 km^2) and dairy (80 km^2, all irrigated) (Brown *et al.* 2011). Since the mid 1980s, the Balmoral Irrigation Scheme has abstracted water on a run-of-the river basis (i.e. no storage) from the Hurunui, downstream of the Mandamus River confluence, and from the Waiau River to the north (Fig. 1), to irrigate 16 800 ha of predominantly pastoral land (70% dairy, 24% sheep and beef). The irrigation scheme has changed, since commissioning, from predominantly flood irrigation to predominantly spray irrigation of fields, with spray now used for 62% of the area irrigated. The Canterbury Water Management Strategy (Morgan *et al.* 2010) identified several potential water supply options to provide for irrigation of up to an additional 25 000 ha in Culverden Basin. These include storage dams within the Hurunui on the South Branch, Mandamus, Pahau and Waitohi, and enhanced storage within Lake Sumner (on the North Branch). These options were estimated to allow for peak irrigation of 5000 to 35 000 ha individually (see Table A1 in Supplementary Material). In addition, the Canterbury Water Management Strategy identified potential to abstract an additional 7.7 $m^3 s^{-1}$ from the Waiau River, irrigating 13 250 ha, and that conversion of all the remaining border dyke-irrigated area to spray irrigation would allow the existing irrigated area to increase by 34% (Morgan *et al.* 2010).

Two National Rivers Water Quality Network (NRWQN) monitoring stations, CH1 and CH2 (Fig. 1), were established

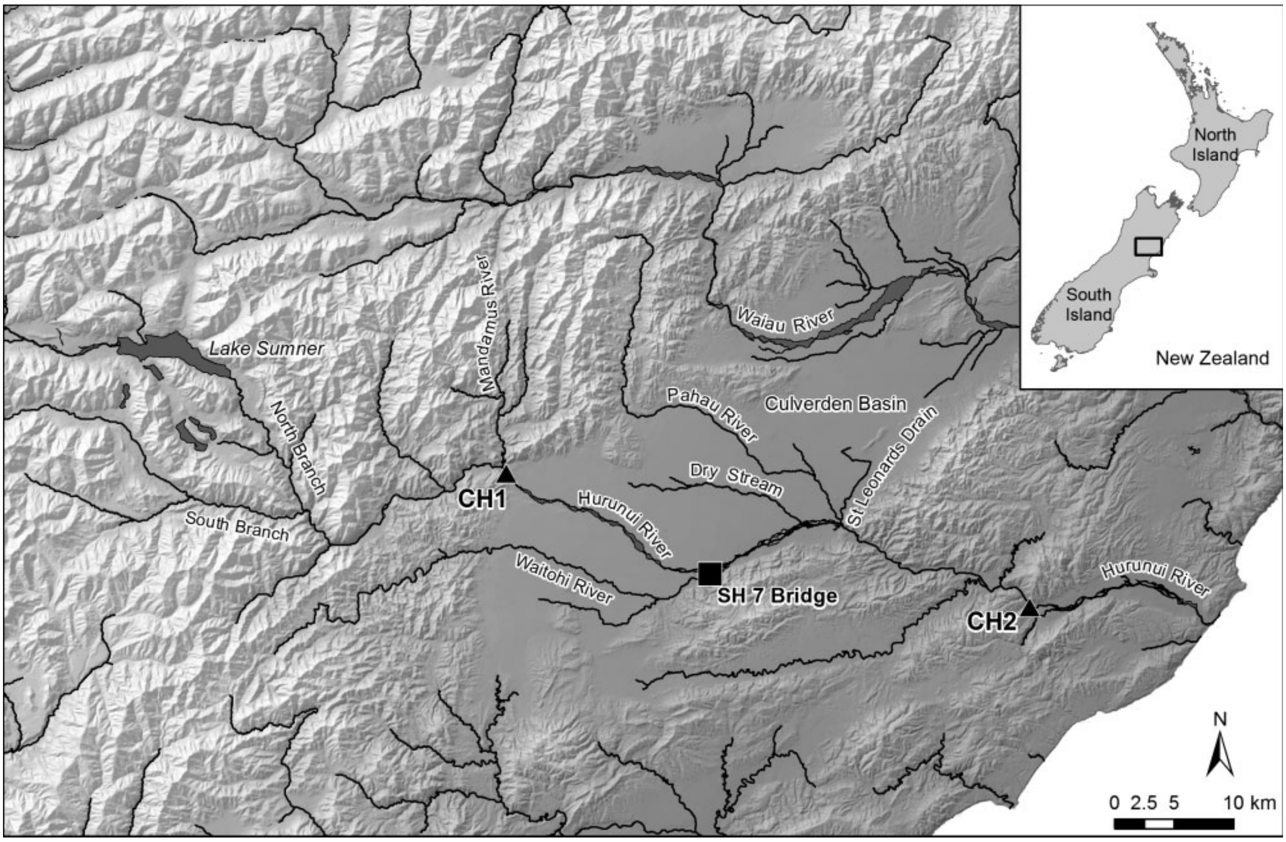

Fig. 1. Location map showing study area of Hurunui River and Culverden basin. Note the location of the National Rivers Water Quality Network monitoring sites at CH1 and CH2.

upstream and downstream of the area suitable for irrigated agriculture in the Culverden Basin in 1989 and have since been monitored continuously for flow, monthly for periphyton cover (assessed visually as percentage cover of filamentous algae and thick mats) and a range of water quality parameters and annually (summer) for benthic invertebrates (Davies-Colley *et al.* 2011). Between these stations, the catchment area increases from 1060 to 2518 km^2, mean flow increases from 51 to 68 $m^3 s^{-1}$ and minimum flow (during 2007–2010) increases from 9 to 14 $m^3 s^{-1}$ (NIWA Hydrometric Database). Part of the flow increase between CH1 and CH2 results from input of water abstracted from the Waiau River.

Current water quality

Comparison of water quality attributes between CH1 and CH2 (see Section I of Supplementary Material for details) shows that it declines downstream of the agriculturally developed Culverden Basin. Nitrate concentrations at CH2 (mean of 370 mg NO_3-N m^{-3}) over the last 5 years were 24-fold higher than at CH1 (NRWQN data) and have increased over the last 20 years (Ballantine and Davies-Colley 2009). Dissolved reactive phosphorus (DRP) increased only 2-fold between CH1 and CH2 (where mean = 3 mg m^{-3}), and both the low concentration and high ratio of dissolved inorganic nitrogen (DIN)/DRP (120) indicate DRP limitation of periphyton growth at CH2. DRP increased at CH2 between 1989 and 2001, when DRP averaged 12 mg m^{-3} during a summer drought. However, DRP declined 35% over the last decade, possibly in response to improved farm management of flood irrigation 'wipeoff' (i.e. overflow discharge into drainage channels).

Periphyton percentage cover, as mats (>3 mm thick) and filamentous algal growths, is typically only slightly higher at CH2 than at CH1, although there was a significant increasing trend in the difference in cover between the sites over time (Quinn and Raaphorst 2009). A period of extended low flows and relatively high DRP in summer (December–April) 2000–2001, coincided with the highest recorder summer average periphyton cover at CH2 (38%) and greatest increase in cover at CH1. However, there have been no significant periphyton blooms (summer average cover <10%) at either site in the last 5 years (NRWQN data, see Fig. 1 in Supplementary Material). Analysis of monthly observations at CH2 during summer indicates a negative relationship between percentage algal cover and flow at the time of observation, and positive correlations with clarity, DIN, accrual period, temperature and DRP when data were lagged by 1 month (i.e. DRP for the previous month correlated with algal cover observations) (see Table I3, Supplementary Material).

The median black disc water clarity (Davies-Colley 1988) of 1.5 m at CH2, downstream of the Culverden Basin over 2005–2010, was lower than at CH1 (2.2 m) and just below the >1.6 m New Zealand guideline for contact recreation (MFE 1994) (see Supplementary Material Section K for details).

The median *E. coli* concentration at CH1 over 2005–2010 was 9 per 100 mL and consistently below the red alert level (>550 per 100 ml^{-1} (MFE/MOH 2003)) but increased to 77 per 100 mL *E. coli* was at CH2 where the red alert level was exceeded on 6% of monthly observations (NRWQN database). A mass balance calculation (assuming no instream die off) indicates that the corresponding median for the Culverden basin tributaries is 350 *E. coli* 100 ml^{-1}, which is in the range of measured medians for four tributaries (125–440 *E. coli* 100 ml^{-1}; Ausseil 2010) (see Supplementary Material Section L for details).

The overall ecological health of rivers is assessed in Environment Canterbury's (ECan) Natural Resources Regional Plan (NRRP) (Environment Canterbury 2011) using the Quantitative Macroinvertebrate Community Index (QMCI; Stark 1993), with a QMCI target of 5 or more (theoretical range 1–10) for the Hurunui. The QMCI was similar at CH1 and CH2 in most summers since 1989 (i.e., in 14 of 21 summers) but was more frequently below 5 at CH2 (10/21) that CH1 (5/21) (see Supplementary Material Section J for details).

Taken together, these measures indicate that, while there is a reduction in water quality and ecological health below agricultural development in the Culverden Basin, the downstream site CH2 still generally meets water quality and ecological guidelines.

Stakeholder engagement, information gathering and BBN development

The present study drew strongly on information developed as part of a Land Use and Water Quality Project (LUWQP), as well as evidence prepared for a Water Conservation Order application for the Hurunui (MFE 2010) from which appellants withdrew in December 2010 to be part of the collaborative LUWQP process. The LUWQP included five catchment stakeholder workshops (Sept 2010–March 2011, involving 11 stakeholder groups), science team workshops and associated research to develop a preferred approach to managing land-use development issues in the Canterbury region (Wedderburn *et al.* 2011). The Project aimed to assess the effects of land use changes on the catchment's groundwater, streams, rivers and their associated ecosystems and links between economic, social and environmental factors. It was designed as a pilot study to support development of a more effective policy framework for establishing limits for nitrate and other contaminants, and management and implementation strategies for improving water quality (Environment Canterbury 2012). The Project involved the Environment Canterbury Regional Council (ECan) working with the primary sector and other stakeholders in a collaborative style to try to ensure workable, science-informed solutions were developed.

At the catchment stakeholder workshops, the project science team solicited stakeholders' views on their values, across the four pillars of sustainability (ecological, economic, social and cultural), and presented information on the current state of a suite of values and potential changes in response to stakeholder-proposed scenarios for irrigation-driven agricultural development in the Culverden Basin, with and without the application of a suite of on-farm mitigations.

BBN structure and mechanics

We selected a range of key values and land development and mitigation scenarios identified in the stakeholder workshops to include in the BBN that covered a suite of socioeconomic and environmental values for which data were available, including environmental targets in the Canterbury NRRP. The overview we developed of the links between these values, proximal drivers and management options is shown in Fig. 2. This overview formed the basis of the BBN. The socioeconomic values were the number of farm jobs, farm cash surplus and contribution of the Culverden Basin to the Regional Gross Domestic Product (Regional GDP). Environmental values included water quality attributes (groundwater average nitrate-N concentration), the proportion of four main Culverden Basin tributaries (Pahua River, Waitohi River, Dry Stream, St Leonards Drain, Fig. 1) meeting the nitrate toxicity threshold for protection of 95% of species (1.7 g NO_3-N m^{-3}) (Hickey and Martin 2009), tributary bathing risk in relation to *E. coli*, the suitability of the mainstem for contact recreation (based on levels of clarity, *E. coli* level and periphyton cover), ecological health of the river based on periphyton cover and QMCI, the natural character of the mainstem and its suitability for wading birds, and the health of the salmon fishery. The BBN includes values at the regional (catchment contribution to regional gross domestic product), catchment (salmon fishery, river natural character, wading birds), and sub-catchment scales (Culverden Basin Nutrient losses, groundwater and tributary average water quality attributes), and at the downstream river monitoring site CH2.

We developed the BBN using the software package NETICA (Norsys 2005). A BBN is a graphical representation of the key factors in a system (nodes) and their conditional dependencies (Reckhow 1999; Stewart-Koster *et al.* 2010; Uusitalo 2007). Arrows connecting 'parent' and 'child' nodes indicate dependencies. The relationships between directly linked nodes are quantified by conditional probability tables (CPTs) that allow estimation of the probabilities of the state of child nodes from those of their parent nodes using Bayes Theorem and the chain rule of probability theory. These 'probabilities' are Bayesian in that they reflect a mixture of understanding and belief about the influence of one state upon another.

BBN node states

The states for decision nodes (rectangles in Fig. 2 and shaded boxes in Fig. 3) were set in relation to management options for water supply, land development and mitigation. The states of nature nodes (ellipses in Fig. 2) were set as one of: (a) ecologically relevant, categorical states, such as true or false statements on whether the node met environmental guidelines or standards (e.g. 'CH2 QMCI >5′ set as whether the Quantitative Macroinvertebrate Community Index complies with the Canterbury NRRP target of >5) and *E. coli* risk categories for safe contact recreation (i.e. green, amber or red alert levels) (MFE/MOH 2003); or (b) the maximum and minimum numeric values predicted by deterministic models (e.g. 'P Loss', 'Farm Jobs').

BBN node relationships

The relationships between the states of parent and child nodes in the CPTs were specified from the literature, evidence of expert witnesses to hearings in 2009 for a Water Conservation

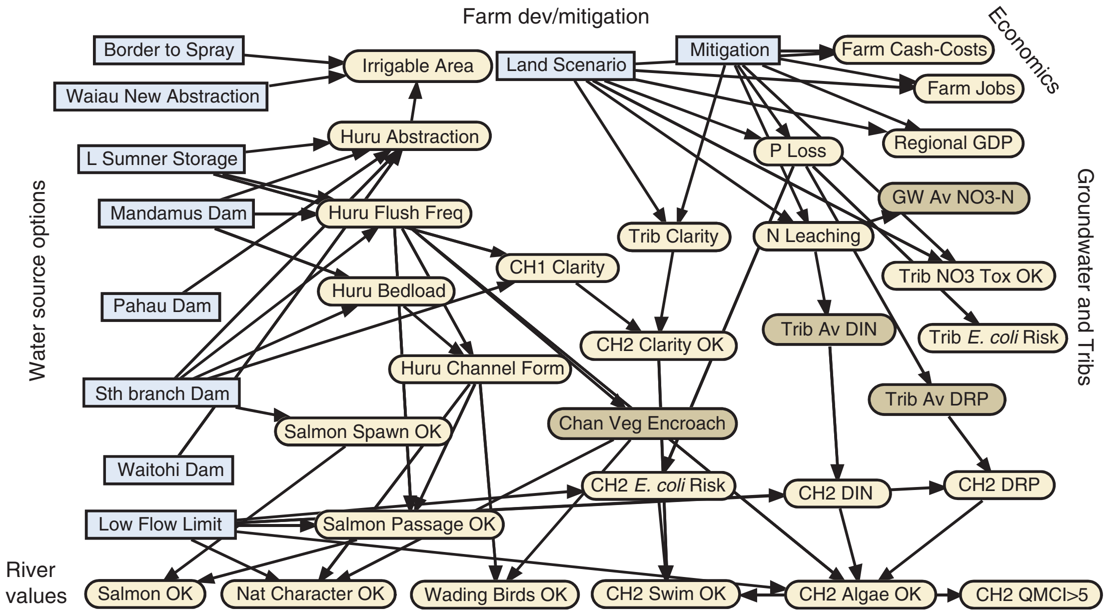

Fig. 2. Conceptual model of linkages between water-source and farm-development options, and stakeholder socioeconomic and environmental values. Rectangles (BN decision nodes) represent management actions and attributes in ellipses (BN nature nodes) respond to changes in actions.

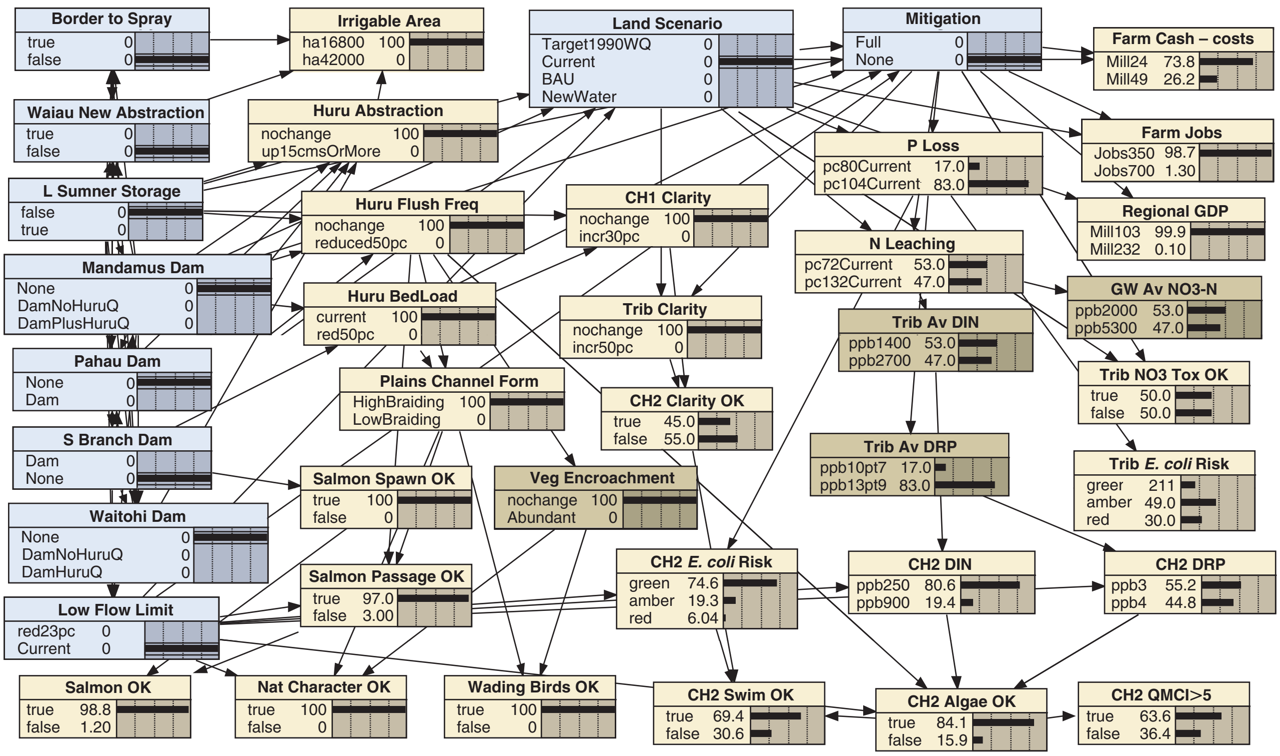

Fig. 3. BBN predictions of the states of network nodes under the Current land scenario. The length of the histogram bars reflect the percentage probabilities (shown) of the node states. 'pc' = percentage; 'ppb' = parts per billion; 'red' = reduced; 'incr' = increased; 'pt' = decimal point (e.g. '10pt7' = 10.7; 'CH1' and 'CH2' are monitoring points upstream and downstream of Culverden Basin (see Fig. 1); 'GW' = groundwater; 'Huru' = Hurunui; 'GDP' = gross domestic product; 'Tox' = toxicity; 'DIN' = dissolved inorganic nitrogen; 'DRP' = dissolved reactive phosphorus; 'CH2 Algae OK' = cross-section mean filament + mat periphyton cover during summer <20%; 'QMCI' = Quantitative Macroinvertebrate Community Index.

Order on the Hurunui River (MFE 2010), model outputs and expert judgement (see Supplementary Material for details). One of the key challenges in the use of BBNs is that environmental and economic parameters often have continuous data distributions, whereas BBN's deal with categories. The usual solution of discretising the data (breaking into several classes) has several drawbacks, including the lack of satisfactory automated discretisation methods, loss of statistical power if the relationship between variables is linear, added model complexity and data requirements (Uusitalo 2007). We applied a simpler approach than discretisation for including nodes within the BBN whose states were informed by discrete numeric outputs from external models and spreadsheets (e.g. 'Huru Abstraction', 'P Loss', 'N Leaching', 'Farm Jobs'). This involved defining two states of such nodes as the maximum and minimum values predicted by the external model. The state probabilities to model predictions for other (intermediate) combinations of the parent node states were then defined using the difference between the predicted values and the maximum and minimum values, and assigning the probabilities for these states, proportionately, by linear interpolation. For example, outputs of the OVERSEER Nutrient Budgets Model (Wheeler *et al.* 2006) in the Nutrient Loss spreadsheet (see Supplementary Material) predicted that combinations of the four 'Land Scenarios' and the application of 'Mitigation' produce annual N leaching rates from 72 per cent to 132 per cent of current leaching; and these minimum and maximum predictions were set at the two states of the BBN node 'N leaching' (Fig. 3). Table F6 of the Supplementary Material shows the N leaching predictions of the Nutrient Loss spreadsheet for all parent state combinations and the translation of these into state probabilities in the BBN.

The left side of the BBN (Figs 2 and 3) has decision nodes for irrigation water source or storage, their effects on the additional land area that can be irrigated and river physical (e.g. bedload) and biological (e.g. salmon access to spawning areas) characteristics. The water source options determine the irrigable area and this constrains the options in the Land Scenario decision node but this link was not built into the model (i.e. no arrow links 'Irrigable Area' and 'Land Scenario') because Land Scenario is a decision node, not a nature node and treating it as a nature node caused problems elsewhere in the model in some circumstances. Instead the user needs to match the 'Land Scenario' decisions with water source options that produce the appropriate 'Irrigable Area'. Appropriate states of 'Land Scenario' and 'Mitigation' then predict the consequences for the states of the economic nodes, the water quality of groundwater and tributaries, and, in combination with the physical effects of the water source options, Hurunui River values.

Land-use Scenarios

We examined the effects of four land-use scenarios developed by the stakeholder workshops:

(i) Maintaining Current State (with 16 800 ha of irrigation);
(ii) Achieving 1990–1995 Water Quality (Target 1990 WQ) – this required ~10% reduction in phosphorus in the Hurunui mainstem and 20% reduction in nitrogen in the Culverden Basin tributaries. A range of land-use/irrigation/mitigation combinations could achieve this target. The combination selected for modelling (involving increases in dairy, forestry and arable land use, and reduced sheep and beef land use; for details see Table F1 in Supplementary Material) was selected by optimising farm cash surplus for the catchment within given nutrient targets using a constrained trial and error approach. The key constraint was ensuring that some mix of sheep and beef, arable and dairy was retained in the catchment combination to achieve this and allow some intensification.
(iii) Business as usual (BAU) – allows for an increase in farm productivity through intensification in line with historic trends, and an increase in irrigation associated with existing water availability and efficiency gains (for details see Table F1 in Supplementary Material).
(iv) New Water – allowing full irrigation to a total of 42 000 ha in the Culverden Basin. This involved increases in the areas of dairy, arable and horticultural land use and corresponding reductions in the area of forestry and sheep and beef land uses (for details see table F1 in Supplementary Material).

Irrigation water sources and effects

Increases in irrigated area to support the land development scenarios could be supported, to varying degrees, by irrigation water provided by efficiency gains (converting border dyke to spray irrigation), increased abstraction from the Waiau River (Fig. 1) and several options for water abstraction and storage within the Hurunui catchment (Fig. 2). The Canterbury Water Management Strategy (Morgan *et al.* 2010) was used to calculate: (i) the water volumes that could be supplied by each of these options; (ii) effects on the peak abstraction from the Hurunui; and (iii) the potential additional irrigated area. Details are provided in Table A1–A3 of the Supplementary Material. The different water source options vary in their likely impacts on the Hurunui River's geomorphic character, flow variability and ecological values. Information on these effects was drawn from the a variety of sources to develop CPT's for effects on salmon, wading birds and natural character, as detailed in sections C, D and E of the Supplementary Material, respectively.

On farm/riparian mitigation of land use effects

The scope for on-farm mitigations to influence the effects of land development on annual nitrogen and phosphorus losses under the scenarios was investigated by applying the scenarios with and without inclusion of reductions in loading through application of a suite of on-farm mitigation tools. The mitigations were: use of nitrification inhibitors to reduce nitrate leaching from grazed pastures (Di *et al.* 2010); changing the remaining border dyke irrigation to spray irrigation; the use of Herd Shelters for standing-off dairy cows during winter and autumn (particularly for farms on shallow soil types); riparian fencing to exclude livestock; larger effluent storage facilities for dairy farms located on poorly draining soil types; and installing wetlands where landscape features allow. These tools were applied to five model farms defined to represent the combinations of land use (dairy or sheep–beef) and soil types (deep, moderately deep and shallow) found within the catchment. These model farms were defined based upon detailed surveys of a limited number of farms in the Culverden Basin and from expert opinion from various extension specialists and agribusiness consultants. Where relevant, estimates of the effects of mitigation measures on farm economic performance were simulated using the Farmax DairyPro and FarmaxPro (www.farmax.co.nz) (sheep and beef) models (Bryant *et al.* 2010; White *et al.* 2010). These models assessed the feasibility of the systems and the interactions between feed supply and production. Data from the Farmax (AgResearch, www.overseer.org.nz) models and farm survey information were then used in the OVERSEER (AgResearch) Nutrient Budgeting model (Wheeler *et al.* 2006) to give an estimate of the N and P losses from the model farms within the catchment.

Economic effects on land use and mitigation

The effects of land and mitigation scenarios on three key socioeconomic indicators: (i) Farm Cash Surplus predicted by the farm model after allowing for annual capital costs of transition to irrigated agriculture (sourced from the Canterbury Water Management Strategy, pers. comm. Stuart Ford, Agribusiness Group, Christchurch); (ii) on-farm employment (job numbers); and (iii) contribution of agriculture in the Culverden Basin to the Canterbury Regional gross domestic product (from a regional input–output model, described by Butcher (2010)). The transition costs to irrigated agriculture were principally on- and off-farm costs of irrigation water supply and farm-system capital costs. Further details are provided in Supplementary Material Section H.

Groundwater nitrate and surface water nutrient effects

The changes in nitrate leaching losses predicted by the farm model for the four scenarios, with and without the suite of mitigations, were fed into an existing groundwater model for the Culverden Basin aquifer to calculate the resulting steady-state nitrate–nitrogen concentrations in the groundwater and tributary streams (Lilburne *et al.* 2011). The basis of this model was an account of steady-state mass flows of water and nitrate-N in the Culverden Basin. Nitrate-N flows included import by streams and rivers, and leaching from land within the basin. Water flow accounting allowed for river losses to and gains from groundwater, as well as the soil-water drainage that transports nitrate-N leachate into groundwater from the land in the basin. This model of combined nitrate-N and water mass flows provides estimates of nitrate concentration for groundwater and surface waters. Further details are provided in Section G of the Supplementary Material.

The effects of land and mitigation scenarios on the Culverden Basin tributaries' current average flow weighted dissolved reactive phosphorus (DRP) of 13.4 mg/m^3 (Ausseil 2010) was assumed to be proportional to change in total phosphorus load predicted by the farm nutrient model (see Supplementary Material, Section G, for details).

The flow-on effects of scenarios on DRP and DIN in the Hurunui at CH2 downstream of Culverden basin inputs (Fig. 2) were calculated by simple mass conservation calculations for the 50 percentile river flow and average current concentrations for CH1 above the Culverden Basin (Fig. 1) and predicted concentrations and flows in the Basin tributary inflows (see Supplementary Material, Section I2, for details).

Periphyton and invertebrate community effects

The CPT describing the influences of flushing-flow frequency and concentrations of DRP and DIN on the BBN node 'CH2 algae OK' ('true' if meets the ECan Natural Resources Regional Plan (NRRP) target of $<$20% filamentous cover) was developed after examination of monthly cover observations since 1989 and associated flows and nutrient concentrations (see Supplementary Material, Section I3, for details). NRWQN monitoring data at CH1 and CH2 from 1989 also provided the basis for the developing the relationships between algal cover and the Macroinvertebrate Community Index (MCI) at CH2 (see Supplementary Material, Section J, for details).

Pathogen risk effects

The current distributions of concentrations of the pathogen indicator organism, *E. coli*, among the Ministry for the Environment (MFE) green, amber and red alert level classes (MFE/MOH 2003) were derived from monitoring data from the Culverden Basin tributaries (Ausseil 2010) and the Hurunui sites CH1 and CH2 (NRWQN, National Institute for Water and Atmospheric Research (NIWA) , unpubl. data). To estimate the effects of land and mitigation scenarios, we assumed that the current *E. coli* concentrations would change in proportion to the changes in phosphorus load (that mainly follows similar surface transport pathways) predicted by the farm models. Hence these predictions should be treated as indicative only. Details are provided in Section L of the Supplementary Material.

Water clarity effects

We assumed that the current levels of water clarity upstream at CH1 (see above) would increase with the installation of upstream water storage impoundments and that land-use change and mitigation scenarios would alter the existing clarity of the Culverden Basin Tributaries in proportion to their predicted effects on P Loss. Clarity downstream at CH2 was assumed to be a function of the background clarity at CH1, the clarity of tributary inflows and the flow limit, which influences the dilution of tributary inflows by clearer upstream water. Details are provided in Section K of the Supplementary Material.

Effects on suitability for swimming

The suitability of the Hurunui mainstem for swimming downstream of the Culverden Basin inflows (at CH2) was predicted as a function of *E. coli*, periphytic algal cover and water clarity, based on national guidelines for these individual attributes but weighted to emphasise effects of *E. coli* $>$ algal cover $>$ water clarity. Details are provided in Section M of the Supplementary Material.

Results

The BBN predictions for the current situation, with no new irrigation development or mitigations in place, are shown in Fig. 3. The predicted state of each of node is shown by the relative length of the histogram bars representing the state probabilities (as also listed on the left of the node boxes). For nodes based on predictions of deterministic models, the relative lengths of the histogram bars reflect these predictions relative to the maximum and minimum states. For example, if the state of

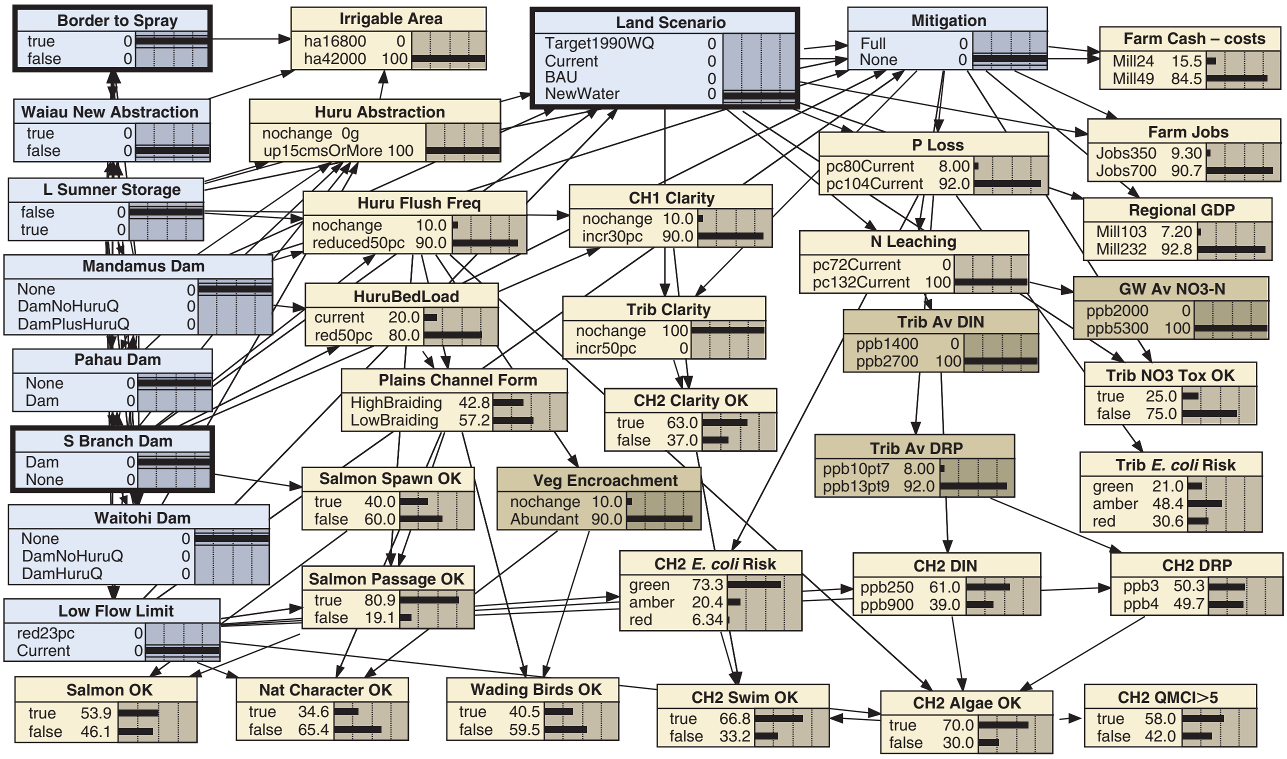

Fig. 4. BBN predictions of the states of network nodes when water sourced from a dam on the South Branch and border to spray conversions support the New Water Land scenario (full development of irrigable area) without on-farm mitigations. See Fig. 3 caption for abbreviation codes. Decision nodes bounded by bold boxes indicate changes from the current state.

'Land Scenario' is 'Current' and the state of 'Mitigation' is 'None', there are just over 350 farm jobs in the catchment area and 'P loss' is just below the maximum predicted by the farm model of 104% of current (Fig. 3). For nature nodes with categorical, true or false, states or *E. coli* alert classes, the bars represent the state Bayesian probabilities as used conventionally in BBNs. For example, under the current situation (Fig. 3), the combined output of the farm and groundwater models predicts that half of the tributary streams will have average nitrate-N concentrations in excess of the 1.7 mg L^{-1} toxicity guideline, so the node 'Trib NO_3 Tox OK' has a 50/50 probability of being 'true' or 'false' (see Supplementary Information for further details). Overall, the BBN for the current situation predicts relatively low levels of the economic indicators ('Farm Cash-costs', 'Farm Jobs', and 'Regional GDP'), moderately degraded groundwater and tributary water quality and Hurunui mainstem values (nodes in lower line of BBN) in generally good condition (Fig. 3).

Fig. 4 shows the BBN predictions for a development scenario involving a water storage dam on the South Branch and conversion of all remaining border irrigated land to spray irrigation to enable increasing the irrigated area from 16 800 to 42 000 ha without application of on-farm mitigations. The BBN predicts this would have substantial economic benefits (increasing 'Farm Cash-costs' by 50%, 'Farm Jobs' by 90% and contribution to 'Regional GDP' by 115%), but would degrade several environmental values (Fig. 4). The latter include: (i) raising average groundwater nitrate to half of the drinking water standard; (ii) increasing the proportion of tributaries that exceed the nitrate toxicity standard from the current 50% to 75%; (iii) doubling the current likelihood that algal cover at CH2 (below the Culverden Basin drainage) exceeds the guideline during summer (via effects of increased nutrients and reduced flushing flows); (iv) degrading the salmon fishery (probability that 'Salmon OK' is 'true' drops from 99% to 54%; due to loss of spawning area; and (v) wading birds (probability 'Wading birds OK' is 'True' drops from 100% to 40%) due to effects on channel form and vegetation encroachment.

Including a 23% reduction in the allowable 'Low Flow Limit' in the above scenario is predicted to further degrade the mainstem environmental values (Fig. 5). This would reduce the flow of cleaner upstream water available to dilute the diffuse load of contaminants in the Culverden Basin tributary inflows to the Hurunui, and is predicted to increase the downstream (at CH2) probability of undesirable levels of periphyton cover and *E. coli*, with consequent degradation of suitability for swimming and QMCI. Lower flow is also predicted to degrade the mainstem river's natural character and salmon marginally, through effects on upstream salmon passage for spawning (Fig. 5).

In contrast to the above scenario, the BBN predicts similar or better-than-current environmental values, while retaining most of the economic benefits (albeit with smaller increase in farm cash-costs), when irrigation is increased to 42 000 ha with application of the suite of on-farm mitigation measures and using water sourced from converting remaining areas of border

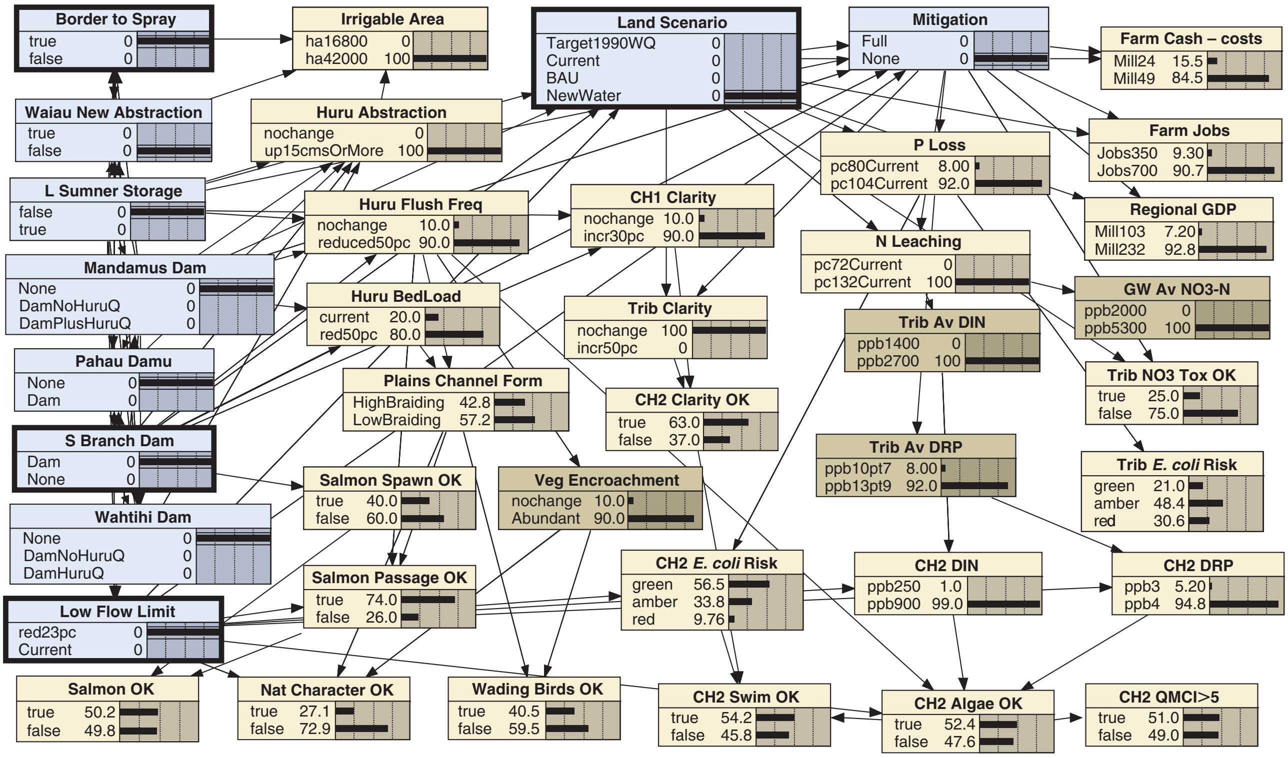

Fig. 5. BBN predictions of the states of network nodes with conditions as in Fig. 4 but with a reduced low flow limit. See Fig. 3 caption for abbreviation codes. Decision nodes bounded by bold boxes indicate changes from the current state.

irrigation to spray irrigation and from high-flow abstraction from the Hurunui mainstem and the Waitohi River stored in a dam on the Waitohi (Fig. 6). The application of on-farm mitigation and conversion from border to spray irrigation is predicted to result in lower farm nutrient losses, lower groundwater nitrate contamination and fewer tributaries exceeding the nitrate toxicity guideline than under the current scenario, despite the new irrigation development. A storage dam on the Waitohi, rather than the South Branch, is predicted to have minimal effect on the mainstem bedload, flushing flows and salmon access to spawning areas, and therefore has no effect on salmon, natural character and wading birds in the mainstem Hurunui (Fig. 6).

Stakeholders also sought advice on the effects of a scenario that would produce water quality in the tributaries and the mainstem at CH2 similar to that of the early 1990s but allow some irrigation development with on-farm mitigation. This ‘Target 1990 WQ’ scenario involved targeting 10% lower P in the mainstem and 20% lower nitrate in the tributaries. This could be achieved by increasing the irrigated area by 8200 ha (total to 25 000 ha) with the application of on-farm mitigations and using water sourced from Lake Sumner (within its natural level range), and efficiency gains from converting remaining areas of border irrigation to spray irrigation. The BBN predicts this scenario (Fig. 7) improves on the current water quality of the groundwater, tributaries and mainstem at CH2, has very minor effects on salmon, birds and natural character, and produces small increases in Farm Jobs (+12%). Although there is predicted to be a moderate increase in Regional GDP contribution (+30%), the costs of development and mitigation result in a 21% reduction in operating profit (‘Farm Cash – Costs’).

The business as usual (BAU) scenario (Fig. 8), involving continuation of existing trends of increased livestock density using irrigation water provided by converting relatively water inefficient border irrigation to spray irrigation and without application of mitigation, was predicted to increase the irrigated area to 19 000 ha. Despite the increase in intensive agriculture, the Farms model predicts this would result in a minor (2%) increase over the current N leaching but 1% less P loss due to less runoff from border irrigation; the BBN consequently predicts little change in nutrient concentrations and algal cover (Fig. 8). Furthermore, this scenario does not include changes to water storage or abstraction. Consequently, the BBN predicts very minor environmental effects. Nevertheless, the continued intensification is predicted to increase ‘Farm Cash – Costs’ by 59%, ‘Farm Jobs’ by 46% and contribution to regional GDP by 45% (Fig. 8).

The BBN predictions for the above scenarios are summarised in Fig. 9. This presentation lacks the information on the mechanisms of scenario effects provided in the BBN outputs for individual scenarios (Figs 3–8) but provides a useful overview for easy comparison of scenario effects on key values. It highlights that the choice of water source for new irrigation is predicted to have strong effects on the mainstem river values (e.g. state probabilities of ‘Salmon OK’ and ‘Wading Birds OK’ differ markedly for dams in the Waitohi and the South Branch) whereas the economic, groundwater and tributary values are

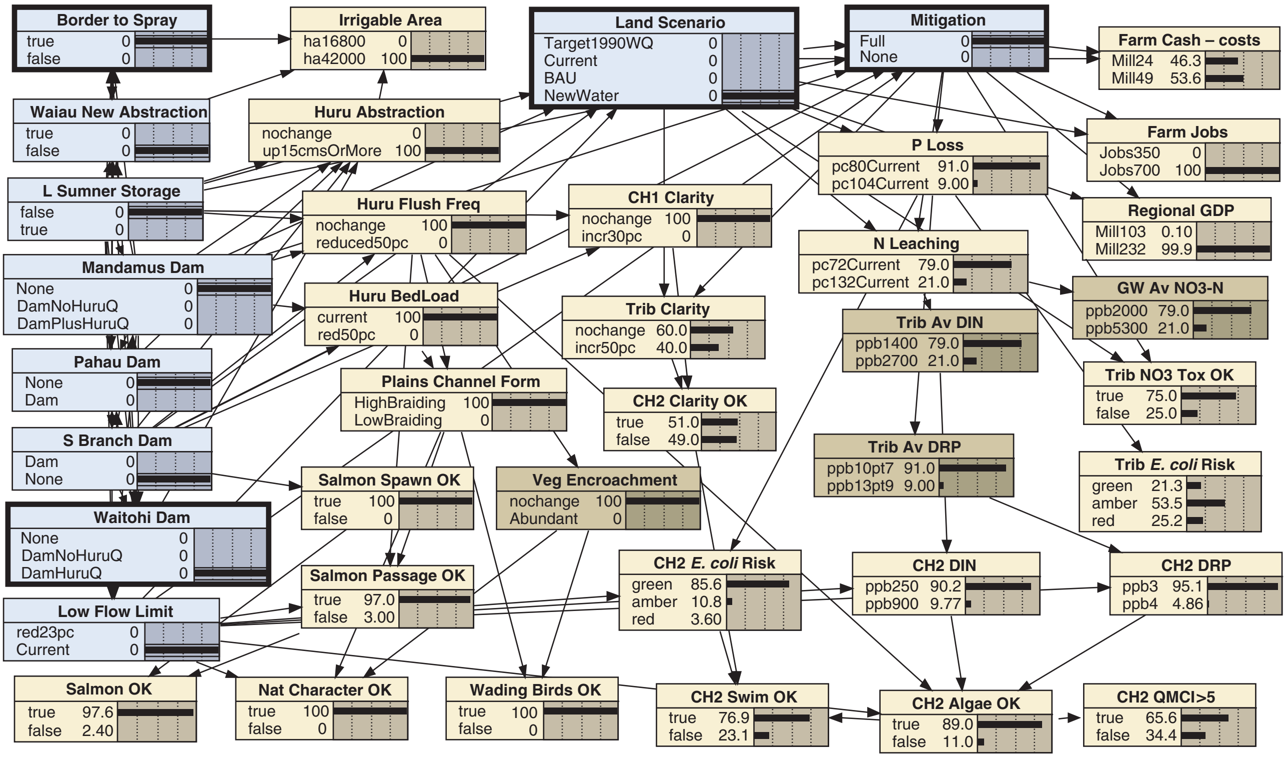

Fig. 6. BBN predictions of the states of network nodes when water sourced from a dam on the Waitohi (supplemented by abstraction from the Hurunui during high flows) and border to spray conversions support the New Water Land scenario (full development of irrigable area) with on-farm mitigations. See Fig. 3 caption for abbreviation codes. Decision nodes bounded by bold boxes indicate changes from the current state.

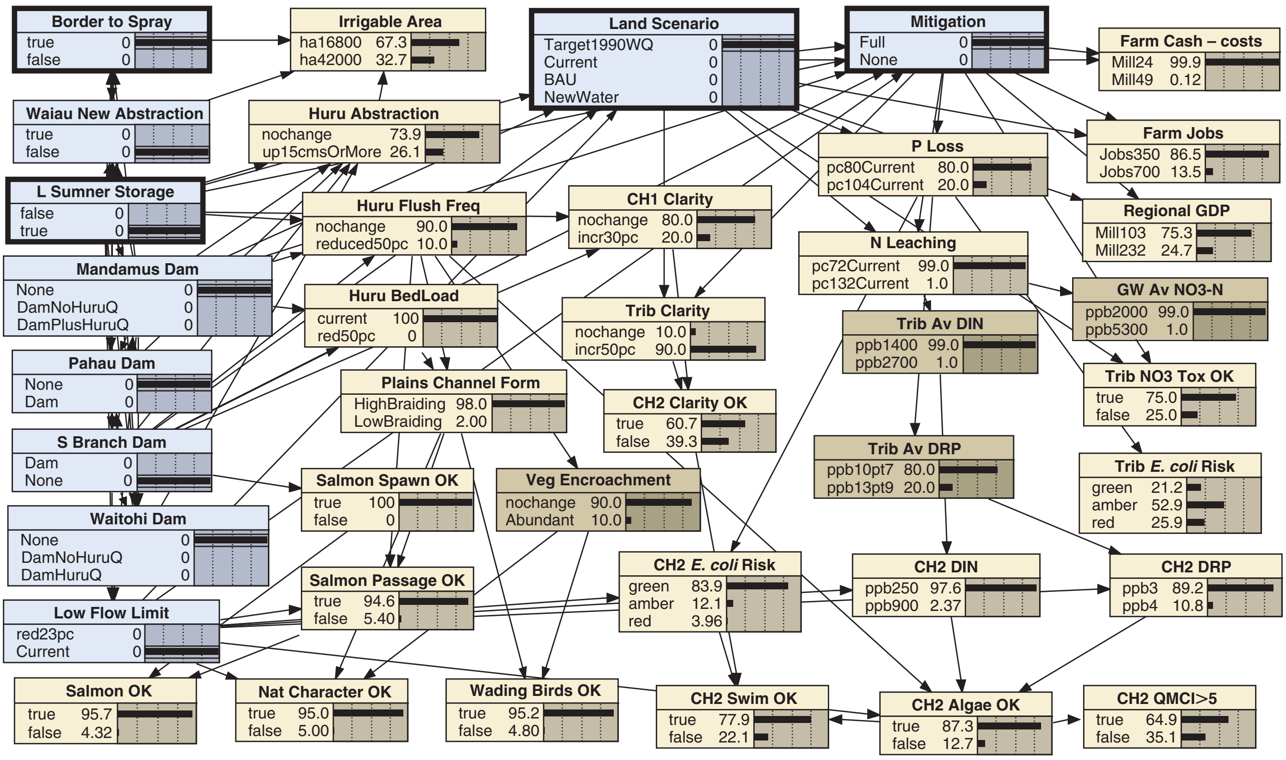

Fig. 7. BBN predictions of the states of network nodes under 'Target 1990's WQ' scenario, involving water storage in Lake Sumner and border to spray conversions and on-farm mitigations. See Fig. 3 caption for abbreviation codes. Decision nodes bounded by bold boxes indicate changes from the current state.

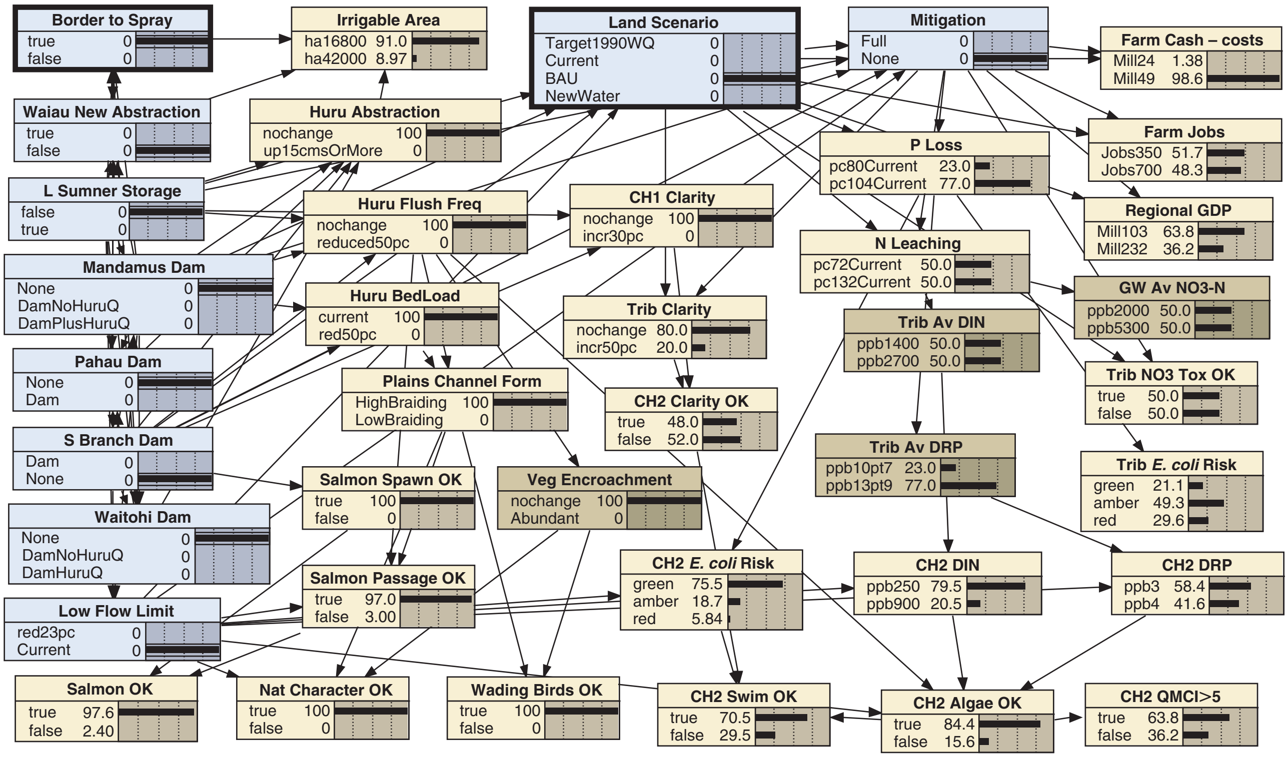

Fig. 8. BBN predictions of the states of network nodes under 'Business as Usual' scenario, involving border to spray conversions continuation of current trends of farm intensification. See Fig. 3 caption for abbreviation codes. Decision nodes bounded by bold boxes indicate changes from the current state.

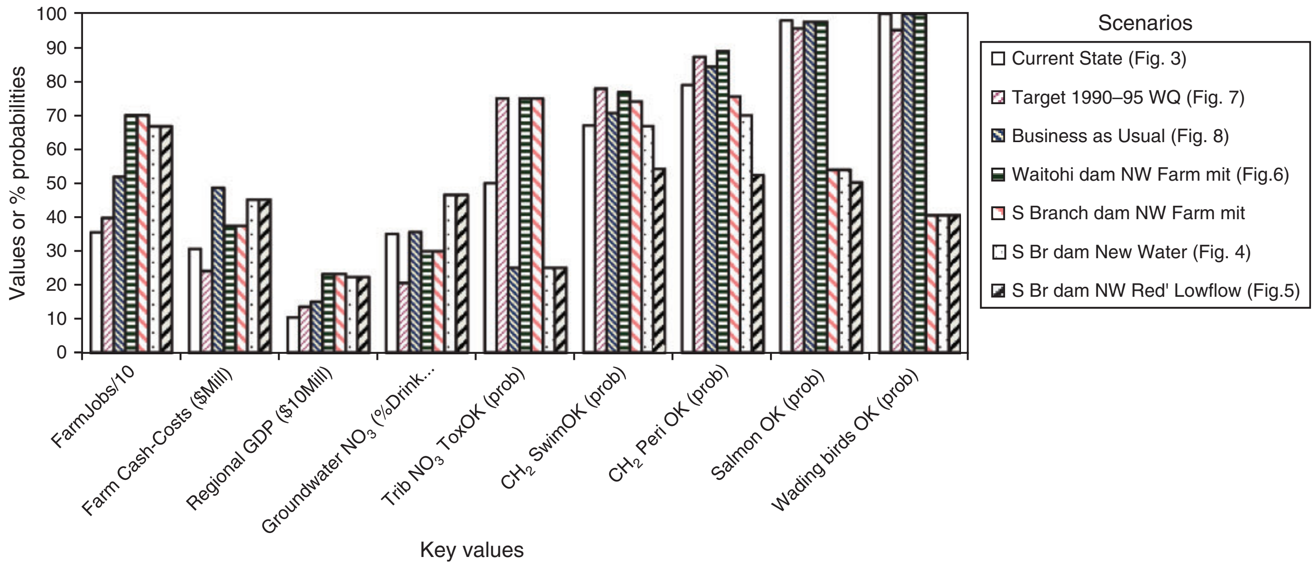

Fig. 9. Summary of BBN predictions for selected scenarios. Note all scenarios, except 'Current', involve conversion of remaining border irrigation to spray. NW = 'New water', see Fig. 3 caption for other abbreviation codes.

predicted to be most responsive to the land-development scenario and application of the suite of on-farm mitigations (Fig. 9).

Discussion

The increased emphasis over the last two decades on integrated catchment management and stakeholder participation in diffuse pollution control and planning have heightened the need for tools to summarise scientific knowledge on the interactions between catchment management options and values (Liu *et al.* 2008). Sustainable management of catchments frequently involves complex trade-offs among diverse societal values that resource management agencies and stakeholders often struggle to conceptualise, integrate and resolve (Bernhardt *et al.* 2006; Falkenmark *et al.* 2004; Jöborn 2005; Stewart-Koster *et al.* 2010). The present study provides support for the use of BBNs as a tool for this integration and decision support.

The conceptualisation of the catchment system is a key step in developing an integrated model to support stakeholder deliberations and decision making (e.g. Kragt *et al.* 2011; Liu *et al.* 2008). We contend that the use of stakeholder-derived values as endpoints in the conceptual model enhances the relevance of the model and the use of scientific and economic information to address stakeholders' concerns. Our conceptual model of the links between irrigation-driven intensification and catchment values in the Hurunui (Fig. 2) provided a summary of complex information that enhanced holistic thinking and acted a stepping stone to the development and use of the more detailed BBN.

The BBN predicted a wide range of states in many values depending on choices on the source of the irrigation water, the low-flow limit, and adoption of a suite of on-farm mitigation practices to reduce contaminant losses. It highlighted where decisions on these management aspects are likely to produce both value clashes (e.g. between a range of environmental values and some socioeconomic values for full irrigation development without mitigation, Fig. 4) and the opportunities for less severe trade-offs and potential win–win outcomes (e.g. Fig. 5). A strength of the BBN is that it links the effects on key values of water-storage infrastructure and abstraction on sediment and flow regimes with the consequences of agricultural intensification on diffuse source pollution. This approach encourages and assists catchment managers and stakeholders to consider multiple stressors, combinations of management actions and their effects on diverse values in a transparent framework.

It is widely recognised that interdisciplinary approaches are needed to resolve many environmental management challenges and forecast future environmental conditions (Jakeman and Letcher 2003; Jöborn 2005; Nilsson *et al.* 2005). The broad scope of the BBN not only necessitates an interdisciplinary approach, but also presents a framework for bringing together diverse models and information sources into a management tool. The Hurunui BBN development was enhanced through input from a diverse science team involved in the Hurunui LUWQP, and access to a large body of information on the state of the river from the national and regional monitoring databases, and evidence on key values from statements of evidence by expert witnesses to recent hearings for the Hurunui Water Conservation Order. In a less information-rich setting, BBN development would need to rely more on general economic and ecological theory, and formal solicitation of expert opinion (Shenton *et al.* 2011).

There is scope for extending the Hurunui BBN by adding further values and refining the underlying models that it draws on. For example, the present BBN applies a uniform (average) cost per hectare of irrigation developed for all the water source options. This aspect could be refined by estimating the costs of individual water source options and linking these to the 'Farm cash – Costs' value. Another area with potential for refinement relates to on-farm mitigations. The present Hurunui BBN investigates the *scope* for reduction in farm-contaminant losses using a *suite* of on-farm mitigations, but this could be refined, if necessary, to investigate the relative effectiveness of individual mitigation actions (e.g. Quinn *et al.* 2010). Such refinements can be added to the BBN as information becomes available and if a deeper understanding of issues becomes important for stakeholder deliberation and decision making. A strength of BBNs is that they can be developed at a range of levels of detail and can evolve to keep them 'fit-for-purpose/useful' as the needs of stakeholder and decision makers change. Another advantage of BBNs is that the underlying assumptions are made explicit in the graphical model output and details are accessible in the CPTs, as shown in the Supplementary Material associated with the present study. This encourages peer review of assumptions, group learning and model transparency.

The BBN user needs to be aware that it includes processes that respond to management decisions at a range of time scales. For example, the geomorphic responses of channel form in the braided plains sections of the Hurunui to a dam on the South Branch are likely to play out over decades to centuries (Petts 1984), whereas the response of river periphyton cover to changes in nutrient concentrations and flow regime are expected to occur in month–year time scales (Biggs and Close 1989). This difficulty of explicitly handling the effects of time is a general limitation of BBNs that could be addressed, if deemed necessary by users, by replicating the BBN structure for different time-steps after management intervention (Hart and Pollino 2009).

BBNs are particularly powerful tools for collective learning around complex issues when scenarios are updated live in meetings so that users can explore a wide range of 'what if' questions and immediately see both the predicted changes in probabilities of state of their values and the mechanisms driving change that are included higher up in the BBN (as shown in Figs 3–8). However, for summary purposes, it is also useful to collate and compare the responses of stakeholder values under key scenarios for easy and direct comparison of outcomes. These two approaches to display are complementary and each has its place in different phases of catchment management deliberation and decision making.

Linking BBN development to stakeholder deliberations over a short timeframe can be challenging because of the time required for stakeholder values to be clarified, scenarios defined and analysed (including supporting models), and for complex system information to be analysed to develop the BBN CPTs. The Hurunui BBN was completed within the 7 months of the stakeholder workshops in LUWQ Project but was not presented directly to the full stakeholder group. Nevertheless, it was presented at formal and informal meetings with stakeholder representatives, planners and researchers supporting the project, and was one of the intersecting lines of information that informed the selection of objectives and targets in the recommendations from the LUWQP for managing irrigation-driven land development in the Hurunui (Brown *et al.* 2011). These recommendations included targets of maintaining current (2005–2009) water quality in the mainstem downstream of the Culverden Basin at CH2 and improving tributary water quality to that of the 1990–1995 period (Brown *et al.* 2011). To achieve this, it was recommended that irrigation expansion occurs in an adaptive management context, with staged development (probably commencing with irrigation based on water efficiency gains using existing water and potentially one of the smaller storage sites or the Waiau River), application of the most cost-effective on-farm mitigations (use of nitrification inhibitors and off-paddock animal wintering) and monitoring to check water quality targets are being maintained (Brown *et al.* 2011).

The LUWQP recommendations (Brown *et al.* 2011) have been taken forward by the Hurunui-Waiau Zone Committee (established under the Canterbury Water Management Strategy) for inclusion in the Hurunui and Waiau Proposed River Regional Plan (HWPRRP, a statutory document prepared under the *Resource Management Act 1991*) (ECan 2011). This next phase includes decisions on the water source(s) for future stages of irrigation development that may proceed. Notably, the HWPRRP states that the Waitohi River is the preferred location for major water-storage infrastructure development in the Hurunui catchment and that the South Branch of the Hurunui and Lake Sumner only be considered for this purpose if the Waitohi, and then other Hurunui tributaries, were determined to not be viable. This preference for the Waitohi over the South Branch of the Hurunui is consistent with the BBN predictions for maintaining a wide range of stakeholder values. The BBN provides a tool for further exploration by the Hurunui-Waiau Zone Committee of how different water source options interact with nutrient losses and land-management mitigations to influence a wide range of catchment social, economic and ecological values.

In conclusion, the present study demonstrates how a BBN can address the effects of complex environmental decisions on a diverse range of stakeholder values and thus assist to bridge the gap between management, biophysical science and economics. Development of such synthesis tools requires interdisciplinary and stakeholder collaboration, and has the potential to accelerate resolution of complex environmental management challenges to achieve sustainable development.

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References

Allan, J. D. (2004). Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics* **35**, 257–284. doi:10.1146/ANNUREV.ECOLSYS.35.120202.110122

Ausseil, O. (2010). Hurunui River – Influence of the middle reaches on water quality of the Lower Hurunui River (2005–2008). Environment Canterbury Report No. R08/55, Christchurch.

Ballantine, D. J., and Davies-Colley, R. J. (2009). Water quality trends at the NRWQN sites for the period 1989–2007. NIWA, Client Report HAM2009–026, Hamilton.

Bernhardt, E., Bunn, S. E., Hart, D. D., Malmqvist, B., Muotka, T., Naiman, R. J., Pringle, C., Reuss, M., and van Wilgen, B. (2006). Perspective: The challenge of ecologically sustainable water management. *Water Policy* **8**, 475–479. doi:10.2166/WP.2006.057

Biggs, B. J. F., and Close, M. E. (1989). Periphyton biomass dynamics in gravel bed rivers: the relative effects of flows and nutrients. *Freshwater Biology* **22**, 209–231. doi:10.1111/J.1365-2427.1989.TB01096.X

Brown, I., Norton, N., Wedderburn, L., Monaghan, R. M., Harris, S., Hayward, S., and Ford, R. (2011). Nutrient management in Hurunui: A case study in identifying options and opportunities, Environment Canterbury Report No. R11/114, Christchurch.

Bryant, J. R., Ogle, G. I., Marshall, P. R., Glassey, C. B., Lancaster, J. A. S., Garcia, S. C., and Holmes, C. W. (2010). Description and evaluation of the Farmax Dairy Pro decision support model. *New Zealand Journal of Agricultural Research* **53**, 13–28. doi:10.1080/00288231003606054

Butcher, G. (2010). Regional economic impacts and cost benefit analysis of the proposed Hurunui Irrigation Scheme. Butcher Partners and The Agibusiness Group, Christchurch.

Davies-Colley, R. J. (1988). Measuring water clarity with a black disc. *Limnology and Oceanography* **33**, 616–623. doi:10.4319/LO.1988.33.4.0616

Davies-Colley, R. J., Smith, D. G., Ward, R., Bryers, G. G., McBride, G. B., Quinn, J. M., and Scarsbrook, M. R. (2011). Twenty Years of New Zealand's National Rivers Water Quality Network: a Review. *Journal of the American Water Resources Association* **47**, 750–771. doi:10.1111/J.1752-1688.2011.00554.X

DeFries, R. S., Foley, J. A., and Asner, G. P. (2004). Land-use choices: balancing human needs and ecosystem function. *Frontiers in Ecology and the Environment* **2**, 249–257. doi:10.1890/1540-9295(2004)002[0249:LCBHNA]2.0.CO;2

Di, H. J., Cameron, K. C., and Sherlock, R. R. (2010). Comparison of the effectiveness of a nitrification inhibitor, dicyandiamide, in reducing nitrous oxide emissions in four different soils under different climatic and management conditions. *Soil Use and Management* **23**, 1–9. doi:10.1111/J.1475-2743.2006.00057.X

Doak, M. 2005. Value of irrigation in New Zealand. In 'OECD Workshop on agriculture and water: sustainability, markets and policies', 14–18 November 2005, Adelaide, Australia.

Doll, P. (2002). Impact of climate change and variability on irrigation requirements: a global perspective. *Climatic Change* **54**, 269–293. doi:10.1023/A:1016124032231

ECan (2011). Proposed Hurunui and Waiau River Regional Plan Prepared under the Resource Management Act 1991. Environment Canterbury Regional Council, Christchurch.

Environment Canterbury (2011).Water Quality. In 'Canterbury Natural Resources Regional Plan'. (Environment Canterbury Regional Council: Christchurch.) Available at http://ecan.govt.nz/publications/Plans/nrrp-chapter-4-operative-110611.pdf

Environment Canterbury (2012). The preferred approach for managing cumulative effects of land use on water quality in the Canterbury Region: A working paper. Environment Canterbury, Christchurch.

Falkenmark, M., Gottschalk, L., Lunqvist, J., and Wouters, P. (2004). Towards integrated catchment management: increasing the dialogue between scientists, policy-makers and stakeholders. *International Journal of Water Resources Development* **20**, 297–309. doi:10.1080/0790062042000248619

Friedl, G., and Wuest, A. (2002). Disrupting biogeochemical cycles – Consequences of damming. *Aquatic Sciences* **64**, 55–65. doi:10.1007/S00027-002-8054-0

Hamill, K. D., and McBride, G. B. (2003). River water quality trends and increased dairying in Southland. *New Zealand Journal of Marine and Freshwater Research* **37**, 323–332. doi:10.1080/00288330.2003.9517170

Hart, B. T., and Pollino, C. A. (2009). Bayesian modelling for risk-based environmental water allocation. Waterlines Report Series No. 14, Water Science Pty Ltd and the Australian National University, Canberra.

Hickey, C. W., and Martin, M. L. (2009). A review of nitrate toxicity to freshwater aquatic species. Report No. R09/57, Environment Canterbury, Christchurch.

Hicks, D. M. (2010). River sediment transport and geomorphology: Draft Statement of evidence of Darryl Murray Hicks on behalf of Environment Canterbury In the matter of the Resource Management Act 1991 And in the matter of an application for a Water Conservation Order pursuant to Section 201 of the Act, and in the matter of the proposed National Water Conservation (Hurunui) Order Application. pp. 50.

Hume, T. M., Snelder, T., Weatherhead, M., and Liefting, R. (2007). A controlling factor approach to estuary classification. *Ocean and Coastal Management* **50**, 905–929. doi:10.1016/J.OCECOAMAN.2007.05.009

Jakeman, A. J., and Letcher, R. A. (2003). Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling & Software* **18**, 491–501. doi:10.1016/S1364-8152(03)00024-0

Jöborn, A. (2005). Summing Up: A 10-y Interdisciplinary Research Venture on Sustainable Water Management. *Ambio* **34**, 270–271.

Kragt, M. E., Newham, L. T. H., Bennett, J., and Jakeman, A. J. (2011). An integrated approach to linking economic valuation and catchment modelling. *Environmental Modelling & Software* **26**, 92–102. doi:10.1016/J.ENVSOFT.2010.04.002

Lilburne, L., Elliott, S., Bidwell, V., Shankar, U., Kelly, D., and Hanson, C. (2011). Hurunui catchment scale land use and water quality modelling report. Technical Report No. R11/15, Environment Canterbury, Christchurch.

Liu, Y., Gupta, H., Springer, E., and Wagener, T. (2008). Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modelling & Software* **23**, 846–858. doi:10.1016/J.ENVSOFT.2007.10.007

McDowell, R. W., van der Weerden, T. J., and Campbell, J. (2011). Nutrient losses associated with irrigation, intensification and management of land use: A study of large scale irrigation in North Otago, New Zealand. *Agricultural Water Management* **98**, 877–885. doi:10.1016/J.AGWAT.2010.12.014

MFE (1994). Water quality guidelines No. 2: Guidelines for the management of water colour and clarity. (Ministry for the Environment: Wellington.)

MFE (2010). 'Application for a Water Conservation Order on the Hurunui River'. Available from: http://www.mfe.govt.nz/issues/water/freshwater/water-conservation/application-water-conservation.html. [Accessed on 12 April 2012]

MFE/MOH (2003). Microbial water quality guidelines for marine and freshwater recreation areas, Ministry of Environment and Ministry of Health, Wellington, 159 pp.

Monaghan, R. M., Carey, P. L., Wilcock, R. J., Drewry, J. J., Houlbrooke, D. J., Quinn, J. M., and Thorrold, B. S. (2009). Linkages between land management activities and stream water quality in a border dyke-irrigated pastoral catchment *Agriculture, Ecosystems & Environment* **129**, 201–211. doi:10.1016/J.AGEE.2008.08.017

Morgan, P., Dark, A., Bright, J., Ward, N., and Sanson, J. (2010). Canterbury water management strategy: North Canterbury storage options. Riley Consultants Ltd, Aqualinc Research Ltd and Pattle Delamore Partners Ltd, Christchurch.

Nilsson, C., Lepori, F., Malmqvist, B., Törnlund, E., Hjerdt, N., Helfield, J. M., Palm, D., Östergren, J., Jansson, R., Brännäs, E., and Lundqvist, H. (2005). Forecasting environmental responses to restoration of rivers used as log floatways: An interdisciplinary challenge. *Ecosystems* **8**, 779–800. doi:10.1007/S10021-005-0030-9

Norsys (2005). 'Netica^{TM} Application: A complete software application to solve problems using Bayesian belief Networks and influence diagrams'.Available from: http://www.norsys.com [Accessed 27 January 2012].

O'Donnell, C. (2004). River bird communities. In 'Freshwaters of New Zealand'.(Eds J.S. Harding, M.P. Mosley, C.P. Pearson and B.K. Sorrell), pp. 18.1–18.19. (New Zealand Hydrological Society and New Zealand Limnological Society, Christchurch).

Petts, G. E. (1984). 'Impounded Rivers'. (John Wiley & Sons, Chichester).

Poff, N. L., Olden, J. D., Merritt, D. M., and Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 5732–5737. doi:10.1073/PNAS.0609812104

Postel, S., and Richter, B. (2003). 'Rivers for Life: Managing Water for People and Nature'. (Island Press, Washington, D.C.).

Postel, S. L., Dailey, G. C., and Ehrlich, P. R. (1996). Human appropriation of renewable fresh water. *Science* **271**, 785–788. doi:10.1126/SCIENCE.271.5250.785

Power, M. E., Dietrich, W. E., and Finlay, J. C. (1996). Dams and downstream aquatic biodiversity: Potential food web consequences of hydrologic and geomorphic change. *Environmental Management* **20**, 887–895. doi:10.1007/BF01205969

Quinn, J. M., and Raaphorst, E. (2009). Trends in nuisance periphyton at New Zealand National River Water Quality Network sites 1990–2006. Client Report: HAM2008–194, NIWA, Hamilton. http://www.mfe.govt.nz/publications/water/periphyton-nz-national-river-quality-network-1990-2006/periphyton-nz-national-river-quality-network-1990-2006.pdf.

Quinn, J. M., Monaghan, R. M., and Wilcock, R. J. 2010. Linking farm and waterway values – the Bog Burn catchment. In 'Farming's future: Minimising footprints and maximising margins', Massey University, Palmerston North, (Eds L.D. Currie and C.L. Christensen.) pp. 63–77 (Fertilizer and Lime Research Centre,Palmerston North).

Reckhow, K. H. (1999). Water quality prediction and probability network models. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 1150–1158.

Reckhow, K. H. (2003). Bayesian approaches to ecological analysis and modelling. In 'Models in Ecosystem Science'.(Eds C.D. Canham, J.J. Cole and W.K. Laueroth), pp. 168–183. (Princeton University Press, Princeton, NJ).

Shenton, W., Hart, B. T., and Chan, T. (2011). Bayesian network models for environmental flow decision-making: 1. Latrobe River Australia. *River Research and Applications* **27**, 283–296. doi:10.1002/RRA.1348

Snelder, T. H., and Biggs, B. J. F. (2002). Multiscale River Environment Classification for water resources management. *Journal of the American Water Resources Association* **38**, 1225–1239. doi:10.1111/J.1752-1688.2002.TB04344.X

Stark, J. D. (1993). Performance of the Macroinvertebrate Community Index: effects of sampling method, sample replication, water depth, current velocity, and substratum on index values. *New Zealand Journal of Marine and Freshwater Research* **27**, 463–478. doi:10.1080/00288330.1993.9516588

Stewart-Koster, B., Bunn, S. E., Mackay, S. J., Poff, N. L., Naiman, R. J., and Lake, P. S. (2010). The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. *Freshwater Biology* **55**, 243–260. doi:10.1111/J.1365-2427.2009.02219.X

Unwin, M. (2008). Statement of evidence on behalf of New Zealand and Otago Fish & Game Council, Before the Minister for the Environment Special Tribunal In the matter of an Application by New Zealand and Otago Fish & Game Council for an Amendment to the Kawarau Water Conservation Order.

Uusitalo, L. (2007). Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling* **203**, 312–318.

Wedderburn, L., Bewsell, D., Blackett, P., Brown, M., Kelly, S., Mackay, M., Maani, K., Montes, O., and Payne, T. (2011). Developing a preferred approach for managing cumulative effects of land uses on freshwater quality. AgResearch, Hamilton.

Wheeler, D. M., Ledgard, S. F., Monaghan, R. M., McDowell, R., and de Klein, C. (2006). Overseer® nutrient budget model – what it is, what it does. In 'Implementing sustainable nutrient management strategies in agriculture'.(Eds L. D. Currie and J. A. Hanly.) pp. 231–236. (Fertiliser and Lime Research Centre, Palmerston North.)

White, T. A., Snow, V. O., and King, W. M. (2010). Intensification of New Zealand beef farming systems. *Agricultural Systems* **103**, 21–35. doi:10.1016/J.AGSY.2009.08.003

Wilcock, R. J., Betteridge, K., Shearman, D., Fowles, C., Scarsbrook, M. R., Thorrold, B. S., and Costall, D. (2009). Riparian protection and farm best management practices for restoration of a lowland stream in an intensive dairy farming catchment: a case study. *New Zealand Journal of Marine and Freshwater Research* **43**, 803–818. doi:10.1080/00288330909510042

Wilcock, R. J., Nash, D., Schmidt, J., Larned, S. T., Rivers, M. R., and Feehan, P. (2011). Inputs of nutrients and fecal bacteria to freshwaters from irrigated agriculture: Case studies in Australia and New Zealand. *Environmental Management* **48**(1), 198–211. doi:10.1007/S00267-011-9644-1

Young, R., Smart, G., and Harding, J. (2004). Impacts of hydro-dams, irrigation schemes and river channel control works. In 'Freshwaters of New Zealand'.(Eds J.S. Harding, M.P. Mosley, C.P. Pearson and B.K. Sorrell), pp. 37.1–37.15. (New Zealand Hydrological Society and New Zealand Limnological Society, Christchurch).