Urban Planning that Sustains Waterbodies: Development of a Bayesian Belief Network for Stream Ecosystem Health

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Executive summary

The Urban Planning that Sustains Waterbodies (UPSW) research programme involves the development of a spatial decision-support system (sDSS) that allows the impacts of urban development scenarios on attributes such as water and sediment quality; ecosystem health; and cultural, amenity and recreation values to be investigated and compared. This report describes the development of the method by which the sDSS will predict indicators of stream ecosystem health.

The effects of urban development on the various aspects of stream ecological health are highly complex. In order to predict the consequences of different urban planning choices on key indicators of stream ecological health, we developed a series of inter-linked Bayesian Belief Networks (BBNs). Each BBN focused on one indicator: hydrology, water quality, instream habitat, aquatic plants, the riparian zone, macroinvertebrates and fish. At one level, called the "conceptual model", the BBNs show the variables of the stream network relevant to each indicator and indicate the cause-effect relationships between them. The variables (called nodes in the BBN) represent "things we know", "things we want to know" or "things that mediate the relationships between them". The "things we know" may be inputs from other models, fixed properties of streams in the catchment, or decisions that the urban planners make.

At the next level, the BBNs show the result of a particular planning decision on the state of a key indicator. They do this through Conditional Probability Tables (CPTs), which quantify the relationships between nodes, either deterministically (if the relationship is known accurately) or probabilistically (if the relationship is known only partially or with significant uncertainty),

The primary aim of these BBNs, therefore, is to support good decision making in urban planning by showing the relative effects of different planning options on valued aspects of stream ecosystems.

This report documents the development of the seven BBNs and the relationships between them. In each case we outline the conceptual model, which represents our understanding of what ecosystem variables affect the relevant indicator and how they are related. We describe the approach we took and why we chose that approach. We then outline, in broad terms, the quantitative relationships among the nodes (as captured in the CPTs). CPTs can be developed through empirical data from scientific studies, through other models, through expert judgement or (in some simple cases) through plain logic. We describe the main sources of knowledge that we drew on, the nature of those sources and their limitations. Finally we make some recommendations for further work to refine the BBNs.

1 Introduction

1.1 Background

The Urban Planning that Sustains Waterbodies (UPSW) research programme aims to help local government to plan the sustainable development of New Zealand's cities and settlements in a way which protects and enhances the values and services associated with urban waterbodies. It involves the development of a spatial decision-support system (sDSS) that allows the impacts of urban development scenarios on attributes such as water and sediment quality; ecosystem health; and cultural, amenity and recreation values to be investigated and compared. The pilot spatial decision support system (sDSS) requires a method to predict environmental wellbeing for freshwater ecosystems (streams) based on a given set of attributes for urban development options.

A literature review was undertaken to review indicators of environmental wellbeing that are influenced by urban development (Gadd et al. 2011). The outcome of this review was a list of possible environmental indicators for use in the sDSS. These indicators were grouped into seven major indicator categories as presented in Table 1-1.

Table 1-1: Environmental wellbeing indicators and sub-indicators.

Sub-indicators	Major indicators
Stream erosion and incision Bank lining and reinforcing Stormwater quantity control Catchment imperviousness	Hydrology score
CCME[1] water quality index based on: Water temperature Water clarity Nutrients Copper Zinc	Water quality score
Instream fines Physical habitat for fish Physical habitat for invertebrates	Instream habitat score
Riparian condition Riparian connection to stream Extent of tall riparian vegetation	Riparian habitat score
Macrophyte cover Periphyton cover	Aquatic plant score
Macroinvertebrate UCI score	Macroinvertebrate score
Number of native fish taxa	Native fish score

A review of literature (Gadd et al. 2011) indicated that there are currently no predictive models available for freshwater ecosystems that incorporate the effects of urban land use change that would be suitable for the pilot sDSS. Based on this, a Bayesian Belief Network

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[1] Canadian water quality guidelines (CCME, 2001)

(BBN) was developed to predict the above sub-indicators and major indicators from the provided attributes for urban development scenarios.

1.2 Report Structure

This report describes the development of the BBN for the pilot sDSS. Section 2 provides an introduction to BBN concepts and the process by which BBNs are developed. Sections 3 to 9 describe each of the networks developed to predict the seven major indicators listed in Table 1-1.

2 BBN Concepts and Overall Development

2.1 Introduction

BBNs, also known as Bayesian Networks or simply Belief Networks, provide a framework for graphically representing logical relationships between variables and for quantifying the strength of these relationships using conditional probabilities (Castelletti & Soncini-Sessa, 2007). An outline of their structure is as follows:

- Key variables within a system are represented as nodes. The condition of each node is described by an associated number of states, which may be either qualitative or quantitative.
- Nodes are connected to other nodes (to show causality) by arrows indicating the direction of influence.
- Behind each node lies a conditional probability table (CPT). These define the probability of a node being in any one of its associated states given the state of the nodes which influence it (i.e., its parent nodes). The probability values in each CPT may be derived from simulation models, from observational data, or from expert information.

BBNs are used widely in decision support tools for environmental management both internationally and in New Zealand (see Gadd et al. 2011 for a brief review). The strength of BBNs is their ability to combine quantitative relationships and poorly-specified relationships in the same network. Some of the links can be based on data from quantitative studies while others are based on “best professional judgement”. The overall process of developing BBNs consists of conceptual mapping of the network based on the key variables (nodes); describing the condition of those nodes in a number of states; and defining the CPTs for each node given the parent nodes. Further information on each of these steps is provided in the following sections.

Although the development of a BBN typically involves a degree of simplification in the representation of a system, they can never the less turn out to be quite complex models with significant computational needs. Fortunately, computer software is available for the development and application of BBNs. The research described here has used the Netica software available from Norsys Software Corp[2].

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[2] http://www.norsys.com/netica.html

2.2 Conceptual Modelling

Conceptual modelling is the process by which the key variables in a network are identified and connected to each other, based on their causal relationships. This step is one of the most important in developing a BBN. Key variables are typically established through literature review. Cause and effect relationships are shown by arrows linking the independent variables (parent nodes) to dependent variables (child nodes).

2.3 Describing Nodes

Once the key variables in the conceptual model are defined, these are described in more detail as nodes. There are multiple options for nodes in the Netica software program. Nodes can be one of four types:

1. Nature. These are chance or deterministic nodes that represent a variable of interest and change depending on the parent nodes.
2. Decision. These are nodes in a decision net that are under the control of the decision maker.
3. Utility. These are nodes in a decision net for which the expected value is optimised while searching for the best decision rule.
4. Constant. These are nodes with a constant value, but may be changed from time to time.

Nature nodes are the most commonly used nodes. When a network is composed entirely of nature nodes, it is known as a Bayes net, or belief network, or BBN. If the network also contains decision or utility nodes, it is known as a decision net. For the pilot sDSS, a Bayes net was considered to be the most appropriate form of a network.

Nature nodes can be either discrete or continuous, depending on whether the node represents a discrete or continuous variable. Continuous variables include variables such as the water temperature in a stream, which can assume a continuous range of values. Continuous variables are discretized with an interval list, for example, from 0 to 5°C; 5 to 10°C, 10 to 15°C, 15 to 20°C, 20-25°C. These intervals must be defined for each continuous node in the network. Discrete nodes include variables such as the type of riparian planting, which may include the options none, long grass, shrubs, or trees. These options represent the different ‘states’ of the discrete node, and must also be defined for each node in the network. Discrete nodes may or may not have a value associated with each state that indicates the level of a function or property it provides. For example, the state “long grass”, may have a value of 2, indicating the amount of shading it provides. Such values enable child nodes to be calculated based on a numeric equation.

2.4 Defining CPTs

The relationships between a node and its parents are defined by conditional probability tables (CPTs). The structure of these tables depends on whether a nature node is a deterministic or probabilistic (chance) node. A deterministic node is a nature node whose relationship with its parents is given as a function of the parents’ values (Norsys 2012). If the parents’ values are known, then the value can be determined with certainty. By contrast, a probabilistic or chance node is a nature node whose relationship with its parents is probabilistic (i.e. not deterministic). If its parents' values are all known, and there is no further information, then its value can only be inferred as a probability distribution over possible values (Norsys 2012). These are most commonly used nodes in a BBN and allow the propagation of probabilities throughout the network. If all nodes are deterministic, a BBN would not be required and a deterministic model could be developed.

There are several ways of developing CPTs. These include expert judgement, deterministic or probabilistic equations from models, and learning from cases using empirical data (often presented in published studies). Learning from cases requires values for each of the variables in a part of the network, and is an automatic way of determining the CPTs. This method has not been used in the development of the pilot sDSS, but may be a very useful way to test the networks if sufficient environmental / field data can be obtained.

Expert judgement is a common way to produce CPTs. A distribution of probabilities is entered into the CPT by the network developer based on the states of the parent nodes. Expert judgement is typically based on relationships established in the literature and empirical models.

Equations can be either deterministic or probabilistic and once written in the Netica software, they are used to generate the probabilities in the CPTs. Equations may be based on numerical relationships (e.g., a × b + c) or logical statements (e.g, if – then). Probabilistic equations use a distribution such as the Normal Distribution to add noise to a variable.

2.5 Overview of Methods used to Develop Networks for the Pilot sDSS

For the pilot sDSS, the input variables or primary nodes are either the attributes of the urban development options (UDOs) that are selected by the sDSS users, or basic properties of the catchment determined from databases. The final outputs of the BBN (or output nodes) are the indicator scores as listed in Table 1-1. Important intermediate variables were established through review of literature. This step of the literature review was targeted towards finding the major drivers of each indicator, and if required, the major drivers of those drivers, based on attributes that are provided by the pilot sDSS for the different urban development options. Conceptual models were then constructed linking the attributes through the intermediate variables to the sub-indicators and finally the major indicators or scores.

It should be noted that the BBNs described in this report remain the subject of on-going development. Their current state, as described in this report, reflects our understanding of key relationships between urban development and stream ecosystem health and has attempted to quantify these relationships from established literature, where available. However, our ability to quantify some of these relationships is limited and in a few places, relationships may need to be altered or other factors included. Although limited testing of the pilot sDSS has been conducted (Moores et al., 2012), more is required as part of completing its development as an operational decision support tool. One aspect of that testing will be to examine the performance of the BBNs for a range of case study areas in order to guide their further development, revision or refinement.

3 Details of the Hydrology Network

3.1 Development process

Urban development typically results in multiple changes to a stream's hydrological regime, including increases in peak flows, more-peaked flood hydrographs (larger floods rising and falling more rapidly), and decreases in baseflow. However some of these effects can be difficult to predict. In some cases increased urbanisation has been shown to result in increases in baseflow rather than the expected decreases (Elliot et al. 2010). As the actual changes to hydrological parameters, such as median flow, can be difficult to predict, the hydrology score is based on the 'Natural Flow Regime' (NFR) function within the first version of the Stream Ecological Valuation (SEV; Rowe et al. 2008). The first version was used instead of the revised SEV (Storey et al. 2011) as the first version of NFR incorporated catchment-scale factors, which are relevant for the present purpose, whereas the revised version focused more strongly on factors within individual stream reaches. The NFR function is based on three aspects:

- The extent of channel bed modification, which may contribute to a changed flow regime (Vbed);
- The degree of bank erosion which reflects upstream changes in flow patterns (Verosn);
- The proportion of impervious land in the catchment, with some modification for mitigation through stormwater management devices that influence quantity control (such as detention ponds) (Vimper).

These three factors are combined in the SEV to provide a score for the Natural Flow Regime function. This is used in the pilot sDSS as the Hydrology Score.

In the pilot sDSS, the proportion of impervious land is calculated by the Catchment Contaminant Annual Loads Model (C-CALM) based on the landuses selected by the user for a given Urban Development Option (UDO) (Moores et al., 2012) The extent of stream channel bed modification and stormwater quantity control are also determined by the pilot sDSS based on attributes of the UDO. Stream erosion is predicted within the BBN.

3.2 BBN Conceptual Model

Figure 3-1 shows the hydrology BBN. This and similar subsequent figures adopt the following colour coding to distinguish between the types of node:

- Mauve – input data (constant values) entered as part of implementing of the sDSS for a given study area;
- Light green – input variables entered by the user for a given UDO;
- Purple – input variables calculated by the pilot sDSS (including other constituent models such as C-CALM) from attributes of the UDO;
- Blue – input variables calculated by one of the other six BBNs;

- Tan – intermediate variables and sub-indicators calculated by this BBN (darker tan nodes had their values manually altered during one of the trial runs); and
- Dark green – the final indicator for this BBN.

The hydrology BBN starts with several nodes that are set as part of implementation of the pilot sDSS (stream substrate, segment slope; provided by FWENZ); calculated by C-CALM (percent imperviousness); or set by the user as part of the UDO (extent of tall riparian vegetation). These are provided to the BBN as parent nodes.

There are also several nodes for which the states are calculated by the pilot sDSS based on the user's selections for the UDO. These are:

- Streambank lining/reinforcing;
- Streambank straightening;
- Stormwater management for quantity control.

The states of these nodes are based on the proportion of low impact landuse in the upstream catchment. Low impact landuse includes rural and low impact design residential. Table 3-1 outlines the states of these nodes based on the proportion of low impact landuse. These states are then used as inputs into the hydrology BBN.

Table 3-1: Streambank and stormwater management states calculated by the pilot sDSS.

Amount low impact landuse	Streambank straightening	Streambank lining/ reinforcing	Stormwater management for quantity control
< 10%	Straightened >75%	Totally reinforced	High
10-25%	Straightened 50-75%	Partially reinforced	High
25-50%	Straightened 25-50%	Partially reinforced	Medium
50-75%	Straightened 1-25%	Not reinforced	None
> 75%	None	Not reinforced	None

A large part of the BBN is associated with predicting stream erosion and incision, which has five parent nodes (Figure 3-1).

The final three nodes that are used in the calculation of the hydrology score are discrete nodes but each state has a numeric value associated with it, which allows the calculation of the hydrology score based on the equation from Rowe et al. (2008):

Hydrology indicator score = (Vbed + Stream erosion & incision) / 2 × Vimper

3.3 Nodes, states and relationships

Table 3-2 lists all the nodes in the hydrology network, describes the possible states for each, the parents (which can also be seen in Figure 3-1), specifies the information used to establish the relationship between the node and its parents; and provides references for these relationships. The colour coding in the table reflects the colour coding in the network diagram (conceptual model) with the exception of the tan nodes which are not coloured in the table below.

The hydrology network is the most simplistic of the networks developed to predict the seven environmental indicators. We recognise that there is potential to develop it further, particularly in relation to the way in which imperviousness is represented and how it influences stream flow regimes. At present, the BBN assumes that imperviousness is ‘connected’, meaning that all impervious surfaces discharge via a reticulated stormwater pipe network to a stream. In the BBN (as in reality) an increase in connected imperviousness results in higher peak flows, lower baseflows and a more ‘flashy’ flow regime. One way to mitigate these effects of imperviousness is to disconnect it from streams and to discharge stormwater to the ground via, for instance, biofiltration measures such as grass swales and rain gardens. In the BBN, the adoption of these types of stormwater management approaches (typically associated with LID) could be reflected in an ‘effective impervious’ variable, with a lower effective imperviousness associated with UDOs in which a greater proportion of land use is specified as LID.

A second matter for consideration in further development of the hydrology BBN is the way in which the modification of the stream flow regime is represented. At present, this is based on the FRE3 metric. This is a measure of the frequency of flows greater than three times the medium. It was developed as an indicator of the effectiveness of flow regimes for flushing periphyton (Clausen and Biggs, 1997). It has been used here as part of the instream habitat BBN (see Section 5) and adopted as a convenient indicator of stream flashiness for predicting stream erosion in the hydrology BBN. However, with stream erosion most influenced by small to medium floods (Walsh et al., 2004), further evaluation is warranted of the extent to which FRE3, or some other metric, is the appropriate node to represent flow variability in the hydrology network.

Several of the CPTs that connect nodes were filled in directly based on expert judgement. The CPT for the FRE3 node is based on a regression equation developed specifically for this network. Other CPTs are from Rowe et al. (2008).

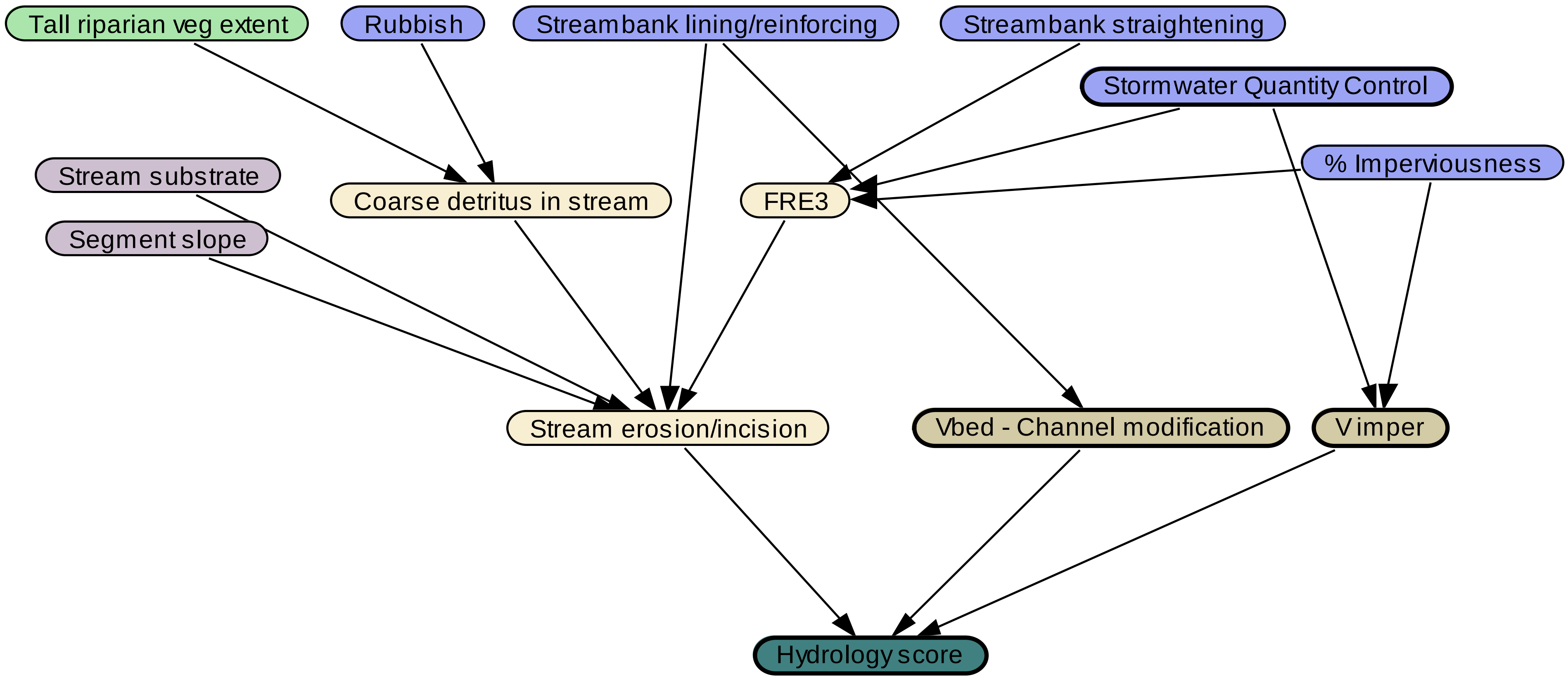

Figure 3-1: Conceptual model of the hydrology network from inputs driven by UDO attributes to major indicator (Hydrology score).

Table 3-2: Hydrology network nodes, states, parents and relationships.

Node	States	Parents	Information used to describe relationship between node and parents	Reference
% imperviousness	7 unevenly spaced	C-CALM	Not applicable for root nodes	N/A

Node	States	Parents	Information used to describe relationship between node and parents	Reference
	discretized continuous states, from 0 to 100%			
Streambank straightening	5 discrete states: none, 1 to 25, 25 to 50, 50 to 75, more than 75%	Pilot sDSS	Not applicable for root nodes	N/A
Streambank lining & reinforcing	3 discrete states: not reinforced, partially reinforced, totally reinforced	Pilot sDSS	Not applicable for root nodes	N/A
Stormwater quantity control	3 discrete states: none, medium, high	Pilot sDSS	Not applicable for root nodes	N/A
Rubbish	3 discrete states: minimal, low, high	Pilot sDSS	Not applicable for root nodes	N/A
Tall riparian veg extent	4 evenly spaced discretized continuous states, from 0 to 100%	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Stream substrate	2 discrete states: soft or hard	Set at implementation	Not applicable for root nodes	N/A
Segment slope	2 discrete states: gentle (0 to 1) or steep (3 to 10)	Set at implementation	Not applicable for root nodes	N/A
FRE3 (a measure of flow variability)	3 discretized continuous states, from 5 to13; 13 to 25 and >25	% imperviousness Streambank management – straightening Stormwater quantity control	Multiple regression equation developed based on published and unpublished data for Auckland urban streams FRE3 = 12 + (0.15 × SWQuantControl × (Imperviousness ×100) × (1.1-(0.1×Chanstrght)))	Developed for this project, unpublished
Coarse detritus in stream	4 discrete states with values: none (0), depleted (10), natural (25), excess (50)	Rubbish Tall riparian veg extent	Expert judgement with probabilities distributed across 2-3 states	
Vbed – channel modification	discrete states with values: not reinforced (1), partially reinforced (0.5), totally reinforced (0.1)	Bank lining & reinforcing	Deterministically related to parent node, only required as node values are different to the parent node values	Node values from Rowe et al. (2008)
Vimper	9 discrete states representing the possible	% imperviousness	Table from NFR score which modifies effects of flood flow controls for	Node values from

Node	States	Parents	Information used to describe relationship between node and parents	Reference
	scores from 0.1 to 1	Stormwater quantity control	catchment imperviousness	Rowe et al. (2008)
Stream erosion and incision	4 discrete states with values: none (1), natural (1), excess (0.7), severe (0.15)	Stream substrate Segment slope Coarse detritus in stream Flow variability (FRE3) Bank lining & reinforcing	Expert judgement with probabilities distributed across 2-3 states	Node values from Rowe et al. (2008)
Hydrology indicator score	5 evenly spaced discretized continuous states, from 0 to 1	Vbed Vimper Stream erosion & incision	Hydrology indicator score = (Vbed + Stream erosion & incision) / 2 × Vimper	Rowe et al. (2008)

4 Details of the Water Quality Network

4.1 Development process

There are a large number of potential water quality attributes that are influenced by urban development, including water temperature, clarity, and concentrations of dissolved oxygen, nutrients and toxic contaminants such as metals. Ideally a water quality indicator integrates several of these ‘sub-indicators’ to provide an overview of the change in water quality. Water quality indices have been widely used to provide this integration.

Water quality indices were briefly reviewed by Gadd et al. (2011) for this project and in more depth by Hudson et al. (2011). That report recommended the use of an integrated index for describing river water quality and suggested the Canadian Council of Ministers (CCME) Water Quality Index (hereafter referred to as the WQI), amended by developing appropriate threshold values for New Zealand.

The WQI is a tool for simplifying water quality data and calculates a water quality index value for a given set of data, with the aim of summarising the complex information and facilitating communication to a general audience (CCME 2001a). The index is based on a combination of three factors:

1. the number of variables whose objectives are not met, (Scope, F1)

2. the frequency with which the objectives are not met, (Frequency, F2) and

3. the amount by which the objectives are not met, (Amplitude, F3).

These are combined to produce a single value (between 0 and 100) that describes water quality (CCME 2001a). This value is then assigned to one of five categories: excellent (value 95-100), good (value 80-94), fair (value 65-79), marginal (value 45-64) or poor (value 0-44).

The index system is extremely flexible with scope for the user to both choose the water quality variables included and define the guidelines or thresholds to which the measured water quality is compared.

For the pilot sDSS the water quality indicator or score is based on this WQI using five water quality parameters: dissolved oxygen, clarity, nitrogen, copper and zinc. Concentrations of each of these parameters are predicted from the attributes of the UDO and from other data that can be readily gathered during implementation of the model (such as catchment size, annual rainfall).

The predicted water quality parameters are compared to water quality guidelines commonly used in New Zealand (Table 4-1).

Table 4-1: Water quality variables predicted in the BBN and guidelines used for comparison in the WQI.

Water quality parameter	Guideline source	Guideline value
Dissolved oxygen	7-day mean daily minimum for protection of early life stages (Franklin 2010)	> 5 g/m^3
Clarity	MfE (1994) guideline for recreational waters	< 1.6 m

Water quality parameter	Guideline source	Guideline value
Nitrate-nitrogen	ANZECC (2000), default trigger value	< 0.444 g/m^3
Copper	ANZECC (2000), trigger value for 95% level of protection	< 0.0014 g/m^3
Zinc	ANZECC (2000), trigger value for 95% level of protection	< 0.008 g/m^3

The calculations of the WQI can be made in a spreadsheet, however in this project, as the water quality variables are predicted rather than measured (through monitoring), the WQI has been implemented within the BBN. This allows the propagation of uncertainty around the water quality variables predicted, the three factors that define the WQI (scope, frequency and amplitude) and the final WQI.

4.2 BBN Conceptual Model

There are two major steps in the Water Quality BBN: first prediction of the water quality variables, then calculation of the WQI.

Predictions of the concentrations of copper, zinc and nitrogen are based on their annual yields and the annual runoff. Water clarity is calculated from concentrations of suspended solids, which in turn is based on annual sediment yields and the annual runoff. Yields of suspended solids, copper, zinc and nitrogen, and the percentage of the catchment that is impervious are provided by the pilot sDSS through C-CALM (see Moores et al. 2012). These nodes are shown in purple in Figure 4-1. The annual rainfall in the catchment is provided by the pilot sDSS and is set at the implementation phase (shown in mauve in Figure 4-1). The dissolved oxygen concentration is driven by the cover of aquatic plants (periphyton and macrophytes) and the reaeration coefficient. These parents are calculated in other BBNs (see Section 7).

Once the water quality variables used for the index have been calculated, the remainder of the network is dedicated to calculating the three factors (F1, F2, F3) required for the WQI.

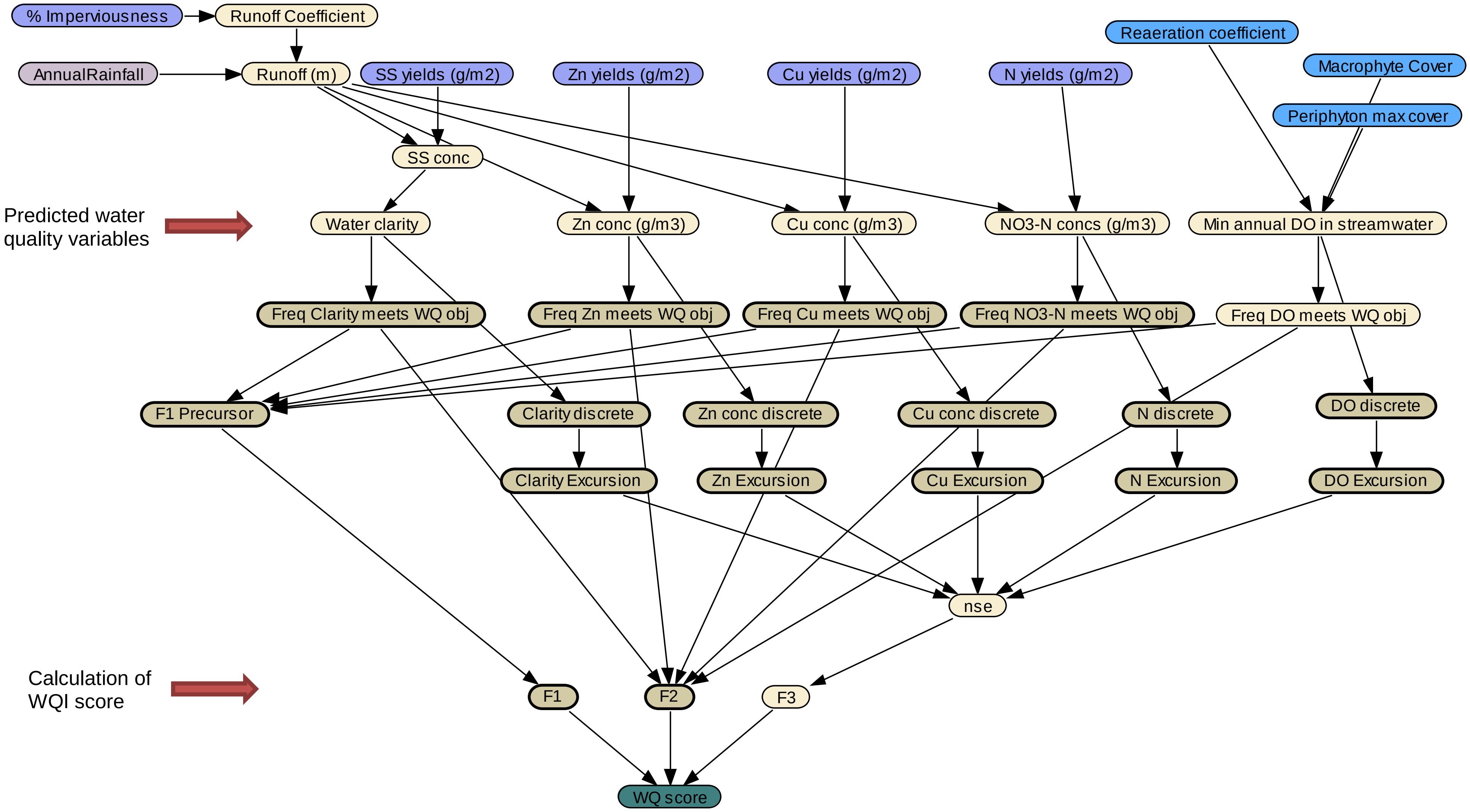

Figure 4-1: Conceptual model of the water quality network from inputs driven by UDO attributes to major indicator (WQ score).

4.3 Nodes, states and relationships

Table 4-2 lists all the nodes in the water quality network, describes the possible states for each, the parents (which can also be seen in Figure 4-1), specifies the information used to establish the relationship between the node and its parents; and provides references for these relationships. The colour coding in the table reflects the colour coding in the network diagram (conceptual model) above with the exception of the tan nodes which are not coloured in the table below.

Most of the nodes in the water quality network are connected through equations. These are then used to generate the CPTs for each node.

Table 4-2: Water quality network nodes, states, parents and relationships.

Node	States	Parents	Information used to describe relationship between node and parents	Reference
% imperviousness	7 unevenly spaced discretized continuous states, from 0 to 100%	C-CALM	Not applicable for root nodes	N/A
SS yields (g/m^2)	6 unevenly spaced discretized continuous states, from 0 to 2300	C-CALM	Not applicable for root nodes	N/A
Cu yields (g/m^2)	5 unevenly spaced discretized continuous states, from 0 to 2.2	C-CALM	Not applicable for root nodes	N/A
Zn yields (g/m^2)	5 unevenly spaced discretized continuous states, from 0 to 3	C-CALM	Not applicable for root nodes	N/A
N yields (g/m^2)	5 unevenly spaced discretized continuous states, from 0 to 10	C-CALM	Not applicable for root nodes	N/A
Annual rainfall	Constant value	Set at implementation	Not applicable for root nodes	N/A
Reaeration coefficient	3 unevenly spaced discretized continuous states: 0-2, 2-10, 10-100	See Section 7	See Section 7	See Section 7
Macrophyte cover	2 discrete states, < 50% cover; > 50% cover	See Section 7	See Section 7	See Section 7
Periphyton cover	2 discrete states, < 30% cover; > 30% cover	See Section 7	See Section 7	See Section 7

Node	States	Parents	Information used to describe relationship between node and parents	Reference
Runoff coefficient (unitless)	5 evenly spaced discretized continuous states, from 0 to 1.0	% imperviousness	Regression equation between imperviousness and runoff coefficient, with a normal distribution around the runoff coefficient to create a distribution of possible states RunoffCoeff =0.05+0.9×imperviousness	Schueler (1987)
Runoff (m)	7 evenly spaced discretized continuous states, from 0 to 1.4	Runoff coefficient Annual rainfall	Product of annual rainfall, runoff coefficient and fraction of annual rainfall events that produce runoff (usually 0.9) Runoff = AnnualRainfall×RunoffCoeff×0.9/1000	Schueler (1987)
SS conc (g/m^3)	10 states, unevenly spaced discretized continuous variable from 0 to 300	SS yields Runoff	Reversal of the Simple Method for calculating loads from EMCs SS Conc = SS yield / Runoff	Schueler (1987)
Cu conc (g/m^3)	16 unevenly spaced discretized continuous states, from 0 to 1	Cu yields Runoff	Reversal of the Simple Method for calculating loads from EMCs Cu Conc = Cu yield / Runoff	Schueler (1987)
Zn conc (g/m^3)	15 unevenly spaced discretized continuous states, from 0 to 2	Zn yields Runoff	Reversal of the Simple Method for calculating loads from EMCs Zn Conc = Zn yield / Runoff	Schueler (1987)
N conc (g/m^3)	5 unevenly spaced discretized continuous states, from 0 to 10	N yields Runoff	Reversal of the Simple Method for calculating loads from EMCs, with factor to convert total nitrogen yield to nitrate-N conc N Conc = N yield / Runoff	Schueler (1987)
Min. annual DO (g/m^3)	3 states, from 0 to 4; 4 to 6; 6 to 12 based on expert judgement	Reaeration coefficient Periphyton cover Macrophyte cover	Professional judgement based on small panel of experts	McBride & Wilcock, pers comm
Water clarity	6 unevenly spaced discretized continuous states, from 0 to 5	SS conc	Regression equation between SSconc and black disc distance, with a normal probability applied to create a distribution of possible states Clarity = 1.065 × log(SSConcs)+3.8228	Based on data from Davies-Colley & Close (1990)
Freq Cu meets WQ obj;	2 discrete states of “Yes”	Either Cu conc;	Equation using if statement to compare water quality objective to the predicted	CCME (2001a)

Node	States	Parents	Information used to describe relationship between node and parents	Reference
Freq Zn meets WQ obj; Freq N meets WQ obj; Freq DO meets WQ obj; Freq Clarity meets WQ obj	or "No"	Zn conc; N conc; Min annual DO conc; Or Water clarity	concentrations	
F1 precursor	6 discrete states from 0 to 5	Freq Cu meets WQ objective; Freq Zn meets WQ objective; Freq N meets WQ objective; Freq DO meets WQ objective; Freq Clarity meets WQ objective	Table that counts the total number of parents with value of "No"	CCME (2001a)
F1	5 evenly spaced discretized continuous states, from 0 to 100	F1 precursor	Equation that converts the F1 precursor to the F1 statistic by dividing by 5 and multiplying by 100	CCME (2001a)
F2	7 discretized continuous states, from 0 to 0.1, 0.1 to 20, then evenly spaced to 80-99 and 99-100.	Freq Cu meets WQ objective; Freq Zn meets WQ objective; Freq N meets WQ objective; Freq DO meets WQ objective; Freq Clarity meets WQ objective	Equation that sums the number of values that do not meet objectives and divides by 5	CCME (2001a)
Cu discrete, Zn discrete, N discrete, DO discrete, Clarity discrete	Dependent on continuous parent node	Either Cu conc, Zn conc, N conc, Min annual DO or Water clarity	Deterministic table converting continuous variable to discrete categories	Intermediate node created to allow calculation of excursions
Cu excursion, Zn excursion, N excursion, DO excursion, Clarity excursion	Between 2 and 8 unevenly spaced discretized continuous states, starting from 0 to 1 then 1 to 5 and up to 500 as required based on parent node	Either Cu discrete, Zn discrete, N discrete, DO discrete or Clarity discrete	Equation that compares the state of discrete nodes to the water quality objective to calculate amplitude of excursion $\text{Excursion} = \frac{\text{Failed test conc.}}{\text{WQ objective}} - 1$	CCME (2001a)
nse (normalised sum of excursions)	5 unevenly spaced (factor of 10) discretized continuous states, from 0 to 954	Cu excursion Zn excursion N excursion DO excursion Clarity excursion	Equation that sums the total excursions for all WQ variables and divides by 500 to normalise (for 5 variables and 100 measurements)	CCME (2001a)
F3	5 evenly spaced discretized continuous states, from 0 to 100	nse	Equation to convert the nse to the F3 statistic	CCME (2001a)

Node	States	Parents	Information used to describe relationship between node and parents	Reference
WQI	5 states defined by CCME (2001a): Poor 0-44 Marginal 45-64 Fair 65-79 Good 80-94 Excellent 95-100	F1 F2 F3	Equation to calculate the WQI from the F1, F2 and F3 statistic 100-((sqrt (F1^2+F2^2+F3^2)) /1.732)	CCME (2001a)

5 Details of the Instream Habitat Network

5.1 Development process

Instream habitat represents the physical characteristics of streams – the channel morphology, flow types, and organic and inorganic substrates including instream structures such as boulders and logs. We regard instream habitat as being habitat for instream biota, mainly fish and macroinvertebrates. Thus the habitat score depends largely on the nodes “Instream habitat for invertebrates” (from the Macroinvertebrates BBN) and “Physical habitat for fish” (from the Fish BBN) The former is derived from the Urban Stream Habitat Assessment (USHA; Suren et al. 1998), in which the key habitat variables driving differences in the macroinvertebrate community among 59 urban stream sites across New Zealand were identified by statistical analysis. The latter is derived from a number of published scientific studies on factors affecting freshwater fish populations.

Deposited fine sediment is known to have a serious effect on habitat quality (Clapcott et al. 2011). However, the effect of deposited fine sediment on habitat quality is largely absent from the habitat scores for invertebrates and fish, therefore we added extra nodes for deposited fine sediment to capture its effect.

“Soft-bottomed” streams, i.e. those with a bed naturally comprised of fine substrates such as sand, silt or clay, provide a very different type of habitat from “hard-bottomed” streams with a bed of pebbles, cobbles, boulders or bedrock. Most macroinvertebrates require hard surfaces to crawl on, and their gills become clogged easily in fine sediments. Therefore the macroinvertebrate community in soft-bottomed streams comprises a rather different species composition from that in hard-bottomed streams, and most species are found on features above the stream bed, such as instream plants, logs or trailing bank vegetation. Thus the effects of deposited fine sediment on soft-bottomed streams are rather different in soft- vs. hard-bottomed streams. To capture this difference, the final habitat score in this BBN depends on whether the streams in the catchment of interest are soft- or hard-bottomed. In Auckland the majority of streams are soft-bottomed but a significant number are hard-bottomed.

The influences of the various stream attributes on “Instream habitat for macroinvertebrates” are defined by the coefficients of the factor analysis in USHA. In USHA a different set of habitat “drivers” was identified for groups of urban streams in similar areas, thus streams characteristic of the Auckland area (Type 3 streams) have their own specific set of habitat drivers (Suren et al. 1998).

5.2 BBN Conceptual Model

The BBN conceptual model for instream habitat is shown in Figure 5-1.

Instream habitat for invertebrates and Physical habitat for fish are described in the Section 8 Macroinvertebrates and Section 9 Fish, respectively.

Sediment deposited in urban streams is derived from two main sources – the catchment and the stream banks and bed. Sediment derived from the catchment is represented by the node SS (suspended solids) yield, values for which are imported from the C-CALM model. Suspended solids yield is high during the process of urbanisation, while construction is disturbing the soil, and for many years afterwards, but eventually, after the catchment has stabilised, it declines to much lower levels (Finkenbine et al. 2000). Sediment mobilisation from stream channel erosion is represented in the BBN by flow variability/flashiness and the baseline urban state (BUS, i.e. pre-development) median stream flow, as these relate to the factors responsible for erosion. Increased flood peaks in urban areas due to rain water rapidly running off impervious surfaces are responsible for channel erosion (Suren and Elliott 2004). Stream bed gradient is also important, with small headwater streams, which typically are on steeper land, tending to experience greater erosion than larger streams that typically flow through gentler topography (Booth 1990). The BBN attempts to capture this influence of gradient through the BUS median stream flow, on the assumption that smaller flows are indicative of steeper streams and, hence, greater potential for erosion in some reaches and deposition in others. However, it is recognised that median stream flow can vary with factors other than gradient (catchment size for instance) and may not always correlate with erosion potential. Further development of the BBN should aim to investigate whether erosion potential is better predicted by some other measure, for instance by stream bed gradient directly.

Over time stream channels reach equilibrium with the more variable flow regime in urbanised catchments, and erosion diminishes. Thus deposited fine sediment in streams gradually decreases over a period of 15-50 years after urbanisation (Finkenbine et al. 2000), and subsequently the amount of deposited sediment may be greater or less than before urbanisation (Walsh et al. 2005). In hard-bottomed streams, deposited fine sediment occurs naturally in small amounts, particularly in areas of low flow velocity. However, a high percentage of deposited fine sediment restricts the area of habitable hard substrate for fish spawning and for invertebrates. Thus the node Substrate % fines (hard bottom stream) refers to the % of the stream bed material that is less than 2 mm diameter. In soft-bottomed streams the entire stream bed is composed of fine material, so a different measure is needed. Depth of deposited sediment is regarded as the most appropriate measure (Clapcott et al. 2011) as it is assumed that thick deposits may adversely affect the invertebrate communities of soft-bottomed streams. This has not been proven, however (Clapcott et al. 2011).

The final habitat score is simply the soft-bottomed or hard-bottomed stream habitat score, whichever is appropriate to the stream being assessed.

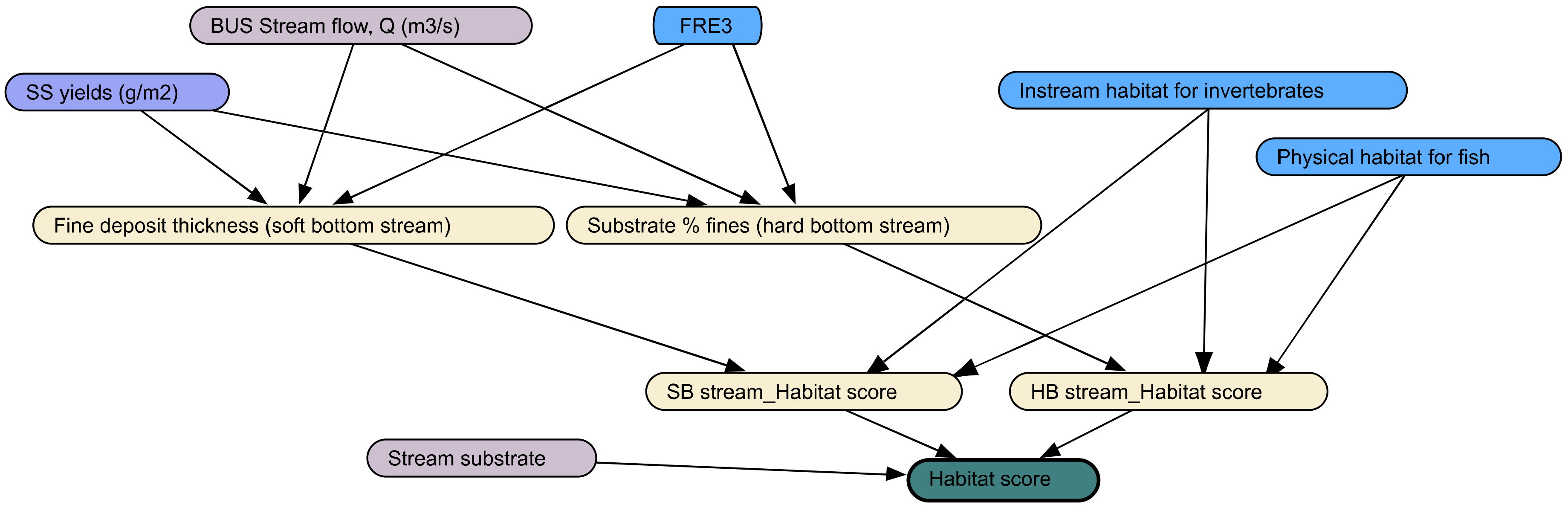

Figure 5-1: Conceptual model of the instream habitat network from inputs driven by UDO attributes to major indicator (Habitat score).

5.3 Nodes, states and relationships

Table 9-1: Instream habitat network nodes, states, parents and relationships.

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
SS yields (g/m2)	6 unevenly spaced discretized continuous states, from 0 to 2300	C-CALM	Not applicable for root nodes	N/A
Stream substrate	2 discrete states, soft-bottomed and hard-bottomed	Set at implementation	Not applicable for root nodes	N/A
BUS median stream flow, Q (m3/s)	5 unevenly spaced discretized continuous states, from 0 to 10	Set at implementation	Not applicable for root nodes	N/A
FRE3	3 discretized continuous states, from 5 to13; 13 to 25 and >25	% imperviousness Streambank management – straightening Stormwater quantity control	Multiple regression equation developed based on data for Auckland urban streams FRE3 = 12 + (0.15 × SWQuantControl × (Imperviousness ×100) × (1.1-(0.1×Chanstrght)))	Unpublished data for this project
Instream habitat for invertebrates	3 unevenly spaced discretized continuous states from 0 to 18.4 (poor, medium, good)	See Section 8	See Section 8	See Section 8
Physical habitat for fish	3 discrete states: poor, medium, good	See Section 9	See Section 9	See Section 9
Fine deposit thickness (soft-bottomed stream)	2 discrete states: thin, thick	SS yields, BUS stream flow, FRE3	Probabilistic table based on expert judgment and literature; thick deposits becoming more probable with lower FRE3, higher SS yields and lower discharge	Suren and Elliott (2004); Finkenbine et al. (2000); Walsh et al. (2005); Booth (1990)
Substrate % fines (hard bottomed stream)	3 discrete states: <10%, 10-30%, >30%	SS yields, BUS stream flow, FRE3	Probabilistic table based on expert judgment and literature; high % fines becoming more probable with lower FRE3, higher SS yields and lower discharge.	Suren and Elliott (2004); Finkenbine et al. (2000); Walsh et al. (2005); Booth (1990)
SB stream Habitat score	5 discrete states: low, lowmed, med,medhigh, high	Fine deposit thickness, instream habitat for invertebrates, physical habitat for fish	Probabilistic table based on expert judgment and literature; probability of high score correlated with probability of high scores in parent nodes	Clapcott et al. (2011)

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
HB stream Habitat score	5 discrete states: low, lowmed, med,medhigh, high	Substrate % fines, instream habitat for invertebrates, physical habitat for fish	Probabilistic table based on expert judgment and literature; probability of high score correlated with probability of high scores in parent nodes	Clapcott et al. (2011)
Habitat score	5 discrete states: low, lowmed, med, medhigh, high	SB stream Habitat score, HB stream Habitat score, Stream substrate	Choice between SB and HB stream habitat scores, based on state of Stream substrate node	N/A

6 Details of the Riparian Network

6.1 Development process

New Zealand lowland streams under natural conditions are surrounded by native bush consisting of a tree canopy, shrub layer and a ground cover of plants and dead plant material. Riparian zones of this type perform a number of important functions that support stream ecological processes. Organic material (leaves, wood and terrestrial invertebrates) falling into streams provides the base of the aquatic food web. Large wood provides structure and complexity to the stream, dissipating the energy in stream flow, creating cover and habitat for fish and invertebrates and providing hard surfaces for microbial biofilms to grow on. Riparian shade keeps stream water cool and prevents excess growth of aquatic algae and higher plants. Tree roots keep the stream banks from eroding. Leaf litter and ground cover plants filter out the particulate material carried by overland runoff before it enters the stream. And organic soils and plant roots process or remove dissolved material in subsurface runoff before it enters the stream. These functions are variously impaired or eliminated when riparian forest is removed, groundcover is replaced by mowed lawns or impervious surfaces, or catchment runoff bypasses the riparian zone in pipes.

Rather than scoring the ecological functions provided by the riparian zone individually, the riparian score estimates these functions by assessing the vegetation and ground surface cover of the riparian zone (“riparian condition”) and the connectivity between the riparian zone and the stream. It is assumed that the nearer these variables are to the natural condition, the better the riparian functions are being performed. The two variables combine to produce “Riparian Vegetation Intact” (RVI), which is derived from the Stream Ecological Valuation (Storey et al. 2011).

6.2 BBN Conceptual Model

Riparian Vegetation Intact” (RVI) is a function of two variables, riparian condition and riparian connection to the stream. It is assumed that intact native forest provides the full range of ecological functions, shrubs provide most, grasses and sedges provide some and bare soil or artificial paving provide none of the functions described above. It is also assumed that native vegetation performs the ecological functions better than exotic vegetation.

Riparian condition is a function of the extent of the riparian zone in existing or newly-planted vegetation, the type of the dominant vegetation (e.g. trees, shrubs or grasses/sedges) and whether the vegetation is native or exotic.

The potential water quality benefits of riparian margins are severely reduced by stormwater pipes, which allow water entering the stream from the catchment to bypass the riparian zone completely. Dissolved and particulate materials in runoff that are usually filtered out, absorbed or processed by the ground cover, organic soils or plant roots of the surface and shallow riparian zone thus enter the stream directly. In the BBN this influence of stormwater pipes translates into a reduction in ‘riparian connection’ to the stream. The extent of ‘stormwater pipes’ in a catchment is a function of land use. Riparian connection to the stream is reduced to a lesser degree by lining or reinforcing of the banks (e.g. culverts, concrete lining or wooden boxing), which block subsurface flow paths, and by down-cutting erosion, which lowers the water table below the riparian organic soil layer and root zone.

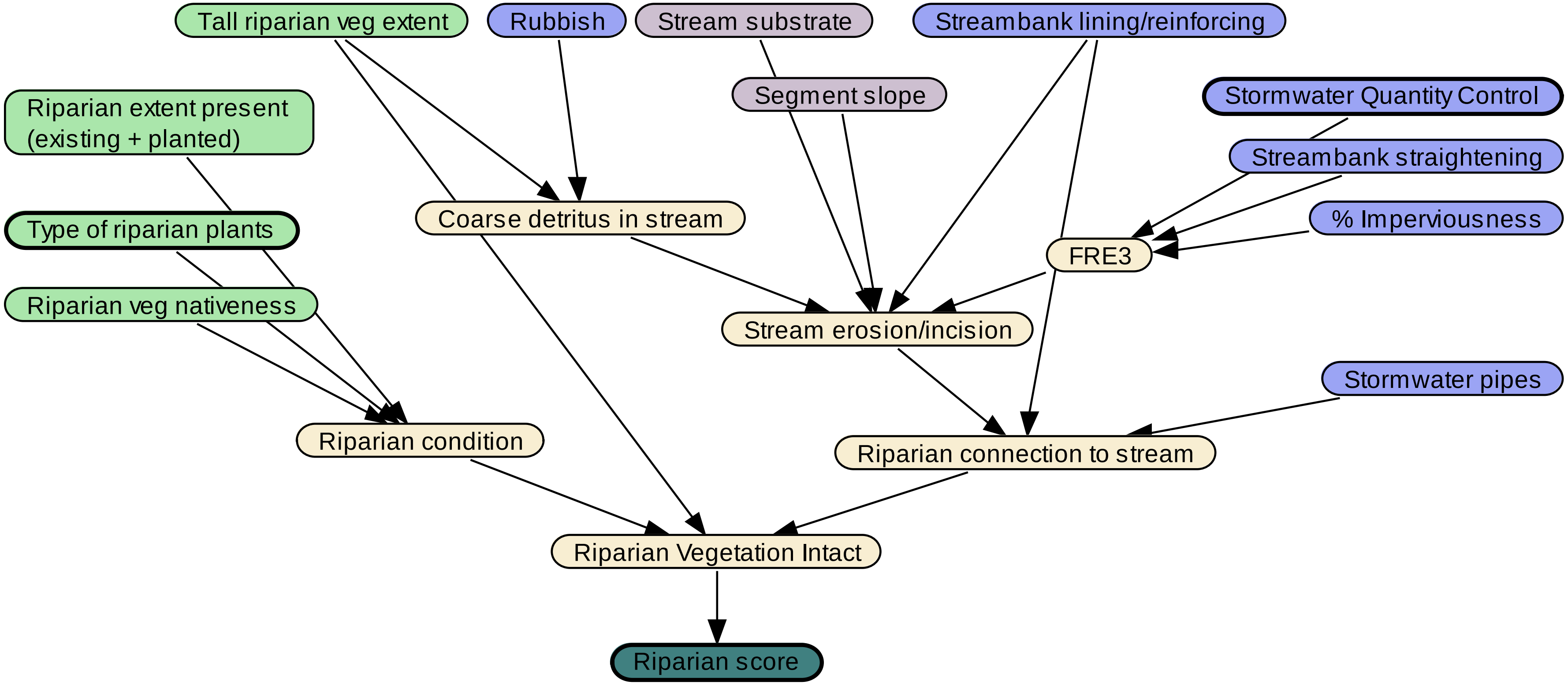

Figure 6-1: Conceptual model of the riparian network from inputs driven by UDO attributes to major indicator (Riparian score).

6.3 Nodes, states and relationships

Table 6-1: Riparian network nodes, states, parents and relationships.

Node	Possible states	Parents	Information used to describe relationship between node and parents	Referenc
Rubbish	3 discrete states: minimal, low, high	Pilot sDSS	Not applicable for root nodes	N/A
Streambank lining/reinforcing	3 discrete states: not reinforced, partially reinforced, totally reinforced	Pilot sDSS	Not applicable for root nodes	N/A
Streambank straightening	5 discrete states: none, 1 to 25, 25 to 50, 50 to 75, more than 75%	Pilot sDSS	Not applicable for root nodes	N/A
Stormwater quantity control	3 discrete states: none, medium, high	Pilot sDSS	Not applicable for root nodes	N/A
% imperviousness	7 unevenly spaced discretized continuous states, from 0 to 100%	C-CALM	Not applicable for root nodes	N/A
Stormwater pipes	4 discrete states	Pilot sDSS	Not applicable for root nodes	N/A
Stream substrate	2 discrete states: soft or hard	Set at implementation	Not applicable for root nodes	N/A
Segment slope	2 discrete states: gentle (0 to 1) or steep (3 to 10)	Set at implementation	Not applicable for root nodes	N/A
FRE3	3 discretized continuous states, from 5 to13; 13 to 25 and >25	% imperviousness Streambank management – straightening Stormwater quantity control	Multiple regression equation developed based on data for Auckland urban streams $FRE3 = 12 + (0.15 \times SWQuantControl \times (Imperviousness \times 100) \times (1.1-(0.1 \times Chanstrght)))$	Unpublished data for
Tall riparian veg extent	4 evenly spaced discretized continuous states, from 0 to 100%	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Riparian extent present	5 discrete states: none, 1 to 25, 25 to 50,	Defined by user of pilot sDSS	Not applicable for root nodes	N/A

Node	Possible states	Parents	Information used to describe relationship between node and parents	Referenc
	50 to 75, more than 75%			
Type of riparian plants	4 discrete states: grasses, flaxes/sedges, shrubs, trees	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Riparian veg nativeness	3 discrete states: indigenous, occasional indigenous, exotic	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Coarse detritus in stream	4 discrete states: none, depleted, natural, excess	Human rubbish Tall riparian veg extent	Expert judgement with probabilities distributed across 2-3 states	none
Stream erosion/incision	4 discrete states with values: none (1), natural (1), excess (0.7), severe (0.15)	Stream substrate Segment slope Coarse detritus in stream Flow variability (FRE3) Bank lining & reinforcing	Expert judgement with probabilities distributed across 2-3 states	Booth (1990); Macrae (1992) Finkenbine et Walsh et al. (2005); N from Rowe et al. (200
Riparian connection to stream	4 discrete states: very low, low, medium, high	Stormwater pipes, stream erosion/incision, bank lining/reinforcing	Expert judgement based on formula $V_{ripconn} = C \times (1-V_{pipe})/2$ where V_{pipe} represents the number and size of stormwater pipes entering the stream	Storey et al. (2011)
Riparian condition	7 discrete states: intact native forest, exotic trees, native shrubs, exotic shrubs, sedges/flaxes/long grass, short grass, bare/artificial surface	Riparian extent present (existing+planted), type of riparian plants, riparian vegetation nativeness	Simple concatenation of information in parent nodes	Storey et al. (2011)
Riparian vegetation intact	5 evenly-spaced discretized continuous states 0-100%	Tall riparian vegetation extent, riparian condition, riparian connection to stream	Simple average of three parent nodes	Storey et al. (2011)
Riparian score	5 discrete states	Riparian vegetation intact: probabilities transferred directly	None required	

7 Details of the Aquatic Plants Network

7.1 Development process

Aquatic plants in streams include periphyton (algae attached to hard surfaces as films, mats of long filaments) and macrophytes (higher plants, generally broad-leaved and rooted in the stream bed). Whether periphyton or macrophytes dominate depends on the stream bed substrate, as periphyton are favoured by large stable particles that they can attach to, whereas macrophytes are favoured by soft sediments that they can root in.

In the their natural state, small New Zealand lowland streams have little growth of either periphyton or macrophytes as most are heavily shaded and contain low nutrient concentrations. Human modifications to stream catchments usually result in increases in both light and nutrients, thus stimulating growth of aquatic plants. However, catchment development, particularly urban development, also results in higher and more frequent flood flows. Since aquatic plants typically are vulnerable to being washed away during high flows (Reeves et al. 2004; Biggs and Kilroy 2004), the effects of increased light and nutrients may be moderated or negated by the effects of increased high flows.

Up to a certain level, periphyton and macrophyte growth in streams is considered good for the aquatic ecosystem. Periphyton provides food for grazing invertebrates and macrophytes provide habitat complexity and surfaces for biofilms and invertebrates to live on. However, excess growth of periphyton and macrophytes is considered negative, from both an aesthetic and an ecological point of view (e.g. Biggs 2000). Periphyton may smother rocks, restricting the amount of hard surface available for crawling invertebrates, while macrophytes may severely reduce stream flow and accumulate fine sediment among their stems and roots. Excess plant growth can also result in extreme fluctuations in dissolved oxygen as the plants alternately photosynthesise and respire over a 24 hour period. The aquatic plant score reflects this, decreasing with macrophyte cover greater than 50% and periphyton cover greater than 30%.

We based the Aquatic Plant score on the factors most strongly influencing the growth of macrophytes and periphyton. These factors were identified in reviews by Parkyn et al. (2010), Reeves et al. (2004) and Biggs and Kilroy (2004).

7.2 BBN Conceptual Model

The aquatic plant conceptual model is shown in Fig. 7-1. The aquatic plant score simply combines macrophyte % cover and periphyton % cover, with greater probability of a high score where macrophyte and periphyton % cover are both low.

Macrophyte growth in urban streams is most strongly affected by stream shading, flood frequency, mean flow velocity and stream substrate (Riis and Biggs 2003; Reeves et al. 2004; Parkyn et al. 2010). Nutrient concentrations and substrate stability also affect growth, but nutrient concentrations have a weaker influence than these other factors, and substrate stability is not expected to vary greatly among Auckland streams. Macrophytes are more common in fine substrates such as clays, silts and sands than hard substrates such as gravels and cobbles (Riis and Biggs 2001; Reeves et al. 2004), although some spring-fed hard-bottomed streams do have significant macrophyte growth. Therefore we have assigned a low probability for >50% macrophyte cover occurring in hard-bottomed streams. In soft-bottomed streams, tall-growing macrophytes are generally absent from waters with mean water velocity >0.9-1.0 m/s (Parkyn et al. 2010) and/or with more than 13 high-flow disturbances (>7x median flow) per year (Riis and Biggs 2003). We have used these figures to estimate the relationships between macrophyte cover, FRE3 (frequency of floods >3x median flow) and mean flow velocity. Finding a threshold value for stream shading that prevents excess growths of macrophytes was not easy. Quinn (2003) recorded that shading of 60-80% is expected to prevent proliferation of filamentous green algae, but 90% shading is needed to prevent growth of some emergent macrophytes in low-gradient streams. According to Matheson et al. (2012), macrophytes require at least 2% of surface-ambient light (equating to <98% shade) and may need up to 29% (equating to 71% shade). Between the minimum required and light saturation, growth may increase linearly. Dennison et al. (1993) report that macrophytes require more light than periphyton. From these various sources of information we estimated that 70% shading may prevent excess growth (>50% cover) of macrophytes, but we intend to further refine the relationship between light and macrophyte growth.

Periphyton in streams experiences frequent cycles of growth and scouring by high flow events. Since its impact on stream aesthetics and ecology occur during periods of maximum growth, we focus on maximum periphyton cover in this BBN. Periphyton grows mostly on hard surfaces, therefore will occur mainly in hard-bottomed streams. Growth is influenced mainly by shading (which affects light and water temperature), dissolved nitrogen and/or phosphorus concentrations and the period of time between scouring high flow events (Biggs and Kilroy 2004; Parkyn et al. 2010). As described in previous sections, shading is a function of riparian vegetation and stream width, whereas nutrient concentrations are determined by nutrient yields from the catchment and the stream discharge. The period of time between scouring floods, during which periphyton can accumulate biomass, is represented here by FRE3, the frequency of flow events >3x the median flow.

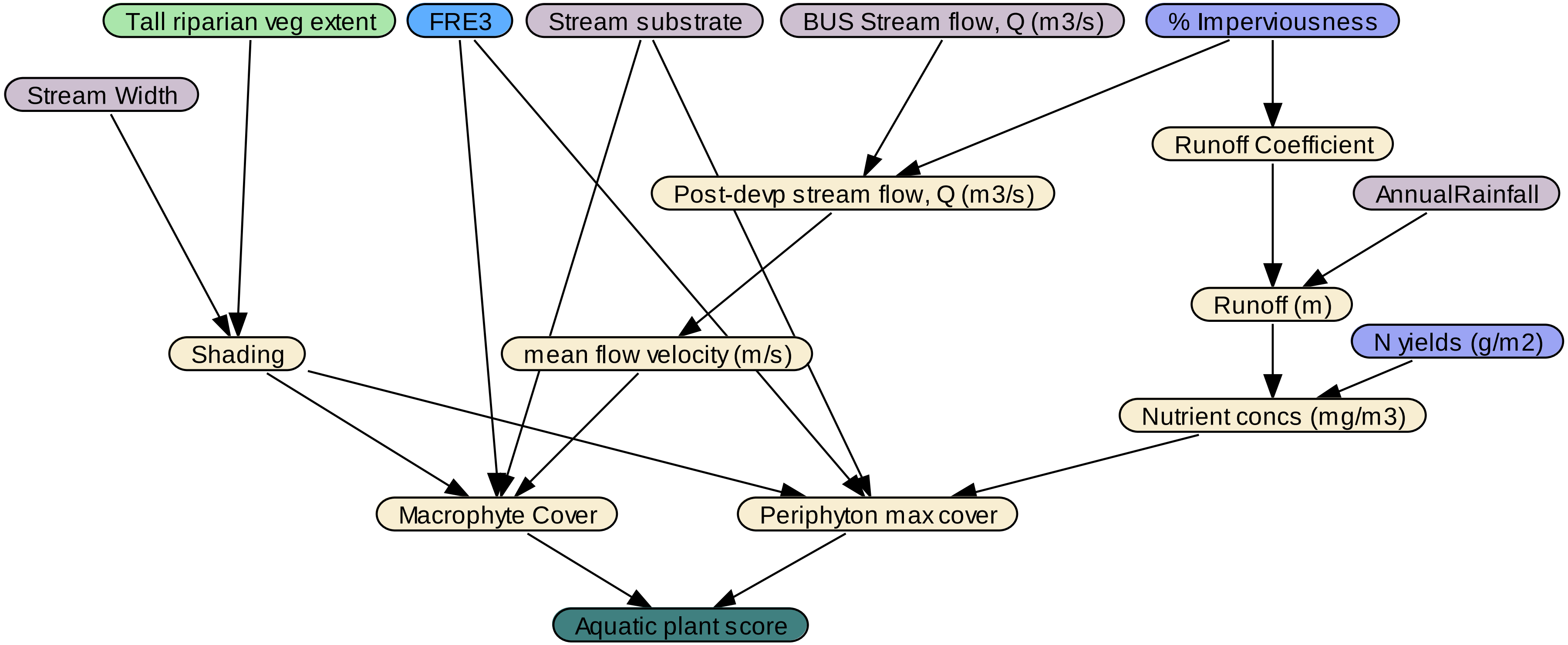

Figure 7-1: Conceptual model of the aquatic plant network from inputs driven by UDO attributes to major indicator (Aquatic plant score).

7.3 Nodes, states and relationships

Table 7-1: Aquatic plant network nodes, states, parents and relationships.

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
% imperviousness	7 unevenly spaced discretized continuous states, from 0 to 100%	C-CALM	Not applicable for root nodes	N/A
N yields (g/m^2)	5 unevenly spaced discretized continuous states, from 0 to 10	C-CALM	Not applicable for root nodes	N/A
Annual rainfall	Constant value	Set at implementation	Not applicable for root nodes	N/A
Stream width	3 discretized continuous states from 0 to 10 m	Set at implementation	Not applicable for root nodes	Davies-Colley and Quinn (1998)
Stream Substrate	2 discrete states: soft or hard	Set at implementation	Not applicable for root nodes	N/A
BUS stream flow, Q	5 unevenly spaced discretized continuous states, from 0 to 10	Set at implementation	Not applicable for root nodes	N/A
FRE3	3 discretized continuous states, from 5 to13; 13 to 25 and >25	% imperviousness Streambank management – straightening Stormwater quantity control	Multiple regression equation developed based on data for Auckland urban streams FRE3 = 12 + (0.15 × SWQuantControl × (Imperviousness ×100) × (1.1-(0.1×Chanstrght)))	Unpublished data for this project

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
Tall riparian veg extent	4 evenly spaced discretized continuous states, from 0 to 100%	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Shading	3 discrete states: <70%, 70-90%, >90%	Stream width, tall riparian vegetation extent	Stream shading = approx. 10% at stream width of approx. 7 m. Assume % shading over a length of stream is proportional to the % bank length with tall riparian vegetation.	Davies-Colley and Quinn (1998)
Post-devp stream flow, Q	5 unevenly spaced discretized continuous states, from 0 to 10	BUS stream flow Q, % imperviousness	Reduction in stream flow based on % imperviousness	Elliot et al. (2004)
Mean flow velocity	5 unevenly spaced discretized continuous states, from 0 to 10	Post-devp stream flow, Q	Equation: Post-devp stream flow ^ 0.458	From Jowett et al. (2008)
Runoff coefficient (unitless)	5 evenly spaced discretized continuous states, from 0 to 1.0	% imperviousness	Regression equation between imperviousness and runoff coefficient, with a normal distribution around the runoff coefficient to create a distribution of possible states RunoffCoeff =0.05+0.9×imperviousness	Schueler (1987)
Runoff (m)	7 evenly spaced discretized continuous states, from 0 to 1.4	Runoff coefficient Annual rainfall	Product of annual rainfall, runoff coefficient and fraction of annual rainfall events that produce runoff (usually 0.9) Runoff =	Schueler (1987)

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
			AnnualRainfall×RunoffCoeff×0.9/1000	
Nutrient (NO3N) concs (g/m3)	5 unevenly spaced discretized continuous states, from 0 to 10	N yields Runoff	Reversal of the Simple Method for calculating loads from EMCs, with factor to convert total nitrogen yield to nitrate-N conc N Conc = N yield / Runoff	Schueler (1987)
Macrophyte cover	2 discrete states, < 50% cover; > 50% cover	Shading FRE3 Stream substrate Flow velocity	Macrophyte cover >50% requires shading <70%, soft stream substrate, median flow <1 m/s and is inversely proportional to flow variability. Multiplication factors assigned to states of parent nodes. Probability of macrophyte cover >50% is the product of these.	Riis and Biggs 2003; Reeves et al. 2004; Parkyn et al. 2010
Periphyton max cover	2 discrete states, < 30% cover; > 30% cover	Shading FRE3 Stream substrate Nutrient concs	Periphyton cover >30% requires hard stream substrate, is proportional to nutrient concentrations and is inversely proportional to shading and frequency of high flow events (FRE3). Multiplication factors assigned to states of parent nodes. Probability of periphyton cover >30% is the product of these.	Biggs and Kilroy 2004; Parkyn et al. 2010
Aquatic plant score	5 discrete states: low, lowmed, med, medhigh, high	Macrophyte cover, Periphyton max cover	High score is possible only with % macrophyte and periphyton cover <50% and <30%, respectively. If either parent node exceeds these thresholds, aquatic plant score is most likely to be low.	Biggs (2000); Suren et al. (1998)

8 Details of the Macroinvertebrates Network

8.1 Development process

The macroinvertebrate index was derived from the Urban Community Index (UCI), part of the Urban Streams Habitat Assessment (USHA; Suren et al. 1998). UCI is based on empirical data representing the main changes in macroinvertebrate community composition across a large number of New Zealand urban stream sites with different degrees of environmental stress. Thus UCI is optimised to represent invertebrate responses to urban stressors, whereas the more commonly used Macroinvertebrate Community Index (MCI) represents invertebrate responses to the stressors associated with pastoral agriculture. The other advantage of UCI is that the key habitat characteristics driving the UCI score most strongly are identified and weighted according to the strength of the relationships, using factor analysis (Suren et al. 1998). A different set of habitat "drivers" is identified for groups of urban streams in similar areas, thus streams characteristic of the Auckland area (Type 3 streams) have their own specific set of habitat drivers (Suren et al. 1998).

Suren et al. (1998) related UCI only to physical characteristics of the stream habitat, but recognised that the macroinvertebrate community may also be affected by stream water quality. In addition, we felt that the state of the riparian zone needed greater emphasis than given in USHA. Therefore, in our BBN, UCI is dependent on "Instream habitat for invertebrates" (representing the physical habitat drivers identified by Suren et al. (1998)), water quality and riparian condition. The influence of the various stream attributes on "Instream habitat for macroinvertebrates" are defined by the coefficients of the factor analysis in USHA, and are described in Section 5 above. The influence of the various stream attributes on Riparian Condition and Water Quality for Invertebrates are based on the Riparian and Water Quality BBN, respectively.

8.2 BBN Conceptual Model

The BBN conceptual model for macroinvertebrates is shown in Figure 8-1 .

According to USHA, the macroinvertebrate community composition of Type 3 streams is driven predominantly by five habitat factors: bank modifications, bank heterogeneity, channel heterogeneity, % of stream banks with tall riparian vegetation, % macrophyte cover and % cover of organic matter (Suren et al. 1998).

Bank modifications include bank straightening and bank lining or reinforcing. These are artificial modifications determined as a result of landuse selections made by the user of the pilot sDSS, therefore in the BBN they were designated as root nodes with no parents. Bank heterogeneity (as defined in USHA) appears to be a product of these same two bank modifications, therefore was considered redundant and omitted from the BBN.

Channel heterogeneity refers to the variety in channel width, depth and flow velocity, i.e. the diversity of flow types (riffles, runs, pools, and chutes). In urbanising catchments, channel heterogeneity is often severely reduced during the morphological adjustment that results from altered hydrology. During this phase, riffles tend to get eroded and pools filled in, resulting in a more uniform stream bed (Gregory et al., 1994; MacRae, 1997; Pizzuto et al., 2000). These changes represent the main effect on channel heterogeneity. However, heterogeneity is also affected by bank modifications (yet to be incorporated into the BBN – see Section 10.2 Further Work) and by "roughness elements" in the channel. A common roughness element in urban streams is macrophytes, which tend to reduce water velocity and promote deposition of fine silt. Thus greater macrophyte growth leads to lower channel heterogeneity. The other main roughness element is coarse detritus, which may be natural or artificial. Natural detritus (large wood) is often depleted in urban streams due to past removal of woody riparian vegetation, channel "cleaning" or increased flooding. Artificial detritus (human rubbish), however, can be very high, so the overall amount of coarse detritus in an urban stream may be greater or less than before urbanisation. Detritus adds complexity to stream channels, forcing stream flow to take a more convoluted path downstream. Therefore, more detritus usually means greater channel heterogeneity. In addition to its effect on channel heterogeneity, macrophyte cover has a direct effect on the habitat for stream macroinvertebrates. Macrophyte leaves and the fine silt that accumulates around the base of stems provide habitat that is suitable for certain macroinvertebrates (e.g. snails, some crustaceans, and a few caddisfly and mayfly genera) but unsuitable for most (Collier 1995). Because fewer macroinvertebrates prefer macrophyte-dominated habitat than hard-bottomed habitat, streams with >50% cover of macrophytes score lower than those with <50% cover. Like macrophytes, organic matter alters the physical habitat for macroinvertebrates. In soft-bottomed streams, large wood or rubbish provide hard surfaces that are required by some macroinvertebrates and are otherwise rare. Coarse detritus therefore increases the habitat score. However, periphyton may overgrow hard surfaces and macrophytes may smother them by accumulation of fine silt, therefore these forms of organic matter reduce the habitat score.

In addition to the habitat factors identified in USHA, the macroinvertebrate community composition is affected by the condition of the riparian zone and by stream water quality. Riparian vegetation is critical to aquatic macroinvertebrates. As well as its effects on shading, strengthening of stream banks, filtering of overland runoff, and provision of large wood, riparian vegetation also provides the food base for the macroinvertebrate community and a habitat for the adult phases of aquatic insects. Riparian condition is a combination of three variables – the extent of the riparian zone planted (as a percent of bank length), the type of planting (grasses, flaxes, shrubs or trees) and whether the plantings are native or exotic. The highest scores are given to riparian zones fully planted in native trees.

The aspects of water quality that most strongly affect macroinvertebrate composition are water temperature, dissolved oxygen, suspended solids and toxic chemicals (in particular, zinc, copper and nitrate). For water temperature and dissolved oxygen, it is the extreme values that may eliminate certain macroinvertebrate species and thus determine the macroinvertebrate community composition. Maximum annual water temperatures are determined primarily by stream shading, though impervious surface also tend to increase temperatures. Minimum dissolved oxygen levels are determined primarily by the amount of aquatic plant growth, but also by deposits of fine organic material that accumulate in urban streams. Concentrations of toxic compounds are determined by a complex range of factors that are described in Section 4.

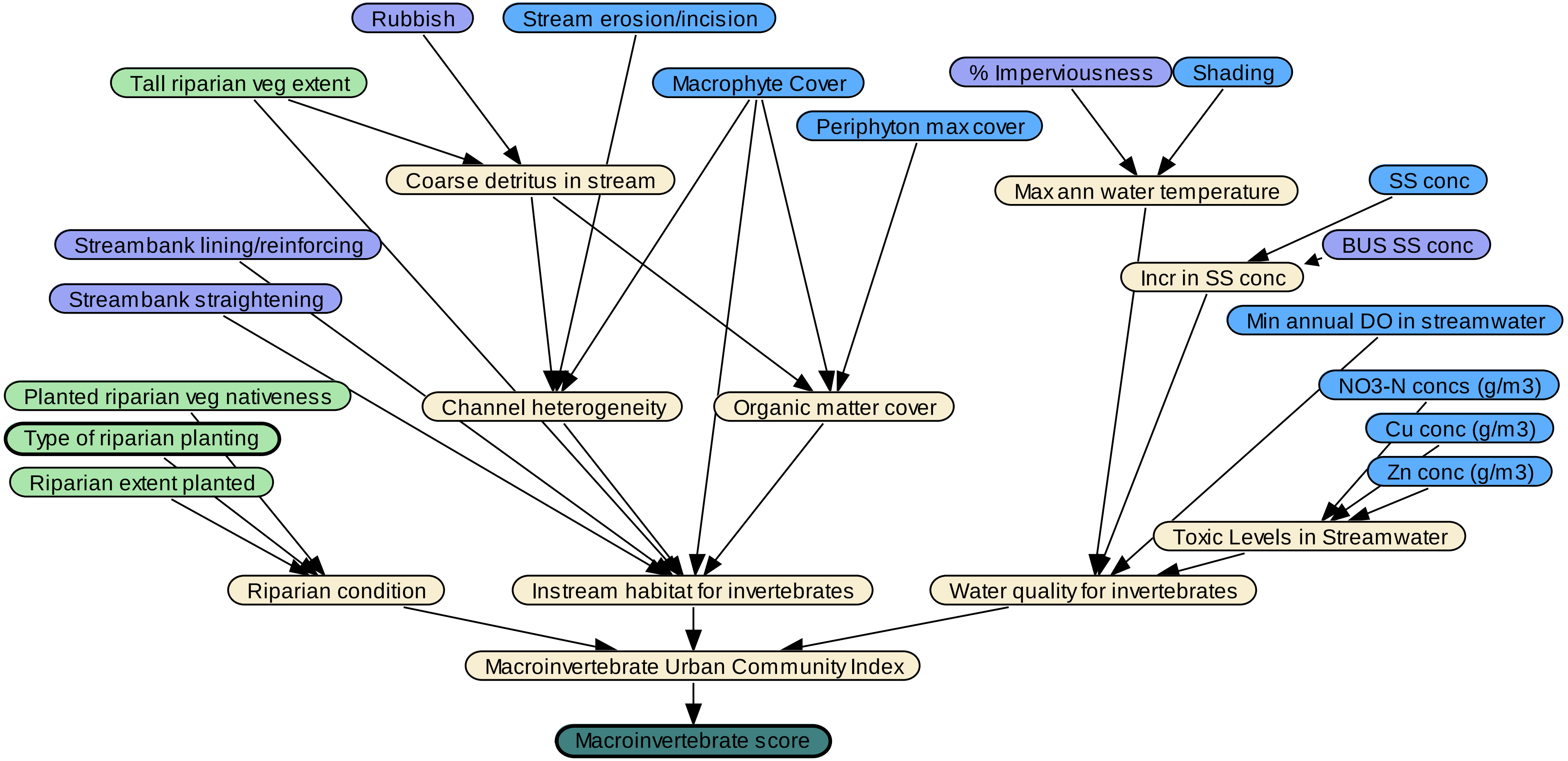

Figure 8-1: Conceptual model of the macroinvertebrate network from inputs driven by UDO attributes to major indicator (Macroinvertebrate score).

8.3 Nodes, states and relationships

Table 8-1: Macroinvertebrate network nodes, states, parents and relationships.

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
% imperviousness	7 unevenly spaced discretized continuous states, from 0 to 100%	C-CALM	Not applicable for root nodes	N/A
BUS SS conc	10 unevenly spaced discretized continuous states, from 0 to 100%	C-CALM	Not applicable for root nodes	N/A
Streambank straightening	5 discrete states: none, 1 to 25, 25 to 50, 50 to 75, more than 75%	Pilot sDSS	Not applicable for root nodes	N/A
Streambank lining & reinforcing	3 discrete states: not reinforced, partially reinforced, totally reinforced	Pilot sDSS	Not applicable for root nodes	N/A
Rubbish	3 discrete states: minimal, low, high	Pilot sDSS	Not applicable for root nodes	N/A
Tall riparian veg extent	4 evenly spaced discretized continuous states, from 0 to 100%	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Riparian extent present	5 discrete states: none, 1 to 25, 25 to 50, 50 to 75, more than 75%	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Type of riparian plants	4 discrete states: grasses, flaxes/sedges, shrubs, trees	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Riparian veg nativeness	3 discrete states: indigenous, occasional indigenous, exotic	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Stream erosion and incision	4 discrete states with values: none (1), natural (1), excess (0.7), severe (0.15)	Calculated in the hydrology network, see section 3	Calculated in the hydrology network, see section 3	Calculated in the hydrology network, see section 3
Periphyton cover	2 discrete states, < 30% cover; > 30% cover	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7
Macrophyte cover	2 discrete states: <50% or >50%	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7
Shading	3 states: less than 70%; 70-90% and >90%	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
SS conc	10 states, unevenly spaced discretized continuous variable from 0 to 300	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Min. annual DO	3 states, from 0 to 4; 4 to 6; 6 to 12 based on expert judgement	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
NO3-N conc	5 unevenly spaced discretized continuous states, from 0 to 10	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Copper conc	16 unevenly spaced discretized continuous states, from 0 to 1	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Zinc conc	15 unevenly spaced discretized continuous states, from 0 to 2	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Riparian condition	7 discrete states: intact native forest, exotic trees, native shrubs, exotic shrubs, sedges/flaxes/long grass, short grass, bare/artificial surface	Riparian extent present (existing+planted), type of riparian plants, riparian vegetation nativeness	Simple concatenation of information in parent nodes	Storey et al. (2011)
Max annual temperature	3 states: from 0 to 20; 20 to 25 and >25	% imperviousness Shading	Model prediction that 70% shade is sufficient to reduce water temperatures to <20C	Rutherford et al. (1997)
Increase in SS conc	2 states: less than 5 g/m3; more than 5 g/m3`	SS conc BUS SS conc	Increase in SS is more important than absolute level. Equation: SS conc – BUS SS conc	Quinn et al. (1992)
Toxic levels in stream water	2 discrete states: yes or no	Copper conc Zinc conc NO3-N conc	Based on exceedance of water quality guidelines: copper > 0.0013 mg/L; zinc >0.008 mg/L; nitrate >1.7 mg/L	ANZECC (2000); Hickey & Martin (2009).
Water quality for invertebrates	2 discrete states: poor, acceptable	Min. annual DO SS conc Max annual temperature Toxic levels in streamwater	Based on exceedance of thresholds. Poor if DO <5 mg/L; Increase in SS >5 mg/L; Temperature >20°C; Toxic levels = yes	Franklin (2010); Quinn et al. (1994); Quinn and Hickey (1990a); Maxted et al. (2005); Quinn et al. (1992); Hickey & Martin (2009)
Coarse detritus in stream	4 discrete states with values: none (0), depleted (10), natural (25), excess (50)	Rubbish Tall riparian veg extent	Natural state for rubbish is considered to be zero, natural state for tall riparian veg is 100%. Probabilities distributed among 4 coarse detritus states according to basic logic.	None required

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
Channel heterogeneity	2 discrete states: high or low	Stream erosion and incision Macrophyte cover Coarse detritus in stream	The state of each parent node given a value between 0 and 1. The probability of high channel heterogeneity is calculated as the product of all the parent node values. Parent nodes having stronger influence have a greater range of values than those with weaker influence (e.g. stream erosion=0.4-1; macrophytes=0.75-1;coarse detritus=0.7-1). Stength of influence estimated from references.	Gregory et al., 1994; MacRae, 1997; Pizzuto et al., 2000; Larson et al. (2001); Champion and Tanner (2000)
Organic matter cover	2 discrete states: detritus or none; algae or macrophytes	Coarse detritus in stream Periphyton cover Macrophyte cover	simple combination of information in parent nodes. Because states in periphyton and macrophyte parent nodes are broad, probabilities for organic matter cover states are rarely 100%.	None required
Instream habitat for invertebrates	3 discrete states with values: poor (0-1.067); medium (1.067-1.558); good (1.558-18.239)	Tall riparian veg extent Streambank straightening Streambank lining & reinforcing Channel heterogeneity Macrophyte cover Organic matter cover	Factor analysis of habitat variables in relation to change in macroinvertebrate community composition among 59 sites. Coefficients of the factor analysis used to parameterise the following equation: InvertHabitat (ChannHetero, Tallripveg, Chanstrght, Bnklin, Macrophytes, Orgcover) = (0.591*ChannHetero)+(0.235*Tallripveg)+(0.699*Chanstrght)+(0.48*Bnklin)+(0.211*Macrophytes)+(0.409*Orgcover)	Suren et al. (1998)
Macroinvertebrate urban community index	5 discrete states: low, lowmed, med, medhigh, high	Riparian condition Instream habitat for invertebrates Water quality for invertebrates	Macroinvertebrate communities are determined primarily by physical habitat, and secondarily by water quality. Riparian condition added according to expert judgment. These combined according to a “limiting factor” approach – a poor score in any one variable will result in a poor MUCI	Suren et al. (1998), Collier et al. (1998), Quinn and Hickey (1990b), Paul and Meyer (2001).

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
			score.	
Macroinvertebrate indicator score	5 discrete states: low, lowmed, med, medhigh, high	Macroinvertebrate urban community index	Deterministic, equivalent to parent node	

9 Details of the Fish Network

9.1 Development process

The distribution of individual fish species can be predicted for streams in New Zealand using a model based on the environmental predictors slope, distance to coast, flow stability, substrate, temperature, number of rain days, shade and low flow (Leathwick et al 2008). However as few of these factors are expected to change with urban development, that model is not of use for providing a fish score based on changes in urban development scenarios.

Predictive models have also been developed to establish changes in fish abundance under changing flow regimes (e.g., RHYHABSIM, WAIORA (Jowett et al 2004)). Such methods were investigated for predicting freshwater fish distributions based on changes in urban development scenarios. However, urban development does not consistently result in reductions in stream baseflow (Elliot et al. 2010). There are currently no other predictive models for freshwater fish diversity or abundance available.

An alternative approach to predicting a fish score was sought.

As native fish diversity varies naturally based on spatial attributes, any fish score must be considered relative to what is possible for any stream. For example, prediction of a fish richness (diversity) of 4 taxa may be considered a high score in a stream where only 4 taxa are likely to be present under natural conditions, but would be considered a poor score for a stream where 10 taxa are likely to be present under natural conditions. This is the basis of the Fish Index of Biotic Integrity, or IBI (Joy & Death 2004). The IBI is based on an “expected” or reference score, to which the score from observed data is compared. Under natural conditions, native fish distribution is dependent on factors such as habitat type, flow, altitude and distance from the coast (as most native fish are diadromous or migratory). The “expected” score can be predicted for streams in New Zealand based on environmental predictors (see Joy & Death 2004). For use in the pilot sDSS, the observed fish score was *predicted*, rather than *measured* as is the usual approach with the fish IBI. This concept of change in fish diversity and abundance from expected to observed was used to develop a fish score for the pilot sDSS.

The primary drivers of *change* in native fish abundance and diversity were established through literature review and consultation with freshwater fish scientists. These include changes in habitat, water quality, flow regime, food sources and the presence of physical barriers to migration. These were used to establish a simplified conceptual model leading to the prediction of a native fish score based on native fish abundance, native fish diversity and the pest fish abundance.

9.2 BBN Conceptual Model

The overall fish score is based on the three attributes of decline in native fish abundance, decline in native fish diversity and the increase in pest fish abundance. These three attributes are linked, both directly, and through their parent nodes (Figure 9-1). Increases in pest fish abundance are expected to result in decreases in native fish abundance, primarily through competition for food. Decreases in native fish abundance are expected to result in follow-on decreases in native fish diversity.

The major drivers of these three attributes were simplified to the following nodes:

- Physical habitat quality;
- Water quality;
- Presence of migration barriers; and for native fish;
- Changes in spawning habitat.

The presence of migration barriers is set at implementation, however the other nodes are predicted within the network, from other parent nodes which can be followed backwards to nodes that are either set during implementation (stream substrate); calculated by the pilot sDSS (streambank lining/reinforcing, streambank straightening, rubbish) calculated by C-CALM (% imperviousness) or set by the user as part of the UDO (extent of tall riparian vegetation). These are provided to the BBN as parent nodes (Figure 9-1).

Several of the nodes used in the fish network are calculated within other networks, such as the water quality variables to the right of the figure. These are imported into the fish network to enable the calculation of the final fish score.

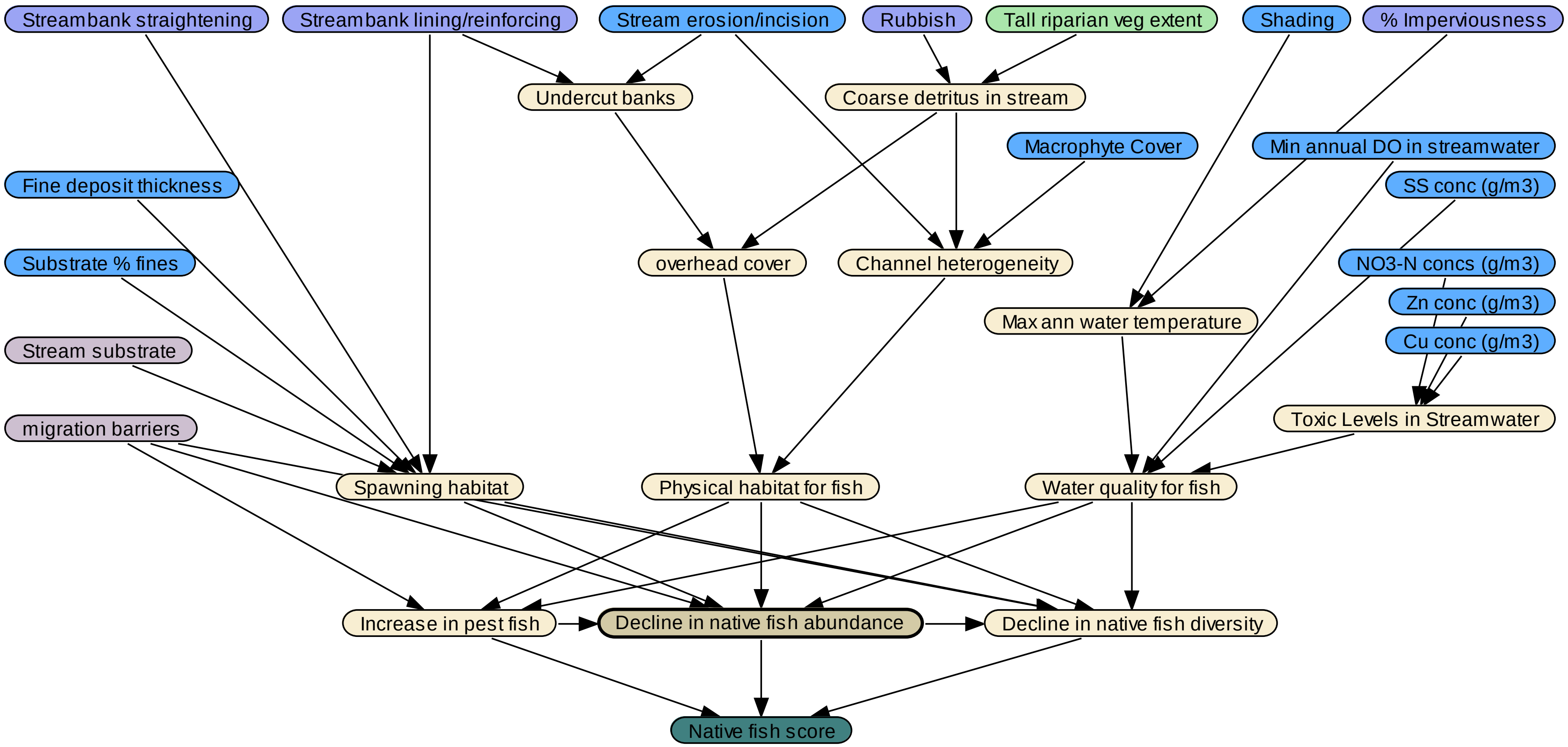

Figure 9-1: **Conceptual model of the fish network from inputs driven by UDO attributes to major indicator (Native fish score).**

9.3 Nodes, states and relationships

Table 9-1 lists all the nodes in the water quality network, describes the possible states for each, the parents (which can also be seen in Figure 9-1), specifies the information used to establish the relationship between the node and its parents; and provides references for these relationships. The colour coding in the table reflects the colour coding in the network diagram (conceptual model) above with the exception of the tan nodes which are not coloured in the table below.

Most of the nodes in the fish network are root nodes or are calculated in other networks. Of the remainder, the majority of the nodes are connected through expert judgement as there are few quantitative relationships available for predicting these nodes.

Table 9-1: Fish network nodes, states, parents and relationships.

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
% imperviousness	7 unevenly spaced discretized continuous states, from 0 to 100%	C-CALM	Not applicable for root nodes	N/A
Streambank straightening	5 discrete states: none, 1 to 25, 25 to 50, 50 to 75, more than 75%	Pilot sDSS	Not applicable for root nodes	N/A
Streambank lining & reinforcing	3 discrete states: not reinforced, partially reinforced, totally reinforced	Pilot sDSS	Not applicable for root nodes	N/A
Rubbish	3 discrete states: minimal, low, high	Pilot sDSS	Not applicable for root nodes	N/A
Tall riparian veg extent	4 evenly spaced discretized continuous states, from 0 to 100%	Defined by user of pilot sDSS	Not applicable for root nodes	N/A
Stream substrate	2 discrete states: soft or hard	Set at implementation	Not applicable for root nodes	N/A
Migration barriers	3 discrete states: none, partial or complete	Set at implementation	Not applicable for root nodes	N/A
Fine deposit thickness	2 discrete states: low or high	Calculated in the instream habitat network, see section 5	Calculated in the instream habitat network, see section 5	Calculated in the instream habitat network, see section 5

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
Substrate % fines	3 discrete states: low (<10%); medium (10-30%); high (>30%)	Calculated in the instream habitat network, see section 5	Calculated in the instream habitat network, see section 5	Calculated in the instream habitat network, see section 5
Stream erosion and incision	4 discrete states with values: none (1), natural (1), excess (0.7), severe (0.15)	Calculated in the hydrology network, see section 3	Calculated in the hydrology network, see section 3	Calculated in the hydrology network, see section 3
Macrophyte cover	2 discrete states: <50% or >50%	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7
Copper conc	16 unevenly spaced discretized continuous states, from 0 to 1	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Zinc conc	15 unevenly spaced discretized continuous states, from 0 to 2	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
NO3-N conc	5 unevenly spaced discretized continuous states, from 0 to 10	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
SS conc	10 states, unevenly spaced discretized continuous variable from 0 to 300	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Min. annual DO	3 states, from 0 to 4; 4 to 6; 6 to 12 based on expert judgement	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4	Calculated in the water quality network, see section 4
Shading	3 states: less than 70%; 70-90% and >90%	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7	Calculated in the aquatic plants network, see section 7
Max annual temperature	3 states: from 0 to 20; 20 to 25 and >25	% imperviousness Shading	Model prediction that 70% shade is sufficient to reduce water temperatures to <20C	Rutherford et al. (1997)
Undercut banks	2 discrete states: yes or no	Stream erosion and incision Streambank lining & reinforcing	Expert judgement	
Coarse detritus in stream	4 discrete states with values: none (0), depleted (10), natural (25), excess (50)	Rubbish Tall riparian veg extent	See macroinvertebrate network (section 8)	See macroinvertebrate network (section 8)
Overhead cover	3 discrete states: low; medium; high	Undercut banks Coarse detritus in stream	Expert judgement with probabilities distributed across 2-3 states	

Node	**Possible states**	**Parents**	**Information used to describe relationship between node and parents**	**References**
Channel heterogeneity	2 discrete states: high or low	Stream erosion and incision Macrophyte cover Coarse detritus in stream	See macroinvertebrate network (section 8)	See macroinvertebrate network (section 8)
Physical habitat for fish	3 discrete states with values: poor (0.1), okay (0.55), good (1)	Overhead cover Channel heterogeneity	Expert judgement, based on strength of the parent influences	
Toxic levels in stream water	2 discrete states: yes or no	Copper conc Zinc conc NO3-N conc	Based on exceedance of water quality guidelines: copper > 0.0013 mg/L; zinc >0.008 mg/L; nitrate >1.7 mg/L	ANZECC (2000); Hickey and Martin (2009).
Water quality for fish	3 discrete states with values: poor (0.1), okay (0.55), good (1)	Min. annual DO SS conc Max annual temperature Toxic levels in streamwater	Based on exceedance of thresholds. Poor if DO <4 mg/L; SS >50 mg/L; Temperature >25°C; Toxic levels = yes	Franklin (2010); Richardson et al. (1994; 2001); Rowe et al (2002; 2003)
Spawning habitat	3 discrete states: okay; minor decline; major decline	Streambank straightening Streambank lining & reinforcing Fine deposit thickness Substrate % fines Stream substrate	Expert judgement based on major influences on spawning habitat. Fine deposit thickness is a parent when stream substrate is ‘soft’; Substrate % fines is parent when stream substrate is ‘hard’.	
Increase in pest fish	2 discrete states with values: few (0.8), lots (0.1)	Migration barriers Water quality for fish Physical habitat for fish	Expert judgement, based on strength of the parent influences	
Decline in native abundance	3 unevenly spaced discretized continuous states: major decline; minor decline; no decline	Migration barriers Water quality for fish Physical habitat for fish Presence of pest fish Spawning habitat	Expert judgement, based on strength of the parent influences	
Decline in native diversity	3 unevenly spaced discretized continuous states: major decline; minor decline; no decline	Migration barriers Water quality for fish Physical habitat for fish	Expert judgement, based on strength of the parent influences. Cut-offs are higher than for ‘Decline in native abundance’ as changes in fish	

Node	Possible states	Parents	Information used to describe relationship between node and parents	References
		Decline in native abundance Spawning habitat	abundance are seen before changes in fish diversity	
Fish indicator score	5 evenly spaced discretized continuous states, from 0 to 1	Presence of pest fish Decline in native abundance Decline in native diversity	Expert judgement	

10 Summary and Recommendations

10.1 Summary

A complex series of overlapping networks has been developed for the pilot sDSS, to predict a set of seven indicators of stream ecosystem health from attributes of different urban development options. The networks have been developed through literature review and where possible, build on existing empirical models.

10.2 Further work

The BBNs described in this report remain the subject of on-going development. Their current state, as described in this report, reflects our understanding of key relationships between urban development and stream ecosystem health and has attempted to quantify these relationships from established literature, where available. However, our ability to quantify some of these relationships is limited and in a few places relationships may need to be altered or other factors included. Although limited testing of the pilot sDSS has been conducted (Moores et al., 2012), more is required as part of completing its development as an operational decision support tool. One aspect of that testing will be to examine the performance of the BBNs for a range of case study areas in order to guide their further development, revision or refinement. In particular, the following matters are noted as requiring investigation as part of that further development:

The Hydrology score was based on the “Natural Flow Regime” (NFR) function in the first version of the Stream Ecological Valuation (SEV; Rowe et al. 2008). SEV was designed to assess stream functions by visual observations during a single site visit and by data obtainable from maps and GIS layers. Because hydrology is difficult to assess from a single site visit, NFR uses a proxy variable, erosion, as evidence that the hydrology of a reach has changed. Thus it may not perfectly represent the cause-effect relationships for urban hydrology, and more work could be done to represent these better.

There is potential to further develop the way in which imperviousness is represented and how it influences stream flow regimes in the Hydrology network. At present, the BBN assumes that imperviousness is ‘connected’, meaning that all impervious surfaces discharge via a reticulated stormwater pipe network to a stream. In the BBN (as in reality) an increase in connected imperviousness results in higher peak flows, lower baseflows and a more ‘flashy’ flow regime. One way to mitigate these effects of imperviousness is to disconnect it from streams and to discharge stormwater to the ground via, for instance, biofiltration measures such as grass swales and rain gardens. In the BBN, the adoption of these types of stormwater management approaches (typically associated with LID) could be reflected in an ‘effective impervious’ variable, with a lower effective imperviousness associated with UDOs in which a greater proportion of land use is specified as LID.

Another consideration in further development of the hydrology BBN is the way in which the modification of the stream flow regime is represented. At present, this is based on the FRE3 metric which was adopted as a convenient indicator of stream flashiness for predicting stream erosion in the hydrology BBN. However, with stream erosion most influenced by small to medium floods (Walsh et al. 2004), further evaluation is warranted to determine whether another metric is more appropriate than FRE3 to represent flow variability in the hydrology network.

In the Habitat BBN stream channel erosion is influenced by median stream flow as a proxy for distinguishing between small, steep headwater streams and larger, low-gradient streams in their lower reaches. However, median stream flow can vary with factors other than gradient (catchment size for instance) and may not always correlate with erosion potential. Further development of the BBN should aim to investigate whether erosion potential is better predicted by some other measure, for instance by stream bed gradient directly.

In the Aquatic plants network, the relationship between shading and excess macrophyte growth was difficult to quantify due to a dearth of information. The level of shading required to avoid excess macrophyte growth (currently set at a threshold of 70%) will be refined after further literature review.

In the Macroinvertebrate BBN, the direct influence of hydrology on macroinvertebrates is not yet shown, but could be incorporated in future developments. The increased frequency of high flow events in urban streams can lead to reduced abundance and diversity of macroinvertebrates as invertebrates are repeatedly scoured from the stream bed (Death & Winterbourn 1995). Also in the Macroinvertebrate BBN, the effect of bank modifications on channel heterogeneity may be incorporated in a future version.

The Native Fish network relies heavily on expert judgement for the CPTs. This network should be further developed and refined where possible using measured data to develop quantitative relationships between nodes.

The BBNs have had little testing against measured data. This is an essential step and should include calibration of the networks at one location, to revise node states, values and CPTs and further validation of the networks at several different locations.

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