Development of a Spatial Decision Support System for Evaluating the Impacts of Urban Development on Waterbodies: Building and Testing the Pilot System

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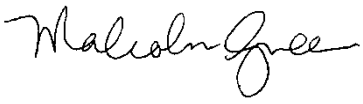

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Executive summary

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 sDSS incorporates a sustainability indexing system which integrates indicators of environmental, social, economic and cultural wellbeing and allows planners to consider these impacts holistically. This report describes progress in the development and testing of a pilot version of the sDSS over the three year period ending 30 September 2012.

The pilot sDSS has been designed and built as a single entity run from an MS Excel platform, calling on each of several constituent methods in a logical sequence. While some of these methods are also executed in MS Excel, others run on different platforms. The pilot sDSS is implemented by specifying a range of baseline characteristics in each of several 'planning units' (PLUs), representing the areas within which development can take place, and in each of several stream and estuary 'reporting units' (SRUs and ERUs), representing the receiving water bodies.

Once implemented, the system is run by specifying the attributes of an urban development scenario in each PLU in terms of its land-use mix, methods of land development, stormwater management, transport characteristics and stream management. These attributes drive models which predict changes in water and sediment quality and indicators of ecosystem health, providing a measure of environmental wellbeing in each SRU and ERU. The environmental indicators are in turn used as inputs to methods which evaluate effects on indicators of social wellbeing and on the resulting economic benefits arising from a given urban development scenario. These economic benefits are compared with the results of stormwater and stream management costing models to give an assessment of changes in economic wellbeing.

The pilot DSS has been tested by implementing it for the Lucas Creek catchment on Auckland's North Shore. This case study involved, firstly, evaluating the performance of the pilot sDSS at hindcasting the effects of historic urban development over the period 1960 to 2010 and, secondly, evaluating the performance of the pilot sDSS for discriminating between outcomes under alternative future urban development scenarios over the period 2010 to 2060. As a result of the case study, and in response to learnings gained as part of the broader development process, a number of tasks have been identified for the development of the sDSS as an operational tool. These include further testing, refinement of the existing methods, developing additional methods and enhancing the functionality and appearance of the system.

1 Introduction

1.1 Research Objective

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 sDSS is to incorporate a sustainability indexing system which integrates the measurement of environmental, social, economic and cultural impacts and allows planners to consider these impacts holistically.

The programme was initially funded by the Ministry of Science and Innovation[1] for a three-year period ending 30 September 2012. The objective was, by the end of this period, to have developed and tested a pilot version of the sDSS.

1.2 Background

New Zealanders have a strong economic, social and cultural connection with natural waters, making extensive use of them for recreation, industry, transport, fishing, trade and tourism. Waterbodies are a fundamental and irreplaceable part of how we define urban life in this country, as borne out by the iconic status of the Waitemata Harbour and Avon River in Auckland and Christchurch, respectively.

However, there is substantial evidence that urban development is harming the very waterbodies beside which our cities were founded. Urban development has resulted in the expansion of the built environment along the margins of many of our most highly valued waterbodies, along with their modification and use for the disposal of urban runoff. This has resulted in declining water and sediment quality, with consequential impacts on ecological and recreational values. Parts of Auckland's harbours, for instance, have suffered from increased rates of sedimentation, toxic metal accumulation, reduced ecological health and a growing unsuitability for recreation and the harvesting of shellfish (ARC, 2010).

These problems are compounded by a rapidly growing urban population - Auckland's population is estimated to increase to between 1.8 and 2.5 million by 2041 (Auckland Council, 2012); raised environmental expectations; and the potential for more extreme rainfall patterns and sea level rise associated with climate change (MFE, 2008). As a consequence, the value of urban waterbodies in providing for the economic, social and cultural needs of urban communities is under increasing pressure. Councils have identified a lack of methods and information to demonstrate and quantify the linkages between alternative forms of development and improved outcomes for our urban waterbodies as being a critical barrier in the planning of sustainable cities.

1.3 Reporting to Date

The development of the pilot sDSS has involved four key tasks:

[1] Since superseded by the Ministry of Business, Innovation and Employment (MBIE).

1. Designing the sDSS, which comprised defining its purpose, scope and the functionality required in order to achieve its purpose;
2. Building the pilot sDSS;
3. Testing the pilot sDSS;
4. Advancing relevant knowledge bases in order to inform the development of the sDSS and its potential extension beyond the term of the initial three year research programme.

The first of these tasks was reported in detail in a preceding report on the context, scope and design of the sDSS (Moores et al., 2011a, see also Chapter 2 of this report) and summarised in Moores et al. (2011b). The present report deals with the second and third tasks: building the pilot sDSS and testing it by implementing the system for a case study location. A number of supporting reports and other publications describe the advancement of relevant knowledge bases and development of methods which are used in the pilot sDSS. These include:

- a review of other sDSSs developed for urban water management (Semadeni-Davies, 2011);
- an assessment of methods for the development of a sustainability indexing system (Batstone et al., 2010);
- a description of the integration of a stormwater contaminant load model into the pilot sDSS (Moores and Semadeni-Davies, 2011);
- a review of marine ecosystem health indicators (Gadd, 2011);
- a description of the development of the method by which the pilot sDSS predicts indicators of urban stream ecosystem health (Gadd and Storey; 2012);
- descriptions of the development of a model for estimating the catchment scale life cycle costs of stormwater management (Ira, 2011; Ira et al. 2012a);
- descriptions of the development of the methods by which the pilot sDSS predicts social and economic indicators (Batstone et al., 2011; Batstone et al., 2012; Ira et al., 2012b);
- a description of the development of a framework for Maori cultural health assessment of urban streams (Tipa & Associates, 2012).

1.4 Structure of this Report

The remainder of this report is made up of the following chapters:

- Chapter 2 provides the background to the development of the pilot sDSS, including a summary of key points from the preceding report on its context, scope and design (Moores et al., 2011a) and the results of subsequent engagement with local government stakeholders, which has had a significant influence on the development of the pilot sDSS.

- Chapter 3 describes the design and build of the pilot sDSS, including its overall structure and individual components which constitute the methods by which predictions of indicator values are made.
- Chapter 4 describes the implementation and operation of the sDSS, summarising the steps involved in entering inputs, running the system and viewing outputs.
- Chapter 5 describes the testing of the sDSS for a case study location in the Auckland region, which included hindcasting the effects of historic urban development in order to verify the system and its implementation to assess the ability of the system for discriminating between outcomes of alternative future urban development scenarios.
- Chapter 6 describes the tasks that will be involved in progressing from the pilot to an operational sDSS and identifies a number of areas for further research which have the potential to lead to an expansion of the scope of the tool.

2 Background

2.1 Introduction

This chapter describes the background to the development of the pilot sDSS. Section 2.2 summarises key points from the preceding report on the context, scope and design of the sDSS. Section 2.3 describes the results of subsequent engagement with a range of local government stakeholders, which has had a significant influence on the development of the pilot sDSS.

2.2 Summary of Preceding Report

2.2.1 Overview

A preceding report (Moores et al. 2011a) describes the development of a 'Proof of Concept' version of the sDSS, including:

- the context within which this research is set, including identifying which of the many facets of urban development planning the sDSS is designed to support;
- the scope of the development of the sDSS, including identifying:
  - the links between urban development and effects on waterbodies;
  - the important characteristics of urban development that need to be represented as inputs to the sDSS;
  - the types of indicator for which predictions will be made as the outputs of the system; and
  - the relevant spatial and temporal scales over which the sDSS operates.
- key concepts for the design of the sDSS, including the steps involved in preparing and using the system, respectively;
- the 'Proof of Concept' version of the sDSS which was developed to apply, test and refine the design of the system; and
- the steps involved in progressing from the Proof of Concept to a Pilot sDSS.

The key points from this preceding report are summarised below.

2.2.2 Context and Role of the sDSS

Planning for urban development is multi-faceted and involves many different agencies. It includes making decisions about the:

- configuration and characteristics of different land uses;
- provision of infrastructure, for instance transport systems, water supply, drainage, energy distribution and communication networks;
- provision of key services, for instance health care, education and social services; and

- management of the environment, not only in relation to natural environmental values, but also in relation to the human use and enjoyment of both the natural and built environment.

While recognizing this multi-faceted and inter-connected nature of urban development planning, this research is primarily focused on assisting local government in its functions of: land-use planning; the planning of infrastructure for stormwater management; and management of receiving waterbodies in and adjacent to urban areas.

2.2.3 Scope of the sDSS

A description of the scope of the sDSS involves identifying: the links between urban development and its effects on waterbodies; the important characteristics of urban development that need to be represented as inputs to the sDSS; the types of indicator for which predictions will be made as the outputs of the system; and the relevant spatial and temporal scales over which the sDSS operates.

Effects of Urban Development

Figure 2-1 represents a simplified view of the way in which the values and services of urban water bodies can be affected by urban development. Urban development comprises a series of changes to the form and function of an area of land, including land-use change, the construction of transport infrastructure and the construction of infrastructure for managing stormwater. These changes are realised by the modification of the physical environment. The activities and outcomes which constitute the process of modification can be characterised as 'stress generators' because they are the source of a range of 'stressors' which have the potential to impact on the values and services of waterbodies. Stress generators (underlined) and associated stressors (in italics) include:

- Increased imperviousness, which alters the *hydrological characteristics* of stream and rivers, for instance by increasing peak flows and reducing baseflows;
- The exposure of areas of bare earth during construction; resulting in increased generation of *sediment*;
- Increased traffic volumes, resulting in increased generation of *contaminants* such as heavy metals and hydrocarbons;
- The use of certain building materials, also resulting in increased generation of *contaminants*;
- The collection and conveyance of runoff via reticulated stormwater systems to receiving waterbodies, exacerbating the effects of increased imperviousness on *hydrology* and providing a pathway for the discharge of *sediments and contaminants* to receiving waterbodies; and
- Modification of waterbodies and their margins, for instance the piping and channelizing of streams or reclamation adjacent to the coastal margin, resulting in *change or loss of aquatic habitat*.

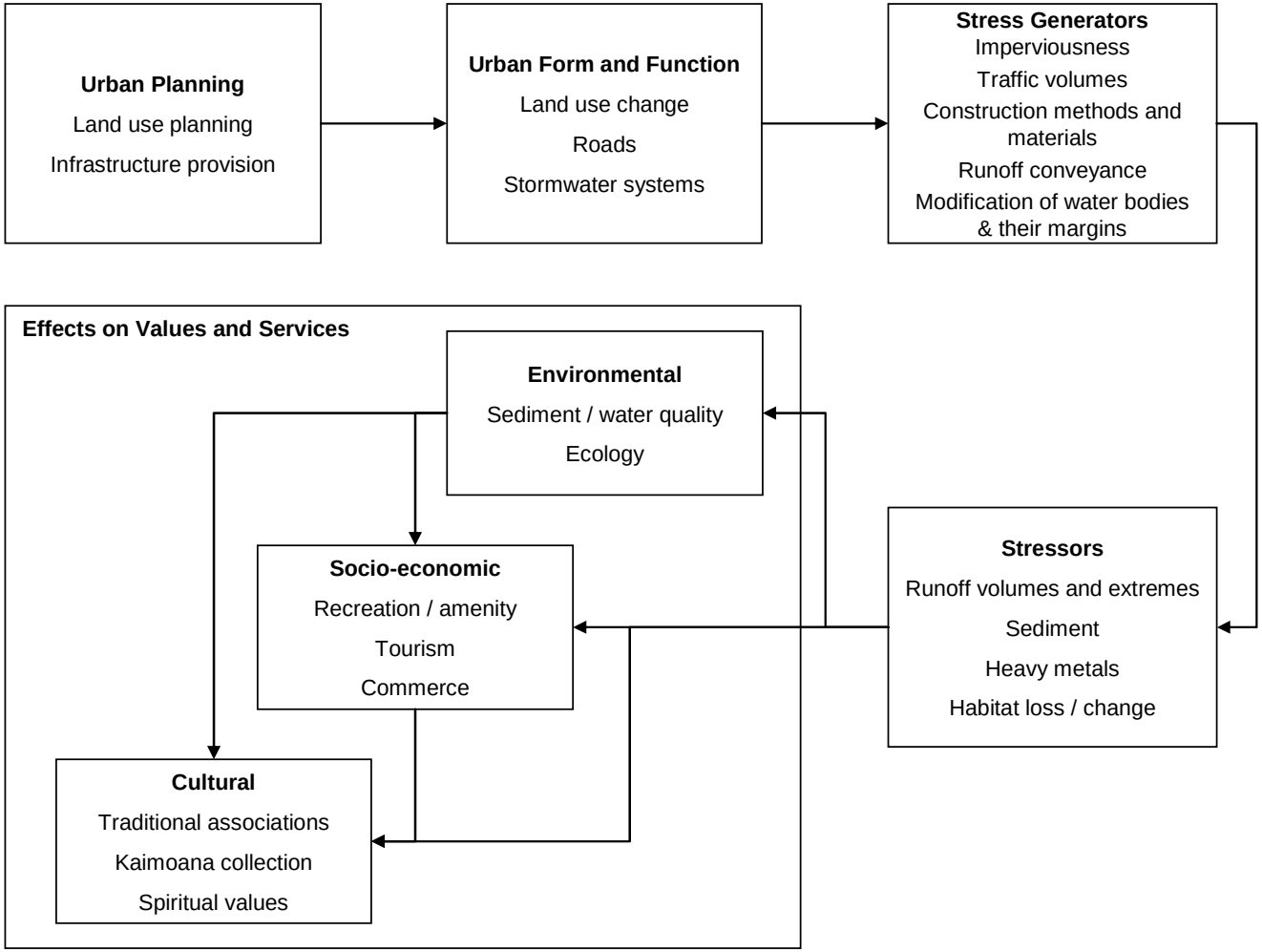


Figure 2-1: Representation of the relationships between urban planning, urban development and effects on the values and services of waterbodies. Examples to illustrate these relationships are shown (these are not intended to be comprehensive).

The end-point of the process by which urban development translates into impacts on aquatic environments is the interaction of the various stressors with the values and services of urban waterbodies. These interactions can be direct or indirect and can be of environmental, economic, social and/or cultural relevance. For instance, some of the direct environmental effects are:

- Increased rates of stream erosion and elevated metal concentrations in stream water;
- Increased rates of sediment accumulation and increased sediment metal concentrations in estuaries and harbours; and
- Reduced freshwater and marine biodiversity, for instance the loss of sensitive macro-invertebrates and fish species in urban streams.

Effects on the social and economic values and services of waterbodies can also be direct, for instance where the encroachment of coastal development results in reduced landscape values and restricted beach access. They can also be indirect, occurring as a result of the impacts of stressors on environmental values, for instance:

- a deterioration in recreational fishing opportunities and related tourism, for instance where fish stocks have been impacted by poor water quality;
- a reduction in use of a freshwater swimming hole, for instance as a result of stream bank erosion and pollution; and
- loss of revenue for commercial activities, for instance for beach front shops and restaurants due to declining beach and bathing water quality.

Effects on the cultural values and services of waterbodies can also be both direct and indirect. For Māori, an example of a direct effect is the denigration or loss of the spiritual value or *mauri* of water resulting from any inappropriate use or modification (MFE, 2005). On the other hand, the reduction or loss of opportunities to collect seafood (*kaimoana*) is an indirect effect, resulting from environmental changes such as sedimentation and increased sediment and water contamination leading to a reduction in fish or shellfish stocks.

Representing Urban Development in the sDSS

The representation of urban development in the sDSS involves identifying characteristics of key ‘stress generators’ which meet the following conditions:

1. They can be assigned values (quantitative or qualitative) thus allowing their use as inputs to the system;
2. Values associated with existing forms of urban development are known and robust projections of values associated with a range of future forms of development can be made; and
3. They can be used to make predictions (directly or indirectly) of the characteristics of one or more stressors, for instance the load of a contaminant or the relative condition of stream habitat.

Examples of characteristics which meet these requirements and which were identified as having potential for representing urban development in the pilot sDSS include:

- Areas and contaminant yields of different land covers and their proportions discharging to stormwater treatment devices, for the prediction of stormwater contaminant loads;
- Areas of impervious surfaces and their proportions discharging to stormwater quantity control measures, for the prediction of hydrological modification of streams; and
- Extent of riparian modification, for the prediction of stream habitat quality.

Representing Effects in the sDSS

While Figure 2-1 provides some examples to demonstrate the ways in which urban development impacts on the values and services of urban waterbodies, these relationships are in reality much more complex and diverse in nature. Clearly, this complexity represents a major challenge for the development of the sDSS. There are many types of effects; these are inter-related in all sorts of ways and, in many cases, relationships are not well defined or understood. The importance of different effects varies from place to place reflecting differences in the types of waterbodies, their character and the values and services associated with them.

The representation of effects in the sDSS therefore involves identifying the set of values and services associated with the waterbodies in any given urban area which:

- are, in themselves, of importance for the sustainable management of the water body;
- have the potential to act as indicators of effects on a broader set of values and services;
- are well understood with respect to the ways in which they are impacted by the stressors associated with urban development; and
- are able to be used in or inform the generation of a combined indicator(s).

The initial conceptualisation of the sDSS considered representing the effects of urban development using a system by which environmental effects and amenity effects were first scored individually and then aggregated to generate a combined indicator. The environmental score would measure effects on ecological values and services while the amenity score would provide an holistic measure of effects on economic, social and cultural values and services. Subsequent engagement with end-users led to the adoption of an alternative system, whereby indicators of the four wellbeings are generated and then combined (see Section 2.3).

Spatial and Temporal Scales

The sDSS needs to allow evaluation of alternative forms of development at the scale of enquiry typically adopted in high-level urban planning exercises. Growth areas are typically in the approximate range 1-10 km^2 (Auckland Council, 2012; GCUDF, 2007) with urban development within these areas often examined at the sub-catchment scale. In the Central

Waitemata Harbour and South-eastern Manukau Harbour contaminant accumulation studies (Green, 2008a; 2008b), urban development was represented at the scale of council-defined 'stormwater management units' (SMUs). SMUs in these two study areas range in size from 0.3 to 20 km^2. The same, or similar, spatial units are likely to be appropriate for the representation of urban development in the sDSS.

High-level planning exercises typically look to plan future development for periods of up to 40-50 years into the future (Auckland Council, 2012; GCUDF, 2007). However, the regional policy statements and district plans which prescribe the policies and rules giving effect to the direction set by high-level strategies and plans have to be reviewed at intervals of no more than ten years. This gives rise to the potential for the direction set in these strategies to change at any time over the 30-40 year planning horizon, although it should be noted that one possible outcome of a review is no change. Despite this uncertainty, it makes sense for the sDSS to provide for the evaluation of urban development over timeframes consistent with those over which high-level planning takes place, for instance as set out in the Auckland Plan (Auckland Council, 2012) and Greater Christchurch Urban Development Strategy (GCUDF, 2007).

2.2.4 Key Design Concepts

The sDSS can be visualised as comprising three distinct functional parts with a flow of information from each part to the next (see Figure 2-2). The first part of the system manages the input of data required by the system; the second part manipulates that data to make predictions; and the third part reports those predictions, including the synthesis of predictions (i.e., the combination of individual indicators). The management of input data and reporting of predictions are delivered via a user interface. However, the generation of predictions is invisible to the user and can occur in one or more of several different ways, for instance look-up tables, simple mathematical formulae and more complex models. The combination of methods might itself be different from one use of the sDSS to the next.

In order to develop the design of the sDSS, it was important to specify the steps that will be involved in, firstly, implementing and, secondly, running the system. Implementation involves getting the system ready to examine alternative development scenarios for a given study area. It will be a significant task relying on the expertise of the system developers and/or other researchers but will only need to be done once for any given study area. Once implemented the system is ready to use: it can then be run to investigate any alternative urban development scenarios the user chooses, within any constraints defined as part of the implementation process.

The following is a summary of the steps involved in implementing and running the system. Note that an important part of designing the sDSS was the development of a vocabulary that describes the functionality and components of the system in unambiguous terms. Key terms are defined in Appendix 1 and appear in bold where they first appear below.

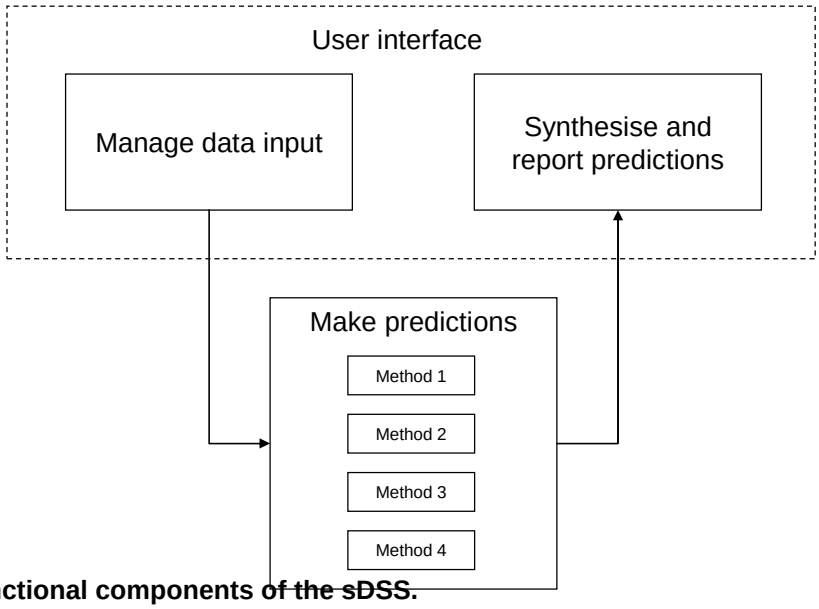


Figure 2-2: Functional components of the sDSS.

Implementation

Implementation is the preparation of the system to examine alternative development **scenarios** for a given **study area**. This activity is described here as a nine step process.

Steps 1-4 establish the spatial and temporal domain over which the system operates and the characteristics of system inputs:

1. Specify the study area, being the spatial extent within which scenarios are tested and inputs to the sDSS are required. Specification of the study area involves defining its external boundaries and also the internal boundaries between the spatial units for which system inputs are specified and outputs reported. These two types of spatial unit are:
   - **planning units (PLUs)**, which are the spatial units for which a unique form of urban development can be specified, possibly coinciding with council stormwater management units; and
   - **reporting units**, which are the spatial units for which **indicator** levels are generated by the system. The nature of these units is likely to vary between implementations, with at least two types readily distinguished: **stream reporting units (SRUs)** and **estuary reporting units (ERUs)**.
2. Specify the **study timeframe**, being the period of time over which the effects of alternative scenarios are investigated. Its specification will include establishing the dates of the following points in time:
   - $\mathbf{T_b}$, which is the time at which indicators for the **baseline system state (BSS)** are reported and also the start date for each scenario; and
   - $\mathbf{T_r}$, which is the time at which the indicators for each scenario are reported and which will coincide with relevant planning timeframes (say, of the order of 50 years or less)
   - $\mathbf{T_s}$, which is the time at which an urban development option commences.

- **T_d**, which is the time at which full development of an urban development option is achieved.

3. Specify the **baseline urban state (BUS)**, which is a representation of the form of urban development at time T_b. It is specified by defining the characteristics of each PLU in exactly the same way as described below in step 4.

4. Specify the **urban development options (UDOs)** that can be investigated and the relationships between **descriptive attributes** and **executive attributes**. Each UDO is a unique representation of the form of future urban development at time T_d. UDOs are specified at the scale of the planning unit. Each UDO is defined by a set of descriptive attributes and a set of executive attributes. Descriptive attributes describe the characteristics of the form of development at time T_d but play no part in generating system outputs. Executive attributes are assigned values which are used by the system to generate outputs, being predictions of future levels of indicators at time T_r. They are the independent variables in the system. Table 2-1 provides an example of two 'fictional' UDOs and their associated descriptive and executive attributes.

Table 2-1: Examples of Urban Development Options.

UDO number		1	2
UDO name		High intensity residential	Low impact residential
Descriptive attributes	**1 - housing type**	Apartments	Clustered individual dwellings
	2 - stormwater treatment	Limited retrofit	High performance treatment trains
Executive attributes	**1 - % impervious**	60 %	30 %
	2 – % contaminant removal	30 %	70 %

Steps 5-7 establish the characteristics of system outputs:

5. Specify the **indicator set** and **indicator attributes**. An indicator is a measure of the state of one environmental, economic, social or cultural attribute of a water body or land area, where 'attribute' means a value or service. The indicator set is the range of possible indicators which may be used to examine the outcomes of different urban development scenarios for any given implementation of the sDSS. The indicator set may differ from one study area to the next, depending on the characteristics of waterbodies present. Indicators may differ in a number of ways. They could be qualitative or quantitative. Quantitative indicators could be measured on a continuous or discrete scale. Those on a continuous scale may be constrained to a range between a maximum and minimum value. Those on a discrete scale will be constrained to fall into one of a number of classes.

6. Specify methods for generating **combined indicators**. A combined indicator is a measure representing the state of a water body or land area based on the

combination of the values of two or more environmental, economic, social or cultural indicators. There are two aspects of the generation of combined indicators which are of particular importance:

- the need to allow **weights** to be assigned to individual indicators (either pre-defined or assigned by end-users). A weight is a value which represents the relative importance of each indicator in a group of indicators which are being combined.

- the need to combine indicators which have different attributes. As noted above, some indicators may be measured quantitatively and others qualitatively. Such differences present a significant challenge for their combination. One method for resolving differences of this nature is to include an additional step in order to express indicators in a consistent format, for instance by assigning them a standardised **indicator score**. This score would be derived by converting the 'raw' score to a value on a scale common to all indicators. The scores for individual and combined indicators are also translated into **indicator levels** based on assigned ranges. For instance, if standardised scores are constrained to the range 0-1, then a score of less than 0.2 could equate with an indicator level of 1, 0.2-0.4 with level 2, and so on up to level 5.

7. Specify **indicator benchmarks**. It is likely that users will want to compare results with external data, for instance established guidelines, criteria or trigger values. These are defined here as indicator benchmarks, each being a value of an indicator associated with a particular environmental, economic, social or cultural condition or threshold against which indicator levels reported by the system can be measured.

Steps 8 and 9 establish the way in which the system generates outputs from inputs:

8. Specify relationships between executive attributes and indicators. The executive attributes of UDOs are the independent variables of the system while the indicators are the ultimate dependent variables. There are three parts to the specification of relationships between these two sets of variables:

   - Establish whether the relationship is direct or indirect. In any indirect relationship there will be one or more **intermediate variables** which act to predict the indicator level from the executive attributes of a UDO.

   - Establish the **predictive methods** for generating values of indicators and intermediate variables from executive attributes. These methods could include: building a link to an external model; specifying an empirical relationship; populating look-up tables (for example based on observations, the results of running models, expert knowledge or stakeholder surveys).

   - Establish the ways in which relationships between executive attributes, intermediate variables and indicators operate in space. As described in Step 4, UDOs are specified for planning units while indicator levels are generated for reporting units. There are a number of ways in which the

value of an indicator for a given reporting unit could be generated from the executive attributes associated with a UDO in one or more planning units, for instance "one to one" where indicator levels are generated for one reporting unit from the executive attributes of the UDO in one planning unit, or "many to one" where indicator levels for one reporting unit are generated by the executive attributes of UDOs in several planning units. The key to the definition of these relationships is being able to establish the extent to which development in different parts of the urban area influences outcomes in different parts of the receiving waterbodies. Some effects are likely to be local, some more widespread.

9. Validate the system by implementing and running it to hindcast the effects of historic urban development. This involves making predictions of the baseline system state (BSS, defined by the value of each indicator at time T_b) based on running the system for a specified preceding period of time over which the development of the BUS has occurred. The predicted indicator scores and/or the values of intermediate variables are compared with relevant available observations.

Running the sDSS

Once implementation is complete, the system is ready for use. This is a four step process. The first two steps represent decisions required of the system user:

1. Specify the scenario, which is a representation of the physical form of future urban development at the scale of the study area. A scenario is specified by the system user by selecting (or custom-defining) an urban development option (UDO) for each planning unit. The user will also specify the rate of development.

2. Specify reporting options, for instance to allow users to examine the results of scenarios with different combinations of indicators. This could include: allowing reporting of either or both individual indicator and combined indicator levels; allowing users to select methods of calculating combined indicators, providing more than one method has been specified as part of the implementation; and allowing users to assign weights to indicators or to select default weights.

The remaining steps generate and report the system outputs:

3. Run the system, which should be as simple as clicking on a menu item or button to make the system run.

4. View **results**, which are the set of levels for the selected indicators associated with a given scenario. Results could be in a number of formats, for instance:

   - Spatial, for example maps showing colour-coded ERUs or SRUs to represent indicator levels.

   - Tabular, for example numeric values (or probabilities) for each indicator and combined indicator, percentage change from BSS or percentage of indicator benchmark.

- Graphical, for example a colour coded report card, time series plots or 'Radar' (or 'Spider web') charts.
- Text, for example an 'audit trail' describing the scenario inputs, any selections made by the user, and results.

2.2.5 Proof of Concept Version

The design of the sDSS was examined for its conceptual soundness and functional performance through the construction of a ‘Proof-of-Concept’ (PoC) version of the system. This PoC version, while adopting deliberately simplistic methods and operating in a completely fictional environment, was developed to apply, test and refine the steps involved in the implementation and use of the system described in Section 2.2.4. It also provided a basis from which to identify and plan for the tasks which would be involved in building and testing the pilot sDSS.

The PoC was developed as a Microsoft Excel workbook comprising linked worksheets which mimicked the sequence of actions that would be available to users of the pilot sDSS. These actions include: making selections which control data inputs: accessing information to help guide the selection of these data; and reviewing outputs from the sDSS. Based on the selections made by the user, the PoC calculated intermediate variables, indicator levels and combined indicator levels using methods which mimic those proposed for the development of the pilot sDSS.

There were two iterations of the development of the PoC. The first version (‘UPSWv01.1.xls’) made predictions of an ecosystem health score and an amenity score for each SRU and ERU, in accordance with the original conceptualisation of the sDSS (see Section 2.2.3). This version is described in some detail in Moores et al. (2011a).

Subsequent engagement with end-users led to the adoption of the four wellbeings as the basis for the indicator system (see Section 2.3). A second iteration of the PoC (‘UPSWv02.1.xls’) was produced which incorporated this revised indicator system and which provided the template for the development of the pilot sDSS. Because the PoC has now been superseded by the pilot SDSS, the second iteration is not described further.

2.2.6 From PoC to Pilot sDSS

The development of the PoC resulted in the identification of three groups of methods that would need to be assembled (and possibly developed or modified) as part of the building of the pilot sDSS. Each group is associated with a sequential step in the prediction of outputs (indicator levels) from inputs to the sDSS (executive attributes of a UDO). The steps are (see Figure 2-3):

- Step 1 – Estimation of the levels of certain environmental stressors (intermediate variables) associated with the land use, stormwater management and other relevant characteristics (executive attributes of UDOs) of each PLU, for instance by using models to estimates loads of stormwater contaminants;
- Step 2 - Using these estimates of intermediate variable values, along with information on their effects, to predict the impacts of urban development (as measured by indicators) in each reporting unit, for instance by using models

which predict contaminant accumulation and consequent effects on the ecosystem health of waterbodies, and

- Step 3 – Combining or integrating individual indicator levels, possibly taking account of user-assigned weights, and reporting individual and combined indicator levels for each reporting unit.

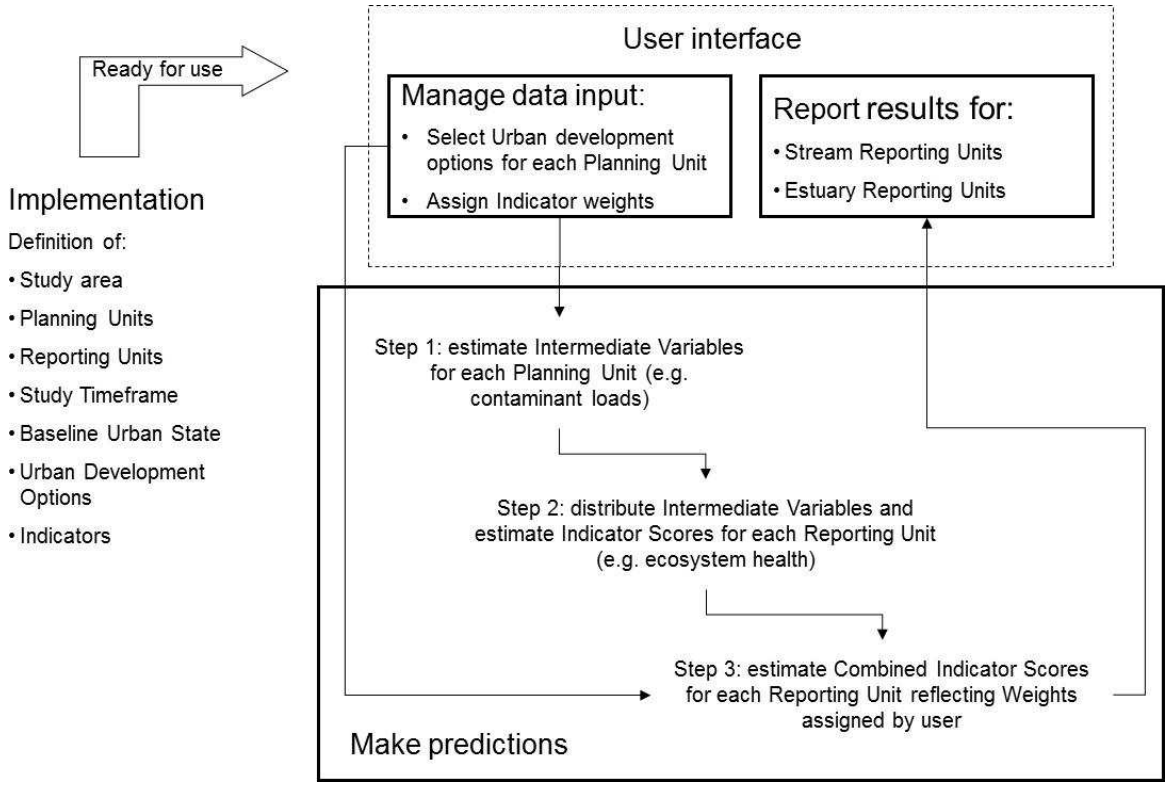


Figure 2-3: Requirements for the pilot sDSS showing the three method steps for prediction of combined indicator levels from the executive attributes of UDOs.

As well as needing to assemble and possibly develop or modify these three groups of methods, the development of the pilot sDSS also required:

- Development of a user interface that manages the input of data representing urban development scenarios and the display of results;
- Development of a structure within which a range of methods for generating predictions could be housed and which couples the methods to the user interface; and
- for selected case studies, populating the structure with relevant methods (which may have been existing, modified or new methods) and implementing the system with relevant input data in order to demonstrate the system.

2.3 Stakeholder Engagement

2.3.1 Overview

Stakeholder engagement is an essential part of this research programme in order to ensure that the sDSS will be fit for its intended purpose. Over the first 18 months of the programme,

a number of discussions were held with staff from Auckland Council (and one of its predecessors, Auckland Regional Council), Environment Canterbury and Christchurch City Council. These discussions provided some broad guidance on the purposes for which the sDSS might be used by councils and this helped the research team develop the first version of the PoC described in Section 2.2.5.

Councils indicated that the sDSS would most likely be used to aid 'high-level' urban planning over time frames of, say, 50 years. Its value might be through evaluating relative rather than absolute changes to urban water bodies. It could be used for communication and community engagement as well as being one of several sources of information used to support policy and planning decisions. As part of evaluating alternative urban development scenarios, council staff indicated that the sDSS should allow users to investigate not only the effects of alternative land uses but the mitigation of these effects, for instance through alternative stormwater management options. In both Auckland and Christchurch, future urban development will most likely occur as some variant of a 'compact city' approach. The sDSS should allow consideration of these different variants, including both greenfield and brownfield development. The effects of development over time, for instance at different points in the development cycle, are of interest. Sub-catchment or 'stormwater management units' of approximate size 1-10 km^2 are an appropriate scale at which to specify different development scenarios.

A workshop held in Auckland in late February 2011 aimed to build on these previous discussions by presenting the PoC and seeking feedback for the detailed design and build of the pilot sDSS. Unfortunately, due to the Christchurch earthquake of 22 February, council staff from Environment Canterbury and Christchurch City that had been planning to attend were unable to participate. However, in order that the development of the sDSS could continue to progress, the workshop proceeded with a solely Auckland focus. The outcomes of the workshop and the way in which these have influenced the development of the pilot sDSS are summarised below.

2.3.2 Influence of Engagement with Auckland Council Staff

The February 2011 workshop was attended by six Auckland Council staff representing a range of local government functions, including: urban planning, regional policy development and stormwater management. The workshop was centred on three themes:

1. **Making sure the sDSS is fit-for-purpose**: the sDSS provides guidance for councils on addressing the urban planning issues that face them; it operates at the right temporal and spatial scales; and it allows scenarios to be investigated that represent real planning options.

2. **Methods for the sDSS**: the methods used in the sDSS are robust and provide useful and appropriate information to councils; it makes its predictions based on a set of logical causal relationships; the representation of these relationships is an appropriate balance between capturing the complex behaviour of natural systems and simplification necessary to deliver the pilot tool within the timeframe and resources available to the project; wherever possible, these relationships are quantified with reference to relevant observations, model predictions and other relevant sources; and where this is not possible,

recognised experts are involved in providing any expert knowledge used to inform the system.

3. **Communication and stakeholder engagement**: the sDSS communicates effectively with users and other potential audiences, for instance technical, planning, political and community; indicators are meaningful to these different audiences; and results are displayed in ways each of these audiences can understand.

The workshop attendees were supportive of many aspects of the design of the PoC and provided guidance on modifications that could be made either in developing the pilot sDSS or as part of any subsequent, aspirational phase of the research. The proposed approaches for representing urban development and the methods by which environmental indicators would be predicted were generally considered appropriate and support was expressed for the development of these aspects of the pilot sDSS to continue as planned. Attendees identified a range of potential uses and audiences for the tool and engagement with a wider group of stakeholders was seen as an important part of any future extension of the research. Practical issues associated with delivery of an operational sDSS were also discussed, including the need for its future-proofing, allowing access by multiple stakeholders, ownership of intellectual property and visualisation methods that could be employed to allow communication to multiple audiences.

The most significant outcome of the workshop, in terms of its influence on the subsequent development of the pilot sDSS, was a suggestion to revise the dual indicator system adopted in the development of the PoC. The grouping of indicators as either ‘environmental’ or ‘amenity’ was shown to be inconsistent with the way in which councils are required to operate under the Local Government Act 2002 (LGA). Under the requirements of the LGA, councils must have regard to outcomes across the four wellbeings (environmental, economic, social and cultural) when making decisions. While, in the PoC, three of those wellbeings were captured holistically through the concept of amenity indicators, workshop attendees felt that a clearer alignment between the indicator system and the four wellbeings would make the sDSS better able to inform council decision-making processes. A related discussion on the communication of results identified a ‘traffic light’ approach as being well suited to a four wellbeing framework. A scorecard could be used to present the results for individual and combined indicators with scores being communicated by their colour, for instance green indicating the best possible score and red the worst possible score.

As a consequence of this feedback, a four wellbeings framework was developed as part of the second iteration of the PoC. Overall scores of each of environmental, economic, social and cultural wellbeing were calculated, based on the combination of relevant indicators developed in each of the four categories. The predictions of the PoC for each indicator were expressed using a simple three colour system: green, amber and red. With some further modifications, this framework provided the template for the indicator system adopted as part of the development of the pilot sDSS (described in Chapters 3 and 4 of this report).

While the impact of these revisions is most apparent in the way the sDSS looks, given that their focus was to better communicate the outputs of the sDSS in line with Council needs, the revisions also necessitated a number of fundamental changes to the predictive methods to be used in developing the pilot sDSS. Instead of amenity indicators, the system would now

need to make separate predictions of a range of individual economic, social and cultural indicators, each group of which would then be combined to generate scores for overall economic, social and cultural wellbeing. This represented a significant new challenge for the research and has led to the a number of significant methodological advances, as summarised in Chapter 3 and described more fully in various supporting documents (see Section 1.3).

3 Design and Build of the Pilot sDSS

3.1 Introduction

This chapter describes the design and build of the pilot sDSS, including its overall structure (Section 3.2) and individual components which constitute the methods by which predictions are made (Section 3.3).

3.2 Structure

3.2.1 Overview

The pilot sDSS operates as a single entity run from an MS Excel platform, calling on each of several constituent methods in a logical sequence. While some of these methods are also executed in MS Excel, others run on different platforms. Figure 3-1 shows the structure of the pilot sDSS, including the principal inputs and outputs and the methods by which outputs are generated.

The inputs to the system include:

- those entered at implementation, such as the number and size of PLUs, SRUs and ERUs and the relationships between them, characteristics of the BUS and receiving environments; and
- those entered by users of the system in order to represent the land use, land development, transport, stormwater management and riparian management characteristics of a UDO in each PLU.

The outputs generated by the system include:

- intermediate variables, which are generated by one method and used as an input to another; and
- indicators, which are reported both individually and in combination as wellbeings for each SRU and ERU.

There are three groups of methods; those which make predictions for PLUs, SRUs and ERUs, respectively. These methods, and the relationships between them, are summarised below and described in further detail in Section 3.3.

Note that the pilot sDSS does not yet include any cultural indicators.

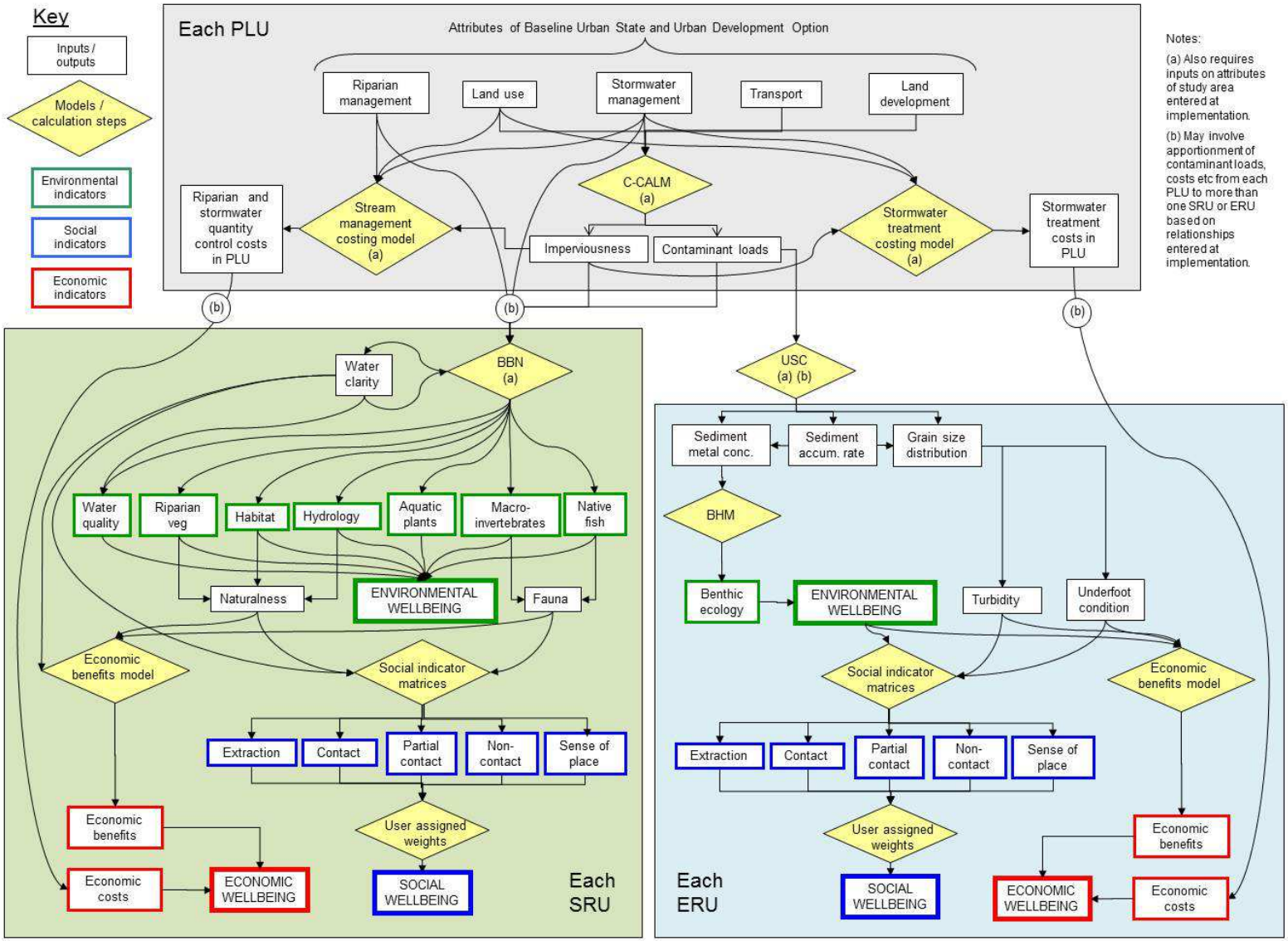


Figure 3-1: Structure of the pilot sDSS.

3.2.2 PLUs

There are three principal methods which make predictions for each PLU:

- The **Catchment Contaminant Annual Loads Model (C-CALM)**, which makes predictions of the level of imperviousness and annual loads of sediments, copper, lead and zinc for each year of the study timeframe based on inputs relating to land use, land development, transport and stormwater management characteristics;
- A **stream management costing model**, which makes predictions of the life-cycle costs of riparian management and stormwater quantity control over the study timeframe (from which the SRU economic costs indicator is calculated), based on inputs relating to the extent and quality of riparian planting and maintenance, stormwater management, land use and level of imperviousness (predicted by C-CALM); and
- A **stormwater treatment costing model**, which makes predictions of the life-cycle costs of stormwater treatment over the study timeframe (from which the ERU economic costs indicator is calculated) based on inputs relating to the extent and desired level of performance of treatment, land use and the level of imperviousness (predicted by C-CALM).

3.2.3 Apportioning outputs from PLUs

Where there is a one-to-one relationship between a PLU and an SRU or ERU, the outputs from the models described above are directly input into dependent methods making predictions for the relevant reporting unit. For instance, where a single SRU is associated with a single PLU, then the entire costs estimated by the stream management costing model are used to estimate the economic cost indicator and economic wellbeing for that SRU.

However, where more complex relationships exist between PLUs and SRUs or ERUs then the system first has to apportion the PLU outputs among the dependent reporting units. This is done according to the distribution of contaminant loads from each PLU to the dependent reporting units; the nature of which is established as part of implementing the system for the given study area. For example, prior or expert knowledge may indicate that the contaminant load generated in a given PLU is deposited in two ERUs in the ratio 3:1. This ratio would then be used in apportioning both the contaminant loads and associated stormwater treatment costs estimated for the PLU to the two recipient ERUs.

3.2.4 SRUs

Three principal methods make predictions for each SRU:

- A **Bayesian Belief Network (BBN)**, which makes predictions of seven indicators of stream ecosystem health based on inputs relating to: riparian and stormwater management characteristics, level of imperviousness and contaminant loads predicted by C-CALM, and various stream characteristics established as part of implementing the system;
- An **economic benefits model**, which makes predictions of the monetised environmental benefits of a UDO (the economic benefits indicator) based on the

change over the study timeframe in water clarity (as predicted by the BBN) and 'naturalness' and 'fauna' (based on combinations of indicators predicted by the BBN); and

- A set of **social indicator matrices**, which act as look-up tables for the prediction of five social indicators, four relating to use values and one to non-use values ('sense of place'), based on relative scores ascribed by focus group participants to combinations of the same three inputs used by the economic benefits model.

Once the indicators predicted by these methods have been normalised to a common scale they are used to generate scores for the environmental, economic and social wellbeing in each SRU as follows:

- Environmental wellbeing is the mean of the expected value (see Section 3.3.9 for an explanation of this term) scores for each of the seven indicators of stream ecosystem health determined from their probability distributions;
- Economic wellbeing is the (un-normalized) ratio of economic benefits to costs; and
- Social wellbeing is the weighted average of the five social indicators, based on weights assigned by the user of the sDSS.

3.2.5 ERUs

There are four principal methods that make predictions for ERUs. The first of these methods makes predictions for all ERUs through a single execution, in contrast to all other ERU (and SRU) methods, which are run independently for each reporting unit. This single method is:

- The **Urban Stormwater Contaminants (USC)** model, which makes annual predictions over the study timeframe of estuary bed sediment concentrations of copper, lead and zinc, sediment accumulation rates and sediment grain size distribution based on inputs of the contaminant loads predicted by C-CALM and various estuary characteristics established as part of implementing the system.

The other three principal methods which make predictions for each ERU are:

- The **Benthic Health Model (BHM)**, which predicts a benthic health indicator score from inputs of the estuary bed sediment concentrations of copper, lead and zinc predicted by the USC model;
- An **economic benefits model**, which makes predictions of the monetised environmental benefits of a UDO (the economic benefits indicator) based on the change over the study timeframe in environmental wellbeing, turbidity and underfoot condition (the latter two being derived from sediment grain size distribution predicted by the USC model);
- A set of **social indicator matrices**, which act as look-up tables for the prediction of five social indicators, four relating to use values and one to non-use values ('sense of place'), based on relative scores ascribed by focus group

participants to combinations of the same three inputs used by the economic benefits model.

Once the indicators predicted by these methods have been normalised to a common scale they are used to generate scores for the environmental, economic and social wellbeing in each ERU as follows:

- Environmental wellbeing is the normalised benthic health score[2];
- Economic wellbeing is the (un-normalised) ratio of economic benefits to costs; and
- Social wellbeing is the weighted average of the five social indicators, based on weights assigned by the user of the sDSS.

3.3 Description of Methods

3.3.1 Overview

The following subsections provide a summary description of each of the principal methods employed in the pilot sDSS, covering:

- the nature of the method (for instance what type of model it is and the platform that it runs on in the pilot sDSS);
- the role of the method in the pilot sDSS;
- the development of the method and, where relevant, its modification for the pilot sDSS;
- inputs to and outputs from the method; and
- how the method generates outputs from the inputs.

Subsection 3.3.9 summarises the methods used to generate combined indicator scores.

3.3.2 C-CALM

Nature

C-CALM is a simple deterministic model[3] that predicts annual catchment loads of certain stormwater contaminants based on annual yields for each land use and applying appropriate load reduction factors for various stormwater management characteristics. The version of C-CALM used in the pilot sDSS is coded in the C programming language and run as an executable by Visual Basic code in the pilot sDSS Excel workbook.

Role

The version of C-CALM used in the pilot sDSS makes predictions of the annual diffuse-source stormwater loads of sediments as well as total, dissolved and particulate copper, lead

[2] Other indicators of ERU ecosystem health have been identified in the conceptual development of the sDSS. The incorporation of methods for their prediction and the use of these indicators in generating ERU environmental wellbeing is noted as a matter for the further development of the system (see Section 6).
[3] C-CALM has been parameterised based on empirical observations of stormwater quality and the running of other, physically-based models of stormwater treatment devices.

and zinc generated in each PLU. These loads are used in the BBN to make predictions of urban stream water quality and in the USC model to make predictions of estuary bed sediment metal concentrations, sediment accumulation rate and sediment grain size distribution. Because C-CALM simulates contaminant loads based on inputs which include land use, it also calculates percentage imperviousness. This is used as an input by the BBN and both the stream management and stormwater treatment costing models.

Development

C-CALM was originally developed as a stand-alone planning tool that operates within a GIS software environment (Semadeni-Davies et al., 2010). It is based on Auckland Council's Contaminant Loads Model (CLM, Timperley et al., 2010) and is a more flexible, spatially distributed alternative to that model. It allows users to evaluate alternative stormwater treatment measures for reducing annual catchment contaminant loads in order to inform stormwater catchment management planning.

As well as changing the model platform, in order to incorporate C-CALM in the sDSS a number of other modifications were made. These are described in Moores and Semadeni-Davies (2011) and include further development of the model to generate:

- time series of annual load estimates (rather than for just a single year) based on changes in land use, traffic numbers and stormwater management over the study timeframe, also allowing for earthworks during development;
- sediment loads split into two size fractions as required by the USC model;
- loads of lead, which are not simulated in the original version of C-CALM or the ARC's CLM[4]; and
- copper, zinc and lead loads partitioned into dissolved and two particulate fractions as required by the USC model and the BBN.

In addition, the way in which stormwater treatment is represented in C-CALM was also simplified. In the original version of the model stormwater treatment can be specified by linking specific treatment devices to individual contaminant source areas. In the version used in the pilot sDSS, stormwater treatment is specified as a catchment-wide target applied to all contaminant sources in a given PLU.

Inputs and Outputs

C-CALM requires inputs for each PLU in the study area. These inputs are: the area of each PLU and characteristics of the BUS (both of which are entered as part of implementation), as well as the characteristics of the UDO as specified by the user. Inputs common to the representation of the BUS and UDO include:

[4] C-CALM simulates loads of sediments, copper and zinc based on the same contaminant source yields developed for the Auckland Council's CLM. Sources of lead are predominantly historical (lead based paints and additives to fuel) and since both the CLM and C-CALM are forward looking planning tools, neither simulate loads of lead. However, in the pilot sDSS lead is required as an input to the BHM. Lead yields for roofs were obtained from Kingett Mitchell and Diffuse Sources (2003). Lead yields for other impervious sources were derived from statistical relationships with TSS, zinc and copper loads in stormwater. Lead yields for pervious source types were estimated as being one order of magnitude less than zinc yields. It is noted that there is significant uncertainty in the estimation of lead yields from other contaminants, as the relationship can be expected to change over time as remaining sources of lead in the environment become depleted. This is noted as a task for further investigation (Section 6.2).

- the proportion of the PLU in each of several rural, residential, commercial, industrial and major road land use types; and
- the effectiveness of stormwater treatment in terms of % sediment removal and effectiveness for removal of metal contaminants (selected from options in the range 'high' to 'none' which translate to different % removal rates for dissolved and particulate metals).

Inputs specific to representing the UDO include:

- the time at the start and end of development and the trajectory of development between these dates (for instance, linear);
- the expected change in vehicle numbers over the entire study timeframe; and
- the type of contaminant source control (if any), which can be either: the replacement of high zinc-yield roofing materials (e.g. unpainted galvanised steel) with low zinc-yield materials (e.g, painted or coated galvanised steel); or the adoption of low yield brakes (copper) and tyres (zinc).

Outputs from C-CALM are, for each PLU: annual estimates of the percentage imperviousness and the stormwater loads of sediment, copper, lead and zinc in the particulate size classes ≤ 63 µm and > 63 µm and in the dissolved phase (metals only). The sDSS treats these contaminant loads as being discharged from a single point in each PLU (i.e. the catchment outlet).

Methods

Land use is represented by a set of common land covers or contaminant sources (e.g., roofs, roads, permeable surfaces) with each land-use type comprising a pre-defined proportion of these sources. For each PLU, the basic annual load calculation for each contaminant is:

$$L = \sum_{m=1}^{M} \left(\sum_{n=1}^{N} A_{m,n} Y_n (1 - T) \right), \quad (1)$$

where L is the annual load (kg year^{-1}), M is the number of land-use types, N is the number of contaminant sources, $A_{m,n}$ (ha) is the total area of source type n, Y_n (kg ha^{-1} year^{-1}) is the contaminant yield from source type n, and T (-) is the fraction by which the untreated contaminant load from all sources is reduced (i.e., the stormwater treatment level). In the case of roads, the contaminant yield is equal to a fixed yield per vehicle (kg ha^{-1} vehicle^{-1}) multiplied by the traffic volume (vehicles year^{-1}) such that an increase in traffic increases the annual load independently of the road area.

The areas of each contaminant source in each year over the study timeframe are calculated by interpolation between the land-use breakdown in the BUS and UDO, according to the time at which development starts and ends and the trajectory of development, all of which are specified by the user. The time series of percentage imperviousness is calculated by summing all impervious source types in each year. Contaminant yields remain constant for all sources other than roads, depending on user-specified inputs regarding growth in vehicle numbers and the application of vehicle source control (low-yield brakes and tyres). Vehicles with source control are assigned a lower per vehicle contaminant yield for copper and zinc. If

the user chooses to apply vehicle source control the existing traffic volume is converted to the lower yield progressively over time, and any increase in traffic volume is automatically assumed to have the lower yield. If the user specifies the replacement of high-yield roofing materials the contaminant yields do not change, rather, the area of each contaminant source is adjusted appropriately.

The load calculation for each PLU is complicated by allowances for earthworks during the development period and changes in stormwater treatment level between the BUS and UDO. There are two different earthworks categories: bulk earthworks (generated by changes from rural to urban land use and changes to major roads) and small-site earthworks (generated by changes between different urban land uses). Changes in land use during the development period are assumed to transition through the appropriate earthworks category first. For instance, if 5 ha of rural land use is to become urban over 5 years, and the development trajectory is linear, then there is 1 ha of bulk earthworks per year until development is complete. Changes in stormwater treatment are also applied progressively; any increase in area for a given land use is automatically treated at the UDO stormwater treatment level, while the existing area is assumed to be retrofitted from the BUS stormwater treatment level to the UDO stormwater treatment level over time following the development trajectory.

3.3.3 Stream Ecosystem Health BBN

Nature

The stream ecosystem health BBN is a probabilistic method which involves building a conceptual model of logical relationships between variables and quantifying the strength of these relationships using conditional probabilities (see Appendix 2 in Moores et al., 2011a for an overview of BBNs). The BBN has been developed using, and runs in, the software Netica v4.16 (Norsys). The pilot sDSS is able to automatically run the BBN, as well as pass input data and pick up outputs, via Visual Basic code through the Netica Application Programmer Interface (API).

Role

The BBN makes probabilistic predictions of the scores of seven stream health indicators in each SRU: water quality; riparian vegetation; habitat; hydrology; aquatic plants, macroinvertebrates; and native fish. As well as being reported individually, these indicators are also used to generate the environmental wellbeing score in each SRU and are inputs to the economic benefits model and social indicator matrices.

Development

The BBN was developed specifically for incorporation in the pilot sDSS (Gadd and Storey, 2012). Literature on existing methods for evaluating stream ecosystem health provided the basis for identifying indicators and building a conceptual model of independent and dependent variables and the relationships between them. Conditional probabilities (and in some cases deterministic relationships) were derived from a range of sources, including literature review, observations and expert judgement.

Inputs and Outputs

The BBN requires inputs for each SRU in the study area. A number of these are constant, being entered as part of implementation. The constant inputs include characteristics such as:

stream length, channel width, slope, substrate and median flow. Other inputs are time-varying and are a function of the development scenario under assessment. The time-varying inputs include characteristics of the riparian vegetation (extent and type) and stormwater management (extent and effectiveness) at the BUS and UDO and in the intervening years, based on interpolation, and the annual contaminant loads and percentage imperviousness calculated by C-CALM.

Outputs from the BBN are, for each SRU, predictions of the seven stream health indicators: water quality; riparian vegetation; habitat; hydrology; aquatic plants, macroinvertebrates; and native fish. These predictions are in the form of probability distributions for the scores to fall into one of five classes ranging from 'low' health to 'high' health. The manipulation of these distributions to generate a single expected value score to report for each indicator occurs later and is not part of the BBN (see Section 3.3.9). There is one other output from the BBN, that being a prediction of 'water clarity', required as an input to the stream economic benefits model and social indicator matrices. While water clarity is an intermediate variable within the BBN, its value in each year is reported for use in these other components of the sDSS (as could be any of the intermediate variables within the BBN).

Methods

An outline of the structure of the BBN is as follows:

- Key variables within the 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), which defines the probability of the node being in any one of its associated states given the state of the nodes which influence it (i.e., its *parent nodes*).

The independent variables of the system (i.e., the input variables) are known as *root nodes*, and do not have an associated CPT. The root nodes in the stream health BBN are the characteristics of the stream and BUS entered at implementation and of the UDO under assessment. Once the values of these inputs are entered the probabilities for all of the remaining nodes in the network are calculated using Bayes' Theorem. The probabilities are calculated as follows: if B_j denotes the j^{th} state of node B, and A_i denotes the i^{th} state of its parent node A, then:

$$P(B_j) = \sum_i P(B_j|A_i)P(A_i), \tag{2}$$

where $P(B_j)$ is the probability of B being in state j, $P(B_j|A_i)$ is the probability of B being in state j given that A is in state i, and $P(A_i)$ is the probability of A being in state i.

3.3.4 USC

Nature

The USC is a process-based model that makes predictions of the accumulation in the estuary of sediments and metals that are delivered in runoff from the land. The model is written in the Fortran programming language and is run as an external executable via Visual Basic code in the pilot sDSS Excel workbook.

Role

The USC makes predictions, at an annual time step, of the concentration of heavy metals in the estuary bed sediment, the sediment accumulation rate, and the bed-sediment grain size distribution in each ERU. The predictions are spatial averages over the ERU. The bed-sediment metal concentrations and grain size distributions are reported for the surface mixed-layer, which is typically 5–15 cm thick. The bed-sediment metal concentrations are used in the BHM to make predictions of a benthic health score, while the bed-sediment grain size distribution is used to derive turbidity and underfoot condition, both of which are inputs to the ERU social indicator matrices and economic benefits model. The bed-sediment grain size distribution is reported as the proportion of sediment in particulate size classes ≤ 63 µm and > 63 µm.

Development

The USC model was originally developed for application to simple estuaries that consist of a single “settling zone” (where settling of suspended sediments and associated contaminants is enhanced). This first version of the model, USC-1, was initially applied in Lucas and Hellyers Creeks, small embayments fed by a single tidal creek (Williamson et al., 1998). The USC-2 model was then developed to apply to more complex estuaries consisting of a number of interlinking settling zones and “secondary redistribution areas” (where waves and/or currents mobilise and redisperse sediments and associated contaminants). The secondary redistribution areas were limited to low energy. The USC-2 model was initially applied in the Upper Waitemata Harbour for the Auckland Regional Council (Green et al., 2004). In another iteration, the USC-3 model was developed to predict contaminant accumulation trajectories over the period 2001-2100 in the Central Waitemata and Southeastern Manukau Harbours (Green, 2008a; 2008b). These are more complex harbours containing secondary redistribution areas that are not limited to low energy. In each of these studies, the inputs to the USC were obtained by running a complex suite of other models and by conducting a significant field programme to collect data to validate the model.

The USC model as used in the pilot sDSS and referred to in this report is an “upscaled” version of the USC-3 model (the meaning of the upscaled term is explained below, see “Methods”). The upscaled version runs significantly faster than the original USC-3 model, which was necessary for its use in the pilot sDSS. The trade-off is a loss of temporal resolution of the predictions, which was not deemed to be a problem given the typical timescale (decades) of sDSS applications.

Inputs and Outputs

The USC requires parameters and initial conditions for each ERU in the study area to be entered as part of implementation. These include the area of each ERU and the thickness of the mixing layer (parameters), and initial bed-sediment characteristics including grainsize

distribution and surface-mixed-layer metal concentration. The USC also requires the connections between PLUs and ERUs to be specified. This involves entering sediment and metal “fate matrices”, which specify the proportion of the contaminant load generated in each PLU that is delivered to each ERU. These specifications can be based on prior knowledge (such as the results of a full USC-3 model run) or expert judgement. The remaining inputs to the USC are time-varying and are a function of the development scenario under assessment; these are the annual loads of sediment, copper, lead and zinc calculated by C-CALM.

The USC model outputs for each ERU time series of: copper, lead and zinc concentrations in the surface mixed-layer (kg metal / kg sediment); fraction of the surface mixed-layer that is composed of sediment grainsizes ≤ 63 µm in diameter; fraction of the surface mixed-layer that is composed of sediment grainsizes > 63 µm in diameter; and sediment accumulation rate (mm $year^{-1}$). Each output is a spatial average over the ERU. Predictions are output at an annual time step.

Methods

The (original) USC-3 model makes predictions at the scale of the subestuary (equivalent to an ERU in the pilot sDSS), which corresponds to km-scale compartments of a harbour with common depth, exposure and bed-sediment grainsize. The catchment is divided into subcatchments (equivalent to PLUs) on a similar scale, each of which is assumed to discharge through one outlet to the harbour. A long-term weather sequence is used to drive the model over time. The model time step is daily.

The model simulates the deposition of sediment that occurs under certain conditions (e.g., in sheltered parts of the harbour, or on days when there is no wind), and the erosion of sediment that occurs under other conditions (e.g., in parts of the harbour where there are strong tidal currents or on days when it is windy). It also simulates the dispersal of sediments and contaminants eroded from the land when it rains, and discharged (or “injected”) into the harbour with freshwater run-off.

Physically-based “rules” are used by the model to simulate the injection into the harbour of land-derived sediments and contaminants from the catchment when it is raining. These rules are based on prior catchment rainfall-runoff modelling. Another set of physically-based rules is used to simulate the erosion, transport and deposition of estuarine sediments and associated contaminants inside the estuary by tidal currents and waves. These rules are based on prior hydrodynamic modelling of the harbour, where this has been conducted, but could also be based on expert judgement.

The model builds up a set of predictions by “adding together”, over the duration of the simulation, injection and resuspension events and the subsequent dispersal and deposition of injected and resuspended sediment. In essence, the model simply moves sediment/contaminants between the various subcatchments and various subestuaries each time it rains (according to the rules), and between the various subestuaries to account for the action of waves of tidal currents (again, according to the rules). Mass is conserved in the model.

A key feature of the model is that the bed sediment in each subestuary is represented as a column comprising a series of layers, which evolves as the simulation proceeds. The sediment column holds both sediments and contaminants. The principal model output is the

change through time of the concentration of heavy metal in the surface mixed-layer of the column. The concentration of heavy metal in the surface mixed-layer is evaluated in the model by taking account of mixing of the bed sediment. Mixing of the bed sediment is caused by bioturbation and/or disturbance by waves and currents. Any number of layers in the sediment column that have been deposited since the beginning of the simulation may be included in the mixed layer. Mixing may also extend down into the pre-existing bed sediment (i.e., the bed sediment as specified by the model initial conditions).

The USC-3 model was adapted for use in the pilot sDSS by "upscaling" the original model. In essence, this involved converting the timescale of the original model from event to annual.

The upscaled model calculates the rate at which sediment is deposited in each subestuary (or ERU) at the base of the catchment in terms of mass at each time step as

$$D_{j,n} = \sum_{m=1}^{M} L_{j,m} F_{j,m,n} \tag{3}$$

where $D_{j,n}$ is the rate at which sediment in size class j is deposited in subestuary n (kg year^{-1}); $L_{j,m}$ is the total mass load of sediment in size class j derived from subcatchment m (kg year^{-1}); $F_{j,m,n}$ is the fraction of the sediment in size class j derived from subcatchment m that deposits in subestuary n (-); and M is the total number of subcatchments. The accretion rate in terms of thickness, $S_{j,n}$ (m year^{-1}), is then given by

$$S_{j,n} = \frac{D_{j,n}}{\rho A_n} \tag{4}$$

where ρ is the density of the deposited sediment (kg m^{-3}), and A_n is the area over which deposition occurs in subestuary n.

Given values for the "sediment fate matrix" $F_{j,m,n}$ (so-called because it describes the fate of sediment from each source) and the sediment loads and grain size distributions predicted by C-CALM, the upscaled USC-3 uses Equations (3) and (4) to predict sedimentation in each subestuary (ERU). Metals are dealt with in an analogous way in the upscaled model, but only the treatment of sediment is described here for brevity. The (original) USC-3 model predicts a sediment fate matrix at every time step of a simulation, using the procedure described above that is intended to simulate a range of physical processes. In contrast, the upscaled model requires the user to specify the sediment fate matrix, which is done as part of the sDSS implementation. This could be achieved by running the full (original) USC-3 model and extracting the predicted sediment fate matrix at one or more time steps through the simulation, or it could be simply estimated by applying expert judgement.

The upscaled USC-3 model runs significantly faster than the original USC-3 model, which was necessary for its use in the pilot sDSS. The reason is that the upscaled model is not having to do the calculations required to predict the sediment and metal fate matrices.

Although there is no provision made for it in the pilot sDSS, the sediment and metal fate matrices can vary with time through a simulation, reflecting changes in sediment-transport patterns as a subestuary fills with sediment.

Compared to the implementation of the original USC-3 model, the implementation of the upscaled model can be very simple, requiring as it does specification of the sediment and metal fate matrices. In contrast, the original USC-3 model requires specification of a large number of model parameters that it uses in a simulation to predict, at every time step, a sediment fate matrix and a metal fate matrix.

It should be noted that the upscaled model does not necessarily produce inferior results to the original model: if the same fate matrices generated by the original model are specified as input to the upscaled model, the same predictions of sedimentation and metal accumulation will be produced. The upscaled model will still run faster, as it is not doing the same calculations that the original models does to predict the fate matrices.

3.3.5 Benthic Health Model (BHM)

Nature

The BHM is an empirical model that predicts a benthic community health score based on estuary bed sediment quality. In the pilot sDSS the model calculations are made in a separate Excel spreadsheet called by Visual Basic code in the sDSS workbook.

Role

The BHM makes predictions, at an annual time step, of the benthic heath score in each ERU. At present this score is the sole environmental indicator for ERUs and so effectively doubles up as the environmental wellbeing score[5]. Environmental wellbeing is an input to the ERU social indicator matrices and economic benefits model.

Development

The BHM was developed from benthic community and sediment chemistry data collected under the ARC's Regional Discharges Project and State of the Environment monitoring programme (Anderson et al. 2002). The version of the model used in the pilot sDSS (Anderson et al., 2006) was constructed using data from 81 sites in the Auckland Region and then validated using data from a further 14 sites. Data for 102 benthic taxa were used for the model and canonical analysis of principal coordinates was used to relate the taxa data to bed sediment concentrations of copper, lead and zinc in the < 63 µm and < 500 µm size fractions. The equation developed for the latter size fraction is used in the pilot sDSS. The model has been further developed to include the influence of mud (Hewitt & Ellis 2010).

Inputs and Outputs

The inputs to the model are the annual bed sediment concentrations of copper, lead and zinc predicted for each ERU by the USC model. These are total sediment metal concentrations, corresponding with the inputs needed to predict benthic health from the < 500 µm version of the BHM used in the pilot sDSS.

The output from the BHM is a benthic health score falling in the range -2.781 to 2.198, where a lower score indicates better benthic health. Scores are assigned to one of five classes (healthy to polluted) based on intervals established as part of the development of the model

[5] Other indicators of ERU ecosystem health have been identified in the conceptual development of the sDSS. The incorporation of methods for their prediction and the use of these indicators in generating ERU environmental wellbeing is noted as a matter for the further development of the system (see Section 6.2).

(Anderson et al., 2006). In the sDSS a score is calculated for each ERU, for each year over the study timeframe.

Methods

The BHM predicts the benthic health score according to the following equation:

$$PC_{1.500} = 0.615(lnx_{Cu} - 2.472) + 0.528(lnx_{Zn} - 4.418) + 0.586(lnx_{Pb} - 2.925), \quad (5)$$

where $PC_{1.500}$ is the score (-), and x_{Cu}, x_{Zn} and x_{Pb} are the concentrations of copper, zinc and lead, (mg kg^{-1}) respectively, in the < 500 µm sediment size fraction.

3.3.6 Stormwater and Stream Management Costing Models

Nature

The stormwater and stream management costing models are empirically-based methods that predict the lifecycle costs of stormwater quality treatment, stormwater quality control and riparian management based on the characteristics of land use and stormwater management. In the pilot sDSS the model calculations are made in separate Excel spreadsheets called by Visual Basic code from the sDSS workbook.

Role

There are three costing models, one to predict the lifecycle costs (total and in each year) for each PLU of each of the following:

- stormwater quality treatment, which is used to generate the economic costs indicator in each ERU;
- stormwater quantity control, which is used to generate the economic costs indicator in each SRU; and
- riparian management, which is also used to generate the economic costs indicator in each SRU.

Note that the latter two models operate in combination to estimate the SRU cost indicator. For convenience they are shown in Figure 3-1 as a single method, being the ‘stream management costing model’.

Development

The costing models were developed specifically for incorporation in the pilot sDSS (Ira, 2011). The models for stormwater quality treatment and stormwater quantity control were developed by using a stormwater device-scale model, $COST_{nz}$, to estimate representative catchment-scale costs under various scenarios. $COST_{nz}$ was developed under a Landcare Research-led programme into low impact design (LID) as a tool for estimating the acquisition (except land) and maintenance costs of a wide range of stormwater management devices based on catchment and device characteristics (Ira et al., 2008).

For the development of the catchment-scale costing models required by the pilot sDSS, a range of plausible catchment management scenarios were developed, each of which included a particular configuration of devices that would achieve a target level of performance (either reduction in sediment loads or level of runoff attenuation). $COST_{nz}$ was

then used in order to establish relationships between level of performance and cost. For stormwater treatment, separate relationships were established for three alternatives: 'end-of-pipe', 'at source' and a combination of the two. Different 'end of pipe' devices were investigated to establish costs associated with treatment that is likely to vary in terms of effectiveness for removal of metal contaminants. Additional analysis was conducted in order to allow the estimation of land acquisition costs for two types of urban development (greenfield and brownfield) as these costs are not estimated by $COST_{nz}$.

The riparian management costing model was developed based on a literature review of the costs associated with riparian restoration (Ira, 2012). Costs for different types of riparian planting and levels of maintenance effort were estimated.

Inputs and Outputs

Inputs to the models are, for the BUS and UDO in each PLU:

- for the stormwater quality treatment costing model, the land use and stormwater management characteristics; and the sediment load and percentage imperviousness calculated by C-CALM;
- for the stormwater quantity control costing model, the land-use characteristics; and the percentage imperviousness calculated by C-CALM;
- for the riparian management costing model, the riparian management characteristics.

Outputs are the total life-cycle costs associated with the change in stormwater treatment, stormwater quantity control and riparian management between the BUS and UDO. The life cycle costs are calculated as the present value of all related expenditure over the analysis period.

The apportionment of these costs to dependent SRUs and ERUs occurs as a subsequent step and is not part of the costing models (see Section 3.3.9).

Methods

The derived relationships between stormwater / riparian management characteristics and costs have been used to populate a series of look-up tables. Acquisition (except land) and maintenance costs are calculated by querying these tables and scaling the unit costs they provide by PLU area. Land costs are calculated separately by multiplying acquisition costs by a 'land cost' factor which distinguishes between greenfield and brownfield land.

Note that the acquisition costs component of the lifecycle costs are estimated based on the change in stormwater and riparian management between the BUS and UDO. It is the additional stormwater treatment and riparian management that is costed. In scenarios where there is no change in the extent or level of stormwater treatment, the model is still called on to calculate maintenance costs despite there being no acquisition costs.

3.3.7 Economic Benefits Models

Nature

The economic benefits models are empirically-based methods that predict the monetised benefits of changes over the study timeframe in two sets of environmental attributes, one set each for streams and estuaries. In the pilot sDSS the model calculations are made in separate Excel spreadsheets called by Visual Basic code from the sDSS workbook.

Role

The two models predict the economic benefits indicator for SRUs and ERUs, respectively. These benefits indicators are used in the prediction of Economic wellbeing.

Development

The economic benefits models were developed through a technique referred to as benefit transfer in which the results of previous research described in Kerr and Sharp (2003) and Batstone et al. (2008) are applied to the pilot sDSS PLUs. The economic benefits were assessed through non-market valuation of changes to the characteristics of urban streams and coastal waterbodies using a method known as a choice experiment. This is a survey technique that asks survey respondents to choose which alternative future scenario they would prefer from each of several "choice sets" and how much they would be prepared to pay to attain the preferred outcome. In the process of developing the choice experiments, it was found that the estuarine attributes of most importance to people were water clarity, the quality of underfoot conditions and ecological health; while the stream attributes of most importance were water clarity, channel shape, riparian vegetation, fish habitat and diversity/abundance of native fish species.

The results of the coastal waterbody choice experiment were readily developed into a method for predicting ERU economic benefits, since the attributes of water clarity, underfoot conditions and ecological health are predicted by (or can be predicted from other outputs of) the USC and BHM models. While the five attributes influencing preferences in relation to urban streams are predicted (or could be predicted from other outputs of) the BBN, in developing the method for predicting SRU economic benefits it was determined to consolidate these attributes into three: water clarity, 'naturalness' and 'fauna'. This decision reflected a desire to achieve consistency with the attributes used in deriving social indicators, for which any more than three was considered impractical (see Section 3.3.8).

Inputs and Outputs

Inputs to the models are, at the start and end of the study timeframe:

- for the SRU economic benefits model: water clarity, 'naturalness' (calculated from the BBN-generated indicators riparian vegetation, habitat and hydrology) and 'fauna' (calculated from the BBN-generated indicators macro-invertebrates and fish);
- for the ERU economic benefits model: environmental wellbeing (the normalised benthic health score), turbidity and underfoot condition (both derived from the USC-generated grain size distribution);

The output is the willingness to pay (WTP) for the change in the conditions of each SRU and ERU between the start and end of the study timeframe. This is the economics benefit indicator.

Methods

The derived relationships between the attribute choice sets and WTP have been used to populate a series of look-up tables. The WTP per household is calculated by querying these tables based on the change in each attribute over the study timeframe. The economic benefits indicator is then calculated by multiplying the WTP by the number of households, which varies depending on the likely extent of the benefits. Where a water body is of local significance, the number of households is calculated from land use within the contributing PLUs. Where a water body is deemed to be of regional significance, then the number of households is estimated from the total population of the greater urban area. In the case study implementation of the pilot sDSS (see Chapter 5) it was assumed that the economic jurisdiction (Bateman et al. 2006) coincides with the study area boundary.

3.3.8 Social Indicator Matrices

Nature

The social indicator matrices are empirically-based methods that predict a number of use and non-use values of urban waterbodies based on two sets of environmental attributes, one set each for streams and estuaries. In the pilot sDSS the matrices are queried in separate Excel spreadsheets called by Visual Basic code from the sDSS workbook.

Role

The matrices predict scores for extraction (fishing, harvesting and provision services), contact, partial contact and non-contact activities (as categories of activities enabled by differing levels of ecosystem services), and sense of place in each SRU and ERU. These indicators are based on the notion of water quality categories that reflect enhancements to ecosystem services (Van Houten et al. 2007) and are used in the prediction of social wellbeing. This wellbeing indicator and its contributing precursors are assessments of the state of the system in socio-economic terms. Through those elements it embraces use and non-use values including option value, and sense of place, defined as a multi-dimensional construct that embraces cognitive, affective and conative relationships with the streams and estuaries (Jorgensen and Stedman, 2001).

Development

The development of these methods was founded on the notion that the environmental attributes used to derive estimates of WTP in the choice experiments described in Section 3.3.7 could also be used as a basis for predicting the suitability of waterbodies for the specific activities described above (Batstone et al., 2012). Expert elicitation methods (Burgman, 2005; Burgman et al. 2011) were used at focus group sessions held in Auckland and Christchurch to develop and trial a visual analogue method to derive assessments of the experienced utility (Kahneman and Sugden, 2005, Hajkowicz et al. 2008) effects of changes to these environmental qualities. Attendees at the focus groups were members of the public selected by a market research company as being broadly representative of the wider urban population, while also being known to take part in water-based activities. The attendees were

asked individually to identify best, worst, and most frequently encountered scenarios of the attribute combinations, then assign scores to combinations of varying quality (high, medium, low) in environmental attributes for specified types of activity and for one non-use category (sense of place). The number of attributes was limited to three because of the cognitive difficulties of representing and attempting to assign scores to combinations of any greater number of attributes. This led to the consolidation of stream attributes previously used in the stream choice experiments (from five to three, as noted above). The results of the focus group sessions were used to derive weighted-average scores for each combination of attribute quality that are assumed to be representative of the wider urban population.

Inputs and Outputs

Inputs to the matrices are:

- for the SRU matrices: water clarity, 'naturalness' (calculated from the BBN-generated indicators riparian vegetation, habitat and hydrology) and 'fauna' (calculated from the BBN-generated indicators macro-invertebrates and fish);
- for the ERU matrices: environmental wellbeing (the normalised benthic health score), turbidity and underfoot condition (both derived from the USC-generated grain size distribution);

The outputs are scores on the scale 0-10 in each SRU and ERU for each of the five social indicators: extraction, contact recreation, partial contact recreation, non-contact recreation and sense of place.

Methods

Respondents made their own assessments of the reliability of their responses through a ten-point scale. This information was used to identify and exclude potentially unreliable scores (reliability less than 8 out of 10), and to weight utility scores retained for inclusion in the sDSS lookup tables. These derived relationships between the attribute sets and representative experienced utility scores have been used to populate a series of look-up tables. Each indicator score is calculated by querying these tables based on the predicted values for each of the three attributes in the SRU and ERU attribute sets, respectively.

3.3.9 Indicator Combination

The combination of indicators toward an overall sustainability indicator is limited to the level of indicators for each of the four wellbeings. The rationale for this approach is based in four considerations:

- loss of information,
- lack of meaning,
- difficulty in interpretation, and,
- construction issues such as double counting of influences.

The calculation of scores for each of environmental, economic and social wellbeing is described below.

SRU Environmental Wellbeing

SRU environmental wellbeing is derived from the seven indicators predicted by the BBN. As noted in Section 3.3.3 the outputs of the BBN are provided as probability distributions of the indicators falling into one of five classes, covering 'low' to 'high' stream health. Before these indicators can be combined it is necessary to generate a single numeric score for each. The first step is to assign numeric scores to each of the five classes: these are the midpoints of five equal intervals on the scale 0 to 1. A value of 0.1 therefore represents the lowest stream health class and 0.9 the highest stream health class. A single numeric score for each indicator is then calculated as the expected value ($\mathrm{E}[\mathrm{X}]$) from the probability distribution:

$$\mathrm{E}[\mathrm{X}] = \sum_{i=1}^{5} x_i p_i \tag{6}$$

where x_i represents the score assigned to stream health class i, which has probability p_i of occurring. This is essentially the weighted average of the distribution predicted by the BBN.

The expected values of the seven indicator scores are then used to calculate the environmental wellbeing. At present this is simply the mean of the seven scores. However, the pilot sDSS could easily allow weights to be assigned to each of the seven indicators in order to calculate a weighted average. Derivation of such weights could be based in expert elicitation processes using formats similar to those used in the derivation of the social wellbeing score (see below) to reflect knowledge that, in a certain study area, stream ecosystem health is better characterised by some of the seven indicators than by others.

ERU Environmental Wellbeing

As noted previously, the benthic health score is presently the only environmental indicator for ERUs. Environmental wellbeing is the normalised value of the benthic health score on the scale 0-1. This normalisation is required in order that the environmental wellbeing score can be assigned to categories corresponding with intervals of 0.2, as required to make predictions of the social and economic benefits indicators. Normalisation of the benthic health score also makes it compatible with future combination with other (normalised) ERU environmental indicators as these are added to the sDSS.

Economic Wellbeing

Economic wellbeing is the ratio of the economic benefits and economic costs indicators expressed in common-base-year dollars. While the economic benefit indicator is calculated directly from environmental attributes within each SRU or ERU this is not the case for the economic costs indicator. Costs are calculated for each PLU by the stormwater and stream management costing models. These costs must then be apportioned between dependent SRUs and ERUs, which occurs in accordance with relationships entered as part of implementation of the sDSS. Stormwater treatment costs, for instance, are apportioned in accordance with the proportion of the contaminant load generated in each PLU which is delivered to each ERU. At present, however, the cost models used in the sDSS do not incorporate an assessment of UDO transaction costs, and thus scenarios may arise for which there is zero cost (for instance, a UDO which involves no stormwater treatment). Under such scenarios, the economic wellbeing is undefined because the denominator of the ratio is zero. While such scenarios are unlikely to occur, their theoretical existence under the present cost framework makes it difficult to apply the normalisation processes used

elsewhere in the sDSS. Recognition of this issue implies the need to incorporate an assessment of UDO transaction costs in future applications of the sDSS.

Instead of reporting economic wellbeing on the normalised scale 0-1, the raw value for the ratio is reported as falling into one of five classes. The middle class represents the situation where benefits and costs are approximately the same, i.e. a neutral benefit-cost ratio. Likewise, the two classes above the middle represent increasing magnitudes of benefit-cost ratios of greater than 1, while the two classes below the middle class represent decreasing magnitudes of benefit-cost ratios of less than 1. If a negative benefit is predicted (i.e. indicating deterioration in environmental quality) then the economic wellbeing is automatically assigned to the lowest class. Finally, if zero cost is predicted then the economic wellbeing is reported as a special case.

Social Wellbeing

Social wellbeing is the weighted average of the five social indicator scores. The individual indicator scores are reported on a common scale of 0-1 so normalisation is not required. The weights for each indicator are assigned by the user of the sDSS using a method known as an analytical hierarchy process (Saaty, 1987). The method involves comparing pairs of indicators at a time and making a judgement as to their relative importance. An overall weight for each indicator is calculated once all pairs have been compared. A consistency measure is also computed which provides an indication of the extent to which the level of importance placed on each indicator follows through from one comparison of pairs to the next. The adoption of this weighting approach in the sDSS allows users to take account of expert knowledge or their own experience to assign more significance to some activities than to others, based on the characteristics of the SRU or ERU in question.

4 Implementing and Running the Pilot sDSS

4.1 Introduction

This chapter describes the steps involved in implementing (Section 4.2) and running (Section 4.3) the pilot sDSS. As noted in Chapter 3, the pilot has been developed as an MS Excel workbook which calls on other Excel workbooks and models which run in other software. The pilot sDSS workbook comprises a number of linked worksheets as shown in Figure 4-1. Implementation data are entered into a separate workbook. Inputs entered into the implementation and pilot sDSS workbooks also populate hidden data arrays which are read when the relevant predictive methods are executed. Inputs to and results from the pilot are also reported in a number of pdfs, while a text file provides an audit trail, listing inputs, outputs and the values of intermediate variables.

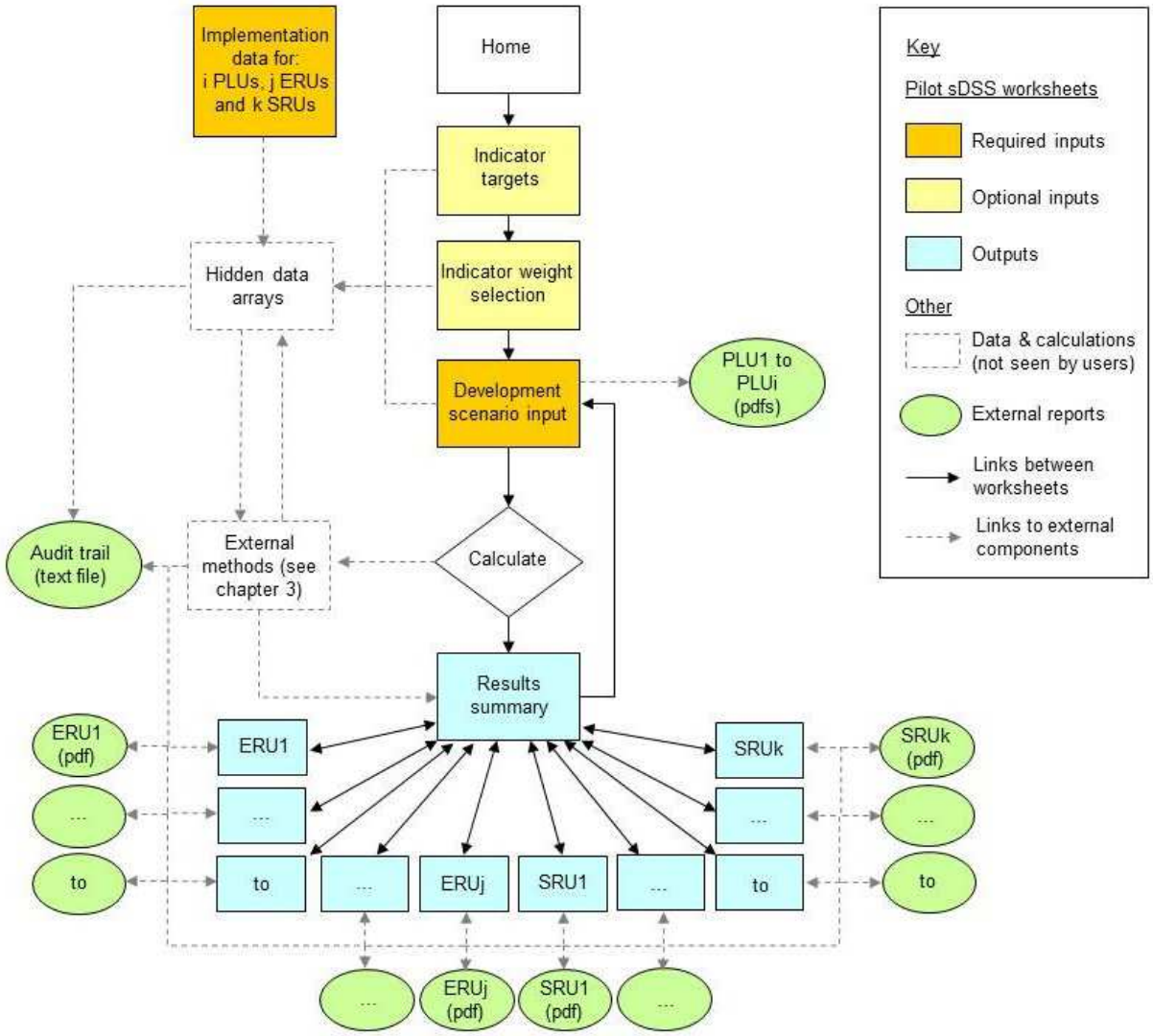


Figure 4-1: The pilot sDSS showing worksheets, external components and the links between them.

Worksheets are linked through hyperlinks in order to guide users sequentially through a series of required and optional inputs before running the system and, finally, viewing results. Links between worksheets can be uni- or bi-directional, as shown by the single- and double-headed arrows in Figure 4-1. Selections are made by the use of a range of methods, including drop-down lists, tick boxes and sliders.

4.2 Implementation Data

4.2.1 Study area and study timeframe

The characteristics of the study area and study timeframe are specified in the 'Study Area' worksheet of the Implementation Data workbook. This involves specifying the number of PLUs, SRUs and ERUs, the baseline year and the reporting year (see Figure 4-2).

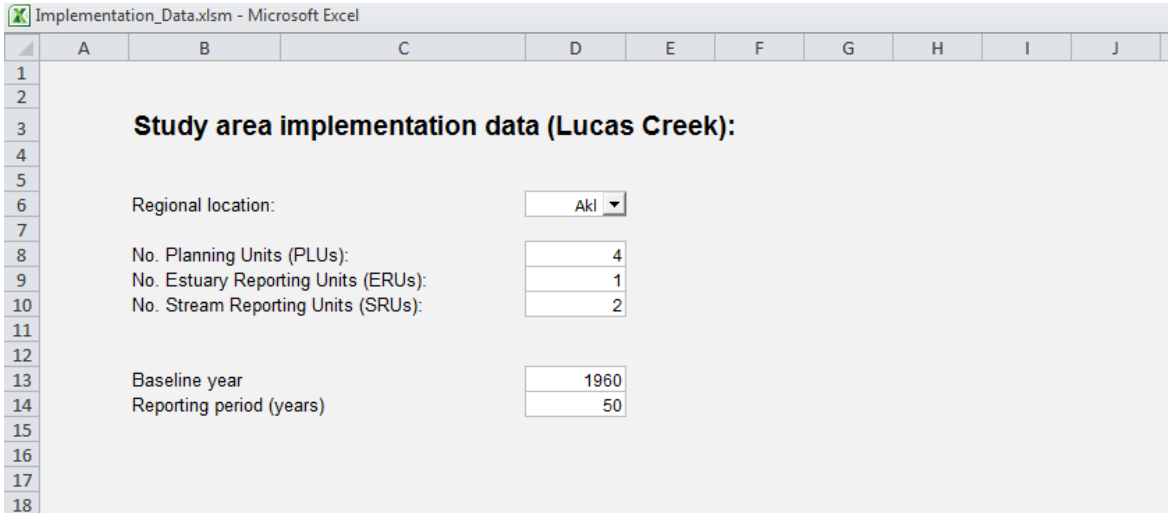


Figure 4-2: Study Area worksheet.

4.2.2 SRUs and ERUs

The characteristics of each SRU and ERU are entered in two worksheets, one for each type of reporting unit (see Figure 4-3). These characteristics represent the baseline system state and include inputs required by the BBN and USC models.

4.2.3 PLUs

The BUS is also specified in the Implementation Data workbook, with a separate worksheet for each PLU (Figure 4-4). Specification of the BUS involves selecting the proportion of the PLU in each land-use class, the existing stormwater treatment characteristics and the existing riparian condition. The selections available are identical to those available for specifying the UDO (see Section 4.3.3) and are inputs to C-CALM, the costing models and the BBN.

Implementation_Data.xlsx - Microsoft Excel

All SRU Baseline System State implementation data

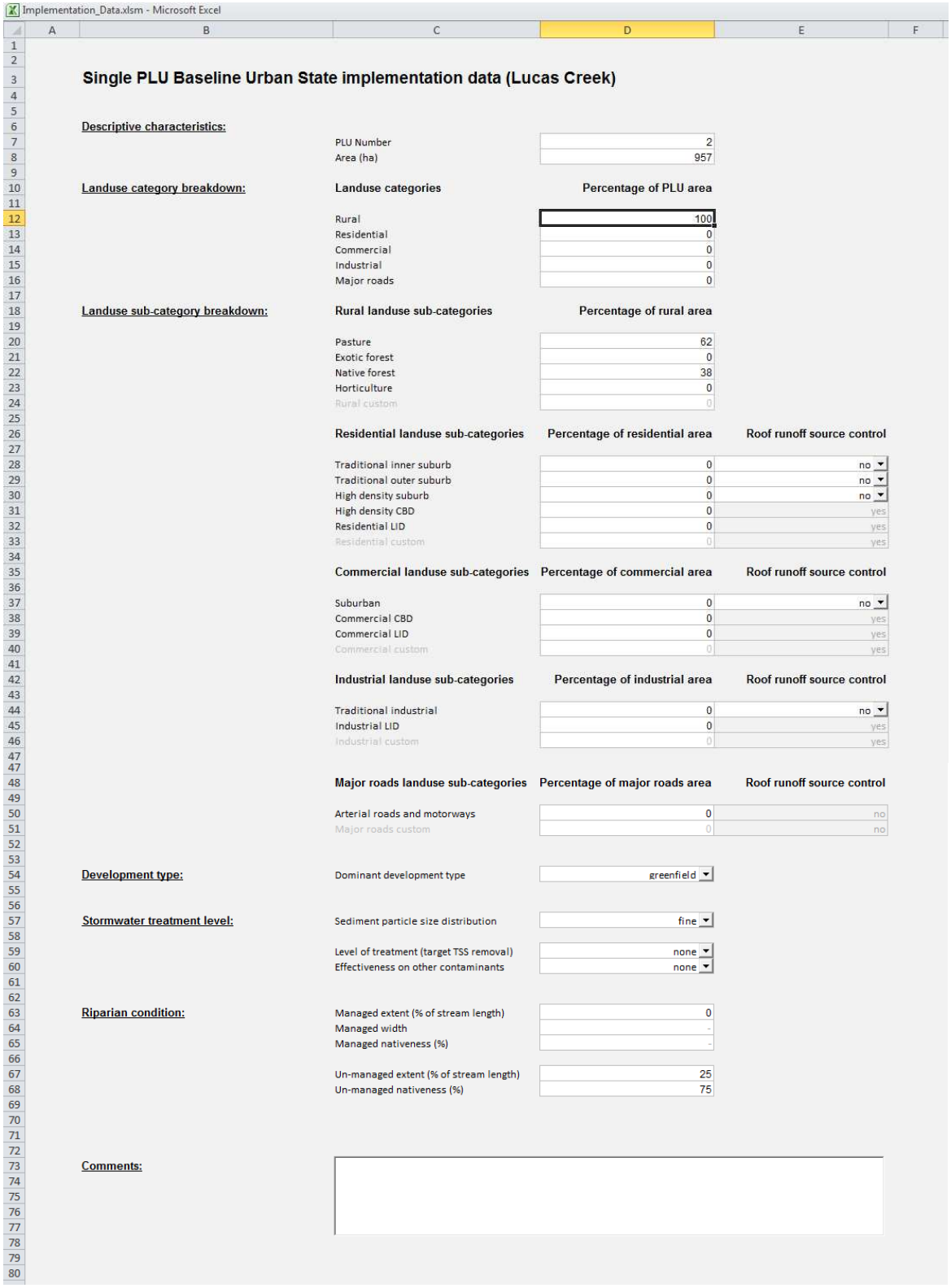
		SRU1	SRU2
Descriptive characteristics:			
	SRU number	1	2
	PLU number SRU sits within	1	2
	Altitude (m)	80	50
	Distance from sea (km)	7	9
	Length (m)	13830	17907
	Channel width (m)	2.2	4
	Channel slope (%)	6.4	4.4
	Substrate	soft	soft
	Median flow (m^3/s)	0.03	0.5
	Weighting for study area average (-)	0.5	0.5
Distribution of PLU contaminant loads between SRUs:		SRU1	SRU2
PLU1	Proportion of particulate load ≤ 63 µm diameter	1	0
	Proportion of particulate load > 63 µm diameter	1	0
	Proportion of dissolved load	1	0
PLU2	Proportion of particulate load ≤ 63 µm diameter	0	1
	Proportion of particulate load > 63 µm diameter	0	1
	Proportion of dissolved load	0	1

Implementation_Data.xlsm - Microsoft Excel

All ERU Baseline System State implementation data

Particle size:	Diameter of sediments ≤ 63 µm (µm)	40
	Diameter of sediments > 63 µm (µm)	100
		ERU1
Descriptive characteristics:		
	ERU Number	1
	Area (ha)	152
	Of regional significance	no
	Weighting for study area average (-)	1
Initial bed sediment properties:	**Mixing depth (m)**	
	Depth of mixing layer	0.1
	Particle size distribution (-)	
	Proportion of bed sediments ≤ 63 µm diameter	0.8
	Proportion of bed sediments > 63 µm diameter	0.2
	Metal concentration (mg/kg)	
	Zn bed sediment concentration	70
	Cu bed sediment concentration	13
	Pb bed sediment concentration	21
Distribution of PLU contaminant loads between ERUs:		ERU1
PLU1	Proportion of particulate load ≤ 63 µm diameter	1
	Proportion of particulate load > 63 µm diameter	1
PLU2	Proportion of particulate load ≤ 63 µm diameter	1
	Proportion of particulate load > 63 µm diameter	1
PLU3	Proportion of particulate load ≤ 63 µm diameter	1
	Proportion of particulate load > 63 µm diameter	1
PLU4	Proportion of particulate load ≤ 63 µm diameter	1
	Proportion of particulate load > 63 µm diameter	1

Figure 4-3: SRU (top) and ERU (bottom) implementation data worksheets.



Implementation_Data.xlsm - Microsoft Excel

Single PLU Baseline Urban State implementation data (Lucas Creek)

Descriptive characteristics:		
	PLU Number	2
	Area (ha)	957
Landuse category breakdown:	**Landuse categories**	**Percentage of PLU area**
	Rural	100
	Residential	0
	Commercial	0
	Industrial	0
	Major roads	0
Landuse sub-category breakdown:	**Rural landuse sub-categories**	**Percentage of rural area**
	Pasture	62
	Exotic forest	0
	Native forest	38
	Horticulture	0
	Rural custom	0

Residential landuse sub-categories	**Percentage of residential area**	**Roof runoff source control**
Traditional inner suburb	0	no
Traditional outer suburb	0	no
High density suburb	0	no
High density CBD	0	yes
Residential LID	0	yes
Residential custom	0	yes

Commercial landuse sub-categories	**Percentage of commercial area**	**Roof runoff source control**
Suburban	0	no
Commercial CBD	0	yes
Commercial LID	0	yes
Commercial custom	0	yes

Industrial landuse sub-categories	**Percentage of industrial area**	**Roof runoff source control**
Traditional industrial	0	no
Industrial LID	0	yes
Industrial custom	0	yes

Major roads landuse sub-categories	**Percentage of major roads area**	**Roof runoff source control**
Arterial roads and motorways	0	no
Major roads custom	0	no

Development type:	Dominant development type	greenfield
Stormwater treatment level:	Sediment particle size distribution	fine
	Level of treatment (target TSS removal)	none
	Effectiveness on other contaminants	none
Riparian condition:	Managed extent (% of stream length)	0
	Managed width	-
	Managed nativeness (%)	-
	Un-managed extent (% of stream length)	25
	Un-managed nativeness (%)	75

Comments:

Figure 4-4: PLU implementation data worksheet.

4.3 Running the Pilot sDSS

The point of entry to the pilot sDSS is a 'Home' worksheet. Users click on an 'enter' button and are led through the sequence of steps involved in running the system.

4.3.1 Indicator targets

The first step is the setting of targets for each indicator. While this is an optional step, the setting of targets provides a benchmark against which the results of any scenario can be compared. Targets are set separately for ERUs as a whole and SRUs as a whole. Although not yet functional, it is also planned that they can be set for individual ERUs and SRUs, to reflect the fact that a target for one estuary or stream might not be appropriate for another. Targets are set using the same classes adopted for reporting indicator levels (see Section 4.3.4).

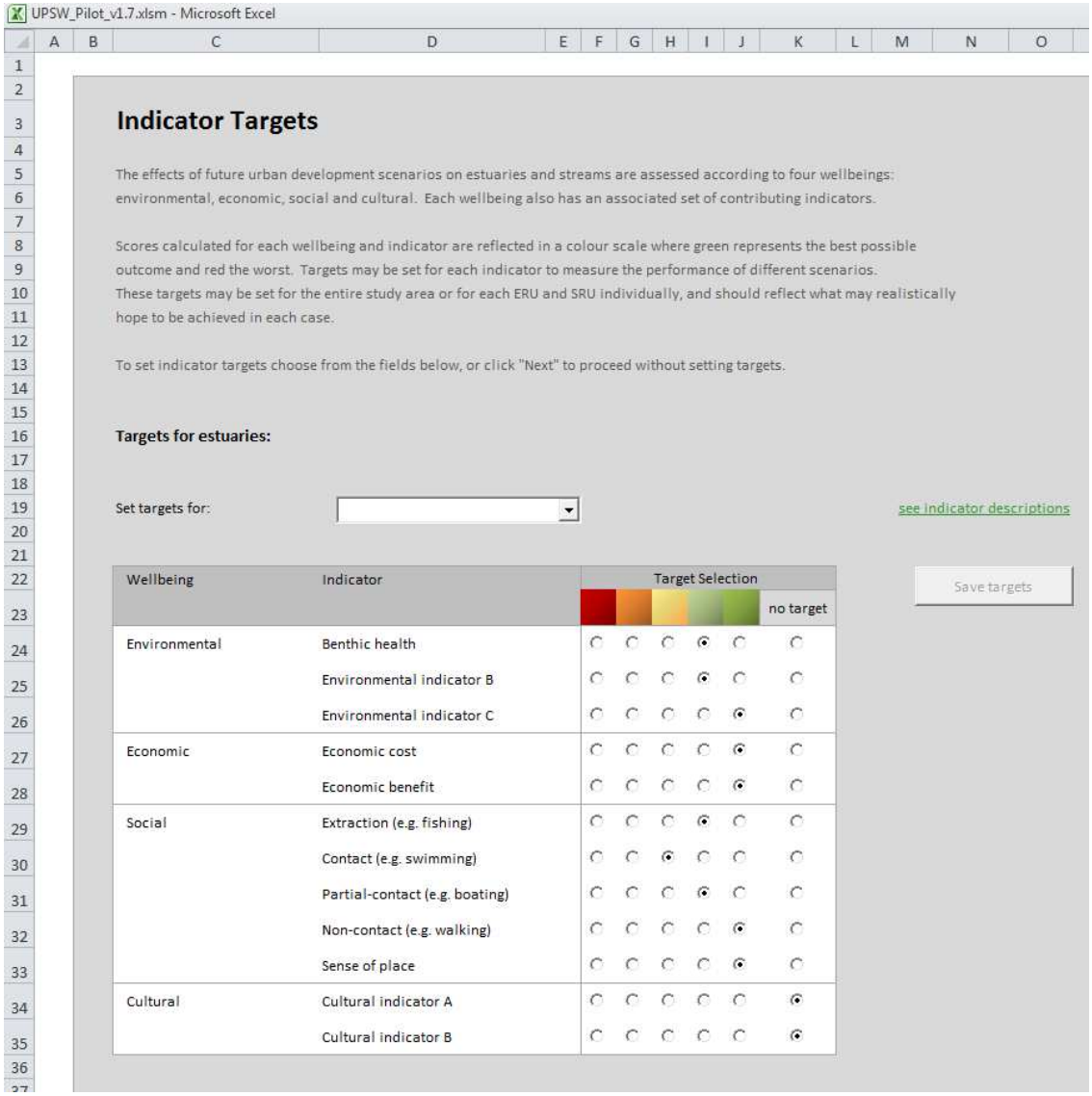


Figure 4-5: Indicator targets worksheet.

4.3.2 Social indicator weights

The next step is to assign weights to social indicators. These weights are used in the calculation of social wellbeing from the scores of the five social indicators. Although the setting of weights is again an optional step, it provides an opportunity for more importance to be placed on some social indicators than others. For example, it might be the case that a particular stream is seldom used for swimming but walking tracks along its banks are in frequent use. In that case, a higher weight could be assigned to 'non-contact' than to 'contact' in calculating social wellbeing.

Weights are assigned by assessing the relative importance of pairs of social indicators until all pairs have been evaluated (see Section 3.3.9). A slider is moved to reflect the relative importance of each indicator in the pair (see Figure 4-6). The calculated weights are shown in a table on the worksheet.

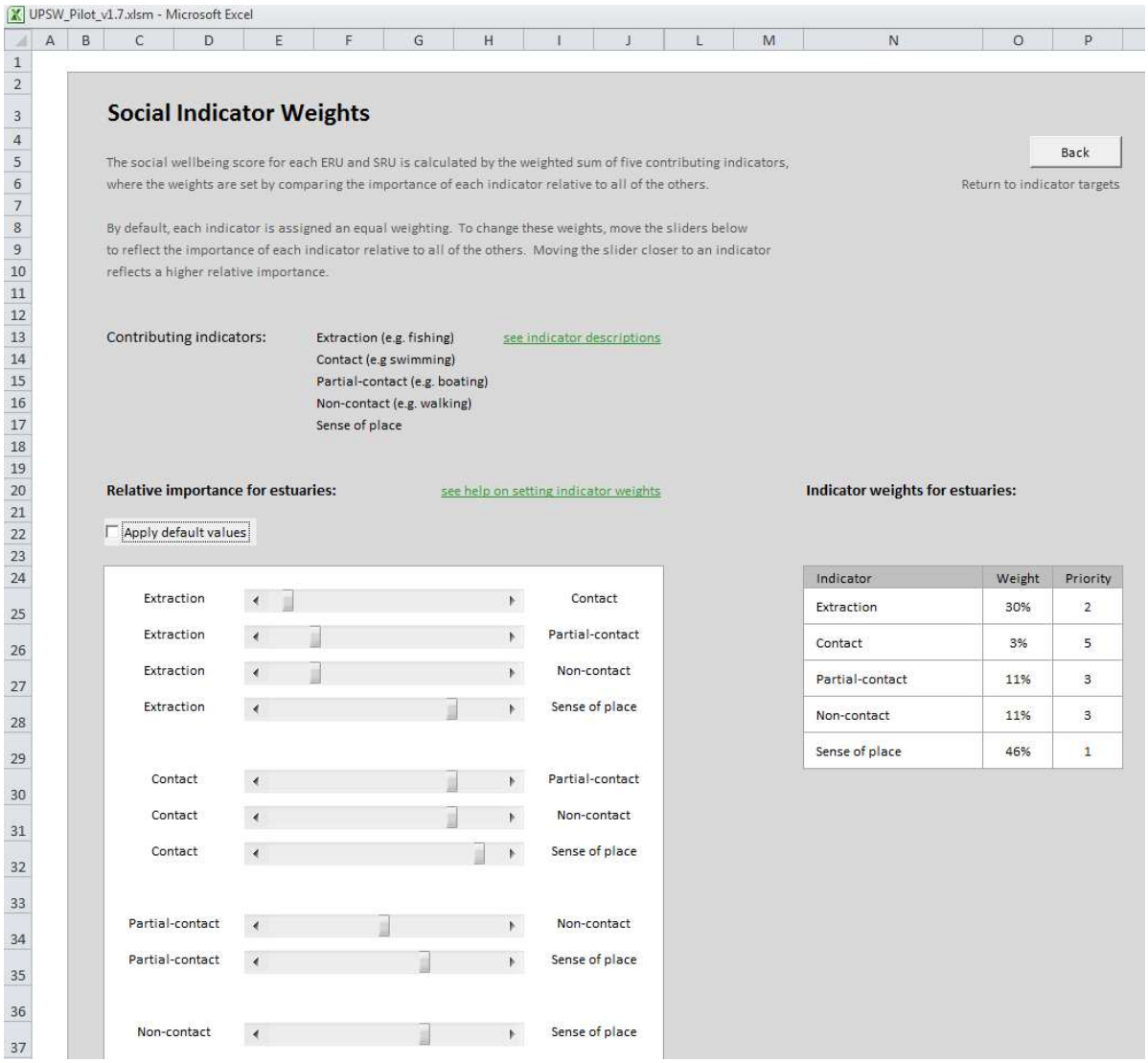


Figure 4-6: Social indicator weights worksheet.

A worksheet has also been constructed to allow weights to be assigned to the cultural indicators. However, because cultural indicators have yet to be incorporated in the sDSS, this step is bypassed when running the pilot system.

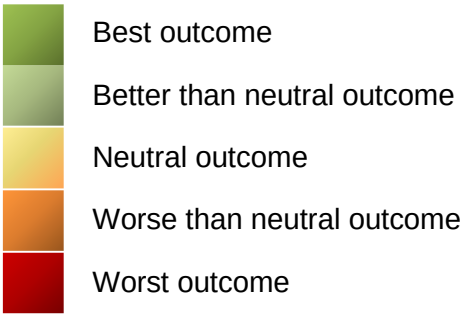
4.3.3 Development scenario input

A development scenario is the combination of UDOs specified for all PLUs in the study area. Specification of a UDO involves entering or selecting the value of each descriptive attribute required to run the sDSS. These are: the time to the start and end of development; the development trajectory; the proportion of the PLU in each land-use category; stormwater treatment characteristics; characteristics of earthworks controls associated with land development; the rate of change in vehicle numbers; and the characteristics of riparian management. The options available are shown in Table 4-1. The options relating to land use, stormwater management, and riparian management are the same as those available for specifying the BUS as part of implementation.

The UDOs for each PLU are entered and saved sequentially. Figure 4-7 shows an example for one PLU. Once the UDOs for all PLUs in the study area have been entered the user clicks on the 'calculate' button on the top right hand corner of the worksheet in order to run the pilot sDSS.

4.3.4 Results

The predicted levels of each indicator and wellbeing are presented on a separate worksheet for each SRU and ERU (see Figure 4-8). In addition, a 'results summary' worksheet presents the wellbeing levels for all reporting units along with the averages for all SRUs and ERUs, respectively. The levels for all indicators and wellbeings are assigned to one of five colour-coded classes:



Indicator levels are shown at the start and end of the study timeframe and compared to any targets set previously (see Section 4.3.1). A change in level from, say, orange (level 2) at the start of the study timeframe to dark green (level 5) at the end would indicate that an improvement in a particular indicator or wellbeing is predicted for the given development scenario. Comparison of the same dark green level with a yellow target (level 3) would indicate that the target set for that indicator is predicted to be surpassed.

Table 4-1: Options for descriptive attributes of UDOs.

	Descriptive attribute	Options
Development period characteristics	Time to start of development (T_s)	Time in years in the range 0 to (T_r - 1) where T_r is the reporting time set at implementation
	Time to end of development (T_d)	Time in years in the range (T_s + 1) to T_r
	Development phasing option	Continuous, phased or stepwise (rate of change in land use over the development period)
Land use	Land use sub-category	0-100% of PLU in each of the following sub-categories: • Rural: pasture, exotic forest, native forest, horticulture , custom • Residential: low density, medium density, high density, CBD, residential LID, custom • Commercial: suburban, commercial CBD, commercial LID, custom • Industrial: traditional industrial, industrial LID, custom • Major roads: three categories based on traffic numbers, custom
	Roof runoff source control	Yes or no (where “yes” results in selection of low yielding roof types)
Methods of land development	Bulk earthworks target TSS removal	0, 25, 75 or 90% (removal of earthworks-generated sediment associated with greenfield land development)
	Other earthworks target TSS removal	0, 25, 75 or 90% (removal of earthworks-generated sediment associated with infill land development)
Transport characteristics	Target change in vehicles per day	0-100% change over period of development
	Direction of change	Increase or decrease
Stormwater management	Target TSS removal	0, 25, 50, 75 (TP10) or 90% (removal of total sediment)
	Effectiveness on other contaminants	Low, medium or high (removal of copper, lead and zinc)
Stream management	Extent of managed riparian vegetation	0-100% of stream length
	Width	Wide or narrow
	Extent of unmanaged riparian vegetation	0-100% of stream length

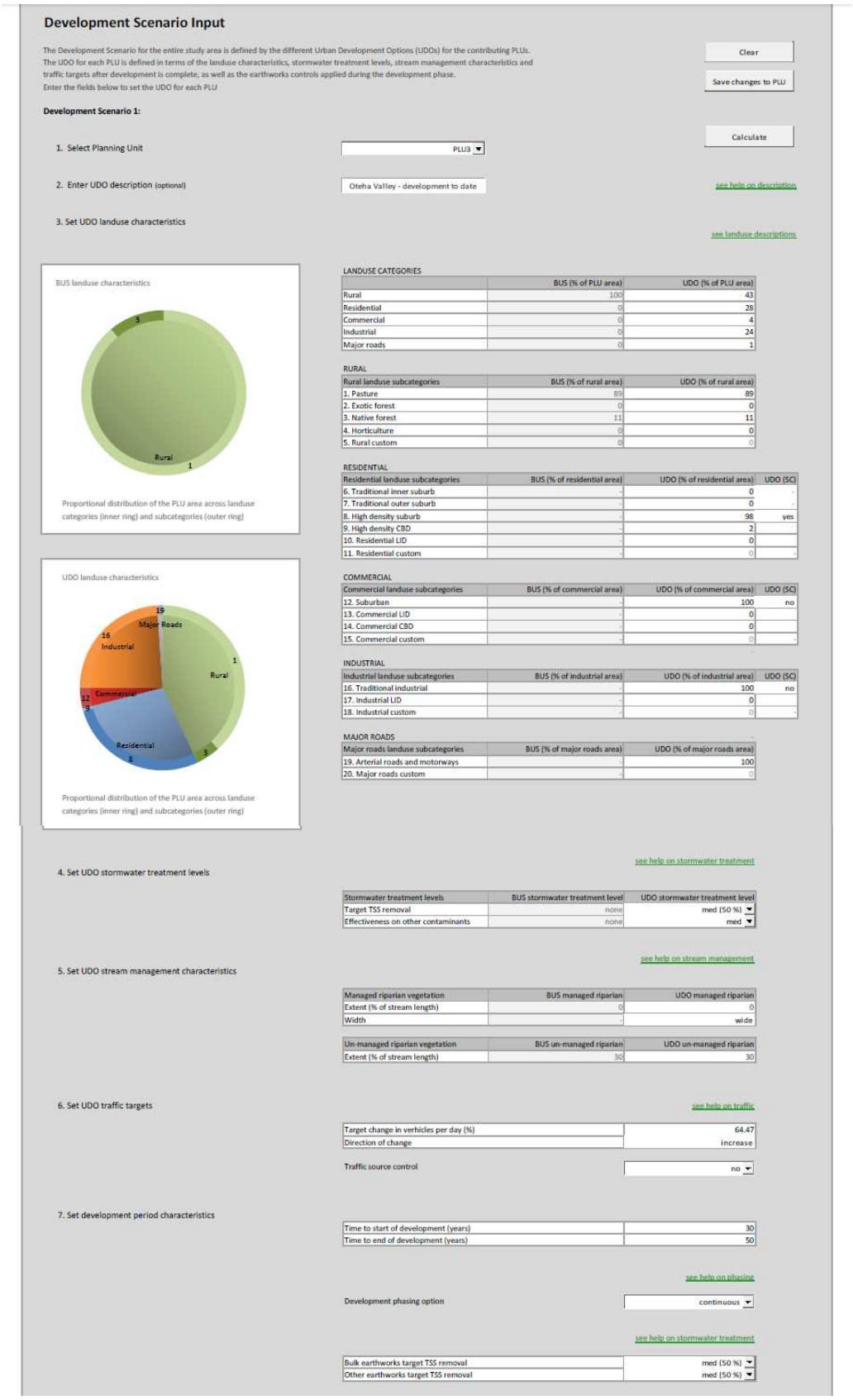


Figure 4-7: Development scenario input worksheet.

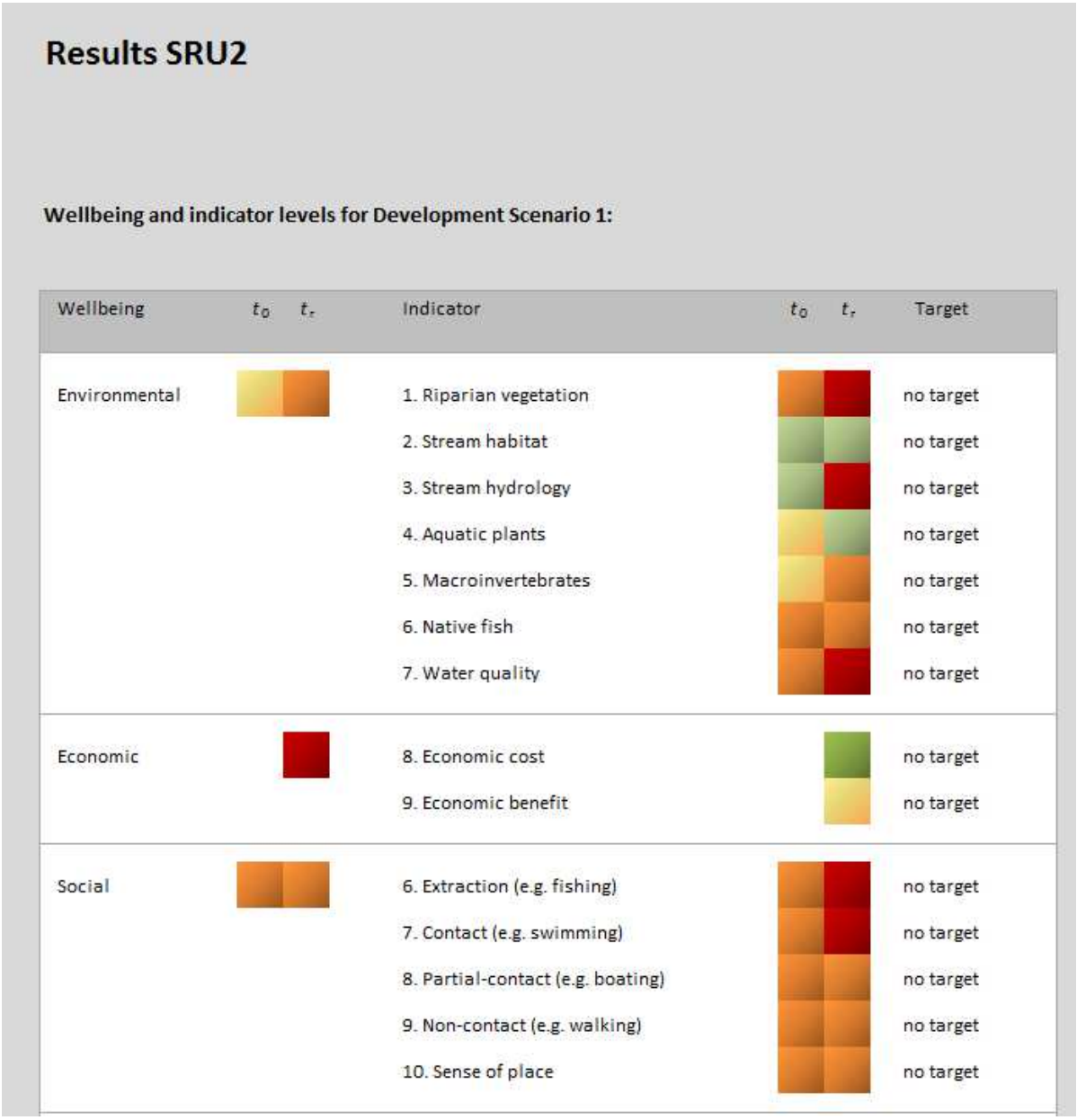


Figure 4-8: Example of a results worksheet.

4.3.5 Report files

When the system is run a number of report files are generated. A series of pdf files record an exact copy of the following worksheets in the pilot sDSS:

- development scenario input (a separate pdf for each PLU);
- results summary; and
- results for each ERU and SRU (a separate pdf for each one).

A text file is also generated which provides an audit trail of the scenario, including:

- study area characteristics;

- for each PLU:
  - input data for the BUS and UDO; and
  - the time series of contaminant loads predicted by C-CALM;
- for each ERU:
  - characteristics entered at implementation;
  - the time series of annual sediment metal concentrations and sediment grain size (% mud) predicted by the USC model;
  - the time series of the annual benthic health score predicted by the BHM;
  - the economic costs, economic benefits and benefit/cost ratio;
  - the social indicator and social wellbeing scores at the start and end of the study timeframe;
- for each SRU:
  - characteristics entered at implementation;
  - the time series of annual environmental indicators predicted by the BBN;
  - values of naturalness, clarity and fauna (required for the prediction of economic benefits and social indicators) at the start and end of the study timeframe;
  - the economic costs, economic benefits and benefit/cost ratio; and
  - the social indicator and social wellbeing scores at the start and end of the study timeframe.

5 Testing the Pilot sDSS: Case Study

5.1 Introduction

This chapter describes the testing of the pilot sDSS for a case study location in the Auckland region, that being Lucas Creek tidal inlet and its catchment. This area has undergone significant urban development since the 1980s and is zoned for further development over coming decades.

There were two objectives of the case study: (1) to evaluate the performance of the pilot sDSS at hindcasting the effects of historic urban development; and (2) to evaluate the performance of the pilot sDSS for discriminating between outcomes under alternative future urban development scenarios.

Section 5.2 provides a summary of the study area while Section 5.3 describes its spatial representation in the pilot sDSS. The implementation and performance of the system to hindcast the effects of historic urban development and to predict the effects of future urban development are described in Sections 5.4 and 5.5, respectively.

5.2 Description of Study Area

5.2.1 Lucas Creek and its catchment

The Lucas Creek tidal inlet is an arm of the Upper Waitemata Harbour located at the northern margins of Auckland's North Shore (Figure 5-1). The inlet covers an area of approximately 150 ha, is around 300m wide in its middle reaches and extends for over 5km in a north-east direction from the main harbour to the tidal limit near Albany. A central channel runs between extensive inter-tidal banks of mud bordered by mangroves.

The creek's catchment covers an area of 3,774 ha and is bisected by Auckland's Metropolitan Urban Limit (MUL). The River Environment Classification (REC) system maps 10 fresh-water stream networks in the catchment with a total stream length of 44km (Figure 5-1). The largest streams are the Lucas Creek and Oteha Valley Stream (including its tributary Alexandra Stream), the confluence of which marks the upper limit of the tidal inlet. Other streams include the Kyle, Orwell and Greenhithe Streams.

The stream catchments largely coincide with stormwater catchments[6] of the same names although the Oteha stormwater catchment amalgamates both the Oteha Valley and Alexandra Streams and the Lucas Creek catchment contains the Lucas Creek and Wayade stormwater catchments, with the latter located largely outside the MUL. There are three other stormwater catchments in the drainage area: Paremoremo and Attwood, which are both on the western side of the inlet outside the MUL, and Albany West, which lies between the tidal inlet and the Kyle and Oteha Valley stormwater catchments.

The stream and channel characteristics of the urbanised section of Lucas Creek (i.e., within the Lucas Creek stormwater catchment) as well as the Oteha Valley, Alexandra, Kyle, Orwell and Greenhithe Streams were described in detail by the former North Shore City Council (NSCC) as part of their Kokopu Connection stream surveys (NSCC, 2005 a, b, c, d, e and f).

[6] As defined by the former North Shore City Council

The Lucas Creek stormwater catchment was further described in the Lucas Creek Stormwater Catchment Management Plan (SWMP, NSCC, 2009a).

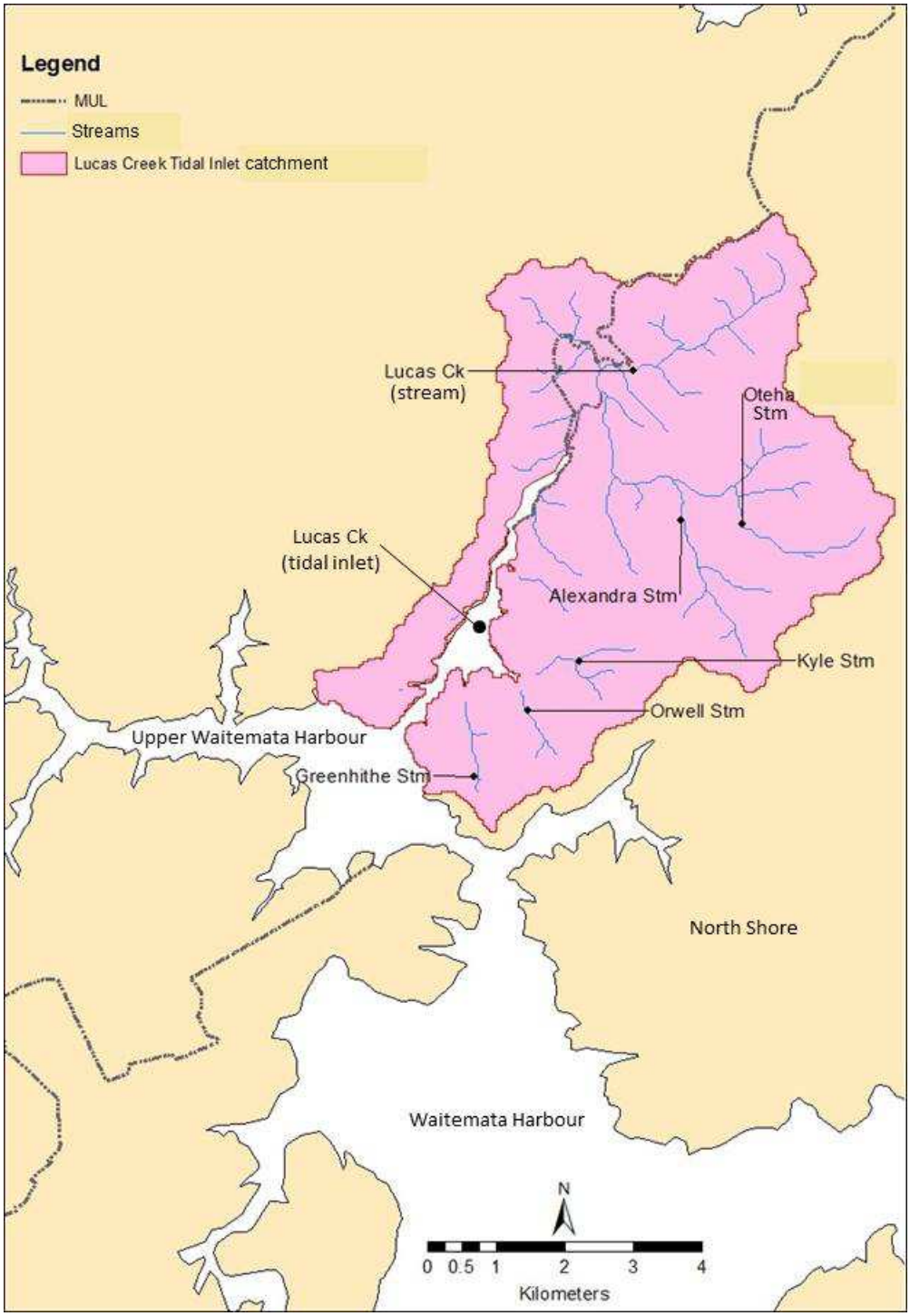


Figure 5-1: Location of Lucas Creek tidal inlet and its catchment in relation to the Upper Waitemata Harbour and Auckland Metropolitan Urban Limits (MUL).

5.2.2 Spatial Representation in the pilot sDSS

For the implementation of the pilot sDSS the catchment of the tidal inlet was split into four PLUs (Figure 5-2). Lucas Creek tidal inlet was the sole ERU while the Lucas Creek stream

and Oteha Stream were defined as SRUs. The relationships between PLUs and reporting units is given in Table 5-1.

The PLUs were defined on the basis of land use and sub-catchment boundaries. Although the Greenhithe and Paremoremo PLUs each contain streams, in order to keep this first implementation of the pilot sDSS relatively simple SRUs were only defined in the Lucas Creek and Oteha Valley PLUs. In the pilot sDSS these SRUs are influenced solely by development in the corresponding PLU while the ERU is influenced by development in all four PLUs.

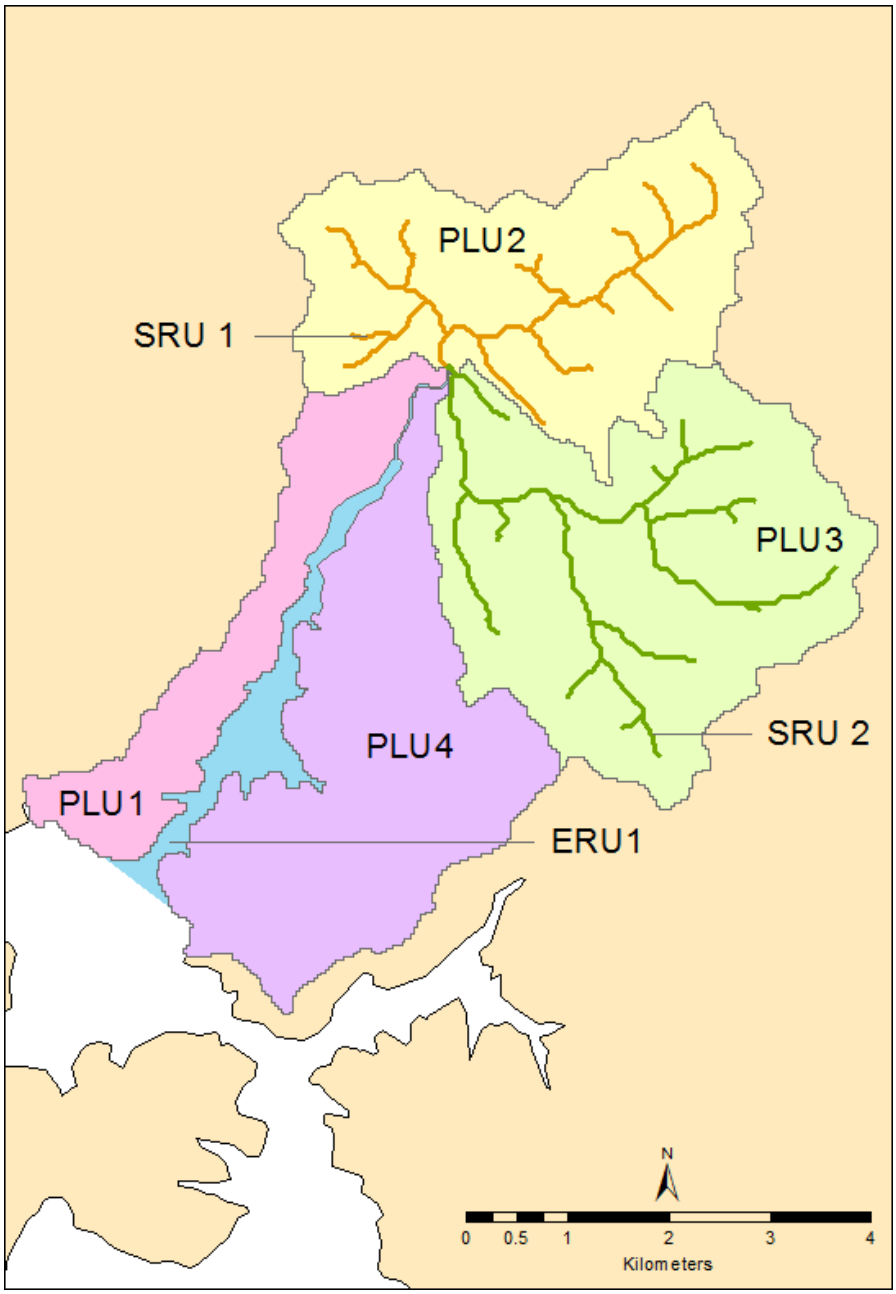


Figure 5-2: Spatial representation of the case study area in the pilot DSS.

Table 5-1: Spatial representation of the case study area in the pilot DSS.

Reporting Unit	Name	Size	Influenced by development in
PLU 1	Paremoremo	411 ha	-
PLU 2	Lucas Creek	957 ha	-
PLU3	Oteha Valley	1258 ha	-
PLU 4	Greenhithe	995 ha	-
SRU 1	Lucas Creek	13.8 km	PLU 2
SRU 2	Oteha Stream (including Alexandra Stream)	17.9 km	PLU 3
ERU 1	Lucas Creek tidal inlet	152 ha	PLUs 1-4

5.2.3 Current land use

For the purposes of the case study, 'current' land use means the land use present in 2010, because 2010 marks the end point of the historical implementation of the pilot sDSS and the starting point for the future implementation. Land use in 2010 was determined from the council reports cited above, local knowledge and from mapping of aerial photographs (i.e., GoogleEarth). Figure 5-3 shows the GoogleEarth image from 2010 used to derive land use mapped in Figure 5-4. Further details of the land-use categories adopted for the case study, along with examples of how they appear in GoogleEarth, are provided in Appendix 2.

The MUL marks the boundary of urban land use in the case study area. PLU 1 lies largely outside the MUL with native bush the predominant land cover (e.g., the Lucas Creek Scenic and Esplanade Reserves). It also contains some pastoral land, including a number of lifestyle blocks in the south. The MUL intersects the western section of PLU 2, so that roughly a quarter of this PLU is rural.

The remainder of the case study area contains significant areas of residential, commercial and light industrial development. PLUs 2 and 3 contain large areas of construction earthworks which were classed as rural pasture as part of the implementation of the pilot sDSS[7]. PLU 3 contains the Rosedale Waste Water Treatment Plant (WWTP) – the sewage works were defined as industrial and the ponds as pastoral in recognition of the low expected yields from the ponds. PLU 4 contains the oldest areas of urban development and despite an increase in residential land use over the past decade, still contains sizable areas of rural land use, including a golf course and cemetery which were both classed as pastoral.

There are two regional roads in the study area, both of which are fairly recent additions to the urban landscape. The Northern Motorway (State Highway 1) runs east-west through PLU 2 and 3. The Upper Harbour Highway (State Highway 18) runs north-south though PLU 3 and 4.

[7] The C-CALM component of the pilot sDSS calculates bulk earthworks as the area under construction for each year based on the projected rate of land-use change from rural to urban land uses for that year.

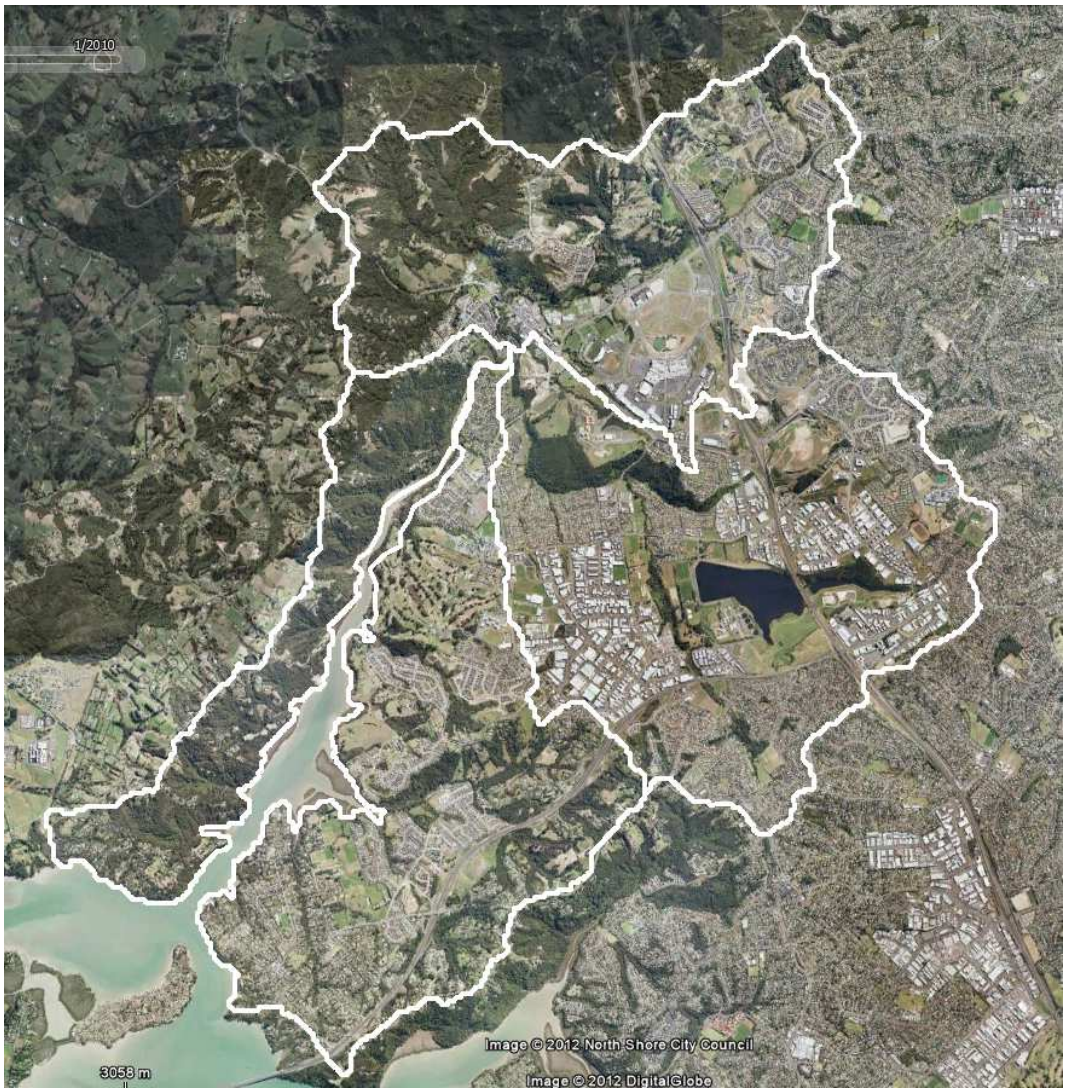


Figure 5-3: GoogleEarth image (January 2010) of the case study area with PLU boundaries overlaid.

As noted above, two SRUs were defined for the case study: Lucas Creek stream and Oteha Stream (including the Alexandra Stream tributary). The results of stream surveys (NSCC, 2005a, b, c) and the Lucas Creek SWMP (NSCC, 2009a) were used to derive SRU characteristics required for implementation of the pilot sDSS and to evaluate the results of the historic implementation.

The Lucas Creek stream assessment and SWMP for the creek note that land clearance and soil disturbance associated with recent development have had significant impacts in some parts of the stream with sediment deposits smothering habitats. It is noted that the creek still retains some excellent native riparian cover, natural character and a range of habitat types. Additionally, sections of Lucas Creek have undergone a stream restoration programme to increase riparian cover over the last few years (Mansell and Stumbles, 2010).

The Oteha Stream and Alexandra Stream surveys note that while the lower reaches retain some natural character, much of the upper stream channels have been modified during

development. There are only small sections of riparian cover, largely remnants of forest cover.

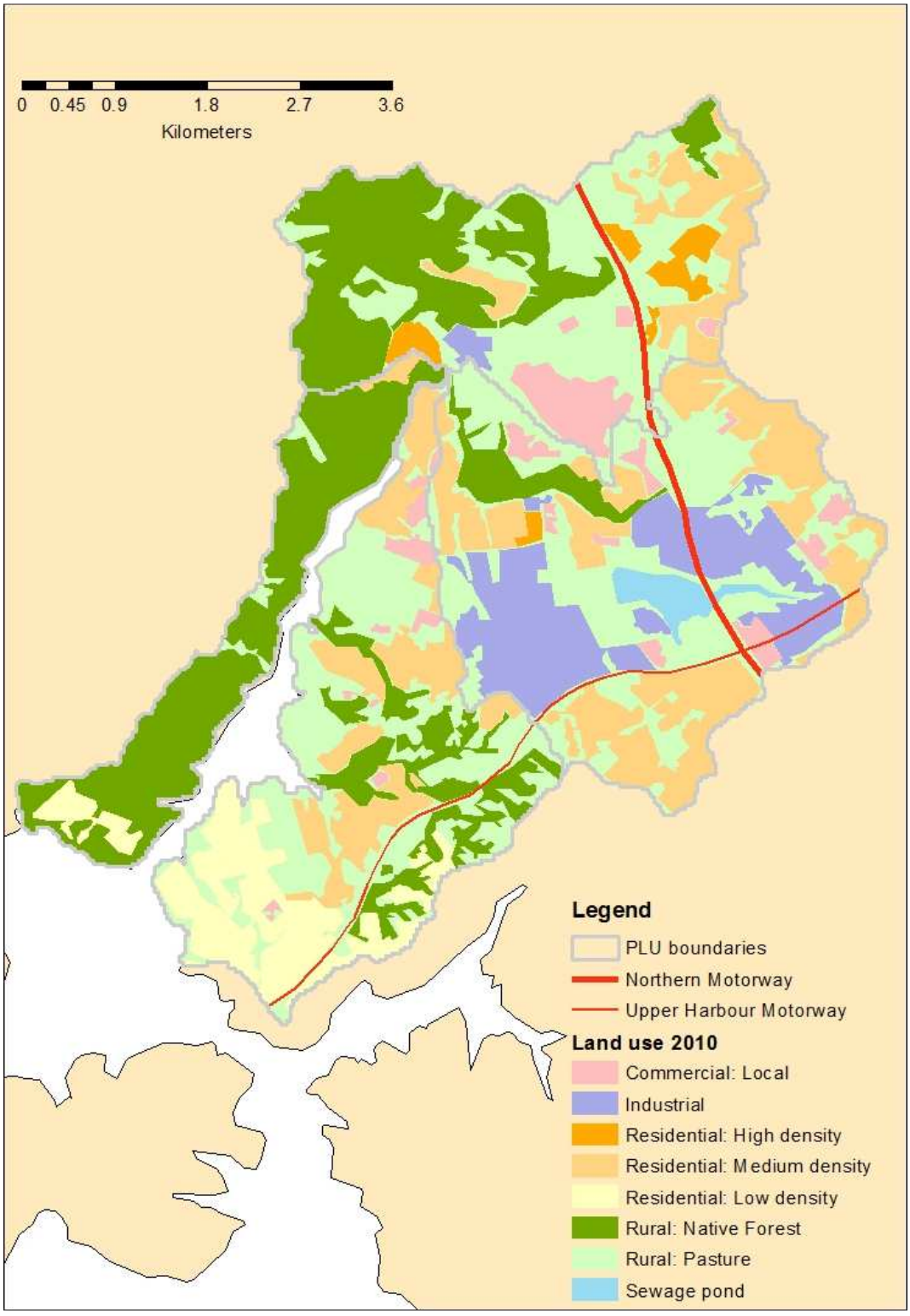


Figure 5-4: Case study area land use in 2010.

5.3 Historic Implementation

5.3.1 Introduction

The aim of the historic implementation was to assess the performance of the pilot sDSS at hindcasting the effects of historic urban development. The historic implementation covered the period 1960 (BUS) to 2010 (UDO).

5.3.2 Data sources

The following data sources were used to, firstly, implement the pilot sDSS and, secondly, to evaluate its performance:

- Aerial photographs (GoogleEarth) to map land-use change and to establish the timing and rate of urban development.
- Census population data (1976 to 2006) and housing stock counts (1960 to present) to establish the timing and rate of urban development[8].
- NZ Transport Agency publications and website (e.g, NZTA, 2008; 2012) to assess traffic numbers and trends.
- NSCC stormwater asset management plan (2009b) and asset consent data to estimate the degree of stormwater treatment in each of the PLUs.
- NSCC stream surveys (NSCC 2005a, b, c) to obtain implementation data relating to the streams and to evaluate model performance.
- Various ARC documents including annual State of Environment reports for freshwater and coastal environments (e.g., Reed and Gadd, 2009; Neale, 2010 a and b) to obtain implementation data relating to streams and the tidal inlet and to evaluate model results.

5.3.3 Representation of urban development

Land use

Land-use change over the historic period is summarised in Table 5-2. The 2010 land use described above was used to represent the UDO. The BUS (1960) land use was determined from GoogleEarth images taken in 1963. At this time, the study area was predominantly rural with the only small areas of urban land use in PLUs 3 and 4 (Figure 5-5 and Figure 5-6).

Land use was also mapped from GoogleEarth images for the years 1997, 2000 and 2005 in order to establish the timing of urban development. The aerial image for 1997 is shown in Figure 5-5 as this is around the time that significant urban development commenced over much of the study area. Information on the timing of development was also obtained from census data and household counts (Figure 5-7 and Figure 5-8). This allowed the area of residential land mapped from aerial photographs to be verified by comparison with the area that would be required to contain the recorded housing stock.

[8] Census data for 1996, 2001 and 2006 were downloaded from the Statistics New Zealand Census website (http://www.stats.govt.nz/Census.aspx). All other census data and housing counts were provided for this study by Auckland Council.

Table 5-2: BUS and UDO land-use percentage break down and timing of development by PLU for the historic implementation.

Land use	PLU 1 Paremoremo		PLU 2 Lucas Creek		PLU3 Oteha Valley		PLU4 Greenhithe	
	BUS	UDO	BUS	UDO	BUS	UDO	BUS	UDO
Commercial: Local	0	0	0	7	0	4	0	3
Industrial	0	0	0	1	0	24	0	0
Residential: High density	0	0	0	5	0	0	0	0
Residential: Medium density	0	2	0	13	0	28	0	20
Residential: Low density	7	7	0	0	0	0	2	22
Rural: Native Forest	82	88	38	35	11	5	21	15
Rural: Pasture	11	4	62	38	88*	38*	77	39
Regional road	0	0	0	1	0	1	0	1
Percent urban	7	9	0	27	0	57	2	45
Year development started		1960		1995		1990		1985
Year development complete		1970		2010		2010		2010

* includes 3% sewage pond

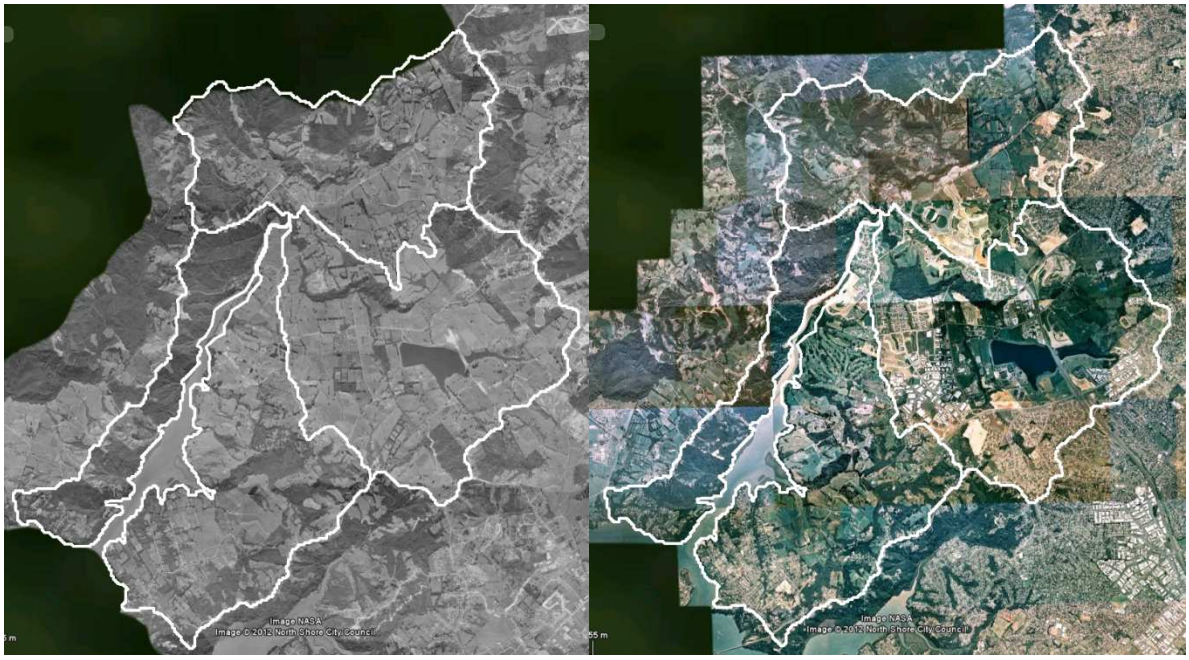


Figure 5-5: GoogleEarth images of the study area for 1963 (BUS) and 1997 (early urban development in PLUs 2 and 3).

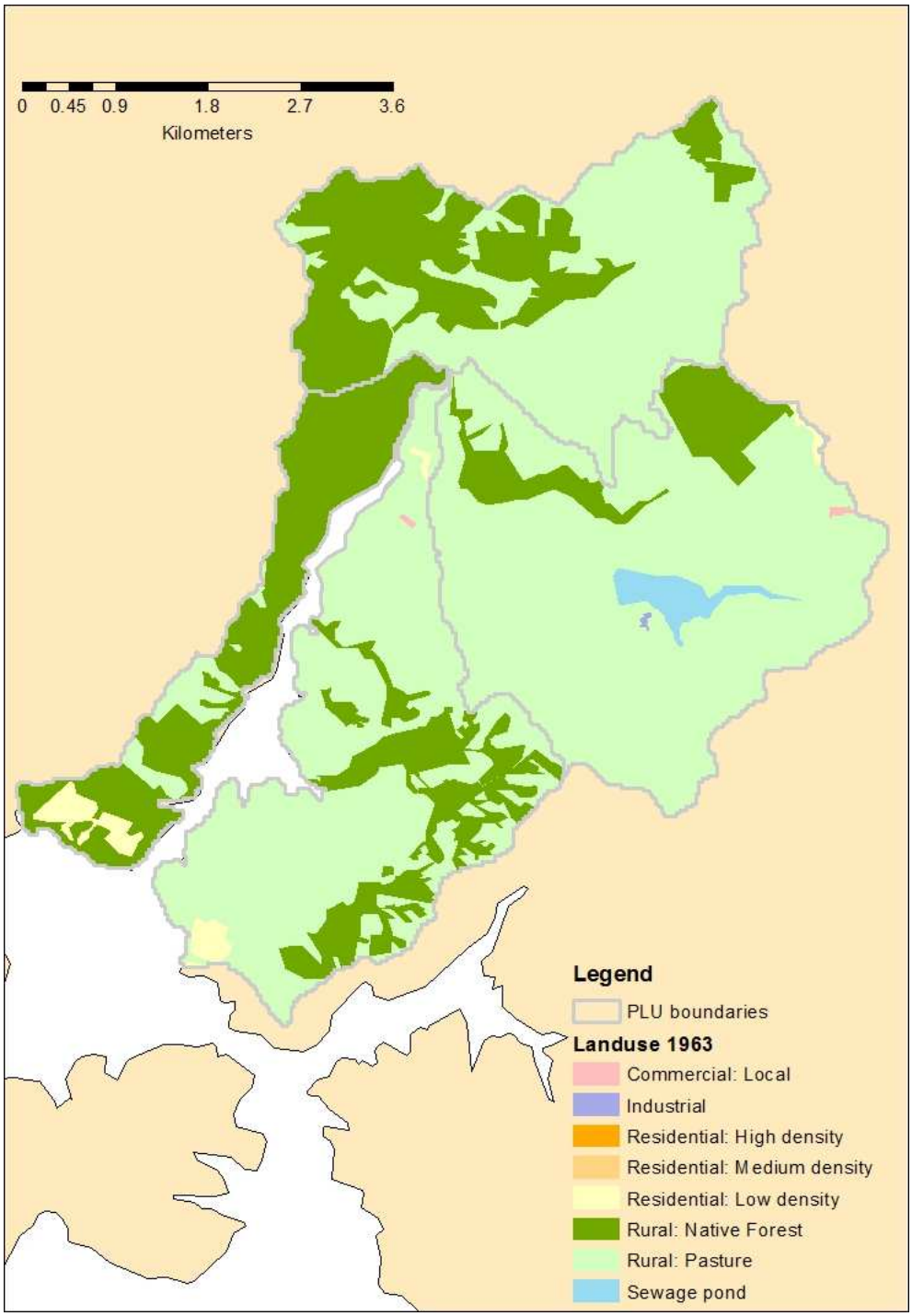


Figure 5-6: Case study area land use in 1963.

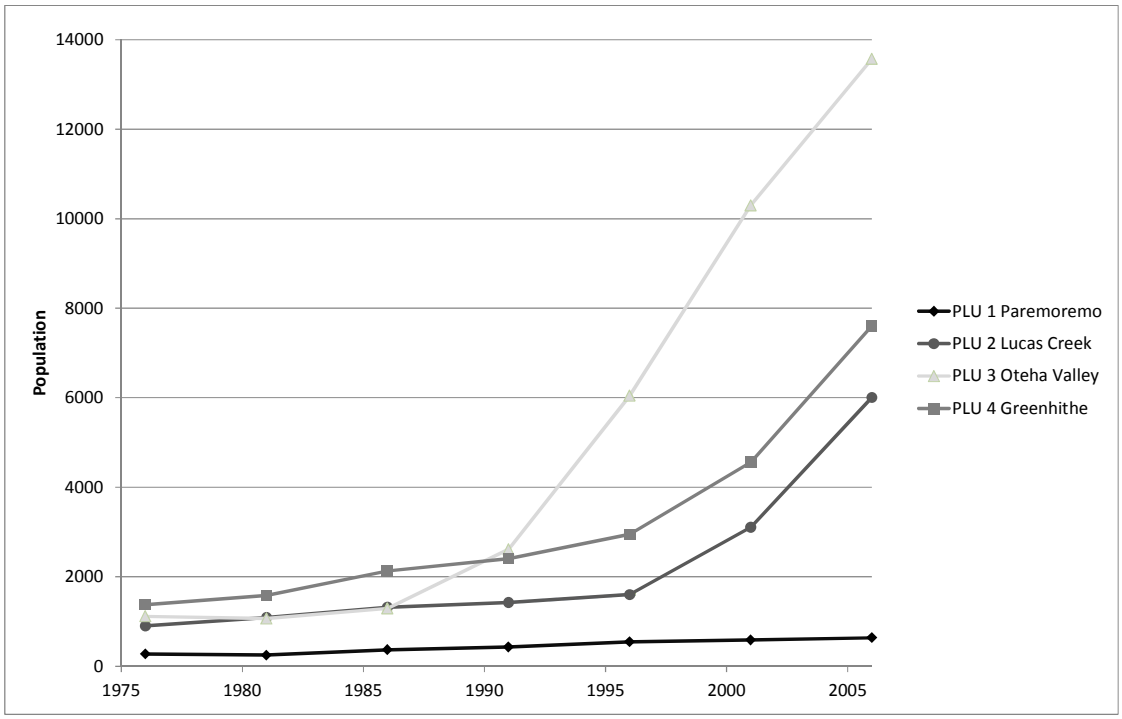
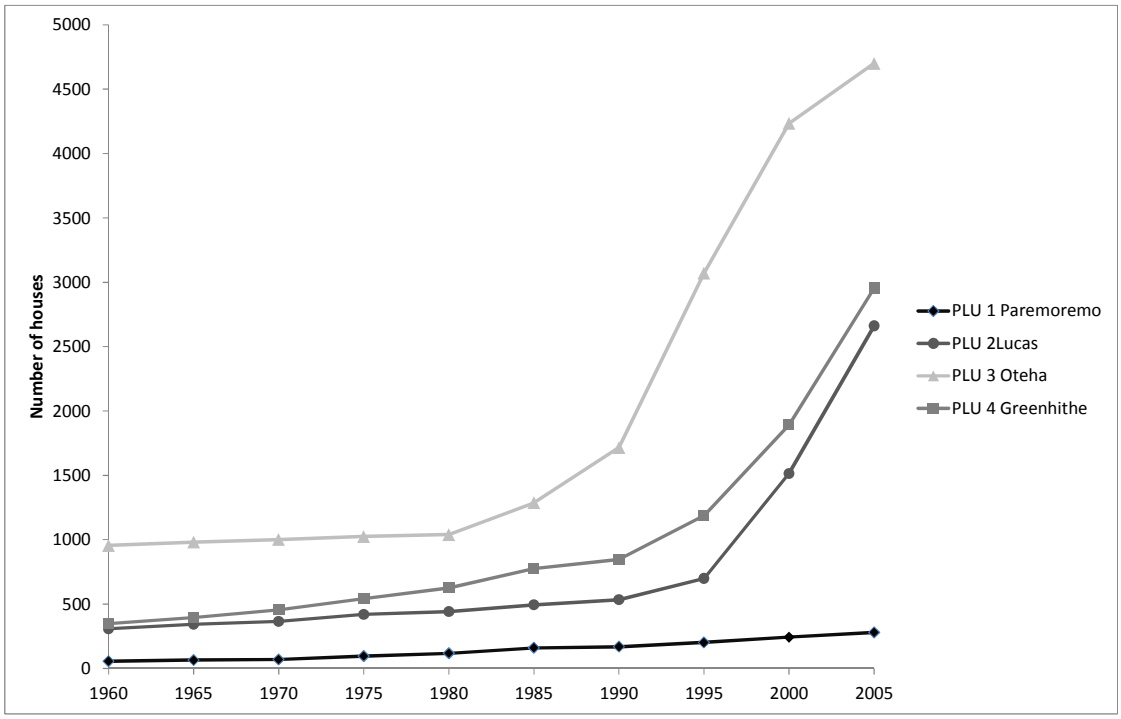


Figure 5-7: Estimated population by PLU[9] (1976-2006). Pre-1996 data provided by Auckland Council. Data for 1996 - 2006 from Statistics NZ.



[9] Since PLU boundaries do not match exactly with those of census meshblocks, the PLU population figures were estimated by spatially weighting the meshblock data.

Figure 5-8: Number of houses by PLU (1960-2005). Data provided by Auckland Council.

The data obtained from these sources show that urbanisation commenced at different times in each PLU and has occurred at different rates. In PLU 1, which is outside the MUL, there has been little development. PLU 4 already had some development (low-density housing) in the south in the early 1960s but the population and number of houses was fairly static until the mid-1980s: since then there has been sustained development, as has been the case in PLU 2. Development in PLU 3 began around 1980 and this PLU now has the greatest proportion of urban land use, with the highest population and housing counts in the case-study area.

Stormwater treatment

The level of stormwater treatment in each PLU was estimated from the NSCC documents described above, which included a comprehensive register of stormwater pond consents in the North Shore area. The register gives the age, location, dimensions (area, depth, volume) and contributing area for each pond in the study area to the year 2007. The location and contributing areas are shown in Figure 5-9.

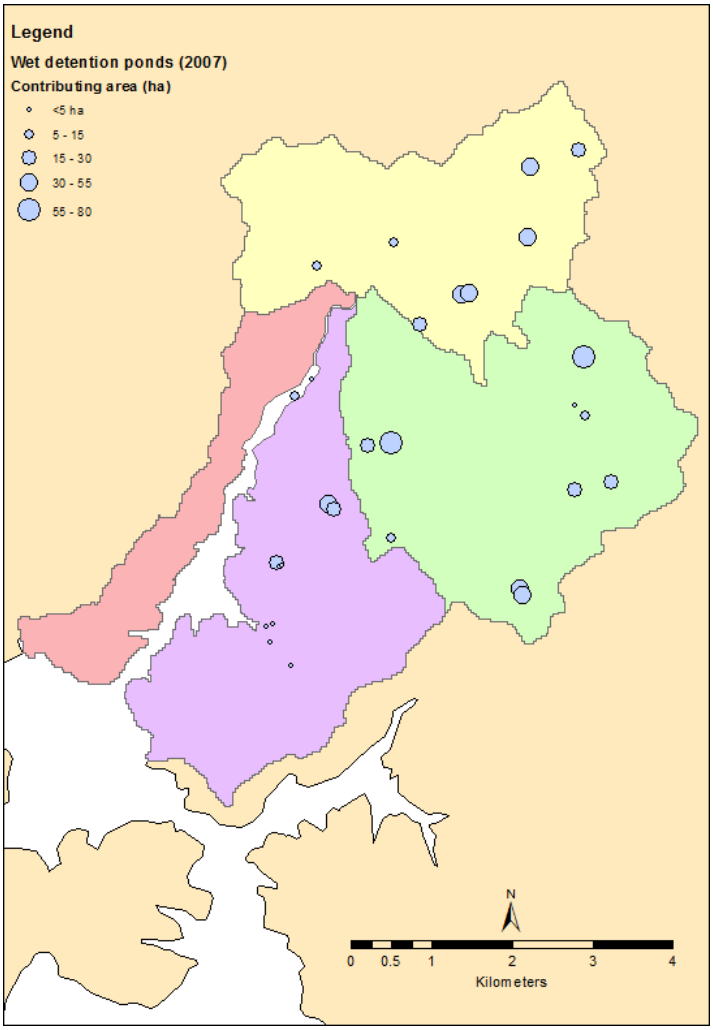


Figure 5-9: Location of stormwater ponds in 2007. The symbol size indicates the contributing area draining to each pond. Data derived from ex-NSCC register of stormwater pond consents.

This information was used to determine the proportion of the urban area in each PLU which drains to stormwater treatment ponds. This enabled the level of stormwater treatment in each PLU to be defined on the assumption that each pond removes the TP 10 (ARC, 2003) target of 75% TSS (and therefore particulate metal) removal. The removal of dissolved metal was assumed to be at the same level as the sediments. The stormwater treatment levels associated with the BUS and UDO in each PLU are shown in Table 5-3.

Earthworks TSS removal targets (i.e., representing sediment and erosion control measures) are given in Table 5-4. It was assumed that the higher removal targets were associated with more recent development, reflecting improved management as a result of increased regulation and monitoring over time. Development commenced latest in PLU 2, hence the higher TSS removal target.

Table 5-3: Estimated proportion of PLU receiving stormwater treatment and stormwater treatment levels, historical implementation.

Contaminant	PLU 1		PLU 2		PLU 3		PLU 4	
	BUS	UDO	BUS	UDO	BUS	UDO	BUS	UDO
Percentage urban area treated by wet detention ponds	0	0	0	100	0	57	0	20
TSS and particulate metals	none	none	none	TP 10	none	med.	none	low
Dissolved metals	none	none	none	med.	none	med.	none	low

Table 5-4: Earthworks TSS removal targets, historical implementation.

Earthworks	PLU 1	PLU 2	PLU 3	PLU 4
Bulk	none	medium/high	medium	low
Secondary	none	medium/high	medium	low

Traffic trends

A challenge for the representation of traffic in the historic implementation was the lack of data from the early years of the case study. Current traffic trends (NZTA, 2008) were extended back to 1960 to give an estimate of the traffic numbers associated with the BUS. For each subsequent year, traffic numbers were assumed to increase by one per cent, giving a 65 % increase in traffic over 50 years.

A specific issue faced by the historic implementation is the change in contaminant yields that is likely to have occurred over the last 50 years (e.g, removal of lead from petrol and the addition of copper to brake linings). However, no data on historical emission rates could be found from which historic yields could be estimated. Contaminant yields from traffic were therefore assumed to remain constant.

SRU characteristics

Table 5-5 summarises implementation data relating to SRU characteristics. These data were obtained from the NSCC stream surveys, GIS analysis of aerial images or the REC geo-database (see Section 5.2.1).

Table 5-5: SRU implementation data.

Stream parameter	SRU1 Lucas Creek		SRU2 Oteha Stream[1]	
PLU number SRU sits within	2		3	
Length (m)	13830		17907	
Channel width (m)	2.2		4	
Channel slope (%)	6.4		4.4	
Substrate	soft		soft	
Median flow (m^3/s)	0.03		0.5	
Of regional significance	no		no	
Riparian planting (% of stream)	BUS	UDO	BUS	UDO
Percentage of stream length with managed riparian planting	0	30	0	0
Width class of managed riparian planting	-	wide	-	-
Percentage of stream length with unmanaged riparian planting	25	25	30	30

Note: [1] With Alexandra Stream

ERU characteristics

Table 5-6 summarises implementation data relating to ERU characteristics. These were obtained from analyses of core samples collected in the Lucas Creek tidal inlet as part of the Upper Waitemata Harbour contaminant accumulation study undertaken for ARC in the early 2000s (Green et al., 2004).

Table 5-6: ERU implementation data. Parameter values derived from Green et al. (2004).

ERU parameter	Value
Depth of mixing layer (m)	0.1
Mud fraction (% sediments ≤ 63 µm)	80
Zinc bed sediment concentration (mg/kg)	70
Copper bed sediment concentration (mg/kg)	13
Lead bed sediment concentration (mg/kg)	21

5.3.4 Results

As described in Section 2.2.4, while the pilot sDSS calculates numeric values (scores) of all indicators, it also assigns an indicator 'level,' in order to allow communication of predictions to technical and non-technical audiences, respectively. There are five indicator levels, each of which corresponds with a quintile (20%) of the range of indicator scores. The BUS and UDO indicator scores and levels calculated for each reporting unit are presented in Table 5-7 and Table 5-8, respectively. Comparison of the two tables shows the way in which the reporting of levels can mask differences in indicator scores, reflecting the difference in the precision of the two schemes. For example, while the reduction in the riparian vegetation

score for SRU 2 (0.40 to 0.19) is reflected in a corresponding reduction in level (2 to 1), this is not the case for SRU 1 because the lesser reduction in score (0.40 to 0.36) is within the range of a single indicator level.

Table 5-7: Indicator scores for the historical implementation.

Indicator	SRU 1 Lucas Creek stream		SRU 2 Oteha Stream		ERU 1 Lucas Creek tidal inlet	
	BUS	UDO	BUS	UDO	BUS	UDO
Environmental Indicators						
Stream hydrology[1]	0.68	0.21	0.68	0.1	-	-
Water quality[1]	0.25	0.21	0.23	0.19	-	-
Stream habitat[1]	0.63	0.65	0.64	0.61	-	-
Riparian vegetation[1]	0.40	0.36	0.40	0.19	-	-
Macroinvertebrates[1]	0.47	0.43	0.47	0.38	-	-
Native fish[1]	0.26	0.27	0.26	0.25	-	-
Aquatic plants[1]	0.47	0.59	0.47	0.60	-	-
Benthic Health[2]	-	-	-	-	0.44	0.30
Environmental wellbeing[3]	0.45	0.39	0.45	0.33	0.44	0.30
Economic Indicators						
Economic cost[4]	-	$5.7M	-	$5.6M	-	$26.8M
Economic benefit[5]	-	$0	-	-$3.8M	-	-$17.2M
Economic wellbeing[6]	-	0	-	-0.67	-	-0.64
Social Indicators						
Extraction[7]	0.29	0.29	0.29	0.17	0.23	0.09
Contact recreation[7]	0.30	0.30	0.30	0.18	0.17	0.06
Non-contact recreation[7]	0.33	0.33	0.33	0.20	0.24	0.12
Partial recreation[7]	0.37	0.37	0.37	0.23	0.14	0.06
Sense of place[7]	0.33	0.33	0.33	0.22	0.23	0.09
Social wellbeing[3]	0.33	0.33	0.32	0.20	0.20	0.08

Notes

[1] Normalised expected values (scale 0-1, higher is better)

[2] Normalised benthic health score (scale 0-1, higher is better)

[3] Mean of contributing indicator scores

[4] Lifecycle cost in net present value (NPV 2010, $NZ)

[5] Change in aggregated household willingness to pay (WTP, $NZ) between 1960 and 2010

[6] Benefit/cost ratio

[7] Normalised median experienced utility scores (scale 0-1, higher is better)

Table 5-8: Indicator levels for the historical implementation. Range 1 to 5 where a higher score indicates a better outcome.

Indicator	SRU 1 Lucas Creek stream		SRU 2 Oteha Stream		ERU 1 Lucas Creek tidal inlet	
	BUS	UDO	BUS	UDO	BUS	UDO
Environmental Indicators						
Stream hydrology	4	2	4	1	-	-
Water quality	2	2	2	1	-	-
Stream habitat	4	4	4	4	-	-
Riparian vegetation	2	2	2	1	-	-
Macroinvertebrates	3	3	3	2	-	-
Native fish	2	2	2	2	-	-
Aquatic plants	3	3	3	4	-	-
Benthic Health	-	-	-	-	3	2
Environmental wellbeing	3	2	3	2	3	2
Economic Indicators						
Economic cost	-	5	-	5	-	5
Economic benefit	-	3	-	3	-	1
Economic wellbeing	-	1	-	1	-	1
Social Indicators						
Extraction	2	2	2	1	2	1
Contact recreation	2	2	2	1	1	1
Non-contact recreation	2	2	2	2	2	1
Partial recreation	2	2	2	2	1	1
Sense of place	2	2	2	2	2	1
Social wellbeing	2	2	2	2	1	1

Environmental wellbeing was assessed to have decreased in all three reporting units over the hindcast period. The reduction in the score is least for SRU 1, reflecting the fact that all environmental indicator levels for this reporting unit, other than stream hydrology, were assessed to be the same in 2010 as in 1960. SRU 2 was assessed to have undergone reductions in the level of four of the seven environment indicators, with the greatest change again for stream hydrology. In both stream reporting units, the score for the aquatic plants indicator was calculated to have increased and, in the case of the SRU 2, this translated into an improvement in indicator level. This was not the case for SRU 1, where the score stayed within the range of a single level. In the ERU, the reduction in the benthic health score was sufficient to be reflected in a corresponding change in level.

Economic wellbeing was assessed to have been at the lowest of the five possible levels in all three reporting units. This reflects the fact that, despite the relatively low cost of stormwater and stream management (level 5, best outcome), economic benefit was assessed as being either neutral or negative. Social wellbeing was assessed to be low (level 1 or 2) and

unchanged in all three reporting units. There was no change in the score, and as a result level, of any social indicator in SRU 1. There was a reduction from 2 to 1 in the level of the extraction and contact recreation indicators in SRU 2 and in the level of the extraction, non-contact recreation and sense of place indicators in the ERU. Reductions in the scores for the other indicators did not translate in to a change in level.

5.3.5 Evaluation of the performance of the pilot sDSS

As noted above, the aim of the historic implementation was to assess the performance of the pilot sDSS at hindcasting the effects of historic urban development.

Differences in the assessed reduction in the environmental wellbeing score are consistent with variations in the extent of urban development, with SRU 1 assessed as being the least impacted reporting unit. Imperviousness in PLU 2 (which surrounds SRU 1) was calculated to have increased from 3% in 1960 to 17% in 2010, compared to increases of 5% to 39% in PLU 3 (which surrounds SRU 2) and 4% to 26% in the study area as a whole. As well as greater imperviousness, stream modification associated with urban development has also been less marked in SRU 1 than in SRU 2. Based on stream surveys, 50 % and 16 % of Lucas Creek stream and Oteha Stream (including Alexandra Stream), respectively, are described as “high value, low disturbance” (NSCC, 2005 a, b and c).

The relativity between post-development environmental indicator scores calculated for the SRUs is supported by monitoring data. Ecological quality rankings derived from sampling of macroinvertebrate communities are ‘fair’ (second worst of four classes) for Lucas Creek stream and ‘poor’ (worst of four classes) for Oteha Stream (ARC, 2010). This compares with macroinvertebrate scores calculated by the pilot DSS of 0.43 (SRU 1) and 0.38 (SRU 2). Water quality rankings derived from state of the environment monitoring are ‘fair’ (second worst of four classes) for both streams (ARC, 2010). This compares with water quality scores calculated by the pilot DSS of 0.21 (SRU 1) and 0.19 (SRU 2). However, while the pilot DSS successfully assessed water quality as being similar in the two streams, it appears to have been over-estimated the absolute extent of water quality degradation. The improvement in the score for the aquatic plants indicator in both streams is consistent with greater flushing of the stream bed associated with more frequent, higher flood flows. The stream assessments reported periphyton to be present below nuisance levels and macrophyte growth to be a possible issue only in some part of both streams (NSCC, 2005 a, b and c).

The post-development benthic health score calculated for ERU 1 is consistent with that reported by state of the environment monitoring (ARC, 2010). This reflects the fact that the ARC (2010) score is derived from observations of sediment metal concentrations and the pilot DSS was able to hindcast these reasonably accurately. Modeled concentrations of copper, lead and zinc in the bed sediment mixing layer were 19, 19 and 169 mg kg^{-1}, respectively, compared with measurements of 21, 23 and 120 mg kg^{-1} (Green et al., 2004).

The assessment of low economic wellbeing in all three reporting units reflects degradation of precursor environmental attributes in the light of low-cost approaches to catchment management. The assessed costs of stream management were 11% and 8% of the maximum possible in SRU 1 and SRU 2, respectively, while the costs of stormwater quality treatment were 12% of the maximum possible in the study area as a whole. In the case of SRU 1, economic benefit was assessed as being neutral because changes in precursor environmental attributes were relatively small and insufficient to trigger a change in

household WTP. In the case of SRU 2 and the ERU1, changes in the precursor environmental attributes were reflected in a reduction in household WTP. This reduction was more marked in relation to the estuary, being 63% of the maximum possible, compared to a reduction of 18% of the maximum in SRU 2.

The low scores and levels assessed for social wellbeing partly reflect the pre-development condition of the streams and estuary, which provided relatively little utility for recreational use or in terms of sense-of-place. The streams were assessed as having has modest scores in 1960 in the three precursor attributes of 'naturalness' (based on combination of scores for riparian vegetation, hydrology and habitat), water clarity and 'fauna' (based on combination of scores for macroinvertebrates and native fish). In the case of SRU 2, reductions in these scores were sufficient to translate into a loss of utility as a consequence of urban development. Low pre-development utility scores for ERU 1 reflect its predominantly muddy bed sediments, low water clarity and modest benthic health score. Again, reductions in these scores were sufficient to translate into a loss of utility by 2010.

5.4 Future Implementation

5.4.1 Introduction

The aim of the future implementation was to assess the performance of the pilot sDSS for discriminating between outcomes under alternative future urban development scenarios. The future implementation covered the period 2010 (BUS) to 2060 (UDO). The input data for the BUS for this implementation were therefore identical to those for the UDO in the historical implementation.

Four scenarios were assessed, each undergoing the same extent of urban development but with variations in the future urban land-use mix, levels of stormwater treatment and the extent of riparian planting. The four scenarios, each of which represents the state of urban development at the UDO, were (see also Table 5-9):

- Scenario 1 – 'Business as usual': additional urban land use in accordance with current zoning; level of stormwater treatment unchanged from the BUS; no change in the extent of riparian vegetation from the BUS.
- Scenario 2 – 'Maximum stormwater treatment': additional urban land use as per Scenario 1; highest level of stormwater treatment; riparian vegetation as per Scenario 1.
- Scenario 3 – 'Maximum riparian planting': additional urban land use as per Scenario 1; stormwater treatment as per Scenario 1; maximum additional riparian vegetation.
- Scenario 4 – 'LID': additional urban land use in accordance with LID forms of development and land-use zoning; highest level of stormwater treatment; maximum additional riparian vegetation.

Table 5-9: UDOs, future implementation scenarios 1 to 4.

	Scenario 1 Business as usual	Scenario 2 Maximum stormwater treatment	Scenario 3 Maximum riparian planting	Scenario 4 LID
Land use	As per zoning	As per zoning	As per zoning	LID, as per zoning
Stormwater treatment	Same as BUS	Maximum level	Same as BUS	Maximum level
Riparian vegetation	Same as BUS	Same as BUS	Maximum extent	Maximum extent

5.4.2 Data sources

The following data sources were used to define inputs to the pilot sDSS for the future development scenarios:

- Land-use zone shape files provided by Auckland Council, to give an indication of the areas of commercial, industrial and residential land use available for development.
- Auckland council population (2011-2041) and housing stock (2051) projections, to guide the timing and rate of development.
- NZ Transport Agency publications and website (e.g, NZTA, 2012; 2008), to assess traffic numbers and trends.

5.4.3 Representation of urban development

Land use

As noted above, land use at the BUS (2010) was the same as the UDO for the historic implementation (see Table 5-2). Land use in 2060 was estimated from GIS land-use zone shape files provided by Auckland Council. It was assumed that all available land within a specific urban land-use zone would be fully developed by 2060. The extent of projected urban development by 2060 by broad land-use classes is shown in Figure 5-10[10].

The extent of future development in each land-use class (i.e. the projected change over the study time frame) was determined by comparison with land use in 2010 (see Figure 5-4). For Scenarios 1 to 3, it was assumed that land uses developed before 2010 would be unchanged; new residential areas would be developed as high density suburban housing (i.e., infill and town houses), and new industrial and commercial development would have the same characteristics as existing areas of these land uses. For Scenario 4, LID options for all urban land-use types were selected, including for areas developed before 2010. The resulting UDO land-use break down for each future scenario is shown in Table 5-10. In all four of the scenarios, development in each PLU commenced immediately (i.e. in 2010) and

[10] In this map, all residential land zones are classed together, land zoned for lifestyle blocks and recreation are classed as rural pasture while land zoned for environmental protection is classed as native forest.

was completed by 2040, based on population and housing projections (e.g., see Figure 5-11).

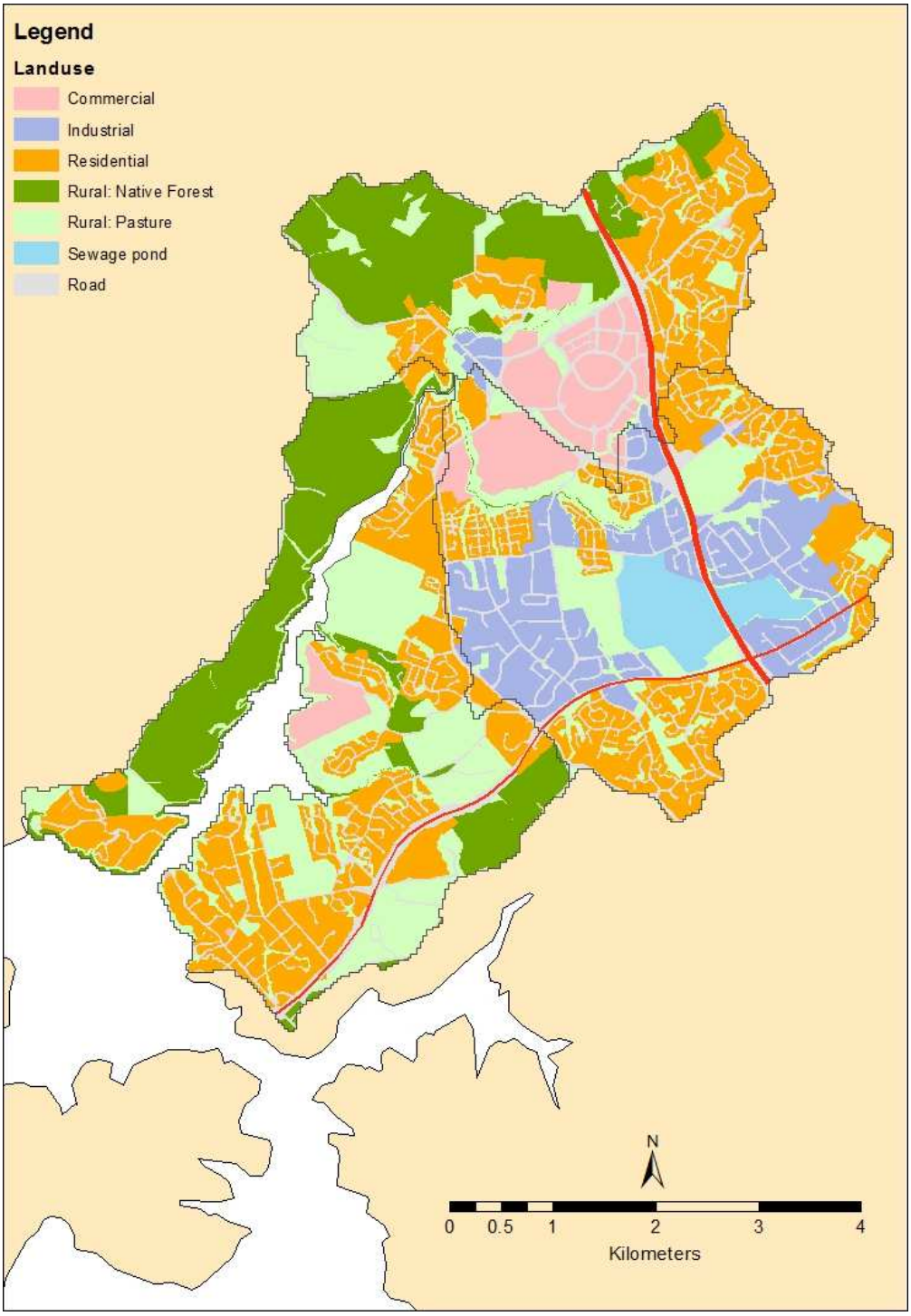


Figure 5-10: Projected land use, 2060. Based on land-use zone shape files provided by Auckland Council.

Table 5-10: Land use at the UDO (2060) by PLU.

Land use	PLU 1 Paremoremo		PLU 2 Lucas Creek		PLU3 Oteha Valley		PLU4 Greenhithe	
	Scen. 1-3	Scen. 4	Scen. 1-3	Scen. 4	Scen. 1-3	Scen. 4	Scen. 1-3	Scen. 4
Commercial: LID	0	0	0	15	0	7	0	5
Commercial: Local	0	0	15	0	7	0	5	0
Industrial: LID	0	0	0	2	0	32	0	0
Industrial	0	0	2	0	32	0	0	0
Residential: LID	0	16	0	28	0	31	0	46
Residential: High density	7	0	15	0	3	0	5	0
Residential: Medium density	2	0	13	0	28	0	20	0
Residential: Low density	7	0	0	0	0	0	21	0
Rural: Native Forest	81	81	36	36	0	0	11	11
Rural: Pasture	3	3	18	18	29	29	37	37
Regional road	1	1	1	1	1	1	1	1
Per cent urban at UDO	17		46		71		52	
Per cent urban at BUS	9		27		57		45	

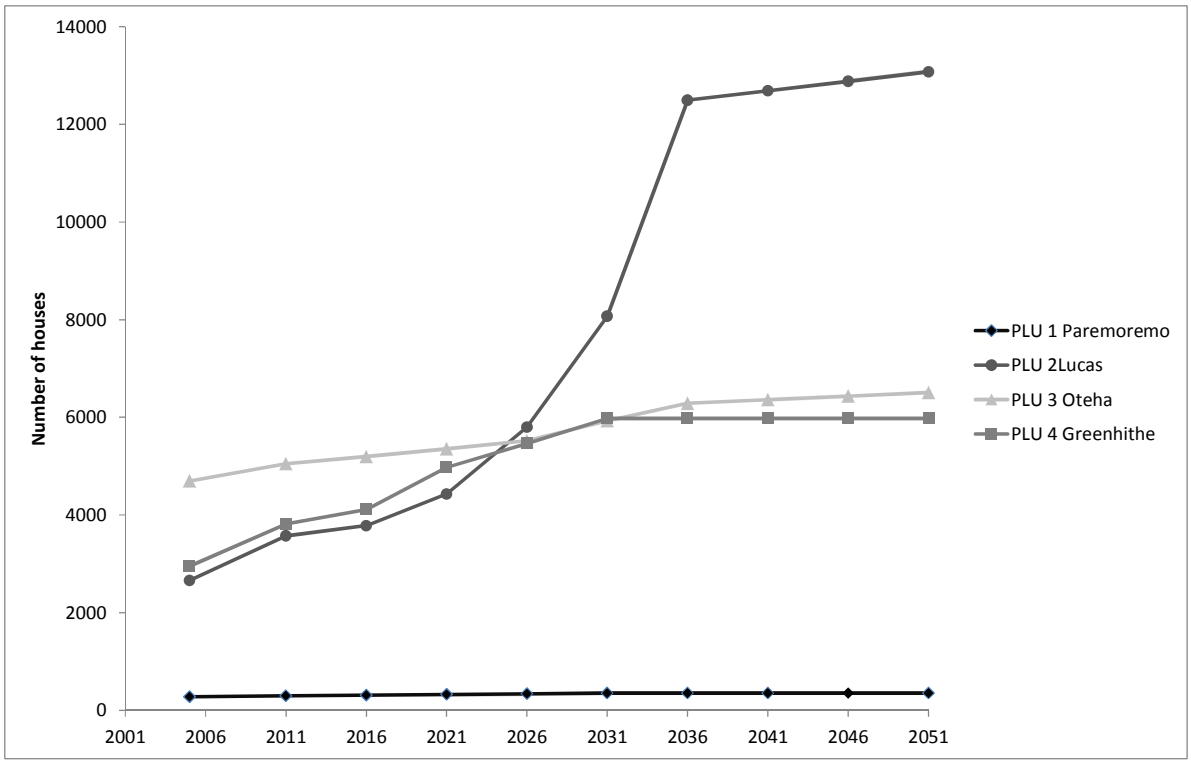


Figure 5-11: Projected number of houses by PLU (2005-2051). Data provided by Auckland Council.

The extent of additional urban development is projected to be greatest in PLU 2, with housing numbers increasing from around 4000 in 2010 to over 12000 in 2030 and population increasing from 9000 to 32000 over the same period. While there are also increases in population and housing projected for PLUs 3 and 4, these are not as dramatic. Very little urban development is projected for PLU1, reflecting the fact that it lies outside the MUL.

Stormwater treatment

As with land use, the level of stormwater treatment for each PLU at the BUS is the same as that of the UDO for the historical implementation (refer Table 5-3). Scenarios 1 and 3 have no change over time in the level of stormwater treatment from 2010, whereas Scenarios 2 and 4 reach the maximum possible level of stormwater treatment (high) in each PLU by the end of urban development in 2040.

Traffic trends

The scenarios all have the same trend in traffic, with a 20% increase in the number of vehicles over the 50-year simulation period and a change from current brake and tyre materials to low-yielding varieties (i.e,. source control).

SRU characteristics

With the exception of riparian planting, the implementation data relating to SRU characteristics were the same as those for the historical implementation (refer Table 5-5). The UDO parameters associated with riparian planting varied from the 2010 values depending on the scenario (Table 5-11).

Table 5-11: UDO parameters associated with riparian planting for the future development scenarios.

Riparian planting	SRU 1 Lucas Creek stream		SRU 2 Oteha Stream	
	Scen. 1 and 2	Scen. 3 and 4	Scen. 1 and 2	Scen. 3 and 4
Percentage of stream length with managed riparian planting	30	75	0	70
Width class of managed riparian planting	Wide	Wide	-	Wide
Percentage of stream length with unmanaged riparian planting	25	25	30	30

ERU characteristics

All the scenarios had the same implementation data relating to ERU characteristics (listed in Table 5-12). These data were taken from the UDO output of the historical implementation.

Table 5-12: ERU implementation data, future scenarios.

ERU parameter	Value
Depth of mixing layer (m)	0.1
Mud fraction (% sediments ≤ 63 µm)	91
Zinc bed sediment concentration (mg/kg)	169
Copper bed sediment concentration (mg/kg)	19
Lead bed sediment concentration (mg/kg)	19

5.4.4 Results

Table 5-13 and Table 5-14 present indicator scores and levels, respectively, for the BUS and UDO in each of scenarios 1 to 4.

Scores for environmental wellbeing in the two SRUs were similar to or slightly worse than those for the BUS under scenarios 1 and 2 and slightly better than those for the BUS under scenarios 3 and 4. In the case of SRU 2 (Oteha Stream), the improvement in score under scenarios 3 and 4 translated into an improvement in indicator level (from 2 to 3). The improvement in overall environmental wellbeing under scenarios 3 and 4 was driven by marked increases in the scores for riparian habitat and aquatic vegetation and, to a lesser extent, stream habitat, macroinvertebrates and native fish. Under scenarios 1 and 2 scores for individual environmental indicators were little changed from those for the BUS. However, scores for stream hydrology followed a different pattern from the rest of the environmental indicators, being very low (0.1) under all scenarios.

The score for the benthic health indicator / environmental wellbeing in the ERU was lower under all four scenarios than for the BUS. This translated into a fall in indicator level from 2 to 1 (lowest possible level).

The economic cost for both SRUs was markedly higher (an order of magnitude) under scenarios 3 and 4 than under scenarios 1 and 2. This higher cost translated into a lower indicator level (level 3 under scenarios 3 and 4, compared to level 5 under scenarios 1 and 2). The economic benefit for both SRUs was zero, except under scenario 4 in SRU 2 (economic benefit of $3.8M). As a result of the zero benefit, economic wellbeing was also zero other than under scenario 4 in SRU2 (0.11). Expressed as an indicator level, economic wellbeing was at the lowest level (1) under all scenarios in both SRUs.

There was similar order of magnitude difference in costs for the ERU, but in this case scenarios 2 and 4 had the higher costs. Economic benefit and economic wellbeing were negative under all four scenarios. Expressed as indicator levels, economic benefit was at level 2 and economic wellbeing at level 1 under all four scenarios.

Social wellbeing and individual social indicator scores in the SRUs were unchanged from those for the BUS under all scenarios, with one exception: there was a reasonably marked improvement in the scores in SRU 2 (Oteha Stream) under scenario 4. This improvement translated into higher levels (2, compared to 1 for the BUS) for the extraction and contact recreation indicators.

Social wellbeing and individual social indicator scores in the ERU were the same under all four scenarios and were lower than those for the BUS. Levels were unchanged, already being at the lowest level (1) for the BUS.

Table 5-13: Indicator scores for the future implementation, BUS and UDOs scenarios 1 to 4 (S1 to S4).

Indicator	SRU 1 Lucas Creek stream					SRU 2 Oteha Stream					ERU 1 Lucas Creek tidal inlet				
	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4
Environmental Indicators															
Stream hydrology[1]	0.22	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-	-	-	-	-
Water quality[1]	0.27	0.25	0.25	0.26	0.27	0.23	0.19	0.23	0.2	0.24	-	-	-	-	-
Stream habitat[1]	0.67	0.67	0.67	0.7	0.7	0.61	0.61	0.61	0.67	0.71	-	-	-	-	-
Riparian vegetation[1]	0.45	0.45	0.45	0.56	0.56	0.19	0.19	0.19	0.42	0.56	-	-	-	-	-
Macroinvertebrates[1]	0.44	0.44	0.44	0.48	0.48	0.38	0.38	0.38	0.44	0.47	-	-	-	-	-
Native fish[1]	0.28	0.28	0.28	0.302	0.302	0.25	0.25	0.25	0.29	0.3	-	-	-	-	-
Aquatic plants[1]	0.62	0.62	0.62	0.78	0.78	0.6	0.6	0.6	0.78	0.78	-	-	-	-	-
Benthic Health[2]	-	-	-	-	-	-	-	-	-	-	0.30	0	0.09	0	0.13
Environmental wellbeing[3]	0.42	0.4	0.4	0.45	0.46	0.34	0.33	0.34	0.41	0.45	0.3	0	0.09	0	0.13
Economic Indicators															
Economic cost[4]	-	$3.3M	$3.4M	$18.6M	$18.8M	-	$3.4M	$3.9M	$34.6M	$35.2M	-	$16.8M	$185M	$16.8M	$323M
Economic benefit[5]	-	$0	$0	$0	$0	-	$0	$0	$0	$3.8M	-	-$15.4M	-$15.4M	-$15.4M	-$15.4M
Economic Wellbeing[6]	-	0	0	0	0	-	0	0	0	0.11	-	-0.91	-0.08	-0.91	-0.05

Indicator	SRU 1 Lucas Creek stream					SRU 2 Oteha Stream					ERU 1 Lucas Creek tidal inlet				
	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4
Social Indicators															
Extraction[7]	0.29	0.29	0.29	0.29	0.29	0.17	0.17	0.17	0.17	0.29	0.08	0	0	0	0
Contact recreation[7]	0.3	0.3	0.3	0.3	0.3	0.18	0.18	0.18	0.18	0.3	0.06	0.01	0.01	0.01	0.01
Non-contact recreation[7]	0.37	0.37	0.37	0.37	0.37	0.23	0.23	0.23	0.23	0.37	0.06	0.02	0.02	0.02	0.02
Partial recreation[7]	0.33	0.33	0.33	0.33	0.33	0.2	0.2	0.2	0.2	0.33	0.12	0.05	0.05	0.05	0.05
Sense of place[7]	0.33	0.33	0.33	0.33	0.33	0.22	0.22	0.22	0.22	0.33	0.09	0	0	0	0
Social wellbeing[3]	0.33	0.33	0.33	0.33	0.33	0.2	0.2	0.2	0.2	0.33	0.08	0.02	0.02	0.02	0.02

Notes

[1] Normalised expected values (scale 0-1, higher is better)

[2] Normalised benthic health score (scale 0-1, higher is better)

[3] Mean of contributing indicator scores

[4] Lifecycle cost in net present value (NPV 2010, $NZ)

[5] Change in aggregated household willingness to pay (WTP, $NZ) between 2010 and 2060

[6] Benefit/cost ratio

[7] Normalised median experienced utility scores (scale 0-1, higher is better)

Table 5-14: Indicator levels for the future implementation, BUS and UDOs scenarios 1 to 4 (S1 to S4). Range 1 to 5 where a higher score indicates a better outcome.

Indicator	SRU 1 Lucas Creek stream					SRU 2 Oteha Stream					ERU 1 Lucas Creek tidal inlet				
	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4
Environmental Indicators															
Stream hydrology	2	1	1	1	1	1	1	1	1	1	-	-	-	-	-
Water quality	2	2	2	2	2	2	1	2	1	2	-	-	-	-	-
Stream habitat	4	4	4	4	4	4	4	4	4	4	-	-	-	-	-
Riparian vegetation	3	3	3	3	3	1	1	1	3	3	-	-	-	-	-
Macroinvertebrates	3	3	3	3	3	2	2	2	3	3	-	-	-	-	-
Native fish	2	2	2	2	2	2	2	2	2	2	-	-	-	-	-
Aquatic plants	4	4	4	4	4	4	4	4	4	4	-	-	-	-	-
Benthic Health	-	-	-	-	-	-	-	-	-	-	2	1	1	1	1
Environmental wellbeing	3	3	3	3	3	2	2	2	3	3	2	1	1	1	1
Economic Indicators															
Economic cost	-	5	5	3	3	-	5	5	3	3	-	5	3	5	1
Economic benefit	-	3	3	3	3	-	3	3	3	3	-	2	2	2	2
Economic Wellbeing	-	1	1	1	1	-	1	1	1	1	-	1	1	1	1

Indicator	SRU 1 Lucas Creek stream					SRU 2 Oteha Stream					ERU 1 Lucas Creek tidal inlet				
	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4	BUS	S1	S2	S3	S4
Social Indicators															
Extraction	2	2	2	2	2	1	1	1	1	2	1	1	1	1	1
Contact recreation	2	2	2	2	2	1	1	1	1	2	1	1	1	1	1
Non-contact recreation	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1
Partial recreation	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1
Sense of place	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1
Social wellbeing	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1

5.4.5 Evaluation of the performance of the pilot sDSS

The aim of the future implementation was to assess the performance of the pilot sDSS for discriminating between outcomes under alternative future urban development scenarios.

Stream environmental outcomes associated with improved stormwater treatment (scenario 2) were virtually indistinguishable from those associated with 'business as usual' (scenario 1) across all indicators. This is likely to be a function of three factors. Firstly, the study area was already largely urbanised at the BUS; secondly, land-use change (and hence, imperviousness, which is an input to the BBN) was identical in both scenarios; and, thirdly, the difference in the level of stormwater treatment was relatively limited (75% TSS removal under scenario 1 and 90% TSS removal under scenario 2). As a result, the loads of contaminants generated and their reduction by stormwater treatment are not markedly different under scenario 1 and scenario 2. This translates into very similar water quality outcomes under both scenarios.

The greater reduction in the benthic health indicator score under scenario 1 (and 3) compared to scenario 2 (and 4) reflects the influence of improved stormwater treatment in reducing metal loads delivered to the estuary. However, the difference between scenarios is limited (and is not apparent in the comparison of indicator levels - Table 5-14) and also informative, in that it suggests that even the highest level of stormwater treatment will not avoid ecological degradation in this type of receiving environment.

In contrast, the pilot sDSS predicted an improvement from the BUS in stream environmental indicators associated with maximum riparian planting (scenarios 3 and 4). While this improvement was most marked for the riparian vegetation indicator, as might be expected, the improvements in the habitat, fish, aquatic vegetation and macroinvertebrate indicators show the influence of increased cover cascading through the BBN to these other indicators. The improvement was greater in SRU2 (Oteha Stream), reflecting the fact that this catchment had a lesser extent of riparian vegetation at the BUS (2010) and consequently underwent more planting in order to achieve maximum riparian cover by the UDO (2060).

These contrasting results provide an indication of the extent to which the pilot sDSS is able to discriminate between environmental outcomes of different scenarios in catchments that are already largely urbanised. Where scenarios are characterised by identical land use and only small differences in stormwater or stream management, environmental indicators are unlikely to differ much, if at all. However, where more significant differences are included in scenarios, i.e. reflecting extensive riparian planting exercises or marked improvements in stormwater treatment (for instance in comparison to a BUS in which there is very limited existing treatment), then the pilot sDSS can be expected to distinguish between environmental outcomes.

The differences in the economic cost under the various scenarios reflect the greater stormwater treatment effort under scenarios 2 and 4 (which raised the cost indicator in the ERU) and the greater stream management effort under scenarios 3 and 4 (which raised the cost indicator in the SRUs). The greater cost in ERU1 under scenario 4 than under scenario 2 reflects the fact that LID forms of development were adopted in the latter scenario. In the pilot sDSS this inflates the cost of stormwater treatment because the selection of LID triggers an 'at source / end-of-pipe' mix of stormwater treatment, while stormwater treatment for non-LID forms of development is assumed to be all 'end-of-pipe'.

The fact that the economic benefit indicator was identical across all scenarios, with one exception, reflects the fact that there was insufficient change in values of the precursor variables between the BUS and UDO in these scenarios. This comes back to the same root cause discussed above for the environmental indicators: the identical land-use change and limited extent of differences in stormwater treatment. The one exception again reflects the greater distinction in riparian management between the scenarios; under scenario 4 there was sufficient improvement in stream environmental indicators to trigger a net environmental benefit ($3.8 M). The negative benefit (i.e. net loss in value) in the ERU under all scenarios indicates a sufficient deterioration in precursor variables to trigger a reduction in willingness to pay.

The low, zero or negative benefit/cost ratios (i.e. the economic wellbeing scores shown in Table 5-13) translate into the lowest economic wellbeing level (Table 5-14) under all scenarios in all reporting units. For the main part, this apparent lack of discrimination merely shows that these scenarios fail to deliver any environmental benefit. As noted above in relation to the ERU environmental wellbeing indicator, this is points to the potential for a general incompatibility between urban development and improved environmental outcomes in catchments that are already extensively urbanised. A more subtle aspect of the lack of discrimination between economic wellbeing scores is the delineation of economic jurisdiction, meaning the geographical area over which the benefits are deemed to accrue. In this case study it was assumed that the sole beneficiaries of any environmental benefits are the local community within the case study area itself. So, in the one example of a positive economic benefit (SRU 2, scenario 4), those benefits were small relative to the costs and, as a result, the economic wellbeing remained at the lowest level and thus appeared the same as in the other scenarios. This suggests reconsideration of how the benefit/cost ratio translates into the economic wellbeing level would be helpful, as would further consideration of the notion of the economic jurisdiction, in order to better discriminate between scenarios that result in some benefit as opposed to none at all (or negative benefit).

The lack of discrimination in social indicators mirrors that in economic benefit, since all are influenced by the same environmental precursor variables. Again, the exception is SRU 2 under scenario 4, in which scores for all indicators were better than in the three other scenarios. In the other three scenarios, minor differences in the precursor variables between the BUS and UDO were insufficient to trigger a movement from one level of experienced utility to another.

As a concluding comment, the limited extent of discrimination between outcomes of development scenarios in this case study predominantly reflects two influences:

- The study area was already extensively urbanised and this limited the extent of any differences between the alternative future development scenarios;
- The characteristics of the receiving environments in the case study area are such that they limit the potential for divergence in outcomes resulting from future development: it would be unrealistic, for instance, to expect Lucas Creek tidal inlet to score highly for any of the indicators given that it has muddy underfoot conditions and elevated sediment metal concentrations.

Having said this, the results of the future implementation demonstrate that, even in a study area with these limitations, the pilot sDSS was able to discriminate between outcomes where there was sufficient distinction in the characteristics of scenarios (i.e. in the specification of the extent of riparian vegetation). In order to further test its ability to discriminate, however, further case studies are required which will allow both greater variation in the specification of scenarios and which contain greater diversity in the character of receiving environments.

6 Building on the Pilot sDSS

6.1 Introduction

This chapter describes the tasks that will be involved in progressing from the pilot to an operational sDSS while remaining within the current scope of the tool (Section 6.2). It also identifies a number of areas for further research which might lead to an expansion of its scope (Section 6.3).

6.2 Tasks for Development of an Operational sDSS

There are four broad groups of tasks involved in progressing towards the development of an operational version of the sDSS:

1. further testing of the existing methods;
2. refinement of these methods;
3. completing the development of additional methods; and
4. enhancing the functionality and appearance of the system.

Tasks in each of these groups have been identified in response to issues flagged at various stages of the research, including: during development of the PoC version; as a result of end-user engagement; during development of the pilot sDSS; and as a result of testing the pilot for the Lucas Creek study area. The tasks are described below.

6.2.1 Further testing of existing methods

Further testing of the pilot sDSS should focus on:

- evaluating its performance (including validation against historic development and ability to discriminate between future scenarios) for other case study areas, both in the Auckland region and in other urban centres in New Zealand, selected on the basis of differences in the characteristics of receiving waterbodies and/or forms of urban development;
- examining sensitivity of the methods to scale, both of PLUs and reporting units;
- examining performance for more complex representations of a study area, for instance incorporating larger numbers of PLUs and reporting units and with more complex interactions between them;
- examining performance for situations in which the calculation of indicators for an SRU take into account the influence of more than one PLU (e.g. an adjacent PLU and an upstream PLU); and
- Independently validating the BBN for urban stream catchments outside of its application in the sDSS.

6.2.2 Refinement of existing methods

Refinements that have been identified as potentially improving the methods already incorporated in the pilot sDSS include the following.

Refinements to the calculation of contaminant loads by C-CALM:

- revising some of the UDO land-use categories, in consultation with end-users of the sDSS, in order to improve representation of the range of possible forms of urban development;
- revising the specification of major roads, so that the proportion in each of three vehicle number classes occurs as part of implementation and UDO specification, rather than in accordance with default values;
- specifying some UDO characteristics (for instance the change in vehicle numbers and traffic source control measures) at the scale of the whole study area rather than individually for each PLU;
- disconnecting the calculation of lead loads from that of other metals in C-CALM by specifying lead yields independently, rather than as a function of copper or zinc yields;
- recognising that riparian vegetation and the character of coastal margins can act to reduce sediment loads by introducing a riparian vegetation treatment factor that applies to land uses where runoff is discharged via overland flow through riparian margins (rural and LID urban land uses) but not where it is discharged via reticulated pipe systems (all other urban land uses); and
- developing and incorporating yields and stormwater treatment load reduction factors for nutrients.

Refinements to the stream ecosystem health BBN:

- reviewing the prediction of nutrient concentrations in the BBN (for instance by further developing C-CALM to predict nutrients, as noted above);
- investigating modifications to the BBN in order to take account of the condition of certain stream characteristics in previous years (for instance to reflect the fact that macroinvertebrate and fish communities are not only influenced by the current state of a stream but also by prior presence / abundance); and
- allowing additional inputs to the BBN in relation to in-stream restoration works such as stream daylighting.

Refinements to the ERU environmental indicators:

- reporting the USC model's predictions of sediment metal concentrations, sediment grain size characteristics and sediment accumulation rate as environmental indicators, in addition to their use as inputs to other methods in the pilot sDSS.

Refinements to the application of the Benthic Health Model in the pilot sDSS:

- investigating the incorporation of the more recent version of the BHM, in which benthic health is related to sediment particle size distribution as well as metal concentrations.

Refinements to the economic costing methods:

- investigating in more detail the costing of stormwater quantity control measures associated with LID, which in the present costing model are assumed to be a fixed proportion of the costs associated with traditional forms of stormwater management.

Refinements to the prediction of economic benefits:

- further investigating the method by which turbidity in ERUs, which is required for the prediction of the economic benefits (and social indicators), is estimated from estuary bed sediment grain size;
- more accurately representing the economic jurisdiction or 'community of beneficiaries' (i.e. number of households) for the calculation of economic benefits, in order to take account of findings on the spatial distribution of benefits;
- further exploration of other non-market valuation techniques, especially with regard to cost, e.g. postal techniques and dichotomous choice contingent valuation;
- collecting data on the influence of the character of coastal margins on willingness to pay as a way of including this factor as a determinant of the economic benefits indicator score; and
- further investigation of the correspondence between turbidity boundaries in the imagery used in the focus groups and in the real world (this is also relevant for the prediction of social indicators).

Refinements to the prediction of social indicators:

- gathering data on 'experienced utility' from a greater sample size in order to give greater statistical significance to these data for their use in predicting social indicators (including experienced utility for combinations of attributes not presented in the original focus groups);
- investigating the reporting of social indicators in terms of utility/cost, i.e. integrating social and economic indicators;
- collecting data on the influence of the character of coastal margins on experienced utility as a way of including this factor as a determinant of the social indicator scores; and
- investigating the performance of the method in relation to generic data compared to location-specific data on experienced utility.

In addition to these tasks, it may also be relevant to consider additional refinements that emerge as part of the further testing of the pilot sDSS set out in Section 6.2.1.

6.2.3 Development of additional methods

The delivery of an operational sDSS in line with the scope established as part of the development of the PoC version of the system requires the development and incorporation of methods to achieve the following:

- the prediction of cultural indicators;
- the prediction of additional ERU environmental indicators, for instance to reflect the condition of the water, habitat and/or faunal quality of the water column; and
- the weighting of environmental indicators as part of the calculation of environmental wellbeing, as an alternative to the calculation of the mean indicator score.

Other methods which could be developed and incorporated, but which are not essential for the fulfilment of the scope established by the PoC are:

- methods which connect streams and estuaries, for instance so that the extent of riparian planting in a PLU exerts some influence on ERU indicators as well as SRU indicators; and
- costing models for in-stream channel modifications such as daylighting and other in-stream restoration works.

6.2.4 Functionality and appearance

There are a number of ways in which the functionality and appearance of the sDSS could be enhanced, some of which were established as part of the development of the PoC version of the system. These include:

- developing a spatial interface for the specification of inputs and visualisation of outputs;
- developing a ‘dashboard’ capable of displaying information at a level of detail lying somewhere between the pilot sDSS results worksheets and the audit trail text file output;
- representing UDO indicator scores as percentage change from the BUS score and/or including representation of the absolute score at the BUS and UDO as a way of showing changes at a finer level of resolution than that provided by the five-colour system;
- incorporating help pages and/or a manual;
- providing for users to customise the specification of inputs, for instance customised land-use sub-categories;
- allowing targets and weights to be set for individual ERUs and SRUs;

- incorporating other ways of presenting results, for instance time series plots and radar plots; and
- providing for the comparison of results from multiple scenarios.

Prior to making these enhancements it will be important to determine the software environment that the operational tool will be delivered in and to plan how the system will be run and by whom.

6.3 Beyond the Operational sDSS

The previous sections describe tasks involved in delivering an operational sDSS in line with the scope established as part of the development of the PoC version of the system. Complementary research has the potential to lead to an expanded scope, for instance by developing methods which could be incorporated in a 2nd generation version of the sDSS.

This research would focus on the application of resilience theory (Folke et al., 2010) as a way of extending our current understanding and the methods for characterising the effects of land-use change on the quality of receiving waters. It would involve analysing the way that key concepts (regime shifts, tipping points, drivers of change and the reversibility of state changes) can be incorporated into indicators (Milman and Short, 2008), and finding ways in which environmental, economic, social and cultural attributes of regimes can be characterised.

The results would be applied to develop indicators of the resilience of New Zealand water bodies to the effects of urban development. This will involve assessing whether the New Zealand experience fits with conceptual models of resilience by looking at New Zealand datasets and published literature for evidence of regime shifts and tipping points, and identifying key characteristics that distinguish one state from another. The utility of resilience indicators for distinguishing between the outcomes of alternative urban development scenarios would be tested in further case studies to hindcast the known effects of an historic urban development.

By implementing a version of the sDSS that incorporates resilience indicators the potential for regime shifts associated with alternative urban development scenarios could be assessed, along with the likely efficacy of management strategies aimed at avoiding negative and/or irreversible regime shifts and promoting restoration to better states.

The output from this research would be a validated system of indicators based on concepts from resilience theory.

7 References

Anderson, M.; Hewitt, J.E.; Thrush, S.F. (2002). The development of criteria for assessing community health of urban intertidal flats. No. Technical Publication 184. Auckland Regional Council, Auckland. 67 p.

Anderson, M.; Hewitt, J.E.; Ford, R.; Thrush, S.F. (2006). Regional models of benthic ecosystem health: prediction pollution gradients from biological data. Technical Publication 317. Auckland Regional Council.

Auckland Council (2012). The Auckland Plan. http://theplan.theaucklandplan.govt.nz/ Accessed 27 September 2012.

Auckland Regional Council (ARC, 2003) Stormwater management devices: design guidelines manual. ARC Technical Publication TP10 (Second Edition).

ARC. (2010). State of the Auckland Region 2009. Auckland Regional Council, Auckland, New Zealand. http://www.aucklandcouncil.govt.nz/EN/planspoliciesprojects/reports/technicalpublications/Pages/stateaucklandregionreport2010.aspx. Accessed 8 October 2012.

Auckland Regional Transport Authority, ARTA (2006) Auckland Urban Density Study. http://www.arc.govt.nz/albany/fms/main/Documents/Auckland/Aucklands%20growth/Auckland%20Urban%20Density%20Study%20-%20Draft%20Report.pdf. Accessed 13 December 2012.

Bateman, I., Day, B., Stravos, G. and Lake, I. (2006) The Aggregation Of Environmental Benefits: Welfare Measures, Distance Decay, And WTP. Discussion paper #14, September 2006, Commerce Division, Lincoln University.

Batstone, C.J., Baines, J.M., Goodwin, E., Morgan, B. and Canard, T. (2010). Methods for Developing Sustainability Indicator Systems for Freshwater and Estuarine Receiving Bodies of Urban Stormwater. Prepared for NIWA. Cawthron Report 1974.

Batstone, C., Moores, J., Semadeni-Davies, A., Green, M., Gadd, J. and Harper, S. (2011). Derivation of Economic and Social Indicators for a Spatial Decision Support System to Evaluate the Impacts of Urban Development on Water Bodies in New Zealand. New Zealand Agricultural and Resource Economics Society 2011 Conference, Nelson, 25-26 August 2011

Batstone, C.J., Roberts, B, and B.M.H. Sharp. (2008). Evaluating Coastal Receiving Environments and The Effects Of Stormwater, Report to the Auckland Regional Council, Cawthron Report 1392.

Batstone, C., Moores, J., Baines, J. and Harper, S. (2012) Investigating the use of experienced utility scores to assess changes in the social wellbeing associated

with estuarine and lowland freshwater water bodies impacted by urban storm water (draft). Cawthron Report.

Burgman, M. (2005). Risks And Decisions For Conservation And Environmental Management, Cambridge University Press ISBN 0521835348.

Burgman, M., Forest, B., Batstone, C., Hopkins, G., Baumgartner, J., and McBride, M., (2011), Getting the best out of experts, International Society for Conservation Biology Conference workshop, University of Auckland, December, 2011.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15(4): 20.

Gadd, J. (2011). Review of marine ecosystem indicators. Urban Planning that Sustains Waterbodies. NIWA Report: prepared under contract C01X0908 funded by the Ministry of Science and Innovation.

Gadd, J. and Storey, R. (2012). Urban Planning that Sustains Waterbodies: Development of a Bayesian Belief Network for Stream Ecosystem Health. NIWA report AKL-2012-037 prepared under contract C01X0908 funded by the Ministry for Science and Innovation.

Greater Christchurch Urban Development Forum (GCUDF), (2007).Greater Christchurch Urban Development Strategy and Action Plan 2007.

Green, M. (2008a). Central Waitemata Harbour Study. USC-3 Model Description, Implementation and Calibration. Prepared by NIWA Ltd for Auckland Regional Council. Auckland Regional Council Technical Report 2008/042.

Green, M. (2008b). Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Implementation and Calibration of the USC-3 Model. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Report 2008/057.

Green, M., Williamson, R., Timperley, M., Collins, R., Senior, A., Adams, A., Swales, A. and Mills, G. (2004). Prediction of Contaminant Accumulation in the Upper Waitemata Harbour – Methods. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Publication No. 261.

Hajkowicz ,S., Spencer, R., Higgins, A. and Marinonic, O. (2008). Evaluating Water Quality Investments Using Cost- Utility Analysis, Journal of Environmental Management, Volume 88, Issue 4, September 2008, Pages 1601–1610.

Hewitt, J.E.; Ellis, J.I. (2010). Assessment of the benthic health model. Technical Report No. 2010/034. Auckland Regional Council, 36 p.

Ira S. (2011). The Development Of Catchment Scale Life Cycle Costing Methods For Stormwater Management. Report commissioned by Cawthron Institute. Cawthron Report No. 2082. 35 p. plus appendices

Ira, S. (2012). Development of a life cycle cost model for urban lowland stream riparian planting and stormwater quantity management, Addendum to Cawthron Report 2082.

Ira, S., Batstone, C., and Moores, J. (2012a). The Development of an Economic Costing Methodology for Stormwater Management within a Spatial Decision Support System used to Evaluate the Impacts of Urban Development. Water NZ Stormwater 2010 conference, Wellington 10-11 May 2012.

Ira, S., Batstone, C., and Moores, J. (2012b). The incorporation of economic indicators within a spatial decision support system to evaluate the impacts of urban development on waterbodies in New Zealand. 7th International Conference on Water Sensitive Urban Design, 21-23 February 2012, Melbourne.

Ira, S., Vesely, E-T. and Krausse, M. (2008). Life cycle costing of stormwater treatment devices: a practical approach for New Zealand. 11th International Conference on Urban Drainage. Edinburgh, Scotland.

Jorgensen, B., and Stedman, R. (2001) Sense Of Place As An Attitude: Lakeshore Owner's Attitudes To Their Properties. Journal of Environmental Psychology(21): 233-248

Kahneman, D., and Sugden, R. (2005) Experienced Utility As A Standard Of Policy Evaluation. Environmental and Resource Economics (2005) 32: 161-181.

Kerr, G., and Sharp, B. (2003) Community Mitigation Preferences: a choice modelling study of Auckland streams. AERU Research Report # 256. Agribusiness and Economics Research Unit, Lincoln University.

Kingett Mitchell Ltd and Diffuse Sources Ltd. (2003). A study of roof run-off quality in Auckland New Zealand Implications for stormwater management. Report to the Auckland Regional Council.

Mansell, T. and Stumbles, C. (2010). A New Approach to Stream Restoration Trialed in North Shore. Water New Zealand Stormwater 2010 Conference, Rotorua, 13-14 May 2010.

Milman, A. and Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. Global Environmental Change 18: 758–767.

Ministry for the Environment (MFE, 2005). Wai Ora: Report of the Sustainable Water Programme of Action Consultation Hui. Ministry for the Environment, Wellington.

MFE (2008). Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. 2nd Edition. Mullan B; Wratt D; Dean S; Hollis M; Allan S; Williams T, Kenny G and MfE. Ministry for the Environment, Wellington

Moores, J., Batstone, C. and Green. M. (2011a). Development of a Spatial Decision Support System for Evaluating the Impacts of Urban Development on

Waterbodies: Context, Scope and Design. NIWA report AKL-2010-042 prepared under contract C01X0908 funded by the Ministry of Science and Innovation.

Moores, J. and Semadeni-Davies, A. (2011). Integrating a stormwater contaminant load model into a spatial decision support system for urban planning. 15th International Conference of the IWA Diffuse Pollution Specialist Group, 18 - 23 September 2011, Rotorua, New Zealand.

Moores, J., Semadeni-Davies, A., Batstone, C., Green, M., Gadd, J. and Harper, S. (2011b). Conceptualising a spatial decision support system to evaluate the impacts of urban development on waterbodies in New Zealand. 12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11-16 September 2011.

Neale, M. W. (2010a). State of the Environment Monitoring: River Water Quality Annual Report 2008. Auckland Regional Council Technical Report 2010/16

Neale, M. W. (2010b). State of the Environment Monitoring: River Water Quality Annual Report 2009. Auckland Regional Council Technical Report 2010/30

New Zealand Transport Agency (2012) State Highway Traffic Data Booklet 2007-2011. http://www.nzta.govt.nz/resources/state-highway-traffic-volumes/

New Zealand Transport Agency (NZTA, 2008) Regional Summary – Auckland. Downloaded from http://www.nzta.govt.nz/resources/regional-summaries/auckland/docs/auckland-regional-summary.pdf

North Shore City Council (2005a). The Kokopu Connection: Lucas Creek Stream Assessment. Report No. KC17

North Shore City Council (2005b). The Kokopu Connection: Oteha Valley Stream Assessment. Report No. KC22

North Shore City Council (2005c). The Kokopu Connection: Alexandra Stream Assessment. Report No. KC3

North Shore City Council (2005d). The Kokopu Connection: Kyle Stream Assessment. Report No. KC14

North Shore City Council (2005e). The Kokopu Connection: Orwell Stream Assessment. Report No. KC21

North Shore City Council (2005f). The Kokopu Connection: Greenhithe Stream Assessment. Report No. KC29

North Shore City Council (2009a). Lucas Creek stormwater catchment management plan.

North Shore City Council (2009b). Stormwater asset management plan 2009.

Reed, J. Gadd, J. (2009) Marine sediment monitoring programme 2007 results. Prepared by National Institute of Water & Atmospheric Research Ltd (NIWA) for Auckland Regional Council. Auckland Regional Council Technical Report 2009/098.

Saaty, R.W. (1987) The Analytical Hierachy Process – what it is and how it is used. Mathematical Modelling, 9(3 – 5):161–176.

Semadeni-Davies, A., Moores, J. and Altenberger, A. (2010). C-CALM development and application of a planning tool for stormwater management in New Zealand. 17th Congress of the Asia and Pacific Division of the International Association of Hydraulic Engineering and Research incorporating the 7th International Urban Watershed Management Conference, 22-24 February, 2010, Auckland, New Zealand.

Semadeni-Davies, A. (2011). Urban Planning to Sustain Waterbodies: Review of Spatial Decision Support Systems (sDSS) for Stormwater Management. NIWA Report: AKL2011-003 prepared under contract C01X0908 funded by the Ministry of Science and Innovation.

Timperley, M.; Reed, J, (2008) Central Waitemata Harbour Contaminant Study. Development of the Contaminant Load Model. Prepared by NIWA Ltd for Auckland Regional Council. Auckland Regional Council Technical Report 2008/038.

Timperley, M., Skeen, M. and Jayaratne, J. (2010) Development of the Contaminant Load Model. Auckland Regional Council Technical Report 2010/004.

Tipa & Associates. 2012. A Framework for a Cultural Health Assessment of Urban Streams, August 2012.

Van Houten, G., Powers, J., and Pattanakak, S. 2007. Valuing water quality improvements in the United States using meta-analysis: is the glass half empty or half full for national policy analysis? Resource and Energy Economics (29): 206-228

Williamson, R., Morrisey, D., Swales, A. and Mills. G. (1998). Distributions of contaminants in urbanised estuaries: Predictions and Observations. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Publication No. 139.

Appendix 1. Glossary

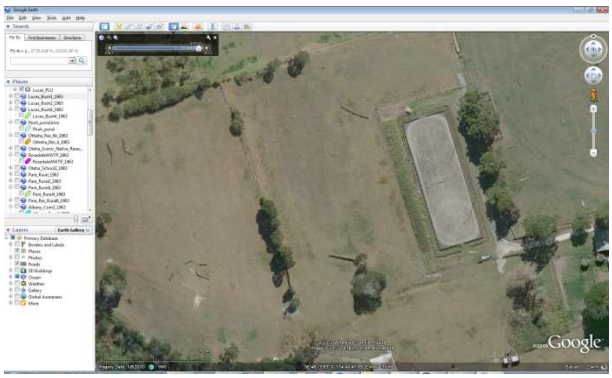
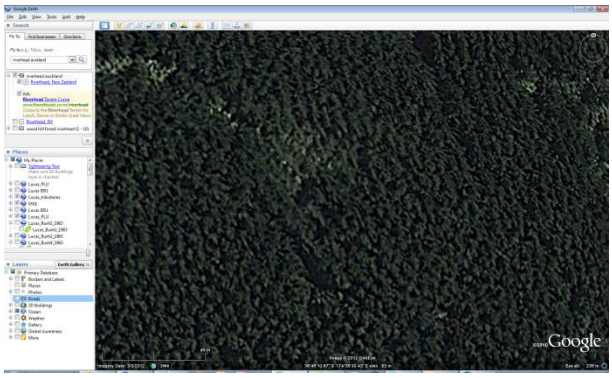
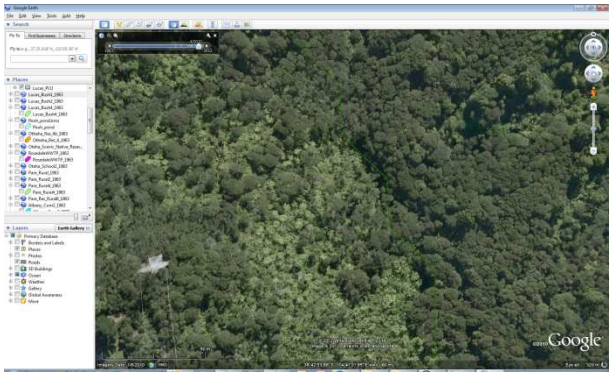
Term	Acronym	Definition
Baseline urban state	BUS	A representation of the form of urban development at time t_b
Baseline system state	BSS	The value of each indicator in the indicator set that represents the state of the system at time t_b.
Combined indicator		A measure representing the state of a water body or land area based on the combination of the values of two or more environmental, economic, social or cultural attributes.
Descriptive attributes		A set of attributes which describe the characteristics of the form of development at time t_d but which play no part in generating system outputs.
Executive attributes		A set of attributes which are assigned values required by the system to generate outputs, being predictions of future values of indicators at time t_r. They are the independent variables in the system.
Implementation		The preparation of the system to examine alternative development scenarios for a given study area.
Indicator		A measure (quantitative or qualitative) of the state of one environmental, economic, social or cultural attribute of a water body or land area.
Indicator attributes		The characteristics of an indicator, for instance qualitative / quantitative; continuous / discrete; range of values; classes of a discrete scale.
Indicator benchmark		A level of an indicator associated with a particular environmental, economic, social or cultural condition or threshold.
Indicator level		Expression of an indicator by a common system of discrete classes. Each class corresponds with an assigned range of indicator scores.
Indicator score		Expression of an indicator on a common continuous scale, following standardisation of raw values.
Indicator set		The range of possible indicators which may be used to examine the outcomes of different urban development scenarios for a given study area.
Intermediate variable		A variable, the value of which is determined by the value of an executive attribute or other preceding independent variable and which determines the value of an indicator or other dependent value.
Planning unit	PLU	The smallest spatial unit for which a unique form of urban development can be specified, likely to coincide with stormwater management units (where already defined) or sub-catchments delineated from analysis of the river network.

Term	Acronym	Definition
Predictive method		A way of generating values of indicators (and intermediate variables) from executive attributes (and intermediate variables).
Reporting units		The spatial units for which indicator levels are generated by the system
Estuary reporting unit	ERU	
Stream reporting unit	SRU	
Results		The set of values for the selected indicators associated with a given scenario.
Scenario		A representation of the physical form of future urban development at the scale of the study area specified by selecting (or custom-defining) an urban development option (UDO) for each planning unit.
Study area		The spatial extent within which scenarios are tested. It includes the existing urban area, any adjacent land for which urban development scenarios are to be examined and the freshwater and marine waterbodies which make up the receiving environment.
Study timeframe		The period of time (likely to be in years) over which the effects of alternative scenarios are investigated.
T_b		Time at which indicators for the baseline system state are reported and also the start date for each scenario.
T_d		Time at which full development of a UDO is achieved.
T_r		Time at which the final results for any scenario are reported.
T_s		Time at which development of a UDO commences.
Urban development option	UDO	A unique representation of the form of future urban development at time T_d
Weight		A value which represents the relative importance of each indicator in a group of indicators which are being combined.

Appendix 2. Land-use categories adopted for the case study

The following land-use categories were adopted for the case study implementation of the pilot sDSS. Each category is characterised by a specified mix of land covers (i.e., roofing materials, roads, pavement, permeable surfaces) based on estimates for Auckland given in Timperley and Reed (2008) and approximations from analysis of aerial photographs.

Rural land uses

Land use	Description	Image
Pasture	Farm land	
Exotic forest	Pine plantations	
Native forest	Native forest and scrub	

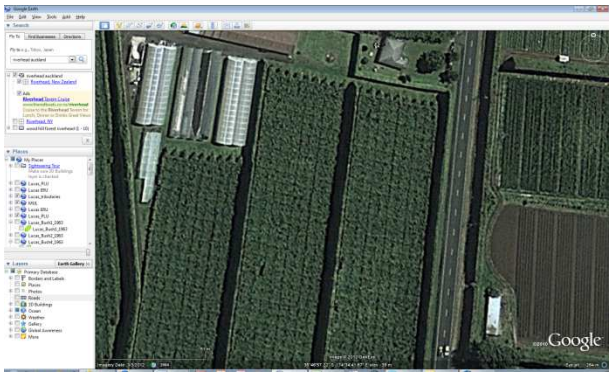
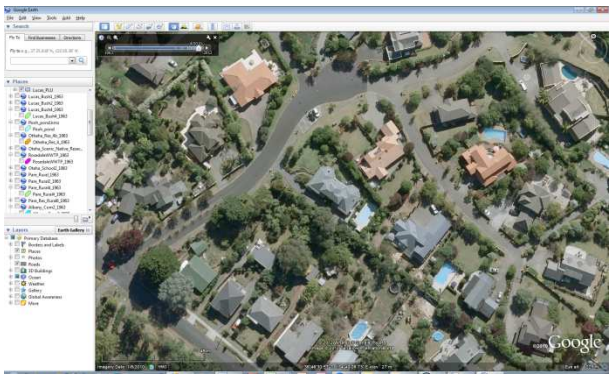
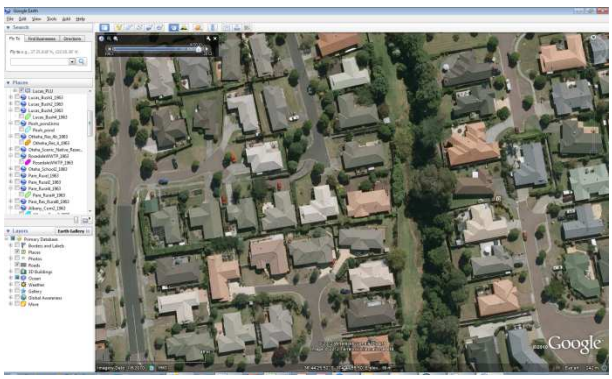
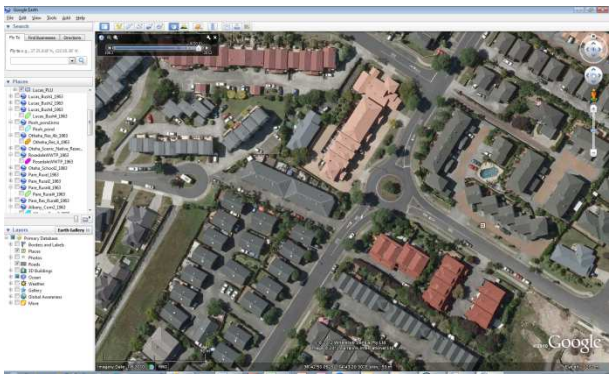
Horticulture / Arable land	Orchards, vineyards, market gardens and crops	

Table A2-1: Proportion of cover type (%) in each rural land-use category.

Cover type	Pasture	Exotic Forest	Native Forest	Horticulture and Arable land
Roofs galvanised steel unpainted	0	0	0	0
Roofs galvanised steel poor painted	0	0	0	0
Roofs galvanised steel well painted	0	0	0	0
Roofs galvanised steel coated)	0	0	0	0
Roofs zinc/aluminium unpainted	0	0	0	0
Roofs zinc/aluminium coated	0	0	0	0
Roofs concrete / tiles	0	0	0	0
Roofs copper	0	0	0	0
Roofs other materials	0	0	0	0
Low traffic <1000 vpd)	0	0	0	0
Roads 1k-5k vpd	5	0	0	5
Roads 5k-20k vpd	0	0	0	0
Main Road (20k-50k vpd)	0	0	0	0
Commercial paved	0	0	0	0
Residential paved	0	0	0	0
Industrial paved	0	0	0	0
Urban grasslands and trees	0	0	0	0
Exotic forest	0	100	0	0
Native forest	0	0	100	0
Pasture	95	0	0	0
Horticulture	0	0	0	95
Impervious	5	0	0	5
Permeable	95	100	100	95

Residential land uses

Residential land use categories were defined according to housing density. Options for high and low yielding roofing materials were defined for each housing density category: in the low-yielding option, un-painted and poorly painted galvanised steel roofs were replaced with painted roofs as a means of source control for zinc. The breakdown of roofing materials shown below are for the former, high yield, option. The housing densities for the different residential categories are consistent with those in ARTA (2006).

Land use	Description	Image
Low density	Quarter acre sections, usually well established. 8-11 dwellings/ha	
Medium density	Colonial villas and modern houses on small sections, infill and crossed leased sections. 14-20 dwellings/ha	
High density	Town houses and flats/apartments 25-30 dwellings/ha	

CBD	Apartment buildings interspersed with commercial land use. 60+ dwellings/ha Note: Residential CBD is defined to have the same land cover mix as commercial CBD.	
LID	Medium to high density housing with cluster housing separated by open space. Roads are often narrow and can have porous paving. Low yield construction materials.	

Table A2-2: Proportion of cover type (%) in each residential land-use category.

Cover type	Medium density	Low density	High density	CBD	LID
Roofs galvanised steel unpainted	1	2	3	3	0
Roofs galvanised steel poor painted	3	2	5	7	0
Roofs galvanised steel well painted	1	1	2	2	0
Roofs galvanised steel coated	2	2	1	1	0
Roofs zinc/aluminium unpainted	0	0	1	1	0
Roofs zinc/aluminium coated	3	1	5	5	25
Roofs concrete / tiles	5	0	5	19	0
Roofs copper	0	0	0	3	0
Roofs other materials	3	7	4	6	3
Low traffic <1000 vpd)	8	7	8	6	8
Roads 1k-5k vpd	5	5	5	6	5
Roads 5k-20k vpd	2	1	2	10	2
Main Road (20k-50k vpd)	2	0	2	4	2
Commercial paved	0	0	0	0	0
Residential paved	13	11	12	12	10
Industrial paved	0	0	0	0	0
Urban grasslands and trees	52	61	45	15	45
Exotic forest	0	0	0	0	0
Native forest	0	0	0	0	0
Pasture	0	0	0	0	0
Horticulture	0	0	0	0	0
Impervious	48	39	55	85	55
Permeable	52	61	45	15	45

Commercial and industrial land uses

Three commercial and two industrial land-use categories were defined, including an LID option for both. The LID options have a higher proportion of green space and a lower proportion of road surfaces than the equivalent non-LID land-use category. Like residential land uses, the non-LID categories are available with low-yield roofing materials. Schools were placed in the same commercial land-use category as local shops, as they were found to have similar proportions of land covers based on analysis of aerial photographs.

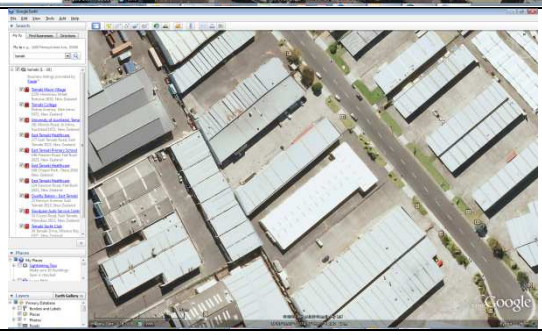
Land use	Description	Image
Commercial - local	Malls, shopping streets etc. Main characteristic is high imperviousness due to parking roofs and roads.	
Commercial - CBD	High rise buildings in central. Note: Commercial CBD is defined to have the same land cover mix as residential CBD	
Industrial	Warehousing, storage yards and manufacturing.	

Table A2-3: Proportion of cover type (%) in each commercial and industrial land-use category.

Cover type	Commercial			Industrial	
	Local	LID	CBD	Industrial	LID
Roofs galvanised steel unpainted	3	0	3	22	3
Roofs galvanised steel poor painted	5	0	7	1	7
Roofs galvanised steel well painted	2	0	2	0	2
Roofs galvanised steel coated	2	0	1	0	1
Roofs zinc/aluminium unpainted	1	0	1	0	1
Roofs zinc/aluminium coated	3	30	5	1	5
Roofs concrete / tiles	0	0	19	0	7
Roofs copper	0	0	3	0	0
Roofs other materials	9	0	6	1	4
Low traffic <1000 vpd)	7	10	6	7	2
Roads 1k-5k vpd	10	5	6	10	6
Roads 5k-20k vpd	7	5	10	7	10
Main Road (20k-50k vpd)	0	0	4	0	2
Commercial paved	27	25	0	0	0
Residential paved	0	0	12	0	0
Industrial paved	0	0	0	27	16
Urban grasslands and trees	24	25	15	24	34
Exotic forest	0	0	0	0	0
Native forest	0	0	0	0	0
Pasture	0	0	0	0	0
Horticulture	0	0	0	0	0
Impervious	76	75	85	76	66
Permeable	24	25	15	24	34

Regional roads

In the case study, regional roads include motorways and other highways carrying in excess of 20,000 vehicles per day (vpd). Regional roads differ from other roads in a PLU as they were defined independently of other land uses. In contrast, local roads were specified as a fixed proportion of other land uses (see Tables A2-1 to A2-3).

VPD	20k-50k	Low traffic	
	50-100k	Medium traffic	
	>100	High traffic	