NIWA
Taihoro Nukurangi

Development of a Spatial Decision Support System for Evaluating the Impacts of Urban Development on Waterbodies: Context, Scope and Design

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Contents

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Tables

Figures

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Executive summary

This report describes progress in the development of a pilot spatial decision-support system (sDSS) for assessing the impacts of urban development on the values and services of urban waterbodies. It describes the context within which the sDSS is being developed, the scope of the tool and its conceptual design, including a description of a proof of concept version of the tool developed to apply, test and refine the design.

The sDSS will be a tool that allows the assessment of urban development scenarios at a sub-catchment, or stormwater management unit (SMU), scale occurring over time periods of several decades. Scenarios may include both greenfield and brownfield forms of development. The tool will allow the prediction of ‘stressors’ such as sediment loads, contaminant loads, hydrological characteristics and habitat modification associated with different development forms. The effects of these stressors on the values and services of both freshwater and estuarine receiving environments will be reflected in the values of a range of indicators. These may include characteristics such as water and sediment quality; ecosystem health; and cultural, amenity and recreation values. The tool will include a sustainability indexing system to integrate the measurement of environmental, social, economic and cultural impacts and allow these impacts to be considered holistically.

The design of the sDSS has been progressed by the development of a vocabulary that describes the steps involved in the implementation, or preparation for use, of the system and the running of the system by a user. The steps in implementing the system will include specifying: the study area; the study timeframe; attributes of urban development options; indicators; and the methods for estimating indicator levels from the attributes of urban development options. The system will run by a user making selections in relation to the nature of each development scenario and methods for weighting and reporting indicators. Development scenarios may vary in terms of their land use mix, methods of land development, stormwater management, transport characteristics and stream management.

The design of the sDSS has been examined for its conceptual soundness and functional performance through the construction of an Excel spreadsheet-based ‘Proof-of-Concept’ (PoC) version of the system. This PoC, while adopting deliberately simplistic methods and operating in a completely fictional environment, has been developed to apply, test and refine the steps involved in the implementation and use of the system.

As a result of the PoC development process, three key method steps have been identified for inclusion in the development of the pilot sDSS: the use of deterministic relationships to estimate the levels of environmental stressors associated with the land use, stormwater management and other relevant characteristics of each sub-catchment; the use of probabilistic Bayesian Belief Networks to predict the effects of these stressors on the values and services of urban waterbodies; and methods to combine or integrate individual indicators of these effects.

The development of the PoC has also provided a basis from which to identify and plan for the tasks which lie ahead. The next step in the development of the system will be resumption of engagement with end-users in order to ensure that the pilot sDSS will be fit-for-purpose, technically robust and communicates with its audience.

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. A sustainability indexing system will be developed within the sDSS to integrate the measurement of environmental, social, economic and cultural impacts and allow planners to consider these impacts holistically.

The programme is being funded by the Ministry of Science and Innovation for a three-year period. The objective is, 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 poor water quality, toxic metal accumulation in harbour sediments, and a growing unsuitability for recreation and other uses such as the traditional harvesting of shellfish by Maori communities. Christchurch's Avon and Heathcote Rivers exceed guideline values for nutrient and microbiological contamination (PDP, 2007) while more than half of sediment sampling sites in Auckland's Waitemata and Manukau Harbours contain heavy metals at concentrations considered moderate or high risk to the harbour ecosystems (Williamson and Kelly, 2003).

These problems are compounded by a rapidly growing urban population - Auckland's population is estimated to increase to 2.2 million by 2050 (ARGF, 1999) and Christchurch's to well over half a million by 2041 (GCUDF, 2007); 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 Tasks

The development of the pilot sDSS involves four key tasks:

- Designing the sDSS, which comprises defining its purpose, scope and the functionality required in order to achieve its purpose;
- Building the pilot sDSS;
- Testing the pilot sDSS for the selected case studies in Auckland and Christchurch;
- Advancing relevant knowledge bases in order to inform the development of the sDSS and its potential extension beyond the term of the current programme.

This report deals with the first of these tasks. While the design of the system is still evolving, key concepts have been advanced to a stage where the detailed design and building of the pilot sDSS can proceed. Note that work completed (or in progress) in a number of other areas will also contribute to that next phase of the programme. That includes a review of other sDSSs (Semadeni-Davies, 2011) and an assessment of methods for the development of a sustainability indexing system (Batstone et al., 2010).

1.4 Structure of this Report

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

- Chapter 2 provides a description of the context within which this research is set and establishes which of the many facets of planning urban development the sDSS is designed to support;
- Chapter 3 describes the scope for the development of the sDSS or, in other words, what it needs to be able to do. The chapter describes the links between urban development and impacts on waterbodies and provides examples of the important characteristics of urban development that will need to be represented (as inputs to the system) and the types of indicator for which predictions might be required (outputs).
- Chapter 4 provides a description of the system design, including the steps involved in preparing and using the system, respectively.
- Chapter 5 describes a ‘Proof of Concept’ version of the sDSS which has developed to apply, test and refine the design of the system.
- Chapter 6 describes the steps involved in progressing from the Proof of Concept to a Pilot sDSS.

2. Context

2.1 Introduction

This chapter provides a description of the context within which the development of the sDSS is set. Section 2.2 summarises the breadth of activities and range of stakeholders involved in planning for urban development while Section 2.3 describes the principal roles of local government in this process. Section 2.4 identifies the diversity of factors that are considered in local government planning processes and establishes the scope of this research, within that broader set of considerations.

2.2 Planning Urban Development

There are many aspects to planning the development of an urban area. They include making decisions about:

- the configuration and characteristics of different land uses;
- the provision of infrastructure, for instance transport systems, water supply, drainage, energy distribution and communication networks;
- the provision of key services, for instance health care, education and social services; and
- the management of the environment, not only in relation to natural environmental values, but in relation to the human use and enjoyment of both the natural and built environment.

Urban development planning is a multi-disciplinary and multi-agency endeavour. In New Zealand, local government is responsible for a range of relevant resource management policy and planning functions, including setting regional development policy and land use planning. Local government is also responsible for the provision of a range of infrastructure needs (e.g. water supply and waste disposal) and the provision of many services (e.g. recreational facilities such as sports grounds and libraries). Central government agencies lead the provision of other services and infrastructure (e.g. hospitals, schools and major roads). Non-governmental organizations, businesses, communities and private individuals can also be involved in many aspects of urban policy and planning, for instance through a range of consultative resource management processes.

While recognizing the 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 certain related infrastructure; and environmental management, described in more detail below. However, the planning of (most) city infrastructure and services lies outside of the scope of this research because it is not relevant for the management of urban waterbodies.

2.3 Urban Planning under the RMA and LGA

The functions of local government in relation to planning for urban development are set out in the Resource Management Act (RMA) 1991 and the Local Government Act (LGA) 2002. Regional councils[1] are responsible for preparing regional policy statements (RPSs) setting out objectives, policies and methods to achieve integrated management of the natural and physical resources of a region. Territorial Local Authorities[2] (TLAs), or city and district councils, are responsible for preparing and implementing district plans setting out objectives, policies and methods to achieve integrated management of the effects of the use, development and protection of land and associated natural and physical resources of a district. In preparing a district plan, a TLA must have regard to the policies of the relevant RPS. Essentially, the RPS establishes a direction and framework for regional development while the District Plan provides the detail on the form of that development by establishing rules about the types and characteristics of land use that are allowed in different locations.

In recent years, urban development planning in New Zealand's two largest cities, Auckland and Christchurch, has been supported by 'high-level' consultative planning processes. The results of these processes, the Auckland Regional Growth Strategy[3] (ARGS; ARGF, 1999) and Greater Christchurch Urban Development Strategy (GCUDS; GCUDF, 2007), respectively, set out the proposed broad pattern of urban development until the middle of the 21st century (see also Section 3.6). Both strategies reflect a response to the continued expansion of the respective urban footprints (for example, Auckland's footprint is projected to expand by 10% over the first half of this century (ARGF, 1999)), and a growing consensus that urban sprawl has a greater environmental impact than evolving alternatives, for example the intensification of land use in established suburbs and inner city regeneration.

Auckland Council (AC) and Environment Canterbury (ECan) are currently involved in reviews of their respective RPSs. In line with the direction set out in the strategies mentioned above[4], one can anticipate as a likely outcome of these reviews, policies which promote a 'compact' form for future urban development, with a strong emphasis on intensification within the existing urban area.

As noted in Section 2.1, local government is not only responsible for land use planning but also for planning and delivering a range of infrastructure and services. Both regional councils and TLAs are required to prepare Long Term Council Community Plans (LTCCPs) under the LGA 2002. These describe the ways in which councils will deliver on their functions over a ten-year period, the costs associated with that service delivery and how these services will be funded. This includes setting out how the council plans to provide and resource infrastructure and services associated with projected urban development over the life of the LTCCP and beyond.

Clearly, in order to enable the co-ordinated planning of a particular form of urban development, there needs to be close alignment between the RPS, District Plan(s) and

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[1] Or unitary authorities, where these exist as single tier of local government in place of Regional and District / City councils (for example, the Auckland Council which came into effect 1 November 2010).

[2] Or unitary authorities, where these exist.

[3] Auckland Council is also currently involved in the preparation of the 'Auckland Plan' in accordance with the requirements of the Local Government (Auckland Council) Amendment Act 2010. While the scope of the plan is likely to be broader than the ARGS, it is expected that it will supercede the ARGS in providing direction for the future pattern of urban development infrastructure provision in Auckland.

[4] Or, in the case of Auckland, the Auckland Plan once it has been adopted by Auckland Council.

LTCCPs. While the RPS and District Plans control the form of urban development, LTCCPs provide the mechanism by which councils discharge those of their functions that enable that form of development to occur.

2.4 Urban Planning and the Sustainable Management of Aquatic Environments

Section 2.3 describes, in broad terms, the roles of regional councils and TLAs in planning for urban development. In implementing their respective functions, councils are required to ensure that development can be achieved in a way which is consistent with the purpose of the RMA 1991[5].

There are, of course, many factors which councils must consider when assessing the extent to which alternative forms of urban development constitute sustainable management of the environment. Some examples are:

- ensuring that policies and plans make adequate provision for residential, industrial and commercial development in order to provide for the social, economic and cultural well-being of communities;
- planning water supply and transport systems that will meet the needs of the current and future generations;
- planning systems for the management of urban runoff and waste that safeguard the life-supporting capacity of rivers, estuaries and groundwater systems; and
- achieving consistency with controls on the use of natural resources (such as rules on earthworks, stormwater discharges, water abstractions, industrial emissions to air, modifications to the beds of rivers, and so on) in order to ensure that development avoids, mitigates or remedies adverse effects on the city's land, air and water resources.

Clearly, there is a large and diverse range of matters which councils must consider. The majority of these lie well beyond the scope of this research. The focus here is the development of a tool which assists with the evaluation of urban development options with respect to the way in which they impact on the values and services[6] of waterbodies. The tool will NOT help with evaluation of whether factors such as the extent to which land use zoning and the provision of water supply, roads and landfills will enable the economic, social and cultural needs of current and future generations to be met, nor with evaluation of the potential impacts on air quality, soils or terrestrial ecosystems. Local government has (or may require) other tools and sources of information to guide the evaluation of those aspects of urban development.

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[5] "(1) The purpose of this Act is to promote the sustainable management of natural and physical resources.
(2) In this Act, sustainable management means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural well-being and for their health and safety while—
(a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and
(b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and
(c) avoiding, remedying, or mitigating any adverse effects of activities on the environment."

[6] Refer to chapter 3 for a description of the values and services of waterbodies.

It is not the case, however, that by focusing on urban waterbodies, this research is limited to an overly narrow field of enquiry. In fact, there are many different aspects of urban development which can impact on the values and services of waterbodies and these impacts can be wide-ranging, of marked intensity and long-lasting. City development can impact on not only the environmental values and services or a river or harbour, but also associated economic, social and cultural ones (see Section 3). The aim of this research is to develop a tool which allows regional councils and TLAs to undertake integrated assessments of the implications of different urban development forms on a wide range of the values and services associated with urban waterbodies.

2.5 Role of the sDSS

In summarising this chapter, it is evident that planning for urban development is multi-faceted and involves many different agencies. Urban development planning is led by local government, which itself has a number of functions in relation to this task. The aim of this research is to provide a tool for local government in relation to its functions of:

> *Planning the location and character of urban land uses and associated infrastructure needs which are of consequence for the way in which a particular land use impacts on the values and services of urban waterbodies.*

The tool will allow comparison of the impacts of alternative:

- land use configurations and characteristics; and
- infrastructure configurations and characteristics of relevance to the way in which land use impacts on waterbodies (i.e., stormwater drainage systems).

The scope of the tool is described in greater detail in Section 3.

3. Scope

3.1 Introduction

Chapter 2 defines those aspects of planning for urban development that the sDSS is intended to help with: the planning of land use and related relevant infrastructure. This chapter describes the way in which changes in land use and the construction of infrastructure, such as stormwater systems and roads, is linked to changes in the values and services of urban waterbodies. Section 3.2 explains what is meant by the term 'values and services' while Section 3.3 describes some of the ways in which urban development can impact on these. Section 3.4 explains the way in which the development and use of the sDSS to evaluate these will be based on a set of representative indicators which may differ from place to place. Section 3.5 describes the main features of urban development that the sDSS will need to represent in order to drive its predictions of effects on the values and services of waterbodies while Section 3.6 identifies the spatial and temporal scales of enquiry.

3.2 Values and Services of Waterbodies

Throughout this report, the terms 'values' and 'services' of waterbodies are used in combination. This reflects the fact that while the terms are not interchangeable, they do describe two closely linked concepts. It can be difficult to precisely distinguish between the two, although the following description is an attempt to do just that.

A dictionary definition of 'value' is "relative worth, merit, or importance[7]." A value of a water body is therefore some attribute or characteristic upon which a comparison with another water body can be based. So, for example, the ecological and recreational value of a harbour with healthy fish stocks will probably be considered higher than that of one in which fish are absent as a result of pollution.

A definition of service is "an act of helpful activity; help; aid[8]." The services of a water body relate to the way it functions and the benefits that these functions deliver. So, for example, while a harbour might be valued for its fish stocks, the fish are only there because the harbour provides services such as habitat and contaminant processing. In the case of a polluted harbour with no fish, at least one of these services is likely to be absent or severely impacted. In this example, it can be seen that the value of a waterbody is dependent upon the nature of the services provided.

There are a number of ways of categorizing values and services of waterbodies. Guidelines for assessing the effects of changed flow regimes on the in-stream values of New Zealand rivers assign values to one of four groups: ecological, landscape, recreation and Maori (MFE, 1998). Guidelines developed for assessing urban stream quality in the Auckland Region adopt a functional (services) approach based on ecology, connectivity, water quality, flood management and amenity / cultural stream functions (ARC, 2004). The UN recognizes four broad categories of ecosystem services: provisioning services, such as water supply;

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[7] http://dictionary.reference.com

[8] http://dictionary.reference.com

regulating services, such as processing of contaminants; supporting services, such as the cycling of nutrients and; and cultural services, such as recreation (MEA, 2004).

In this report, the values and services of waterbodies are assigned to one or more of four categories (some fall into more than one[9]). The categories, and some examples of each, are shown in Table 1.

Table 1: Categories and examples of values and services of waterbodies.

	Environmental[10]	**Economic**	**Social**	**Cultural**
Values	Water Quality Plants Fish and other animals Natural character	Wealth generation Subsistence Property values	Natural character Heritage Aesthetics Recreation	Traditional associations Spiritual
Services	Habitat Migration Spawning Contaminant processing Nutrient cycling Sediment transport	Tourism Water supply Wastewater disposal Drainage Trade & commerce Industry Energy generation Sporting & civic events Fishing	Tourism Water supply Wastewater disposal Drainage Energy generation Sporting & civic events Contaminant processing Passive amenity Contact recreation Fishing Boating Community engagement	Food gathering Passive amenity Contact recreation Fishing Boating Community engagement

3.3 Impacts of Urban Development on Waterbodies

Figure 1 represents a simplified view of the way in which the values and services of waterbodies can be affected by urban planning decisions. As described in Section 2, for the purposes of this research the aspects of urban planning which are of interest are; (1) the planning of controls on the use of land, and (2) the provision of infrastructure which is of relevance to effects on the values and services of waterbodies. Urban development resulting from these planning processes comprises a series of changes to the form and function of an area of land, including:

- Land use change, for instance the development of residential subdivisions in areas of ‘greenfield’ rural land or the re-development of ‘brownfield’ inner-city industrial land for commercial and/or residential uses;
- The construction of transport infrastructure, especially roads but also including railways and airports; and

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[9] Note for instance the close relationship between economic and social values and services of waterbodies. These can also be grouped as socio-economic values and services, an approach which has been adopted for convenience in Figure 1 (page 16).

[10] Refering to ecological and other natural environmental values and services

- The construction of infrastructure for managing urban runoff, including reticulated stormwater systems and flood and erosion protection measures.

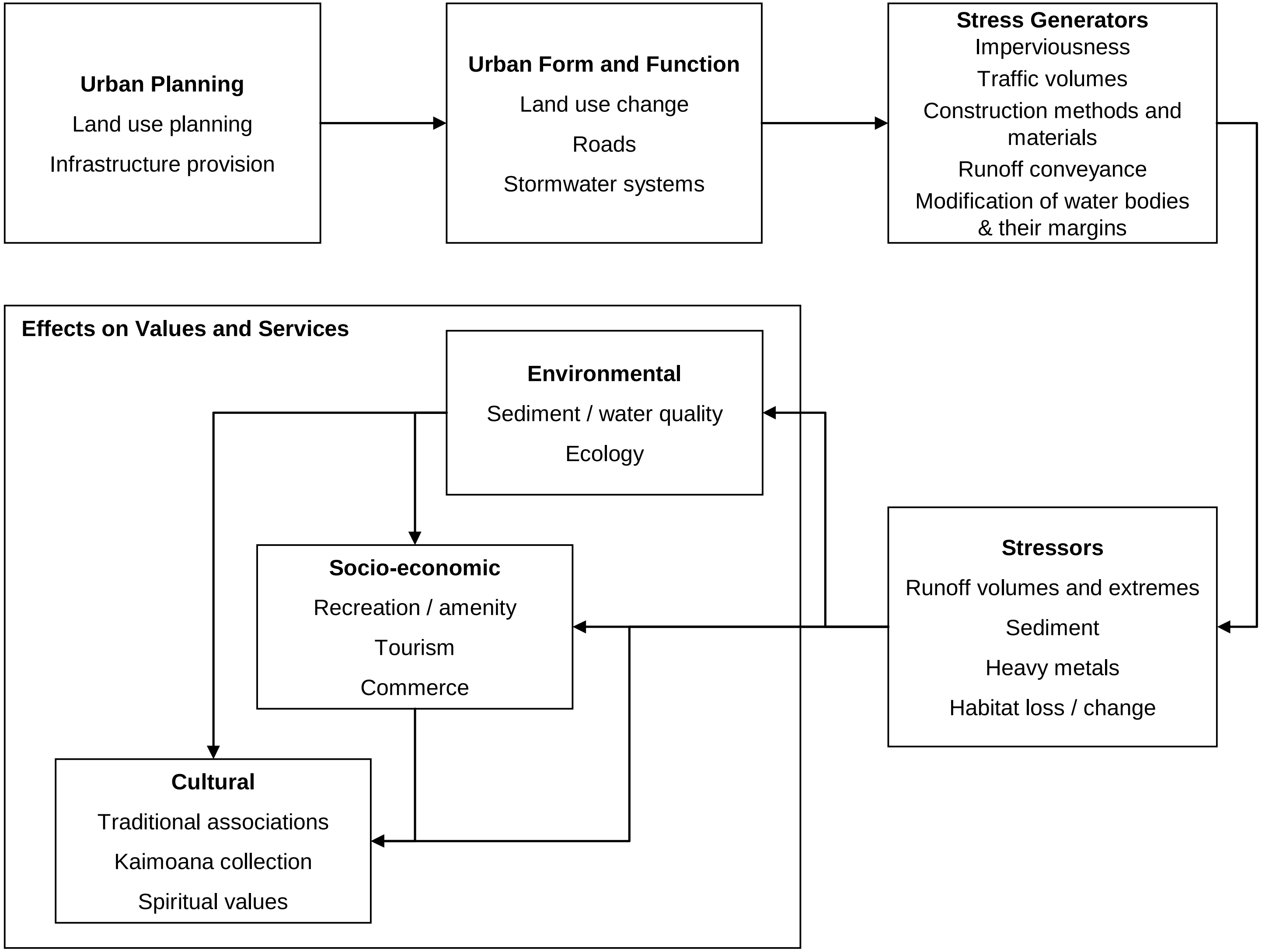

Figure 1: **Representation of the relationships between urban planning, urban development and effects on the values and services of waterbodies.** Examples to illustrate these relationships are shown in red text (these are not intended to be comprehensive).

These changes are realised by the modification of the physical environment. The activities and outcomes which constitute the process of modification are characterised here 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*.

Stress generators can vary in their intensity to the extent that, at one end of the spectrum, they can also act as ‘stress moderators.’ In fact, the aim of this research is to provide assistance for planners and decision-makers to help identify forms of urban development which lead to less stress generation and more stress moderation.

By way of an example, increased imperviousness is clearly a stress generator in a situation in which an area of rural land use is developed for residential use with small lot sizes, large houses and wide roads. Adopting an alternative low impact design (LID) approach, larger areas of open space might be retained, house footprints made smaller and roads narrower and the role of imperviousness as a stressor would be less important. In yet another situation, the redevelopment of industrial land originally occupied by large buildings and fully paved yards to a housing development and neighbourhood park might result in a reduction in imperviousness. In this latter case, the reduction in imperviousness would be expected to have a ‘moderating’ influence on the pre-redevelopment hydrology.

Another example is the construction of systems to collect and convey urban runoff. These systems generally include provision to control and treat stormwater to a design standard in order to limit flooding, erosion and the contamination of receiving waterbodies. The notion of constructing to a design standard carries with it an acceptance that not all flooding, erosion and contamination will be avoided. More innovative approaches, again associated with LID concepts, aim to deal with these problems more effectively by controlling the generation of stormwater runoff and contaminants at source. Alternatively, there can again be situations in which the upgrade of stormwater systems leads to moderation (or improvement) in hydrological and contaminant regimes, for instance as a result of the separation of stormwater and wastewater systems and retrofitting of stormwater treatment devices in older areas of cities.

As a final example, while the modification of waterbodies associated with urban development is generally a source of stress generation, for instance where the piping or channelizing of a stream leads to a loss of habitat, again the reverse can be true. The day-lighting of a piped section of stream or riparian restoration associated with a greenfield development are examples where development has the potential to moderate existing stressors.

The end-point of the process by which urban planning 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 impacted 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.

Consistent with the discussion above on the characteristics of stress generators, effects on the values and services of urban waterbodies can also vary in their direction and intensity in response to different forms of urban development. So, not only will some forms of development result in lesser adverse effects than others (for instance LID in comparison to ‘traditional’ forms of development), but some urban development also has the potential to enhance these values and services. In the examples described above, the re-development of existing urban land was shown to have the potential to result in reduced imperviousness and improved stormwater treatment while the development of rural land may be accompanied by the opportunity to undertake riparian restoration. In these examples, one would anticipate an improvement in the environmental values and services of receiving waterbodies as a consequence of a reduction in the discharge of stormwater contaminants and the provision of improved habitat for aquatic animals. Similarly, these forms of urban development can also lead to enhanced economic, social and cultural values and services. This could occur for instance, through the incorporation of a harbourside park as part of an inner-city redevelopment and the setting aside of a riparian reserve, with walkways and interpretative signage, as part of a stream restoration effort associated with a greenfields development.

3.4 Representing the Impacts of Urban Development in the sDSS

While Section 3.3 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. The upper of the two large rectangles shown in Figure 2 provides an example of the ways in which urban development can impact on stream health. Changes in catchment and riparian characteristics affect the physical and chemical characteristics of a stream in many ways. Multiple inter-relationships then drive impacts on biota.

The lower part of Figure 2 represents the fact that similarly complex systems can be described to represent cause and effects on lacustrine, estuarine and marine environments. The complexity grows further when one considers relationships between two or more of these types of environment, for instance where a city's receiving environment constitutes freshwater streams discharging to estuarine creeks discharging to an open harbour (Auckland, for instance). Yet more complexity is introduced by the need to take account of effects not only on environmental values and services but a whole range of economic, social and cultural factors in each system (or combined system).

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 present, their character and the values and services associated with them.

The key for this research is therefore to identify the set of values and services associated with the waterbodies in any given urban area which:

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

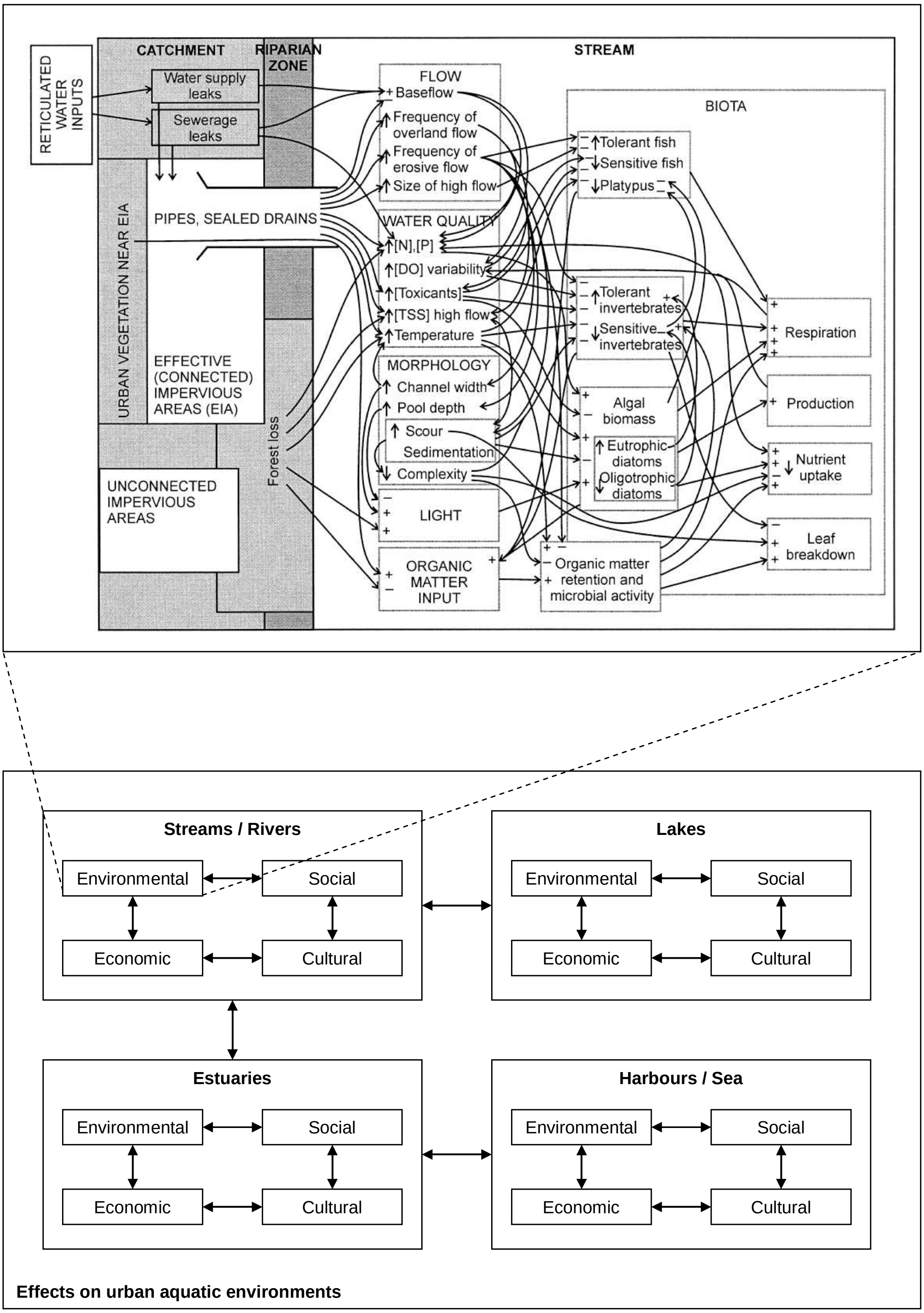

Figure 2: Representation of the complexity of effects of urban development on urban aquatic environments, with detailed example of effects on stream ecosystem health (adapted from Walsh et al. (2005).

The sDSS is then intended to provide a framework within which the effects on these values and services, resulting from different forms of urban development, can be evaluated. As noted above, the importance of different values and services vary from place to place and that being the case, the range of effects that the sDSS will allow evaluation of will not be fixed,but will vary from city to city.

Part of the development of the pilot sDSS involves testing the system for case studies in Auckland and Christchurch. A key part of that testing will be deciding how best to evaluate the impacts of urban development on waterbodies in each city: in other words, identifying the stressors, values and services that allow the most meaningful comparison of different forms of development (as measured by the four criteria described above).

While that is a task for a future stage of the research, Figures 3 and 4 provide two examples of how the sDSS could be configured. In Figure 3, the effects of urban development on freshwater streams are evaluated using a ‘habitat score’ and an ‘amenity score.’ These scores measure impacts of development on ecological and human use values and services, respectively. They could be derived from physical stream characteristics associated with different forms of development, for instance measures of attributes such as the degree of stream modification, bed characteristics and riparian cover. Alternatively, a surrogate for physical characteristics, such as the proportion of the catchment under impervious cover, could be used, providing that the relationships between this and stream habitat and amenity scores can be established.

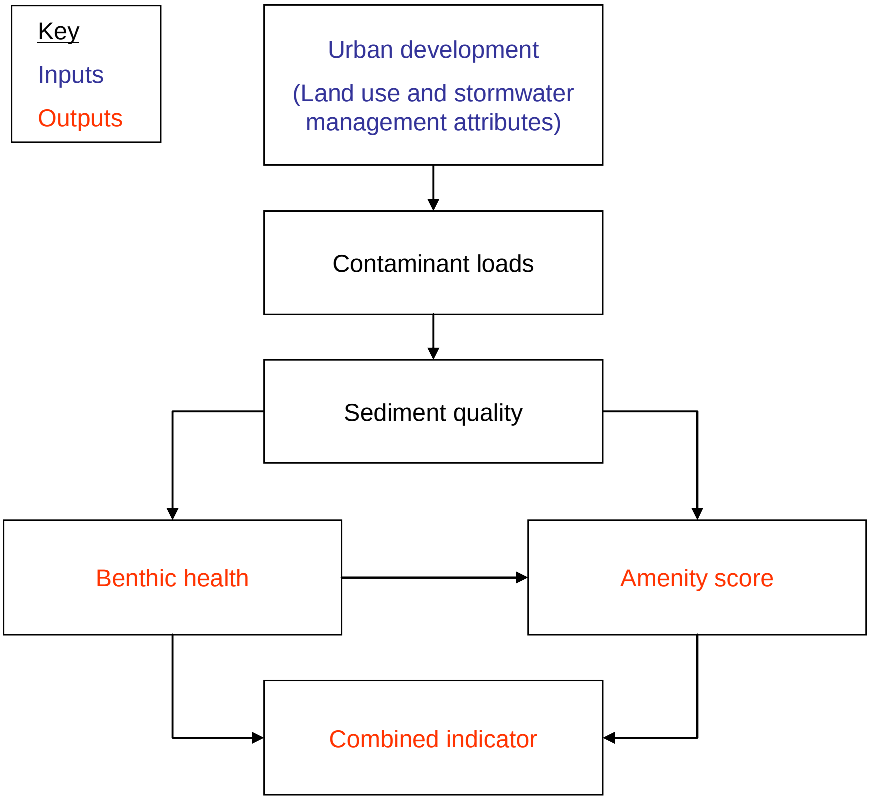

Figure 3: Example of configuration of sDSS to evaluate the effects of urban development on a stream.

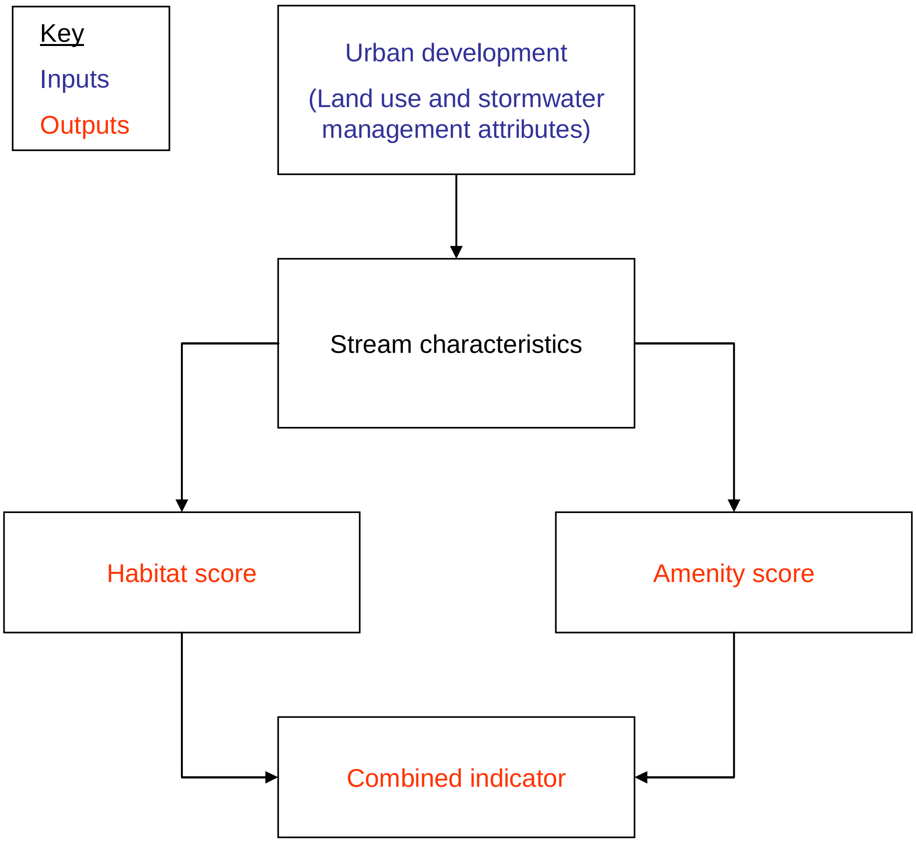

Figure 4: Example of configuration of sDSS to evaluate the effects of urban development on a harbour.

One of the key tasks currently under way is a review of the potential for the sDSS to incorporate or be informed by the results of research linking contamination and modification of urban waterbodies with measures of ecosystem health[11].

The final criterion set out above is that the scores for the effects on individual values and services can be used to generate a combined indicator score. While Figures 3 and 4 indicate that this is the case in these examples, no attempt is made here to describe how this might be done. The development and application of methods to allow indicators to be combined is one of the key tasks currently in progress as part of this research programme (Batstone et al., 2010).

3.5 Representing Urban Development in the sDSS

In the examples described in Section 3.4, urban development is represented by ‘land use change’ and ‘stormwater management attributes.’ As already discussed in Section 3.3, it is not these things *per se* that can impact on the values and services of waterbodies, but a range of associated activities and outcomes defined here as ‘stress generators.’

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[11] An interim technical report describing the review of existing data sources and their potential for future inclusion in the sDSS is scheduled for delivery in June 2011.

Table 2 provides some examples of the ways in urban development could be represented in the sDSS. Essentially, this involves identifying those attributes of stress generators which have the following characteristics:

- They can be assigned values (quantitative or qualitative) thus allowing their use as inputs to the system;
- 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
- These attributes can be used to make predictions of the characteristics of one or more stressors, for instance the load of a contaminant or the relative condition of stream habitat.

One example of the representation of urban development is that adopted in both the CLM and C-CALM contaminant load models (Timperley, 2008; Semadeni-Davies et al., 2010). Both models estimate annual sediment, copper and zinc loads generated from each of range of surface cover types based on the area of that cover type and an associated yield for each contaminant. The load discharged to receiving waterbodies is estimated by applying load reduction factors (LRFs) representing the efficacy of one or more stormwater treatment measures. Both models are relatively sophisticated in the range of cover types for which contaminant yields are specified with C-CALM adopting the cover types and yields of the CLM. Yields vary by residential, industrial and commercial land use for each of eight categories of roofing material, four classes of road and paved surfaces. Contaminant yields are also specified for urban grasslands, bare earth and motorways. Both models also allow a range of different treatment measures to be specified, although differ in that contaminant removal efficiency is fixed in CLM but varies with catchment and device characteristics in C-CALM.

The system developed for representing land use and stormwater management in these models has the potential to provide the basis for representing urban development in the sDSS. However, further development of such a system will be required in order to enable the attributes of other stress generators to be represented in inputs to the sDSS. For example, where the values and services under assessment include ecological functioning of urban streams, the system inputs could include attributes which represent the extent modification of streams such as the proportion channelized, piped or subject to erosion protection measures. In another case, it might be necessary to represent the extent of modification of the coastal margins in order for the sDSS to make predictions of amenity values associated with access to and use of the foreshore. Clearly, the specification of system inputs is dependent on which values and services of waterbodies are important in a given location.

Table 2: Examples of attributes of stress generators (and moderators) that could be used to represent urban development in the sDSS.

Stressor	Stress generators / moderators	Characteristics of stress generators
Sediment	Change in land cover, especially during earthworks phase	Area of earthworks (absolute or proportional) Area of other land covers by type (absolute or proportional) Yield by land cover type (or attributes which determine yield: soil, slope, climate)
	Erosion and sediment control measures, stormwater treatment measures	Area subject to control measures (absolute or proportional) Efficacy of control measures (for instance percentage sediment removal)
Contaminants (e.g. heavy metals, hydrocarbons)	Change in land cover, especially to/from impervious surfaces, or change in characteristics of land cover, for instance associated with change from industrial to residential land use	Area of land / surface cover by type (absolute or proportional) Yield by surfaces type (or attributes which determine yield: land use, slope, climate)
	Change in transport fleet make-up, vehicle numbers, levels of congestion	Road lengths, vehicle numbers and traffic characteristics (congested or free-flowing) Yield by traffic characteristics
	Stormwater treatment and source control measures	Area subject to control measures (absolute or proportional) Efficacy of control measures (for instance percentage contaminant removal)
Hydrological modification	Change in land cover, especially to/from impervious surfaces	Area of impervious surfaces (absolute or proportional)
	Stormwater conveyance measures	Area served by reticulated network (absolute or proportional)
	Stormwater quantity control measures	Area subject to control measures (absolute or proportional) Efficacy of control measures (for proportion of events meeting design standard)
Stream habitat modification	Change in land cover, especially to/from impervious surfaces	Area of impervious surfaces (absolute or proportional)
	Channel modification	Extent of channelisation, piping, erosion protection (absolute or proportional)
	Riparian modification	Extent of riparian cover by cover type (absolute or proportional) Characteristics of riparian cover by cover type (for instance % shade)

3.6 Spatial and Temporal Scales

The GCUDS and ARGS provide direction on the pattern of future urban development in Christchurch and Auckland, respectively. In Christchurch, a significant proportion of development is provided for in an ‘indicative growth area’ on the south-west fringes of the city. Development is also likely to occur through intensification of areas of the inner city and in satellite towns such as Rangiora, Kaiapoi, Rolleston and Lincoln (see Figure 5).

Urban growth in Auckland is also provided for through a combination of the development of greenfield land around the urban fringes, intensification of existing areas and the growth of rural townships (see Figure 6). Development in some of the areas mapped as ‘future urban’ is already well-advanced, for instance in the Flat Bush and Hingaia areas in south Auckland.

As described in Section 2, while the GCUDS and ARGS have been developed as ‘high-level’ strategies to guide the future form of urban development, the general location and mix (e.g., greenfield vs intensification) of future development that they[12] promote will be given further weight through current reviews of relevant regional policy statements and district plans. Councils in each region have indicated that, as part of these reviews, the focus of continued planning is moving from the regional to the local scale. Current planning processes involve establishing the land use mix, land use intensity and infrastructure needs in each growth area (whether located on the city fringe, in the existing urban area or in satellite towns).

The size of growth areas identified in both the GCUDS and ARGS are in the approximate range 1-10 km^2. The sDSS needs to allow evaluation of alternative forms of development at this scale of enquiry. In the Central Waitemata Harbour and South-eastern Manukau Harbour contaminant accumulation studies (Green, 2007; 2008), 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[13].

The GCUDS and ARGS set the direction for Christchurch’s development to 2041 and Auckland’s to 2050, respectively. However, the regional policy statements and district plans which prescribe the policies and rules giving effect to this direction 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 take place, for instance as set out in the GCUDS and ARGS.

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[12] Or, in the case of Auckland, the pattern of development promoted in the Auckland Plan once it has been adopted by Auckland Council.

[13] Note, however, that it is likely that the units used to represent receiving waterbodies will differ in both form and scale from those used to represent urban development on the land (refer to Section 4.3.2). It is also likely that the representation of the urban area will have to include areas for which no change in urban development is considered likely, wherever these areas contribute to the effects on receiving environments.

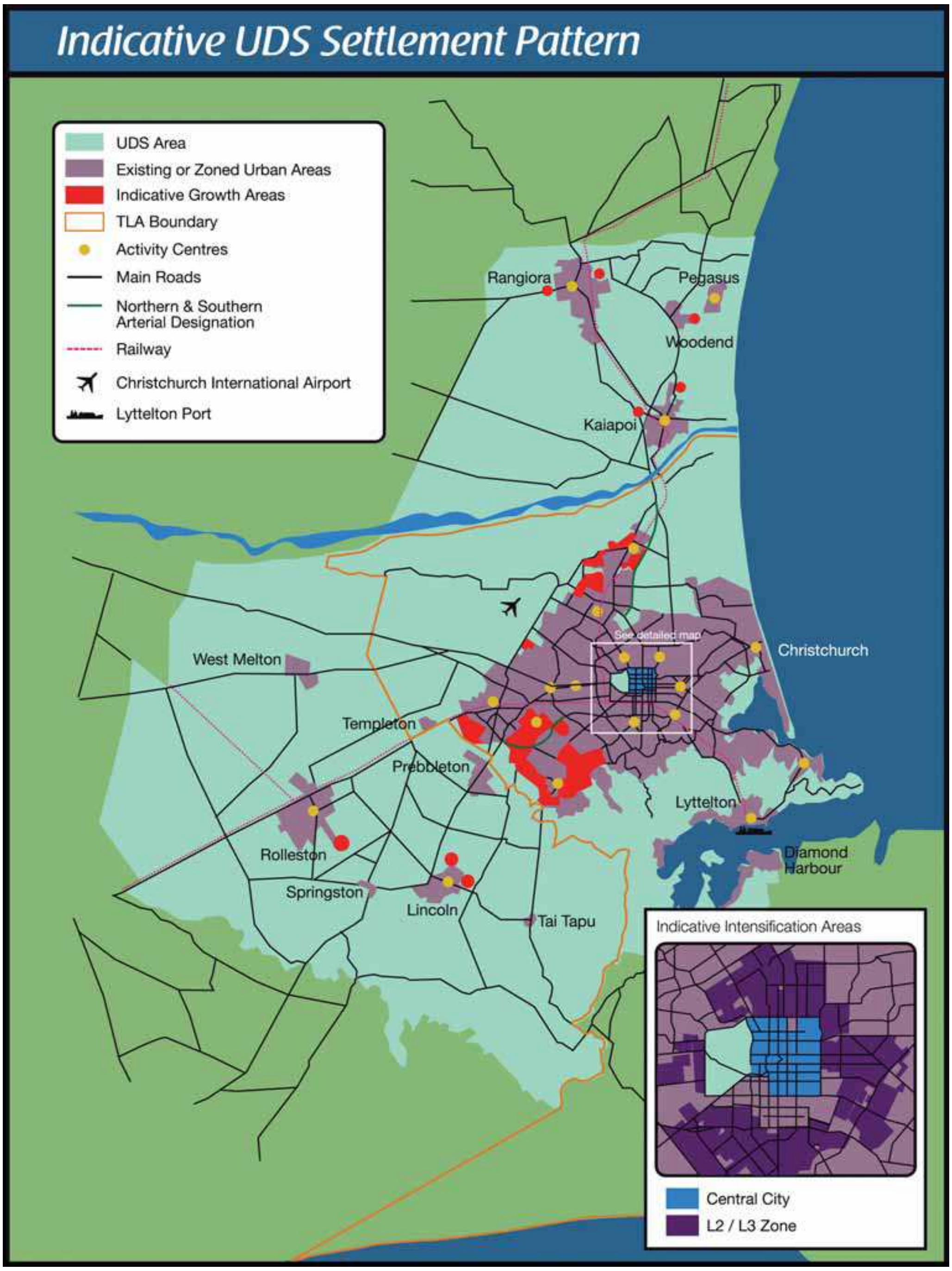

Figure 5: **Indicative location of planned urban development, Greater Christchurch Urban Development Strategy** (source: GCUDF, 2007).

Figure 6: Indicative location of planned urban development, Auckland Regional Growth Forum (source: ARGF, 1999)**.**

4. Design

4.1 Introduction

Having outlined the context within which the sDSS will be applied and the scope of its application in previous chapters, this chapter describes the design of the system. Section 4.2 provides a functional overview of the system while Sections 4.3 and 4.4 describe the steps involved in preparing and using the system, respectively.

An important part of the description of the sDSS has been the development of a vocabulary that describes the functionality and components of the system in unambiguous terms. Key terms are defined (see Appendix 1 for consolidated table of definitions) and appear in capital letters where they first appear in Sections 4.3 and 4.4.

The design of the sDSS has been 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 operating in a completely fictional environment, has allowed improvements to the design to be made and the key tasks on the pathway ahead to be defined. It is described in Section 4.5.

While the description provided here captures the key functions and components of the system, the design will continue to evolve. A number of text boxes describing ‘design considerations’ appear in Sections 4.3 and 4.4. These flag unresolved issues, many of which translate into key tasks for the next phase of the development of the pilot sDSS.

4.2 Functional Overview

The following description considers three key questions for the design and build of the sDSS[14]:

- What will the user enter as inputs?
- What sort of outputs will the system provide?
- How will the system generate the outputs from the inputs?

In fact, these questions provide a neat functional split for the design and build of the sDSS. According to this split, the system can be visualised as comprising three distinct functional parts with a flow of information from each part to the next (see Figure 7). 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, see below). The management of input data and reporting of predictions are delivered via a user interface. The generation of those predictions is likely to be invisible to the user. It could 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.

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[14] A fourth key question is what software environment will the pilot sDSS operate in ? Reference should be made to Semadeni-Davies (2011) for a description of platforms used in the development of other systems. Section 6.3 of this report identifies the need to address software requirements as an important task in progressing from the Proof-of-Concept to the pilot sDSS.

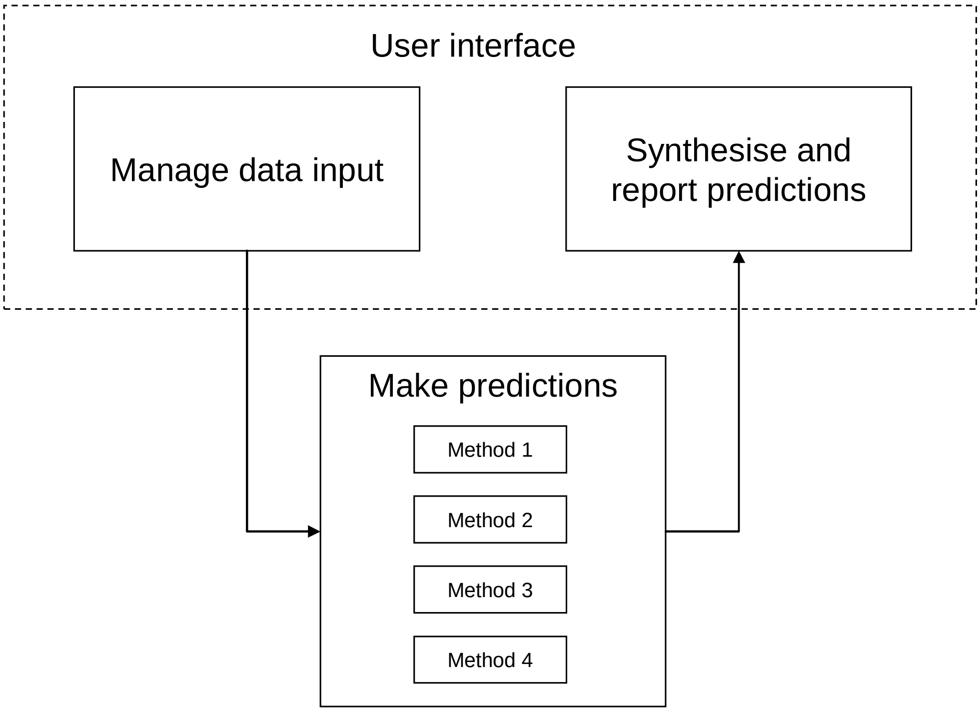

Figure 7: **Functional components of the sDSS.**

In order to deliver on each of these functional parts, the key tasks for the design and build phases of the project are to:

- Develop a user interface that manages the input of data representing urban development scenarios and the display of results;
- Within the reporting function, build in methods(s) for combining indicators;
- Develop a structure within which a range of methods for generating predictions can be housed and which couples the methods to the user interface; and
- For selected case studies, populate the structure with relevant methods in order to demonstrate the system.

In order to break down these tasks further, it is helpful 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: end-users will then run it to investigate any alternative urban development scenarios they choose, within any constraints defined as part of the implementation process.

The following description sets out in some detail the steps involved in implementing and running the system.

4.3 Implementing the sDSS

4.3.1 Overview

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
2. Specify the STUDY TIMEFRAME
3. Specify the BASELINE URBAN STATE
4. Specify the URBAN DEVELOPMENT OPTIONS that can be investigated and the relationships between DESCRIPTIVE ATTRIBUTES and EXECUTIVE ATTRIBUTES

Steps 5-7 establish the characteristics of system outputs:

5. Specify the INDICATOR SET and INDICATOR ATTRIBUTES
6. Specify methods for generating COMBINED INDICATORS
7. Specify INDICATOR BENCHMARKS

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

8. Specify relationships between executive attributes and indicators
9. Validate the system against the BASELINE SYSTEM STATE

Each step is described in detail in the sections below.

4.3.2 Step 1 - Specify the Study Area

The study area is the spatial extent within which scenarios are tested and inputs to the sDSS are required. It may include the areas of undeveloped land for which urban development scenarios are to be examined, the existing urban area and any adjacent and the freshwater and marine waterbodies which make up the receiving environment.

Specification of the study area will involve 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 defined here as:

- PLANNING UNITS; and
- REPORTING UNITS.

Planning units are the spatial units for which a unique form of urban development can be specified, possibly coinciding with council stormwater management units (where already defined) or sub-catchments delineated from analysis of river networks.

Reporting units are the spatial units for which INDICATOR levels are generated by the system. The nature of these units are likely to vary, with at least two types readily distinguished: stream reporting units and estuary reporting units. These two types of reporting unit will be different both in terms of how they are represented in the sDSS and in their relationships with planning units (see Section 4.3.9 for more on this).

4.3.3 Step 2 - Specify the Study Timeframe

The study timeframe is 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:

- T_b, which is the time at which indicators for the baseline system state are reported and also the start date for each scenario; and
- 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).

These points in time are fixed as part of the implementation of the system. That means that results will always be reported at the same point in time in order to allow comparison of the outcomes of different scenarios, each of which has run from the same start date.

However, the user may wish to examine the effects of different rates of development in which case the system needs to allow for the time at which full development of an urban development option is achieved (T_d) to vary. Varying T_d is likely to result in differences in the rate at which changes from the baseline system state occur. The system will need to take T_d into account when reporting indicator levels at time T_r.

Design consideration: One way of allowing for alternative rates of development might be to include T_d as an executive attribute in each urban development option (UDO – see section 4.3.5). For example, there could be a UDO called 'Residential-Fast' and another called 'Residential-slow', both resulting in the same land use and stormwater management characteristics once full development is achieved, but with that state reached more quickly in the first case. The date of T_d would be earlier in the former of these two UDOs.

Another option is for the system to treat T_d as a completely independent variable, to be specified (or selected from a range of possible values set up as part of the implementation) by the user as a separate step from selecting UDOs. This is the approach that has been adopted in developing the PoC version of the system (see Section 4.5).

In addition to T_b, T_d and T_r there is a fourth (and highly critical) point in time which will need to be established as part of the implementation of the system. This is T_{ss}, which is the time at which the environmental response to the effects of each urban development option reach a steady-state. T_{ss} marks the point in time beyond which an indicator has a constant value. If the timeframe for an environmental system to respond to development happens to coincide with the planning timeframe then T_{ss} and T_r will be the same or similar, but this does not have to be the case.

While the need to specify T_{ss} may at first appear to add an unnecessary level of complexity to the way in which the sDSS makes and reports its predictions, this is actually a fundamentally important part of the design. Without it, indicator levels reported at T_r will be independent of values of T_b. In other words, predictions of the effects of any given form of urban development would always be the same, irrespective of initial conditions. Intuitively this does not make sense: one would expect initial conditions to have some influence on indicator levels within a planning timeframe.

In order to overcome this problem, the sDSS will make its prediction of indicator levels associated with any urban development option at time $T_{ss,}$ rather than at time T_r. However, it will report the indicator level at time T_r, based on the trajectory that the indicator level takes between predictions that have been made at times T_b and T_{ss}.

Figure 8 illustrates the way in which this approach allows indicator levels reported at time T_r to be influenced by initial conditions.

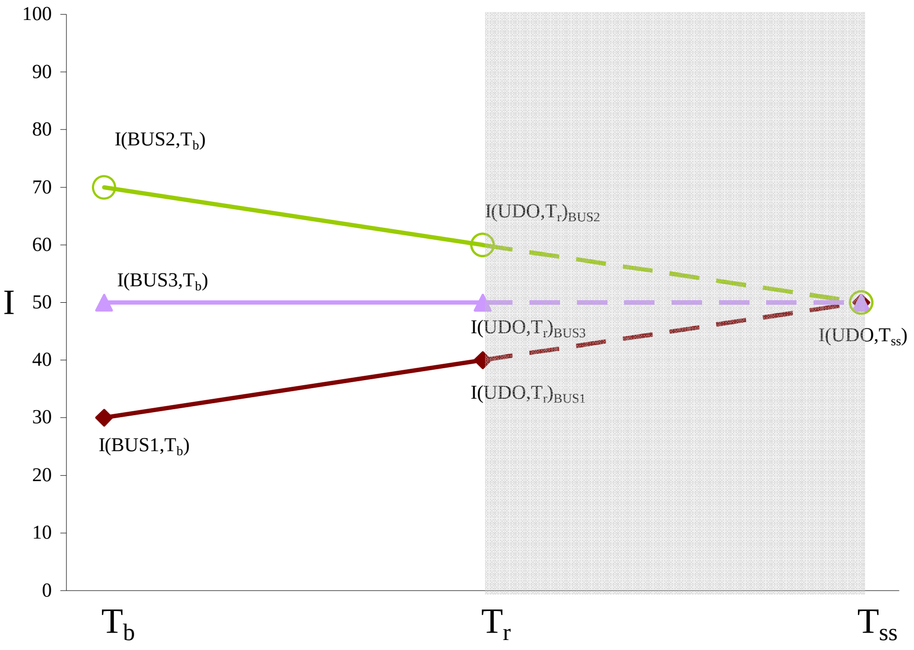

Figure 8: Illustration of the way in which the predictions of indicator levels reported by the sDSS will be influenced by initial conditions.

In this illustration:

- Indicator levels associated with three different baseline urban states are predicted at time T_b;
- Indicator levels associated with a common urban development option are predicted at time T_{ss}; but
- Indicator levels associated with this urban development option are reported at time T_r. Indicator levels over the period between T_r and T_{ss} (shaded grey in Figure 8) are not reported.

Indicator levels converge when the system response reaches steady-state (at time T_{ss}) but have not yet converged by time T_r. In other words, the influence of the initial conditions are reflected in the predictions reported within the planning timeframe. One further aspect of the study timeframe is also described in relation to the VALIDATION of the system (See Step 9).

Design consideration: In the PoC the calculation of indicator levels at time T_r has been achieved by linear interpolation of indicator levels for every year between T_b and T_{ss}. The values for T_r is then extracted from this time series. If this approach is to be adopted in the development of the sDSS, consideration will need to be given to the nature of change in indicator levels over time: change could be linear or non-linear and may vary between indicators.

An additional benefit of using this method is that it also allows extraction of indicator levels at any other interim points in time (T_i) between T_b and T_r. This provides for the evaluation of effects at multiple points in time, for instance coinciding with different phases of the development cycle.

An alternative approach might involve fixing any interim time points (T_i) at which reporting is required as part of the implementation of the sDSS. The reporting of indicator levels at times T_i and T_r might then involve, for instance, the system querying one look up table for 'effects when development in progress' and another for 'effects when development complete.' This level of functionality may lie beyond the scope of the pilot sDSS.

4.3.4 Step 3 - Specify the Baseline Urban State

The baseline urban state (BUS) is a representation of the form of urban development at time T_b. It is specified by defining the characteristics of each planning unit in exactly the same way that future urban development options (UDOs) are defined (see Section 4.3.5). The BUS for each planning unit will therefore consist of a set of descriptive and executive attributes selected from a series of alternatives that best represents the characteristics of urban development at time T_b.

The BUS provides a point of reference for the system when making predictions. In any scenario in which there is a change in the form of urban development, the BUS and the UDO will be different and some difference between indicator levels at times T_b and T_r can be anticipated.

In the event of a user wanting to examine a scenario in which there is no future change in the form of urban development in one or more planning units, the BUS and UDO for those planning units would be identical. However, there could be lagged and/or continuing trends in the effects associated with that form of development and the sDSS needs to be able to take account of these in making predictions of indicator levels. This will involve specifying the MATURITY of a BUS as part of the implementation of the system. The maturity of a BUS is represented by descriptive and executive attributes that reflect whether the response to the BUS is in a dynamic or steady state. The environmental response (as represented by indicator levels) to a 'mature' BUS will be unchanged if the BUS and the UDO are identical. In contrast, if the BUS is 'immature' then indicator levels can be expected to be different at times T_b and T_r even though there has been no change to the form of urban development over this period of time.

The BUS is also used in the validation of the system (See Step 9).

Design consideration: In the PoC, the maturity of the BUS influences indicator levels at time T_b by making arbitrary adjustment (multiplication by 0.66) if the BUS is 'immature.' In the further development of the sDSS, the basis for the extent of any differences in indicator levels between mature and immature BUSs will need to be established, for instance, by consideration of the timing and form of historic trends in environmental responses to urban development.

4.3.5 Step 4 - Specify the Urban Development Options that can be investigated and the relationships between their Descriptive Attributes and Executive Attributes.

Each urban development option (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[15]. Executive attributes are assigned values which are used 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[16].

Table 3 provides an example of two 'fictional' UDOs and their associated descriptive and executive attributes. A user would select one of these two UDOs for each planning unit based on the descriptions of the future form of housing and stormwater treatment (the descriptive attributes). The system would then use the associated values of percentage imperviousness and percentage of contaminants removed (the executive attributes) to drive predictions of future environmental outcomes (i.e. Indicator levels).

Table 3: 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 %

While the executive attributes are the critical aspect of each UDO in terms of the generation of system outputs, as this example demonstrates, the way in which the user of the system will select UDOs will be based on their descriptive attributes. A key step in the definition of UDOs for a given study area will be establishing the range of future development possibilities that the user may wish to investigate and ensuring that descriptive attributes adequately capture the critical characteristics of these different forms of development.

It is also of fundamental importance that relationships can be defined between descriptive and executive attributes. A descriptive attribute is of no value unless it can be expressed as,

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[15] descriptive attributes are the way in which the characteristics of 'urban form and function' shown in Figure 1 (Section 3.3) are represented.

[16] executive attributes are the way in which the characteristics of the 'stress generators' shown in Figure 1 (Section 3.3) are represented. See also Table 2 (Section 3.5).

or influences, an executive attribute. By way of illustration, in the example given in Table 2, two forms of residential development are described in terms of their housing and stormwater treatment characteristics. These characteristics influence the quality of water discharged to receiving waterbodies because they effect the generation and removal, respectively, of contaminants in urban runoff. So there are two descriptive attibutes, two executive attributes and a clear relationship between each pair. A number of other descriptors could be added to this example to provide further characterisation of the form of urban development. For instance, a third descriptive attribute might be “3 – level of public transport investment” with options such as ‘high’ and ‘low.’ For the purposes of making predictions about the future state of urban waterbodies, the inclusion of this information is of no value unless a related executive attribute is also added. In this example, this could be something along the lines of “zinc and copper emissions” with values expressed as a proportion of some baseline value (there is likely to be an inverse relationship between the descriptive and executive attribute value in this case). As discussed earlier[17], there are many other aspects of urban development which have little or no bearing on the values and services of waterbodies, for instance the level of provision of services such as education and health care or infrastructure such as telecommunications networks. Anything of this nature will play no role in the definition of either descriptive or executive attributes.

Design consideration: a key step for any given implementation will be the specification of the set of executive attributes of UDOs required to drive the system. This will depend on the indicator set (see below) and the information needed in order to make a prediction of the value of each indicator. While Table 2 provides some examples of characteristics of urban development which might provide the basis for the specification of some executive attributes, an important task is to identify as full a range of likely executive attributes as possible in order to ensure that the system is adequately configured to accommodate them as input data.

Note that some executive attributes may only influence indicator levels at particular stages of the development cycle. For instance, executive attributes reflecting the extent and nature of earthworks might only influence the generation of indicator scores up to T_d (this is the case in the PoC version of the sDSS).

UDOs will be developed in consultation with end-users of the system. The number of UDOs will depend upon the range of alternative forms of urban development that are of interest to the user. Each UDO needs to be sufficiently different from all other UDOs that one could expect to see some difference in predictions resulting from the replacement of one UDO with another. The system should also allow users to add their own ‘customised’ UDOs by entering or editing values for executive attributes. Returning again to the example given in Table 1, a user could add a third UDO with ‘% impervious’ = 10% and ‘% contaminant removal’ = 90%. There would be no necessity to add any descriptive attributes, although provision should be made for this in order for the use to characterise the new UDO with their own description.

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[17] See Section 2.4.

Design consideration: this description envisages that the values of descriptive and executive attributes associated with any given UDO will be fixed. In this situation, the effects of changes to the form of urban development can only be examined by the selection of an alternative UDO (even if the user is only interested in changing a couple of attributes). This could lead to the need to specify many UDOs, each of which differs from others by the value of only a small number of attributes.

An alternative approach is allow UDOs to be constructed from constituent parts, for instance groups of descriptive and executive attributes that represent land use, methods of land development, stormwater management, transport systems and river management. So instead of selecting from UDO1, UDO2, … UDOn, a user would create the UDO for each PLU by selecting:

- A land use option (LUO) from LUO1, LUO2, … LUOn

- A land development option (LDO) from LDO1, LDO2, … LDOn

- A stormwater management option (SMO) from SMO1, SMO2, … SMOn

- A transport system option (TRO) from TRO1, TRO2, … TROn

- A river management option (RMO) from RMO1, RMO2, … RMOn

Users can then mix and match selections, for instance to examine the effects of different stormwater management options combined with a fixed land use. Adoption of this approach need not prevent the system from allowing users to completely customize UDOs by specifying values for each executive attribute individually, rather than by selection from pre-determined sets of attribute values (as described in the main text above).

4.3.6 Step 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[18], 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 which are likely to be included in the pilot sDSS or future extensions of it include:

- stream health indicator(s), including cultural indicator(s) of stream health
- marine sediment quality indicator(s)
- benthic ecology indicator(s)
- indicator(s) of amenity value, for instance recreational use of waterbodies
- economic indicators, for instance measuring the relative costs of different development and stormwater management options.

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.

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[18] indicators are the way in which the ‘effects’ on the values and services of waterbodies shown in Figure 1 (Section 3.3) are represented.

Design consideration: specification of the INDICATOR SET is a key step for any given IMPLEMENTATION. While recognizing that it is likely to vary, an important task is to identify as full a range of likely INDICATORS as possible in order to ensure that the system is adequately configured to accommodate them in generating, synthesising and reporting the system outputs.

4.3.7 Step 6 - Specify methods for generating COMBINED INDICATORS

An important part of the functionality of the system will be its ability to report the results of any scenario on a number of different levels, including scores for individual indicators and a range of 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. The combination of indicators could include, for instance, the generation of:

- a combined score for a group of like indicators (e.g. ‘all environmental’, ‘all social’, ‘all economic’ or ‘all cultural’) in a particular reporting unit;
- a score combining all four of the above groups of indicators in a particular reporting unit;
- a combined score for a group of like indicators (e.g. ‘all environmental’, ‘all social’, ‘all economic’ or ‘all cultural’) in the whole study area; and
- a score combining all four of the above groups of indicators in the whole study area.

With greater aggregation of indicator scores, the level of precision associated with the information that they convey can be expected to decrease. However, it might be the case that high-level combined scores will suit some end-users who really just want to know what the ‘big picture’ is. Others, who want to know a bit more, can drill down a few levels back to the root indicator levels.

Methods for combining indicators include Composite Index approaches and Multi-criteria analysis. An evaluation of the suitability of methods for their inclusion in the sDSS is described elsewhere (Batstone, et al. 2010). It may be the case that the method differs from one implementation to the next, or that system provides the user with flexibility to generate combined indicators by one of two or more methods.

Design consideration: the specification of the methods for generating combined indicators is a key step for any given implementation. This could be best approached by building all appropriate methods for combining indicators into the reporting functionality of the system, rather than having to create (or re-create) them as part of the predictive methods. The specification of methods for combining indicators for a given implementation would then involve turning selected methods on (or off).

While work is continuing to identify appropriate methods for combining indicators, there are two aspects of the generation of combined indicators which are likely to feature in the functionality of the system. The first is the need to allow WEIGHTS to be assigned to individual indicator levels (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.

Table 4 provides an example of the use of weights in the generation of combined indicators for one reporting unit [RU(x)] for one scenario [S(y)]. Individual indicators are assigned weights and combined in groups of like indicators to generate four combined indicators.

These four ‘group’ combined indicators are then assigned weights and combined again to generate an overall combined indicator for the reporting unit. Group combined indicators across the whole study area can then be generated by combining the like combined indicators from each reporting unit. For instance, an environmental combined indicator would be generated by combining $\text{CombA}_{RU(1),S(1)}$, $\text{CombA}_{RU(2),S(1)}$ and so on, up to and including $\text{CombA}_{RU(n),S(1)}$. An overall indicator for all groups and the whole study area would be generated by combining the overall combined indicators from each reporting unit, ie: $\text{Comb}_{RU(1),S(1)}$, $\text{Comb}_{RU(2),S(1)}$ and so on, up to and including $\text{Comb}_{RU(n),S(1)}$.

Table 4: Example of generation of combined indicators for one reporting unit [RU(x)] for one scenario [S(y)].

Group	Indicator	Weight	Group Combined Indicator	Weight	Overall Combined Indicator
(A) Env.	$A1_{RU(x),S(y)}$	w_{A1}	$\text{CombA}_{RU(x),S(y)}$	W_{CompA}	$\text{Comb}_{RU(x),S(y)}$
	$A2_{RU(x),S(y)}$	w_{A2}			
	$A3_{RU(x),S(y)}$	w_{A3}			
(B) Soc.	$B1_{RU(x),S(y)}$	W_{B1}	$\text{CombB}_{RU(x),S(y)}$	W_{CompB}	
	$B2_{RU(x),S(y)}$	W_{B2}			
	$B3_{RU(x),S(y)}$	W_{B3}			
(C) Econ.	$C1_{RU(x),S(y)}$	W_{C1}	$\text{CombC}_{RU(x),S(y)}$	W_{CompC}	
	$C2_{RU(x),S(y)}$	W_{C2}			
	$C3_{RU(x),S(y)}$	W_{C3}			
(D) Cult.	$D1_{RU(x),S(y)}$	W_{D1}	$\text{CombD}_{RU(x),S(y)}$	W_{CompD}	
	$D2_{RU(x),S(y)}$	W_{D2}			
	$D3_{RU(x),S(y)}$	W_{D3}			

An approach known as an Analytical Hierarchy Process (AHP) has been identified as being a preferred option for developing a weighting method (Batstone et al., 2010). It involves establishing weights for a set of indicators based on surveys of expert panels and / or stakeholder groups.

The second key aspect of the functionality required to generate combined indicators reflects the fact that different indicators are likely to have different indicator attributes. For example, one indicator may be measured quantitatively and another 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 value within a fixed range. The system would report results for indicators in two forms: the ‘raw’ indicator score and a STANDARDISED INDICATOR score. This latter score would be derived by converting the ‘raw’ score to a value on a scale common to all indicators.

Table 5 provides a ‘fictional’ example of the combination of four indicators, each of which has different indicator attributes. The score for each indicator is converted to a standardised indicator score of between 1 and 5, with 5 representing the best environmental condition. In this example, the combined indicator score is simply the mean of the individual scores for each of the standardised indicators.

Table 5: Example of generating standarised indicator scores in order to allow their combination.

Indicator	Indicator attributes range of values (& type of scale)	Score	Standardised indicator score based on common discrete scale (1 – 5, higher is better)
Stream health	0 – 1 (continuous)	0.8	4
Stream amenity	0 – 20 (discrete)	12	3
Harbour sediment-metal concentration	0 - 500 (continuous)	125	4
Harbour amenity	Low, Med, High (discrete)	High	5
Combined indicator score (mean)	1 – 5 (discrete)	-	4

4.3.8 Step 7 - Specify Indicator Benchmarks

The weighting and combination of indicators provides for the results of different scenarios to be compared at a number of different levels. It is likely that users will also 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.

An example of an indicator benchmark might be a threshold sediment metal concentration marking the point above which adverse effects on ecosystem health become likely. Alternatively, an indicator benchmark could be some target condition that represents a desired end point, for instance an upper-level sediment metal concentration that the user wants to try and remain below. Part of the job of the system will be to report the difference between the predicted indicator levels and the indicator benchmark values.

Design consideration: It may be possible to generate a combined indicator benchmark, simply by combining the benchmark indicator scores in the same way that the scores for any given scenario are combined. This requires further consideration.

4.3.9 Step 8 - Specify Relationships Between Executive Attributes of UDOs 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[19].

(i) Establish whether the relationship is direct or indirect

Returning to the example of the UDOs presented in Table 2, in which the executive attributes are "% impervious" and "% contaminant removal," a simple example of a direct relationship might be:

Stream Health Indicator = f (% impervious)

An example of an indirect relationship might be:

Benthic health Indicator = f (sediment metal concentrations)

Where:

Sediment metal concentrations = f (metal load, sediment load)

and

Metal load, sediment load = f (% impervious, % contaminant removal)

In this indirect example the generation of the benthic health indicator from the executive attributes "% impervious" and "% contaminant removal" involves two intermediate steps (for instance requiring the system to make some calculations or query a look-up table). Sediment load, metal load and sediment metal concentrations are INTERMEDIATE VARIABLES. The value of an intermediate variable is determined by the value of an executive attribute (or some preceding intermediate variable) and determines the value of an indicator (or some succeeding intermediate variable).

(ii) Establish the predictive methods for generating values of indicators and intermediate variables

A PREDICTIVE METHOD is a way of generating values of indicators (and intermediate variables) from executive attributes (and intermediate variables).

This is the key step in the implementation of the system because it is the point at which the ways in which outputs will be generated from inputs is determined. There is a range of ways in which this might be achieved and they are likely to differ from one implementation to the next. They include:

- Specifying an empirical relationship, for instance by coding in formulae; and

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[19] The relationships between EXECUTIVE ATTRIBUTES of UDOs and each INDICATOR are the way in which the actions of 'stressors' shown in Figure 1 (Section 3.3) are represented in the system.

- Populating look-up tables with values of indicators (or intermediate variables) and coinciding values of executive attributes. These tables are queried by the system to return a relevant (for instance closest) indicator level from the given value of the executive attribute.
- Defining a set of probabilities associated with a range of possible indicator (or intermediate variable) values which are conditional on the combination of executive attribute values. This is really a variation on the use of look-up tables except that it allows for uncertainty in the system response to be recognised. This method would be applied by defining a Bayesian Belief Network, an approach which appears promising based on a review of its application in comparable studies (refer to Appendix 2).

In these cases, the relationships between independent and dependent values could come from any number of sources, for instance: observations, the results of running models, expert knowledge, stakeholder surveys, and benefit transfer (applying information gained in one setting to another comparable setting). An alternative option is:

- Building a link to a model. In this case, the system would actually take information from a scenario, feed it into a model, take the results from the model run and return that information to the system for it to report.

Design consideration: The system may need to be capable of delivering the necessary inputs (executive attributes) and recovering the predictions (values of indicators) to and from range of predictive methods. A key task is to map out the pathways linking UDOs, executive attributes, intermediate variables and indicators in order to identify the likely range of predictive methods to be accommodated. This exercise will also allow inputs and outputs from alternative methods to be compared and their consolidation or standardisation investigated.

Design consideration: So far the description of the system assumes uni-directional functionality. In other words, the user specifies an urban development scenario and the system makes predictions about environmental (and other) outcomes. An alternative approach is to allow the user to specify a target environmental outcome and for the system then to provide guidance on the forms of urban development that would allow this target to be met. While this could be done using a uni-directional system simply by running a number of iterative scenarios, a system that works either way is likely to be attractive for end users. While this level of functionality may lie beyond the scope of the pilot sDSS, consideration should be given to a design that would make ‘reverse’ evaluations possible, at least to flag it as a potential future extension of the system.

(iii) Establish the ways in which relationships between executive attributes, intermediate variables and indicators operate in space.

As described in Step 4, UDOs are specified at the scale of planning units while indicator levels are generated for reporting units. As noted earlier, there are likely to be different types of reporting unit, for instance stream reporting units and estuary 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:

- “One to one”: indicator levels are generated for one reporting unit from the executive attributes of the UDO in one planning unit (for example, stream ecosystem health in that part of a stream located in a given planning unit is a function of “% impervious” in that planning unit).

- “Many to one”: a variation on the above, with indicator levels for one reporting unit generated by the executive attributes of UDOs in several planning units (for example, harbour sediment quality in a particular estuary reporting unit is a function of “% impervious” in several contributing planning units).
- “One to many”: the opposite of the above, with indicator levels in many reporting units generated by the executive attributes of a UDO in one planning unit (for example, harbour sediment quality in several estuary reporting units as a function of “% impervious” in a single planning unit).
- “Many to many”: the executive attributes of the UDOs in several (or all) planning units generate the indicator levels in several (or all) reporting units, but indicator levels are still independently reported for each reporting unit.
- Aggregation: another step on from the example above, with a single indicator level reported for several reporting units (possibly the whole study area) generated from the executive attributes of UDOs in several (or all) 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.

Design consideration: an important step is the definition of the spatial scales over which the relationships between executive attribute and indicators operate. This will drive the specification of the scale and location of reporting units for each indicator.

4.3.10 Step 9 - Validate the system against the Baseline System State

The baseline system state (BSS) is given by the value of each indicator in the indicator set that represents the ‘current’ state of the system (at time T_b). The values of each indicator that comprise the BSS will be generated as part of validation of the system. Validation involves configuring the system so that predictions of indicators associated with the BUS and changes to these indicators that have occurred over some historic time period are consistent with reality, as represented by observations. The steps involved in validation are:

- defining the historic HISTORIC URBAN STATE (HUS) that represents the form of urban development in each planning unit at the start of the validation period (T_h);
- defining and selecting UDOs that represents the baseline urban state (BUS) of each planning unit at the end of the validation period (T_b);
- running the system to make predictions of indicator levels at time T_h and T_b, based on the executive attributes of the HUS and the BUS;
- comparing the predictions of indicator levels at times T_h and T_b with observations; and
- refining relationships between executive attributes, intermediate variables and indicators until a satisfactory fit is achieved between indicator levels at times T_h and T_b and observations.

Discussion point: The approach set our here is to validate the sDSS so that it makes a good prediction of the baseline system state and then run it to investigate the ways in which different forms of urban development will alter this state. However, there are other (non-anthropogenic) drivers of change, notably climate change. While functionality that allows climate change to be accounted for may lie beyond the scope of the pilot sDSS, consideration should be given to a design that allows for its impacts to be evaluated.

One approach might be to allow for a range of alternative future system states to be specified, for instance using expert knowledge of projections of climate change in the mid and late 21st century. The user might be able to select from these future system states, each of which could reflect a different IPCC emissions scenario. Urban development scenarios would then selected on top of these alternative future system states. If the sDSS was run with no change in the form of urban development then any changes in indicator levels would solely reflect the influence of the projected climate change.

4.4 Running the sDSS

4.4.1 Overview

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
2. Specify reporting options

The remaining steps generate and report the system outputs:

3. Run the system
4. View RESULTS

4.4.2 Step 1 - Specify the Scenario

A scenario 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, either as a pre-determined executive attribute of any UDO, or as an additional independent variable (see earlier).

The default UDO is the BUS, which will already have been established for each planning unit as part of the implementation of the system. The user can specify a new UDO for any planning unit or leave it as the BUS, with the option of selecting a different level of maturity. The UDO is selected from the range of pre-determined options or a custom-UDO can be specified by the user, providing that values of all executive attributes are entered and are of the required format (see earlier). The system will need to be configured to provide a check on this.

4.4.3 Step 2 - Specify reporting options

The system will allow the user to select which indicators they wish to see reported from those available in the indicator set. This could be any number between one and the full set. This approach allows users to examine the results of scenarios with different combinations of indicators. This flexibility has the potential to reveal some important information since the choice of indicators could influence the ranking of different scenarios.

The system will also provide flexibility in the ways in which Indicator levels are combined and reported. 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.

4.4.4 Step 3 - Run the system

This should be as simple as clicking on a menu item or button to make the system run.

4.4.5 Step 4 - View RESULTS

The results are the set of values for the selected indicators associated with a given scenario.

The user should be able to view results for each reporting unit and for any combined indicators selected for the study area as whole. Results could be in a number of formats, for instance:

- Spatial, for example maps showing:
  - Colour coded estuary reporting units
  - Colour coded stream reporting units
- Tabular, for example:
  - Numeric values (or probabilities) for each indicator and combined indicator
  - percentage change from BSS
  - percentage of indicator benchmark
  - Qualitative assessments (‘much better’, ‘better’, ‘worse’)
- Graphical
  - Histograms
  - Trend lines
  - ‘Radar’ or ‘Spider web’ charts (see Figure 9)
- Text
  - An ‘audit trail’ describing the scenario inputs, any selections made by the user, and results.

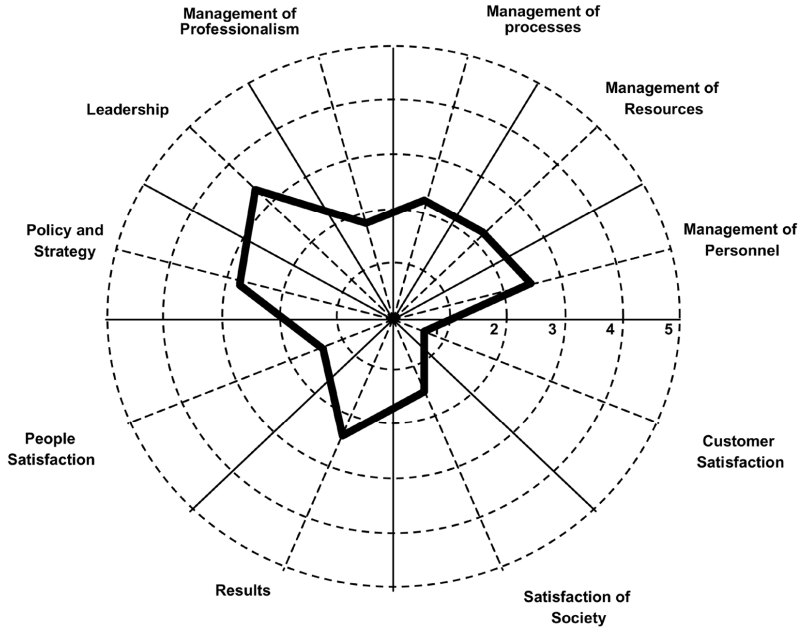


Figure 9: **Example of Radar or Spider-web chart.**

Design consideration: the specification of the options for reporting results should rest with the user. Making allowance for this is best approached by building all appropriate options into the reporting functionality of the system, rather than having to create (or re-create) them as part of the implementation. The specification of methods for reporting results then involves turning selected methods on (or off).

Design consideration: consideration should be given to how uncertainty should be reported, if at all. The use of a Bayesian Belief Network (BBN) approach provides for uncertainty to be recognised explicitly because outcomes are reported as probabilities (see Appendix 2).

If the BBN approach is not adopted, an alternative approach might be for the system to run in Monte Carlo mode with executive attributes varying by ± x % around the specified value. The results could then be reported as ±y %, for a difference of ± x% in input values. However, this level of functionality may lie beyond the scope of the pilot sDSS.

5. Proof of Concept Version

5.1 Introduction

The design of the sDSS has been 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, has been developed .to apply, test and refine the steps involved in the implementation and use of the system described in Chapter 4. It has also provided a basis from which to identify and plan for the tasks which lie ahead.

The PoC has been developed as a Microsoft Excel spreadsheet. It comprises 20 linked worksheets, represented by the rectangular boxes shown in Figure 10.

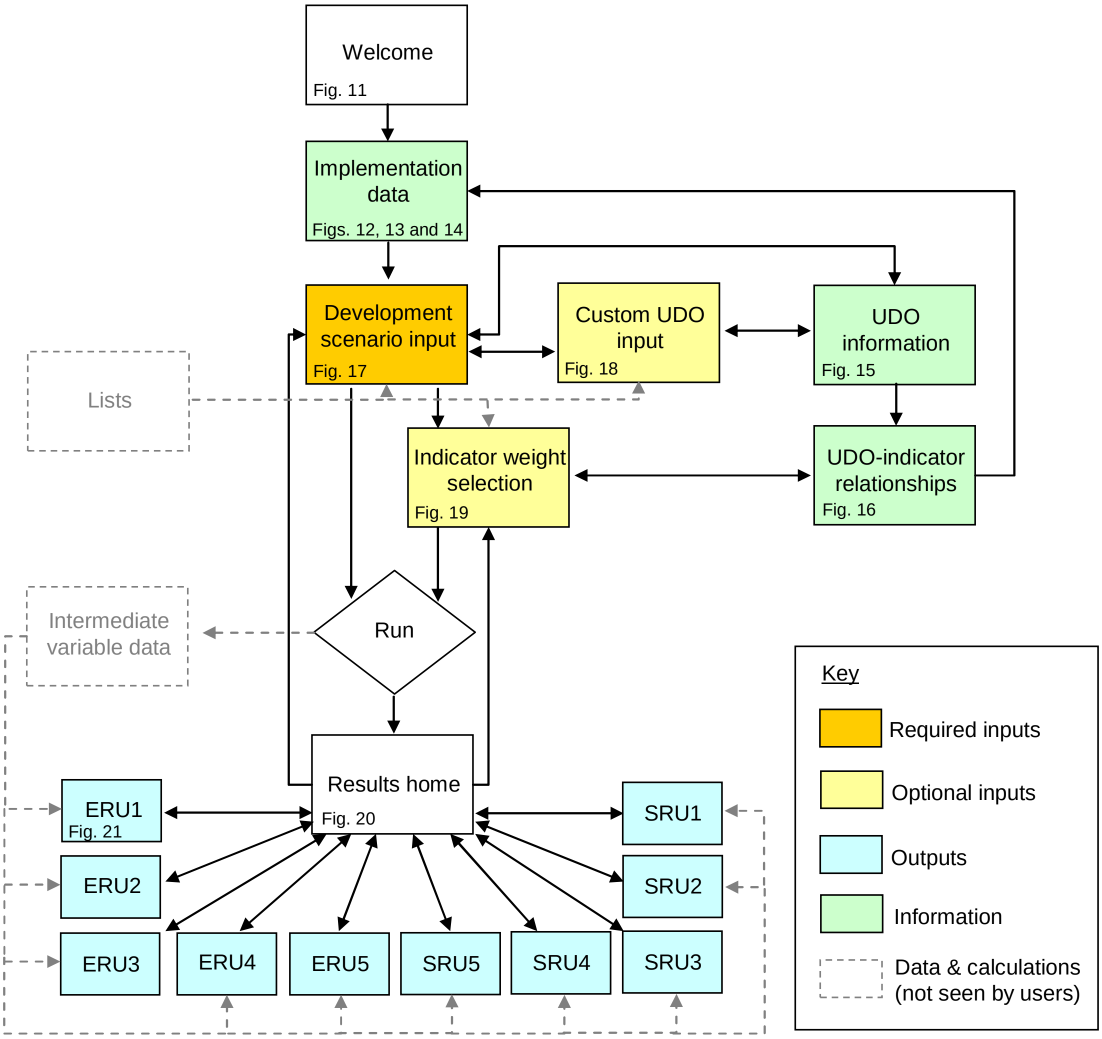
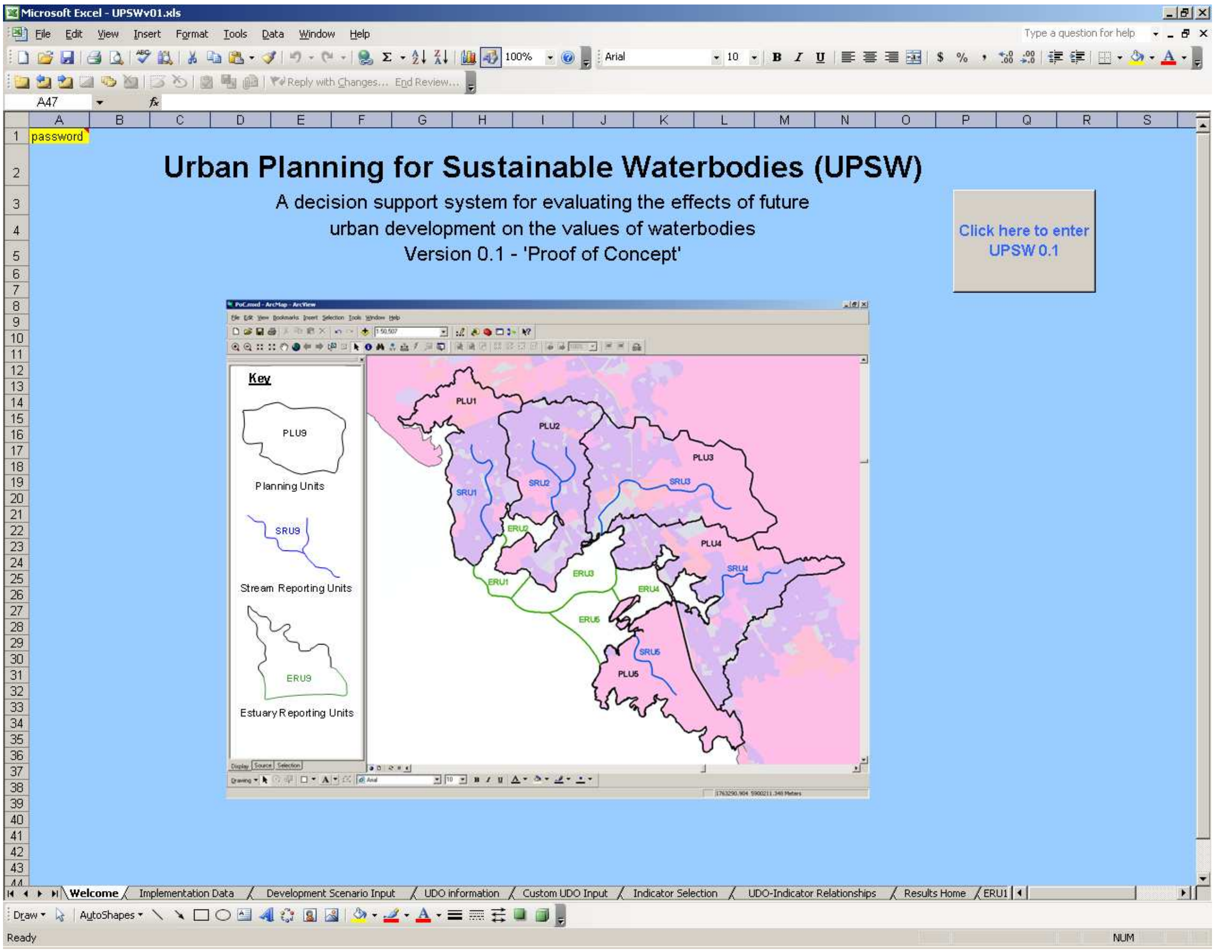


Figure 10: Proof-of-Concept version of the sDSS showing worksheets (rectangular boxes) and the relationships between them. Screen dumps of worksheets are shown be below where indicated by the relevant Figure number.

The worksheets are configured as if they were a view of the screen in the pilot sDSS – in other words a user sees everything that they need to see without any need to scroll across or down the worksheet (for example, see Figure 11).



Urban Planning for Sustainable Waterbodies (UPSW)

A decision support system for evaluating the effects of future urban development on the values of waterbodies

Version 0.1 - 'Proof of Concept'

Figure 11: Proof of concept: “Welcome” worksheet.

Worksheets are linked through hyperlinks as a way of mimicking the sequence of actions that will 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. Links between worksheets can be uni- or bi-directional, as shown by the single- and double-headed arrows in Figure 10.

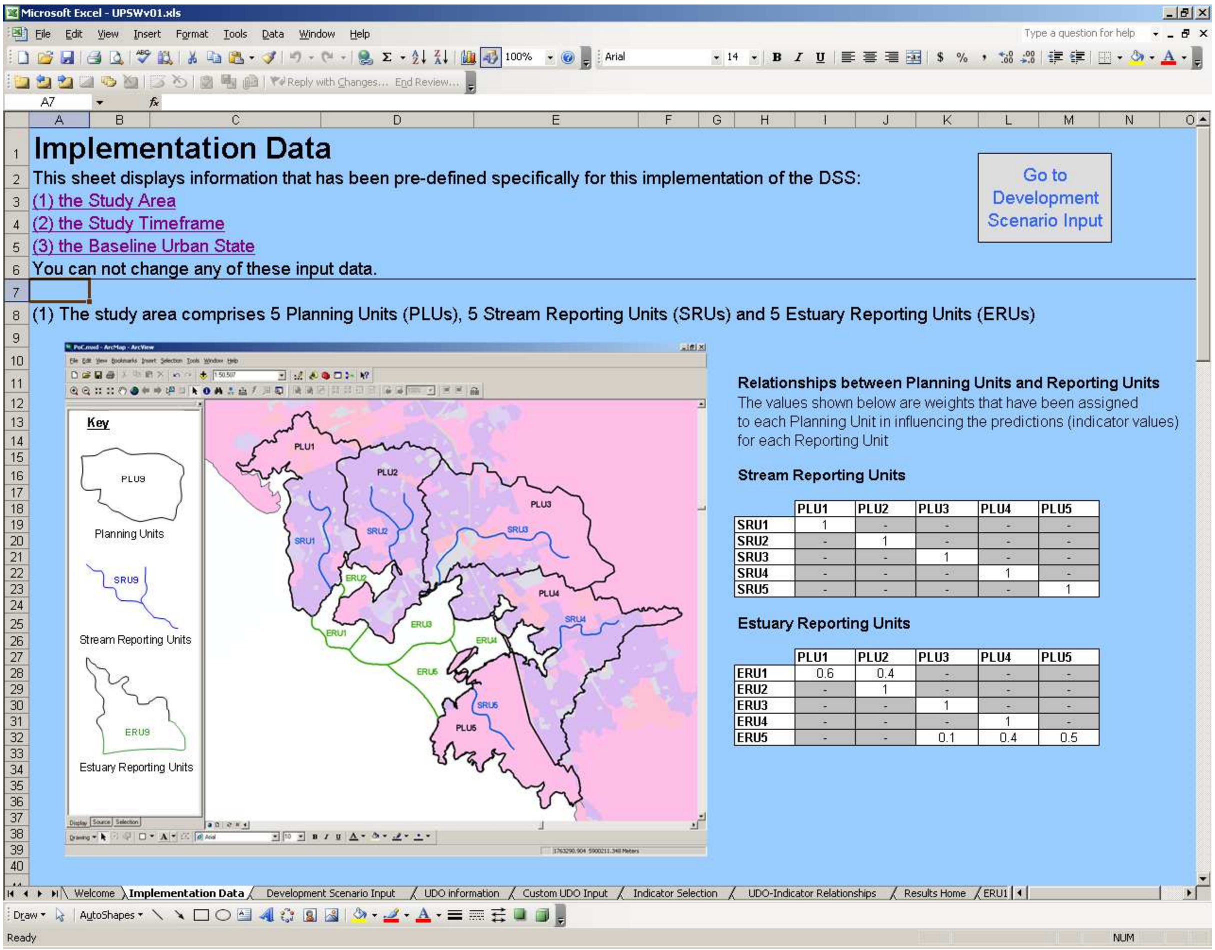
Selections are made by the use of drop-down lists. These lists are populated with data held on a common worksheet (“Lists”) which represents the system’s database. Based on the selections made by the user, the PoC calculates intermediate variables, single Indicator levels and combined indicator levels using methods which mimic those proposed for the development of the pilot sDSS. These data and calculations are closed to users of the PoC, as indicated by the dashed boxes and arrows in Figure 10.

The following description summarises the way in which the PoC captures the steps involved in the implementation of the system (as described in Section 4.3) and running the system (as described in Section 4.4)

5.2 Implementation

Step 1 - Specify the study area

The study area is specified on the "Implementation Data" worksheet. There are five of each of the following units: planning units (PLUs); estuary reporting units (ERUs); and stream reporting units (SRUs) (see Figure 12). Spatial links between PLUs and reporting units are specified in a pair of matrices. The values of indicators in SRUs are influenced solely by the executive attributes of the PLU within which they are located. The values of indicators in ERUs are influenced by the executive attributes of between one and three PLUs, with the level of influence weighted based on their relative location.



Implementation Data

This sheet displays information that has been pre-defined specifically for this implementation of the DSS:

(1) the Study Area

(2) the Study Timeframe

(3) the Baseline Urban State

You can not change any of these input data.

(1) The study area comprises 5 Planning Units (PLUs), 5 Stream Reporting Units (SRUs) and 5 Estuary Reporting Units (ERUs)

Relationships between Planning Units and Reporting Units

The values shown below are weights that have been assigned to each Planning Unit in influencing the predictions (indicator values) for each Reporting Unit

Stream Reporting Units

	PLU1	PLU2	PLU3	PLU4	PLU5
SRU1	1	-	-	-	-
SRU2	-	1	-	-	-
SRU3	-	-	1	-	-
SRU4	-	-	-	1	-
SRU5	-	-	-	-	1

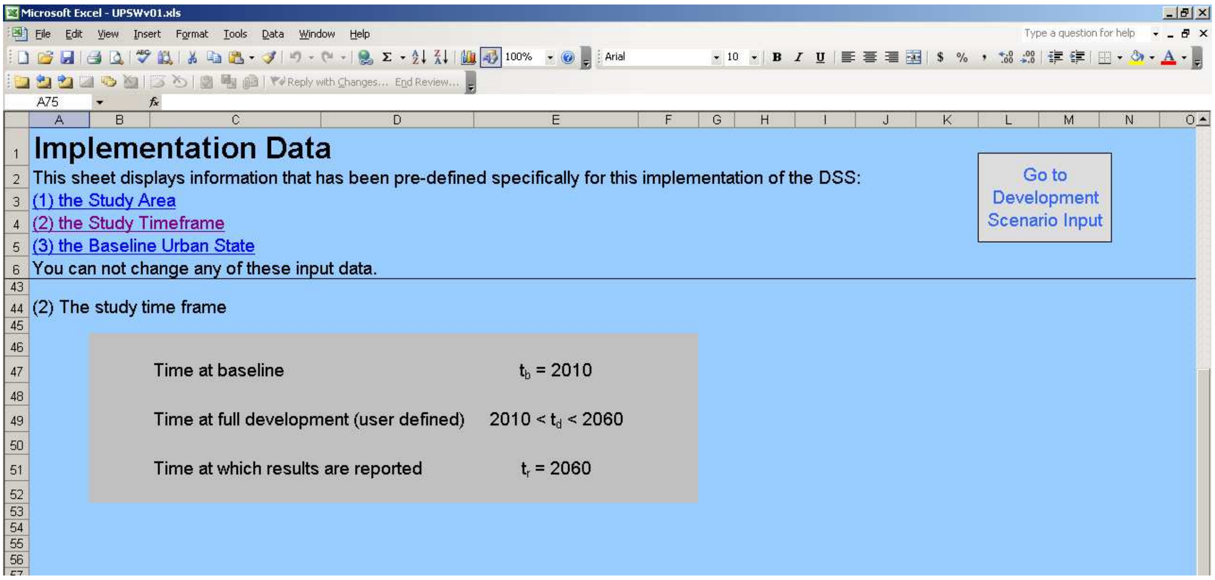
Estuary Reporting Units

	PLU1	PLU2	PLU3	PLU4	PLU5
ERU1	0.6	0.4	-	-	-
ERU2	-	1	-	-	-
ERU3	-	-	1	-	-
ERU4	-	-	-	1	-
ERU5	-	-	0.1	0.4	0.5

Figure 12: Proof of concept: "Implementation Data" worksheet showing the study area.

Step 2 - Specify the study timeframe

The study timeframe is also specified on the "Implementation Data" worksheet, with a hyperlink taking the user to this information (see Figure 13). T_b is 2010, T_r is 2060 and T_d is a year between these (to be selected by the user). T_{ss} is 2110 but is not revealed to the user, as it is required only as part of the unseen calculations.



Implementation Data

This sheet displays information that has been pre-defined specifically for this implementation of the DSS:

(1) the Study Area

(2) the Study Timeframe

(3) the Baseline Urban State

You can not change any of these input data.

(2) The study time frame

Time at baseline	$t_b = 2010$
Time at full development (user defined)	$2010 < t_d < 2060$
Time at which results are reported	$t_r = 2060$

Figure 13: Proof of concept: "Implementation Data" worksheet showing the study timeframe.

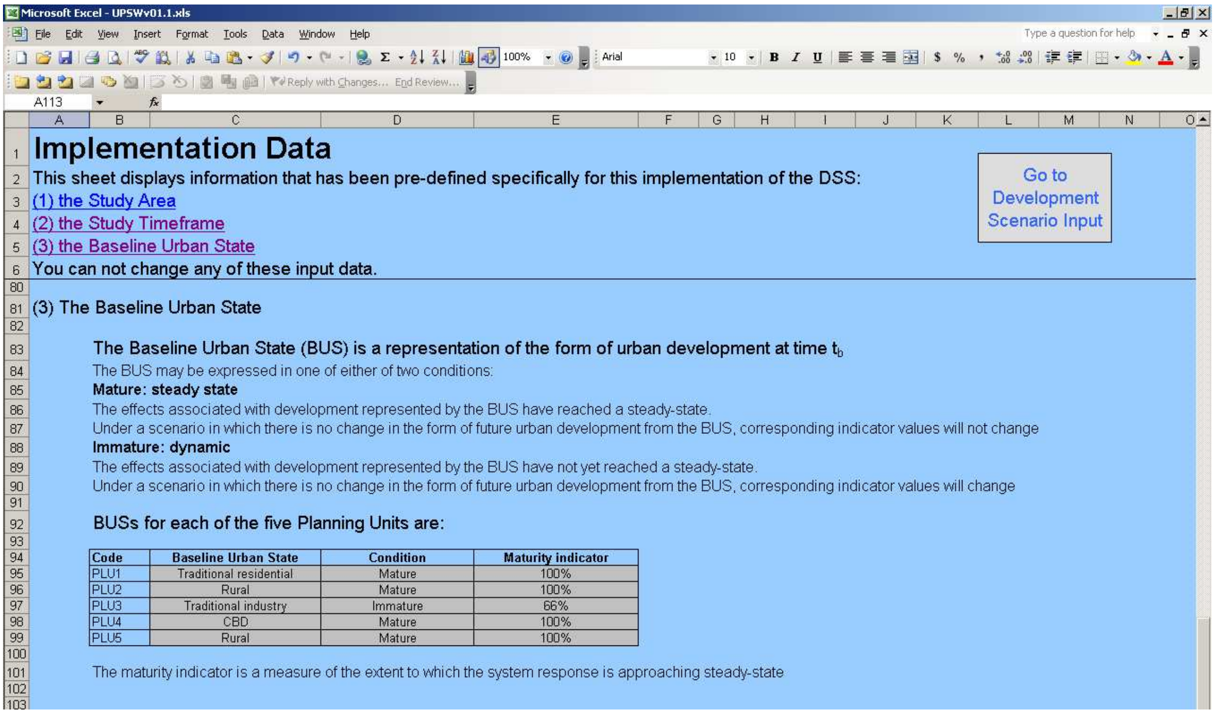
Step 3 - Specify the baseline urban state

The BUS in each PLU is also specified on the 'Implementation Data" worksheet (see Figure 14). Again, the user views this information via a hyperlink. Each BUS has been pre-selected and locked in (by protecting the worksheet). Because these are fictional examples they can be changed (once the worksheet has been un-protected) by selecting from a sub-set of the available UDOs (those that are relevant to the representation of the historic form of urban development). The maturity of each BUS is also specified: an arbitrary correction factor (the 'Maturity indicator') of 0.66 is applied in calculating the intermediate variable values associated with an immature BUS.

Step 4 - Specify the urban development options that can be investigated and the relationships between descriptive attributes and executive attributes

A set of seven UDOs are specified on the (hidden) "Lists" worksheet. The UDOs are: rural; traditional residential; traditional industry; CBD (central business district); Low Impact Development (LID) residential; LID industry; and high intensity residential. Each UDO has ten descriptive attributes and ten corresponding executive attributes which characterise methods of land development, land use, stormwater management, transport systems and stream management. The relationship between each pair of attributes is shown in Table 6.

In the PoC, each executive attribute takes on one of four values: for instance '% riparian vegetation' can be 0%, 30%, 60% or 90%. Information on each UDO, including the value of each executive attribute is provided on the "UDO Information" worksheet (see Figure 15). This worksheet is provided only for reference and cannot be altered by the user.



Implementation Data

This sheet displays information that has been pre-defined specifically for this implementation of the DSS:

(1) the Study Area

(2) the Study Timeframe

(3) the Baseline Urban State

You can not change any of these input data.

(3) The Baseline Urban State

The Baseline Urban State (BUS) is a representation of the form of urban development at time t_b

The BUS may be expressed in one of either of two conditions:

Mature: steady state

The effects associated with development represented by the BUS have reached a steady-state.

Under a scenario in which there is no change in the form of future urban development from the BUS, corresponding indicator values will not change

Immature: dynamic

The effects associated with development represented by the BUS have not yet reached a steady-state.

Under a scenario in which there is no change in the form of future urban development from the BUS, corresponding indicator values will change

BUSs for each of the five Planning Units are:

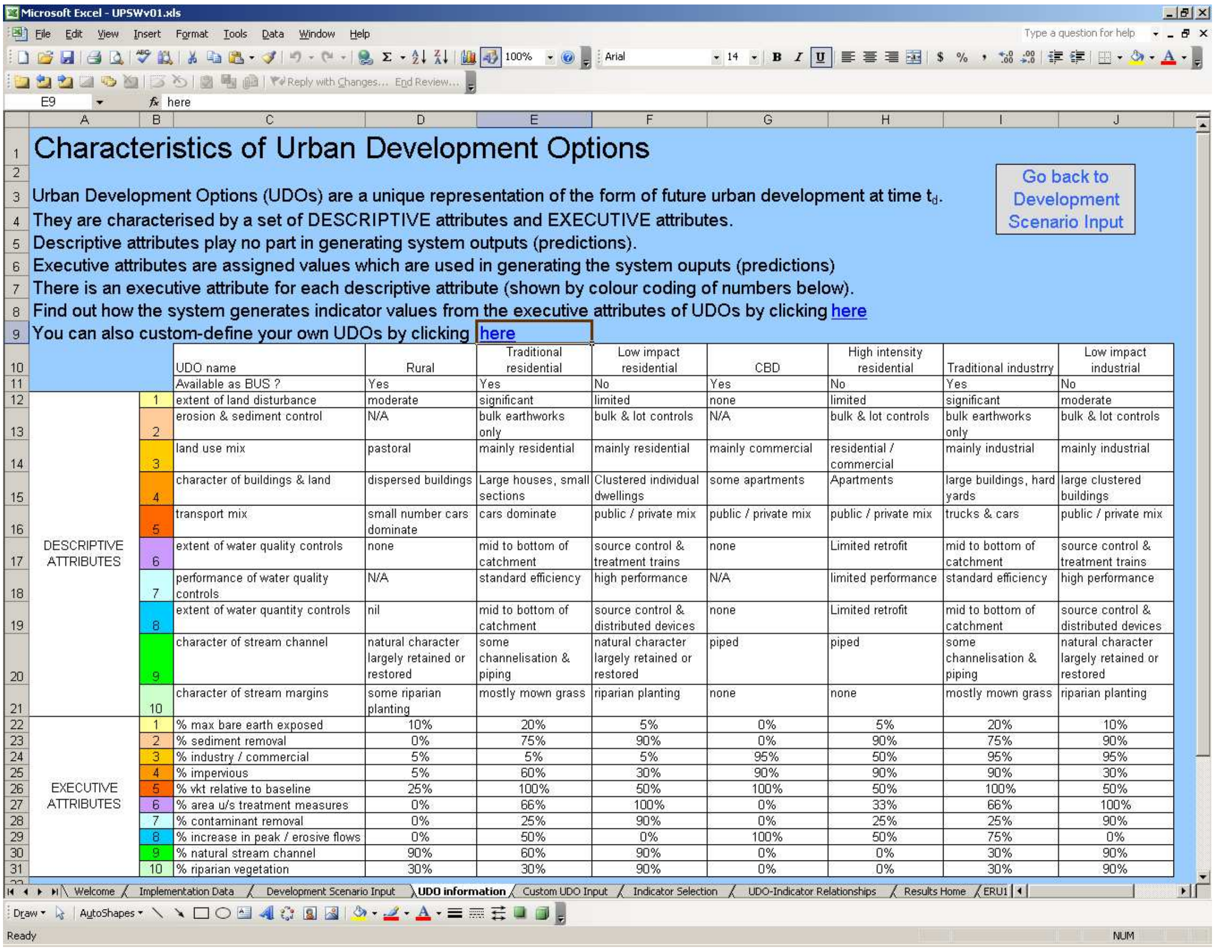
Code	Baseline Urban State	Condition	Maturity indicator
PLU1	Traditional residential	Mature	100%
PLU2	Rural	Mature	100%
PLU3	Traditional industry	Immature	66%
PLU4	CBD	Mature	100%
PLU5	Rural	Mature	100%

The maturity indicator is a measure of the extent to which the system response is approaching steady-state

Figure 14: Proof of concept: "Implementation Data" worksheet showing information about the Baseline Urban State.

Table 6: descriptive and executive attributes of UDOs in the Proof of Concept version of the sDSS.

	Descriptive Attribute	Executive Attribute
Methods of land development	extent of land disturbance	% max bare earth exposed
	erosion & sediment control	% sediment removal
Land use	land use mix	% industry / commercial
	character of buildings & land	% impervious
Transport systems	transport mix	% vkt relative to baseline
Stormwater management	extent of water quality controls	% area u/s treatment measures
	performance of water quality controls	% contaminant removal
	extent of water quantity controls	% increase in peak / erosive flows
Stream management	character of stream channel	% natural stream channel
	character of stream margins	% riparian vegetation



Characteristics of Urban Development Options

Urban Development Options (UDOs) are a unique representation of the form of future urban development at time t_d.
They are characterised by a set of DESCRIPTIVE attributes and EXECUTIVE attributes.
Descriptive attributes play no part in generating system outputs (predictions).
Executive attributes are assigned values which are used in generating the system ouputs (predictions)
There is an executive attribute for each descriptive attribute (shown by colour coding of numbers below).
Find out how the system generates indicator values from the executive attributes of UDOs by clicking here
You can also custom-define your own UDOs by clicking here

		UDO name	Rural	Traditional residential	Low impact residential	CBD	High intensity residential	Traditional industrry	Low impact industrial
		Available as BUS ?	Yes	Yes	No	Yes	No	Yes	No
DESCRIPTIVE ATTRIBUTES	1	extent of land disturbance	moderate	significant	limited	none	limited	significant	moderate
	2	erosion & sediment control	N/A	bulk earthworks only	bulk & lot controls	N/A	bulk & lot controls	bulk earthworks only	bulk & lot controls
	3	land use mix	pastoral	mainly residential	mainly residential	mainly commercial	residential / commercial	mainly industrial	mainly industrial
	4	character of buildings & land	dispersed buildings	Large houses, small sections	Clustered individual dwellings	some apartments	Apartments	large buildings, hard yards	large clustered buildings
	5	transport mix	small number cars dominate	cars dominate	public / private mix	public / private mix	public / private mix	trucks & cars	public / private mix
	6	extent of water quality controls	none	mid to bottom of catchment	source control & treatment trains	none	Limited retrofit	mid to bottom of catchment	source control & treatment trains
	7	performance of water quality controls	N/A	standard efficiency	high performance	N/A	limited performance	standard efficiency	high performance
	8	extent of water quantity controls	nil	mid to bottom of catchment	source control & distributed devices	none	Limited retrofit	mid to bottom of catchment	source control & distributed devices
	9	character of stream channel	natural character largely retained or restored	some channelisation & piping	natural character largely retained or restored	piped	piped	some channelisation & piping	natural character largely retained or restored
	10	character of stream margins	some riparian planting	mostly mown grass	riparian planting	none	none	mostly mown grass	riparian planting
EXECUTIVE ATTRIBUTES	1	% max bare earth exposed	10%	20%	5%	0%	5%	20%	10%
	2	% sediment removal	0%	75%	90%	0%	90%	75%	90%
	3	% industry / commercial	5%	5%	5%	95%	50%	95%	95%
	4	% impervious	5%	60%	30%	90%	90%	90%	30%
	5	% vkt relative to baseline	25%	100%	50%	100%	50%	100%	50%
	6	% area u/s treatment measures	0%	66%	100%	0%	33%	66%	100%
	7	% contaminant removal	0%	25%	90%	0%	25%	25%	90%
	8	% increase in peak / erosive flows	0%	50%	0%	100%	50%	75%	0%
	9	% natural stream channel	90%	60%	90%	0%	0%	30%	90%
	10	% riparian vegetation	30%	30%	90%	0%	0%	30%	90%

Figure 15: Proof of concept: "UDO Information" worksheet.

Step 5 - Specify the indicator set and indicator attributes

There are four indicators in the PoC: a Stream Health Score (SHS) and a Stream Amenity Score (SAS) are reported for each SRU while an Estuary Health Score (SHS) and an Estuary Amenity Score (EAS) are reported for each ERU. These represent the (pre-combination) indicator set. The 'health' scores are continuous variables on a scale 0-100, while the 'amenity' scores are discrete variables which can take on one of three values: 33 ('low'), 66 ('medium') or 100 ('high'). This difference in indicator attributes is deliberate: it means that the PoC incorporates one of the key challenges in generating combined indicators, being the need to deal with differences in indicator attributes.

Step 6 - Specify methods for generating combined indicators

There are two combined indicators in the POC: a Stream Combined Score (SCS) is estimated for each SRU from the SHS and SAS while an Estuary Combined Score (ECS) is estimated for each ERU from the EHS and EAS. The values of combined indicators are calculated on hidden parts of the "ERUn"[20] and "SRUn"[20] worksheets as a weighted-average of the individual indicator scores, based on weights assigned by the user (see below).

---

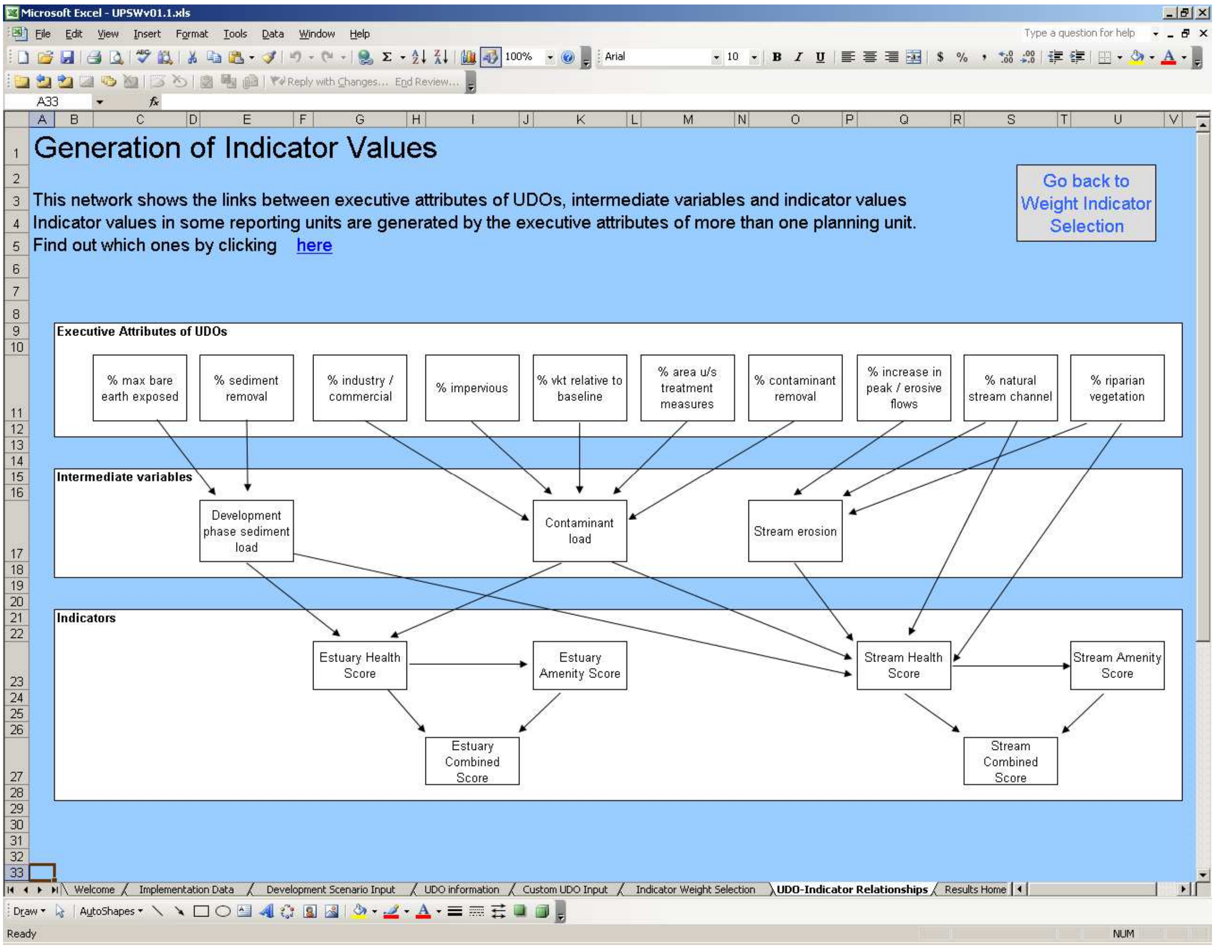
[20] Where n = 1 to 5

Step 7 - Specify INDICATOR BENCHMARKS

Indicator benchmarks have not been specified in the PoC.

Step 8 - Specify relationships between EXECUTIVE ATTRIBUTES and INDICATORS

A network representing relationships between executive attributes, intermediate variables and indicators is shown on the “UDO-Indicator relationships” worksheet (see Fig 16). The spatial nature of these relationships is shown in the matrices linking PLUs and reporting units on the “Implementation Data” worksheet (see Fig 12). Again, this worksheet is provided for reference and cannot be altered by the user.



Generation of Indicator Values

This network shows the links between executive attributes of UDOs, intermediate variables and indicator values
Indicator values in some reporting units are generated by the executive attributes of more than one planning unit.
Find out which ones by clicking here

Figure 16: **Proof of concept: “UDO-Indicator Relationships” worksheet.** .

In the PoC, a series of arbitrary formulae have been defined in order to calculate intermediate variable values from executive attributes values. While arbitrary, these formulae do correctly represent the expected nature (i.e. positive or inverse) of relationships between independent and dependent variables. For example, an increase in the value of the executive attribute “% impervious” results in an increase in the value of the intermediate variable “contaminant load” while an increase in the value of the executive attribute “% contaminant removal” results in a decrease in the value of “contaminant load.”

These calculations are made for time T_b based on the executive attributes of the BUS and time T_{ss} based on the executive attributes of the UDO. The value of the intermediate variable at T_d is also calculated as being (arbitrarily) 0.75 of the value at T_{ss}, unless there is no change in the form of development (i.e. if the BUS and UDO are the same). In this way, the results generated by the PoC are influenced by the time to full development, which (as described in Section 4.3.3) is likely to be an important variable of interest to users. All of the calculations described thus far occur on the (hidden) “Intermediate variables” worksheet.

The calculation of Indicator levels from intermediate variables occurs in similar fashion, based on arbitrary formulae located on hidden parts of the “ERUn”[20] and “SRUn”[20] worksheets. In the case of those ERUs for which Indicator levels are influenced by the executive attributes of UDOs in two or more PLUs, intermediate variable values for the relevant PLUs (weighted according to the values in the matrices on the “Intermediate variables” page) are used in the calculation of the Indicator levels. In all other ERUs and SRUs, the calculation of the Indicator levels is based solely on the intermediate variable value of the single corresponding PLU.

These calculations generate ‘raw’ EHS and SHS values at times T_b, T_d and T_{ss}. Values for all intervening years are interpolated. This time series of ‘raw’ scores are then indexed to give them a value on a common continuous scale of 0-100. This mimics an important part of the process of combining indicators discussed in Section 4.3.7.

Values of EAS and SAS are calculated from the EHS and SHS values, respectively. As noted above, these amenity scores can only take on one of three values: 33 (‘low’), 66 (‘medium’0 or 100 (‘high’). The EAS and SAS values are assigned on the basis of the corresponding EHS and SHS values falling within separately defined ‘low’, ‘medium’ and ‘high’ ranges. In the pilot sDSS, amenity Indicator levels will be generated from intermediate variables rather than from other indicators. However, the important step in the PoC is the generation of an indicator with discrete value classes to feed into the process of indicator combination, rather than the specific methods used in its derivation.

While the PoC makes predictions of Indicator levels based on arbitrary formulae, importantly this occurs by the two step approach set out above, i.e.:

1. Executive attributes of UDOs are used to predict the values of intermediate variables for each PLU; and then
2. these intermediate variables are used to predict Indicator levels in each SRU and ERU (following, in some cases, their distribution among more than one ERU).

The way in which these two steps have been isolated is likely to be a fundamental feature of the methods used in developing the pilot sDSS: that is, one method (for instance a deterministic model or empirical relationship) may be used to generate the intermediate variables and another (for instance a Bayesian Belief Network – see Appendix 2) to generate the indicator levels. Step 1 involves making predictions relating to PLUs while step 2 involves making predictions relating to each reporting unit.

Step 9 - Validate the system against the BASELINE SYSTEM STATE

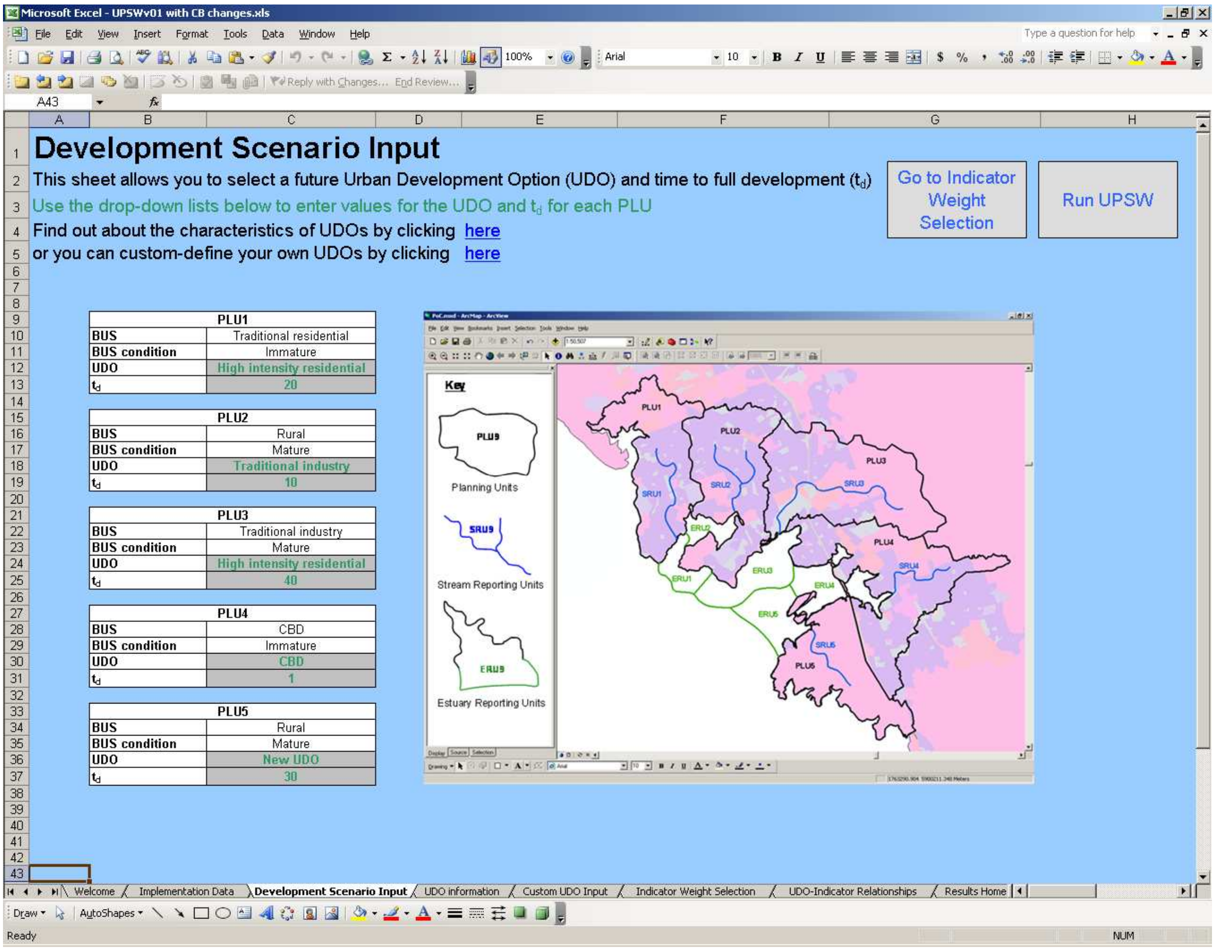
Given the fictional nature of the PoC environment, this step has not been undertaken.

5.3 Running the PoC

Step 1 - Specify the SCENARIO

The user specifies the scenario by selecting a UDO for each PLU from drop-down lists on the “Development Scenario Input” worksheet (see Fig 17). As noted above, information to help guide the selection of UDOs is presented on the “UDO Information” worksheet (see Figure 15). Users are also required to select the time to full development (t_d) of each PLU, from drop-down lists giving options of 10, 20, 30, 40, 50 yrs[21].

Users can also custom-define up to two of their own UDOs on the “Custom UDO input” worksheet (see Figure 18). This involves assigning a name to the custom UDO and selecting a value for each of the ten executive attributes from drop-down lists. As noted above, each value can be selected from one of four options. Once a custom UDO has been defined, the user can then select it for any PLU on the “Development Scenario Input” worksheet.



Development Scenario Input

This sheet allows you to select a future Urban Development Option (UDO) and time to full development (t_d)

Use the drop-down lists below to enter values for the UDO and t_d for each PLU

Find out about the characteristics of UDOs by clicking here

or you can custom-define your own UDOs by clicking here

PLU1	
BUS	Traditional residential
BUS condition	Immature
UDO	High intensity residential
t_d	20

PLU2	
BUS	Rural
BUS condition	Mature
UDO	Traditional industry
t_d	10

PLU3	
BUS	Traditional industry
BUS condition	Mature
UDO	High intensity residential
t_d	40

PLU4	
BUS	CBD
BUS condition	Immature
UDO	CBD
t_d	1

PLU5	
BUS	Rural
BUS condition	Mature
UDO	New UDO
t_d	30

Figure 17: Proof of concept: “Development Scenario Input” worksheet.

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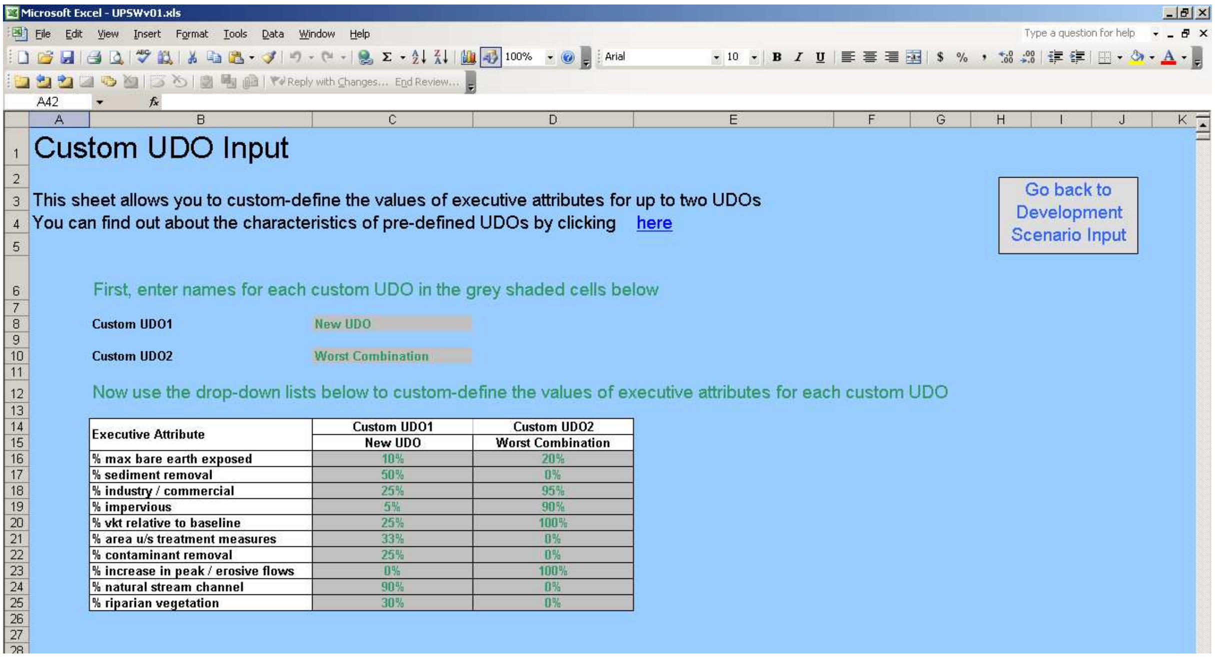
[21] If the user wishes to examine a SCENARIO in which there is no change between the BUS and UDO then t_d has to be set at 1 in order to avoid a zero value appearing as the numerator in a particular formula.



Custom UDO Input

This sheet allows you to custom-define the values of executive attributes for up to two UDOs
You can find out about the characteristics of pre-defined UDOs by clicking here

First, enter names for each custom UDO in the grey shaded cells below

Custom UDO1: New UDO

Custom UDO2: Worst Combination

Now use the drop-down lists below to custom-define the values of executive attributes for each custom UDO

Executive Attribute	Custom UDO1	Custom UDO2
	New UDO	Worst Combination
% max bare earth exposed	10%	20%
% sediment removal	50%	0%
% industry / commercial	25%	95%
% impervious	5%	90%
% vkt relative to baseline	25%	100%
% area u/s treatment measures	33%	0%
% contaminant removal	25%	0%
% increase in peak / erosive flows	0%	100%
% natural stream channel	90%	0%
% riparian vegetation	30%	0%

Figure 18: Proof of concept: “Custom UDO Input” worksheet.

Step 2 - Specify reporting options

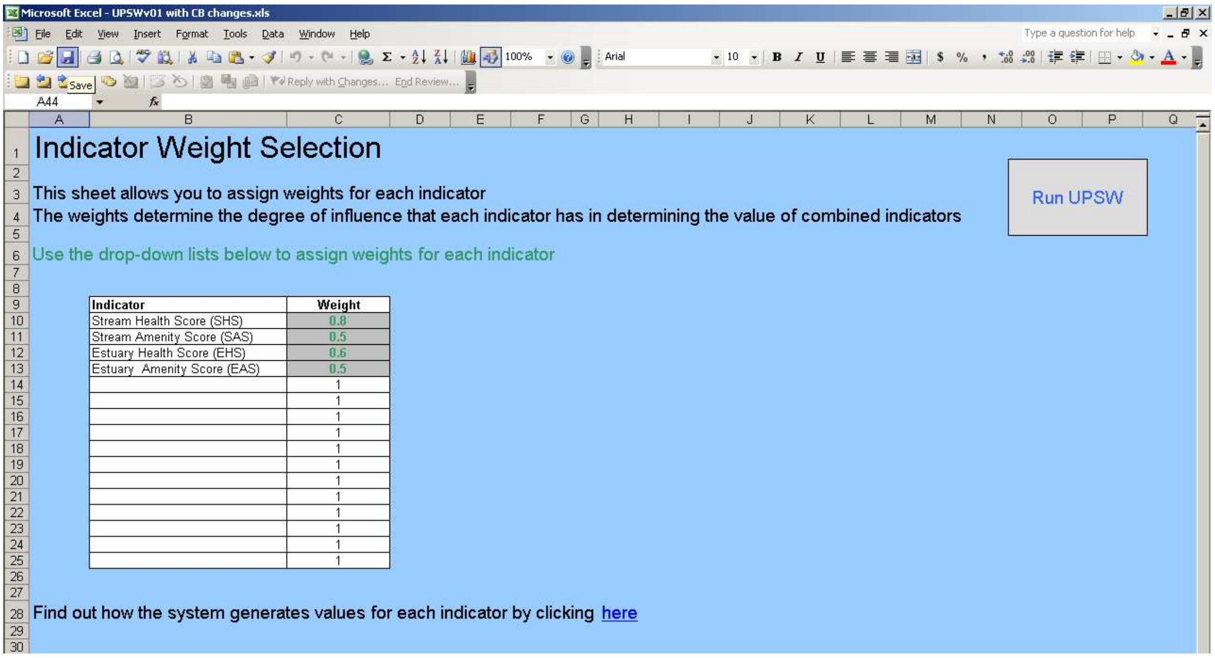
Given that the PoC only calculates two indicators for each reporting unit, the user is not asked to select which indicators they wish to see the results reported for. However, they are given the option of selecting weights for each indicator which are used in calculating the combined indicator levels for each reporting unit. This selection is made from drop-down lists on the “Indicator weight selection” worksheet (see Fig 19). Note that the user does not have to repeat this step for each new scenario they wish to evaluate providing that they are content with the weights selected previously.

Step 3 - Run the system

The calculations that constitute ‘running’ the system occur instantaneously with the selection of UDOs and indicator weights. However, in order to mimic the functionality of the pilot sDSS, a hyperlink labelled “Run UPSW” which appears on both the “Development Scenario Input” (See Figure 17) and “Indicator Weight Selection” (see Figure 19) worksheets takes the user to the “Results Home” worksheet.

Step 4 - View RESULTS

The “Results Home” worksheet provides a summary of the scenario and a map showing the PLUs, ERUs and SRUs (see Fig 20). The results for any reporting unit are viewed by clicking on the ERU or SRU label. These labels are hyperlinked to the “ERUn”[20] and “SRUn” [20] worksheets (of which there is one for each reporting unit).



Indicator Weight Selection

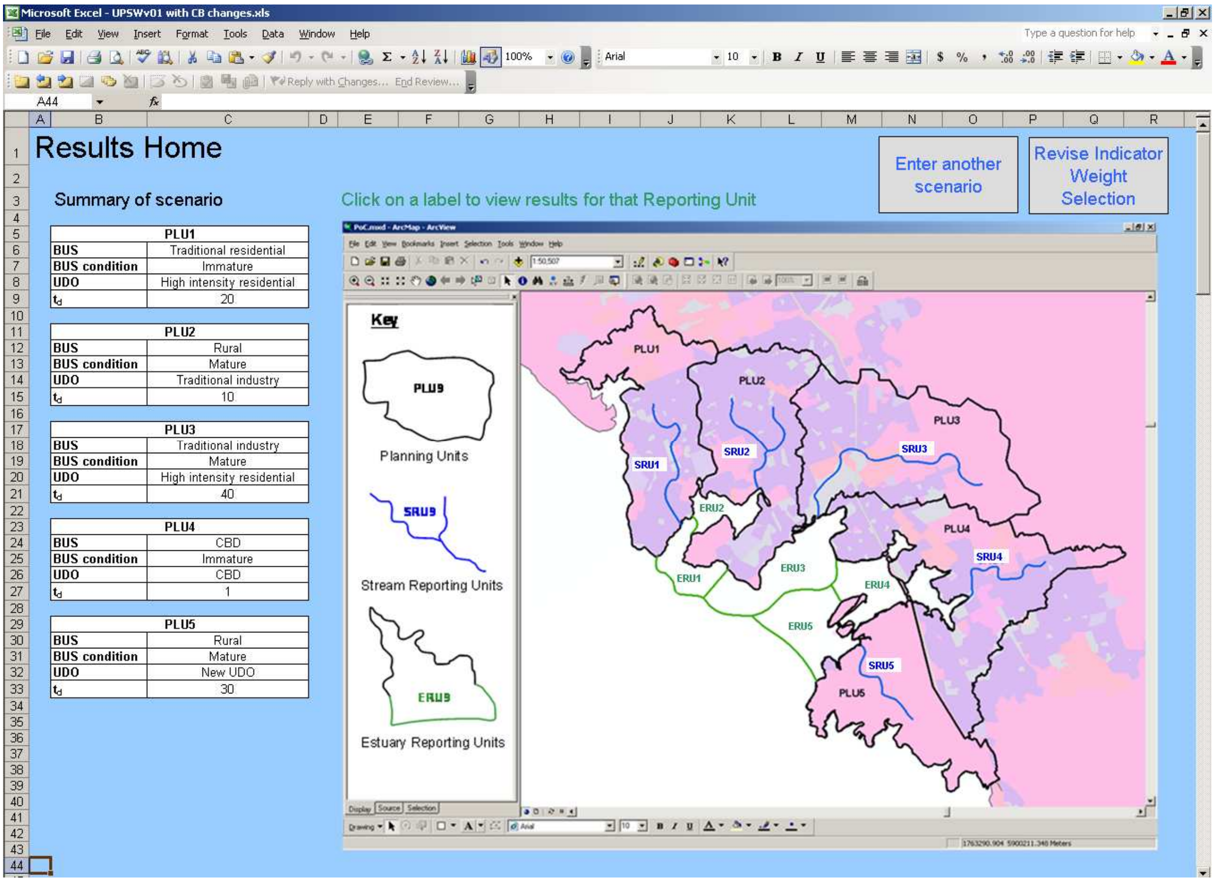
This sheet allows you to assign weights for each indicator
The weights determine the degree of influence that each indicator has in determining the value of combined indicators

Use the drop-down lists below to assign weights for each indicator

Indicator	Weight
Stream Health Score (SHS)	0.8
Stream Amenity Score (SAS)	0.5
Estuary Health Score (EHS)	0.6
Estuary Amenity Score (EAS)	0.5
	1
	1
	1
	1
	1
	1
	1
	1
	1
	1
	1
	1

Find out how the system generates values for each indicator by clicking here

Figure 19: Proof of concept: “Indicator Weight Selection” worksheet.



Results Home

Summary of scenario

Click on a label to view results for that Reporting Unit

PLU1	
BUS	Traditional residential
BUS condition	Immature
UDO	High intensity residential
t_d	20

PLU2	
BUS	Rural
BUS condition	Mature
UDO	Traditional industry
t_d	10

PLU3	
BUS	Traditional industry
BUS condition	Mature
UDO	High intensity residential
t_d	40

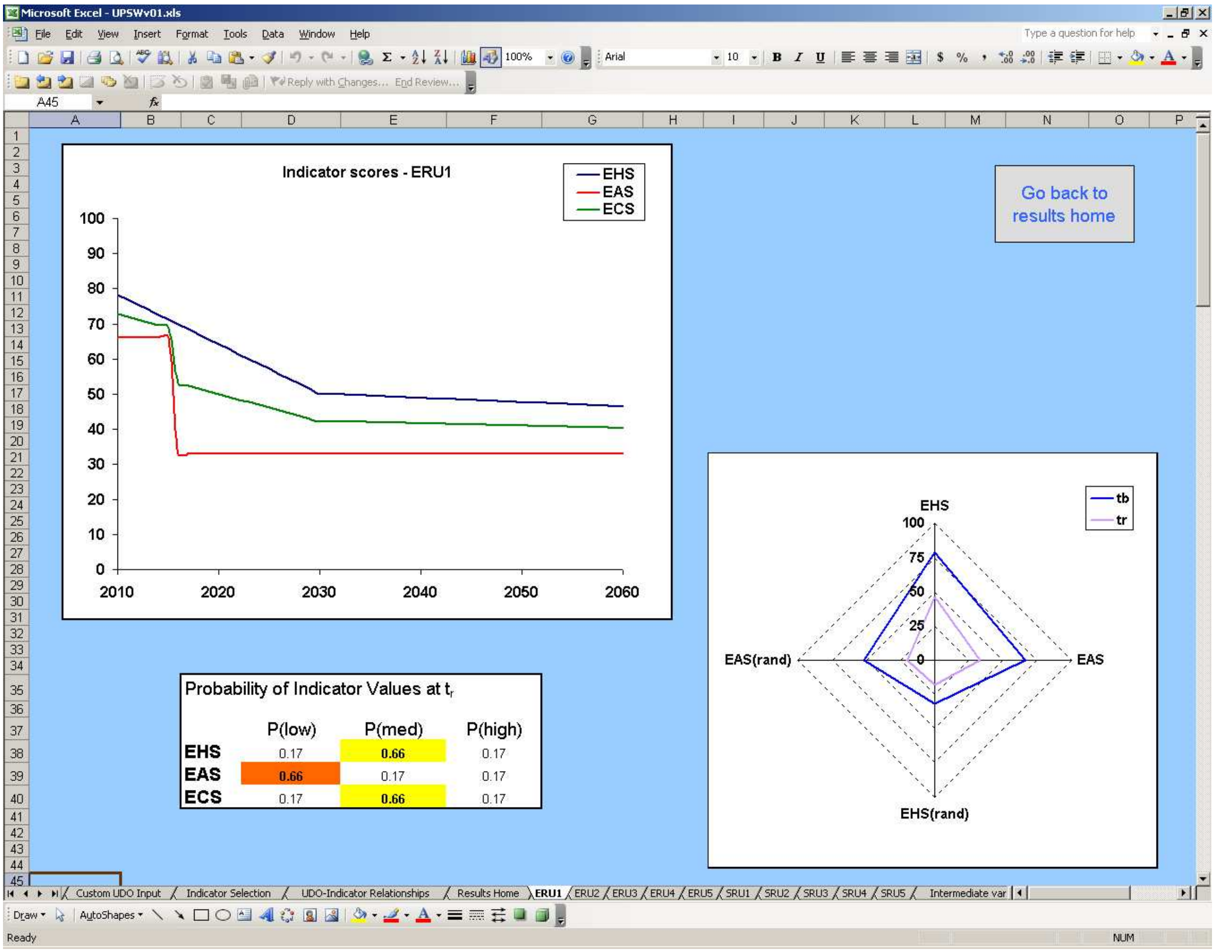
PLU4	
BUS	CBD
BUS condition	Immature
UDO	CBD
t_d	1

PLU5	
BUS	Rural
BUS condition	Mature
UDO	New UDO
t_d	30

Figure 20: Proof of concept: “Results Home” worksheet.

The “ERUn”[20] and “SRUn”[20] worksheets display the results for the reporting unit in three forms, in order to illustrate a selection of the types of outputs that may be available in the pilot sDSS (see Figure 21). These are:

- A time series chart of the individual indicators and combined indicator over the period t_b to t_r;
- A spider-web chart of the individual indicators at times t_b and t_r. Since the PoC only generates two indicators for each reporting unit, these plots also show randomly-generated values for two-additional fictional indicators, simply to better illustrate the use of these charts; and
- A table showing the probability that an Indicator level falls in a high, medium or low class. These values are generated simply by assigning a probability of 0.66 to the class that the Indicator level calculated by the PoC falls within. Equal probabilities of 0.17 are assigned to the other two classes. Results are presented in this form in order to illustrate the way in which the outputs of a Bayesian Belief Network might be presented.



Probability of Indicator Values at t_r

	P(low)	P(med)	P(high)
EHS	0.17	0.66	0.17
EAS	0.66	0.17	0.17
ECS	0.17	0.66	0.17

Figure 21: Proof of concept: “ERU1” worksheet, showing result for one reporting unit.

In the pilot sDSS, results could also be displayed spatially (for example see Figure 22).

Once the user has reviewed the results for the reporting units of interest, further scenarios or changes to indicator weights can be made via hyperlinks on the “Results Home” worksheet.

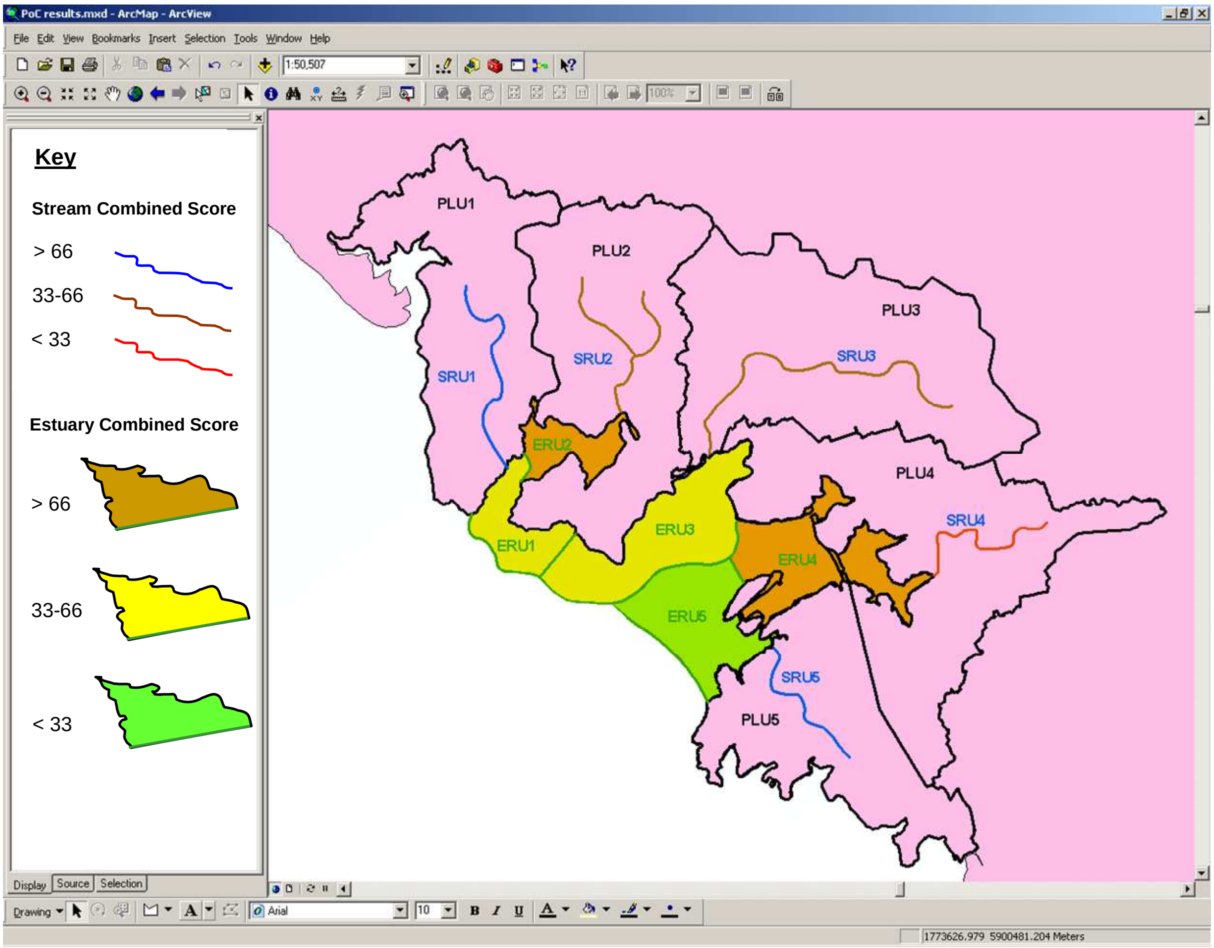


Figure 22: Illustration of spatial display of indicator levels.

6. From Proof of Concept to Pilot sDSS

6.1 Introduction

As described Chapter 5, the PoC has been developed to apply, test and refine the steps involved in the implementation and use of the sDSS. It has also provided a basis from which to identify and plan for the tasks which lie ahead in the development of the pilot sDSS.

Section 6.2 summarises the methodological steps identified during the development of the PoC and which are proposed as the basis of the pilot sDSS. Section 6.3 provides an outline of the tasks involved in the development of the pilot sDSS while Section 6.4 sets out some key considerations for this next phase of the project.

6.2 Methods for the Pilot sDSS

The development of the PoC has identified the methods, and the relationships between them, proposed for estimating outputs from inputs in the pilot sDSS. Three method steps are involved (see Figure 23):

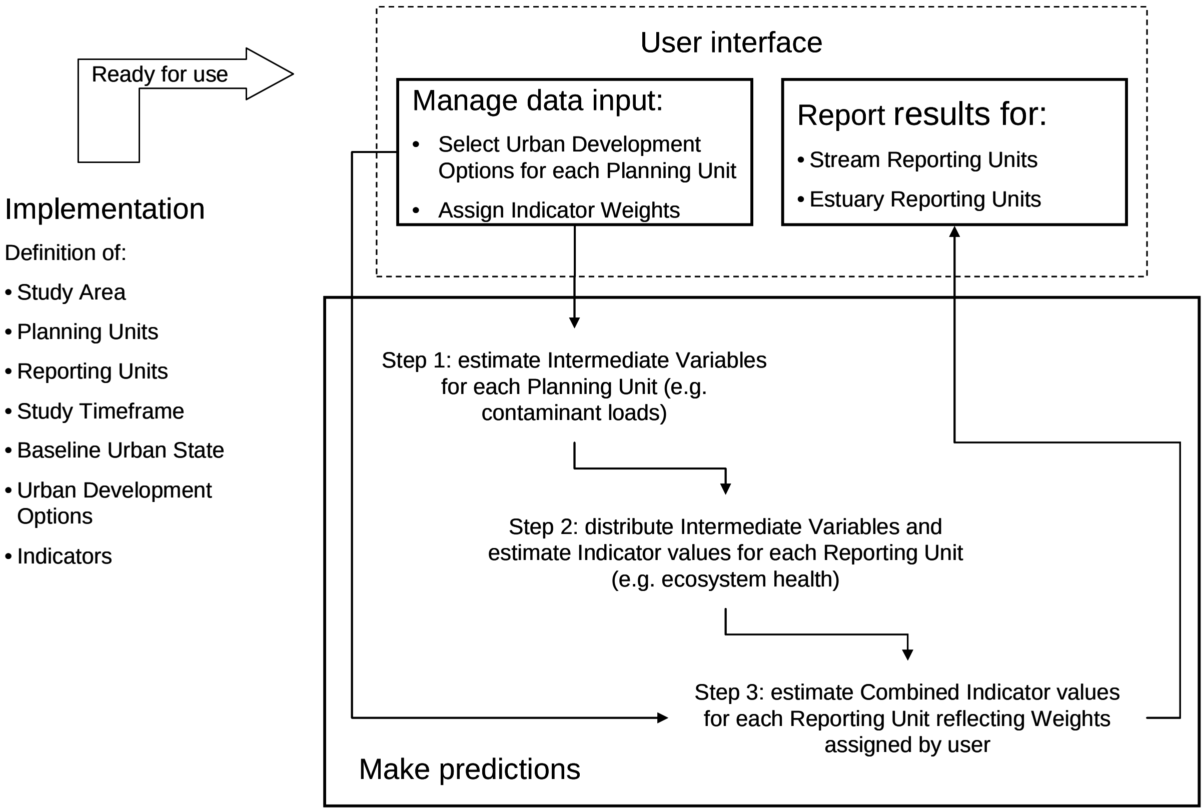


Figure 23: Design of the pilot sDSS showing the three method steps for prediction of combined Indicator levels from the executive attributes of UDOS.

- 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 planning unit using established deterministic methods, such as models used to estimates loads of stormwater contaminants;.
- Step 2 - Using these estimates of intermediate variable values, along with information on the effects of these stressors, to predict the impacts of urban development (as measured by indicators) in each reporting unit, for instance using a probabilistic Bayesian Belief Network approach (refer to Appendix 2); and
- Step 3 – Combining or integrating individual Indicator levels, for instance using composite index approaches, multi-criteria analysis and analytical hierarchy processes and reporting individual and combined indicator levels for each reporting unit.

6.3 Tasks for Development of the Pilot sDSS

The identification of the three methods steps described above provides a framework for defining the next set of tasks involved in the development of the pilot sDSS. These include a set of 'foundation' tasks which will need to be undertaken before the tasks associated with each of the method stages can start. Broadly, the tasks involved in the development of the pilot sDSS are:

Foundation tasks

- Identification and representation of case study locations;
- Definition of networks including the nodes representing the executive attributes of UDOs, intermediate variables and indicators and the relationships between them;
- Identification of those relationships which will be represented deterministically (method stage 1) and those which will be represented probabilistically (method stage 2);
- Defining the representation of the spatial and temporal aspects of these relationships;
- Determining the software environment:
    - for the user interface, where the study area is represented, data selections are made and results reported;
    - for the estimation of intermediate variable values from the executive attributes of UDOs;
    - for the estimation of indicator levels from intermediate variable values via a Bayesian Belief Network;
    - for the combination of Indicator levels; and

    - which will allow all these elements to talk to each other.

Tasks associated with method stage 1

- Specification and quantification of UDO attributes in order to represent alternative urban development forms; and
- Specification and application of the methods, models and data sources for estimation of intermediate variable values from UDO attributes.

Tasks associated with method stage 2

- Specification of data sources to populate conditional probability tables defining the relationships between intermediate variables and indicators; and
- Development and population of the conditional probability tables.

Tasks associated with method stage 3

- Specification of the methods for combining indicators, including weighting individual indicators;
- Specification of the methods for reporting indicators, including defining indicator benchmarks.

6.4 End User Input

In undertaking these tasks to progress the development the pilot sDSS, there are three key considerations:

1. The sDSS must be fit-for-purpose, i.e., it will help deal with the planning issues that face local government. This means that:
    - it operates at the right temporal and spatial scales; and
    - it allows scenarios to be investigated that represent likely urban development options.

    This consideration is about getting the representation of urban development (system inputs) right.

2. The sDSS must be technically robust, i.e.:
    - 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.

This consideration is about making the most of the available knowledge and expertise to inform the sDSS's predictive ability.

3. The sDSS must communicate effectively with its audience(s); i.e.:
    - indicators are meaningful to different audiences: for instance technical, planning, political and community; and
    - results are displayed in ways which each of these audiences can understand.

    This consideration is about ensuring that the information which the sDSS provides is presented in ways which meet the needs of a range of audiences.

Clearly, the involvement of end-users will be crucial to ensuing that these considerations are adequately reflected in the development of the pilot sDSS. The next step in this research is therefore the presentation of the Proof of Concept version of the system for discussion with and to receive feedback from council staff.

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Appendix 1. Glossary of terms used in Chapter 4

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.
HISTORIC URBAN STATE	HUS	A representation of the form of urban development at the start of the validation period (t_h)
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 value of an indicator associated with a particular environmental, economic, social or cultural condition or threshold.
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.
MATURITY of a BUS		Descriptive and executive attributes of a BUS that reflect whether the response to the BUS is in a dynamic or steady state.
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.
STANDARDISED INDICATOR		Expression of the value of an indicator on a common scale.
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_h		Time at the onset of the historic period of urban development over which predictions of the indicators at time t_b are made to validate the system.
T_i		Time at which interim results for any scenario are reported.
T_r		Time at which the final results for any scenario are reported.
T_{ss}		Time at which the environmental response to the effects of an urban development option reach a steady-state.
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. Bayesian Networks and their potential use for UPSW.

S. Harper, September 2010

Introduction

This appendix provides a brief overview of Bayesian Networks, with emphasis on how they may potentially be of use within the pilot decision support system (sDSS) to be constructed within the Urban Planning that Sustains Waterbodies (UPSW) project.

What are Bayesian Networks?

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

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

The independent variables of a system (i.e., the input variables) are known as *root nodes*, and do not have an associated CPT. Similarly, the final output variables of a system are known as *leaf nodes*. A very simple example of a BN representing water quality in a lake (from Castelletti & Soncini-Sessa, 2007) is shown in Figure 24. The system input variables are nitrogen and phosphorus loads, defined qualitatively as low or high; these then influence the trophic level of the lake, which in turn alters the water quality. The CPTs for trophic level and water quality are shown in.

Once probability distributions have been specified for the input variables, the probabilities for all of the remaining nodes in the network can be calculated using Bayes' Theorem. The process can also be applied from the "bottom up", which means that BNs can be used for two types of reasoning: (i) deductive (or "top down") reasoning, to predict a most likely effect given a cause, and (ii) inductive (or "bottom up") reasoning, to diagnose a most likely cause given an effect.

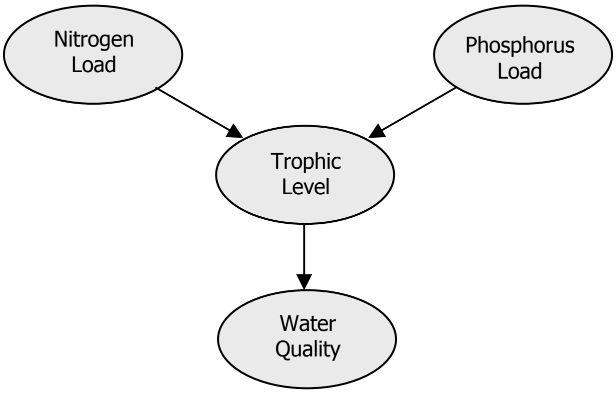

Figure 24: A simple example of a Bayesian Network representing water quality in a lake.

Nitrogen Load	Phosphorous Load	Trophic Level Low	Trophic Level High
Low	Low	1.0	0.0
	High	0.3	0.7
High	Low	0.5	0.5
	High	0.0	1.0

Trophic Level	Water Quality Low	Water Quality High
Low	0.0	1.0
High	0.8	0.2

Figure 25: Conditional probability tables for trophic level (left) and water quality (right) for the Bayesian Network shown in Figure 24.

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 for deductive reasoning

$$P(B_j)=\sum_{i=1}^{n} P(B_j \mid A_i)P(A_i),$$

and for inductive reasoning

$$P(A_i \mid B_j)=P(B_j \mid A_i)P(A_i)\left(\sum_{k=1}^{n} P(B_j \mid A_k)P(A_k)\right)^{-1},$$

where $P(B_j)$ is the probability of B being in state j, $P(B_j \mid A_i)$ is the probability of B being in state j given that A is in state i, and n is the total number of states of A.

Figure 26 shows the probabilities which propagate throughout the BN from Figure 24 as a result of deductive reasoning with the specified probability distributions for nitrogen and phosphorus. In this example, a management strategy that results in a 90 % probability of high nitrogen loads and a 70 % probability of high phosphorous loads is expected to induce a 70 % probability of low water quality.

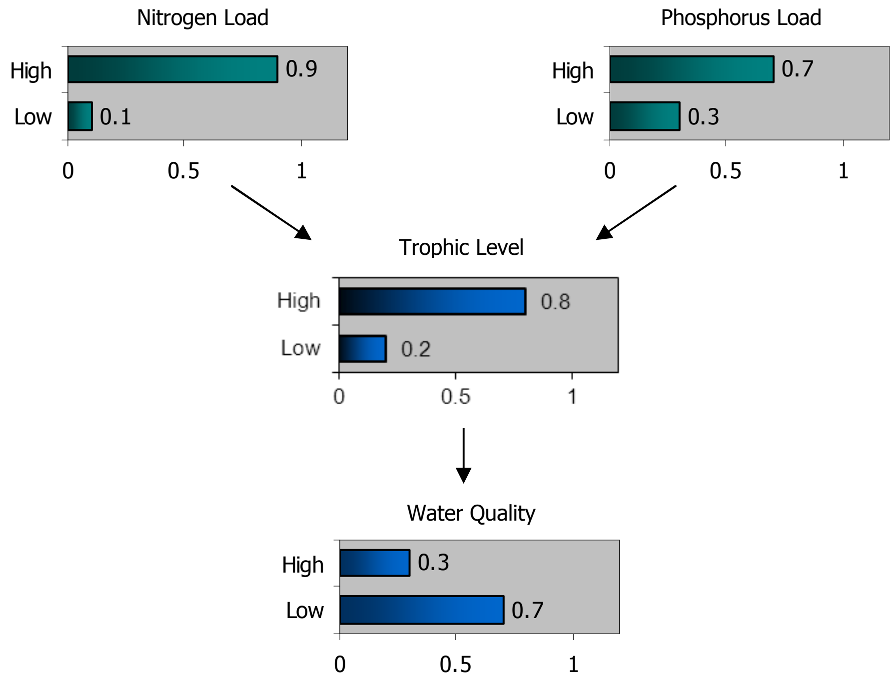

Figure 26: Probabilities calculated for the conditions of trophic level and water quality as a result of the given probability distributions for nitrogen and phosphorus.

Bayesian Networks in Decision Support

BNs are increasingly being used in environmental and natural resource modelling, particularly where there is a focus on the interface between science and management (Merritt et al., 2010). Cain *et al*. (1999) succinctly sum up their usefulness in decision support: “Belief networks provide an approach to holistic formulation of management plans by supporting a mathematically based analysis of environmental systems while not excluding a more descriptive approach. Moreover, they allow uncertainty in decision making to be explicitly accounted for and their superficial simplicity facilitates the participation of a wide variety of people”.

Some particular advantages of BNs include:

- They have the capacity to use different types and sources of data from diverse disciplines, and enable expert knowledge to be incorporated on the same basis as scientific data (Arancibia & Moriarty, 2003; Marcot *et al*., 2006; Merritt *et al*., 2010).

- They explicitly consider uncertainty, as links between nodes are defined by conditional probability distributions (Merritt *et al*., 2010).
- They often produce very convincing results when information in the CPTs, or the evidence known, is inexact (Charles River Analytics, 2005).
- The conditional probability values in the CPT of each node are independent of the values in the CPTs of other nodes. As a result they can be locally updated, meaning each CPT can be independently updated as new data or knowledge becomes available (Castelletti & Soncini-Sessa, 2007).

At the same time, some limitations of BNs identified in the literature include:

- For complex systems with many variables (nodes) the networks can become very large. The number of probability distributions required to populate the CPT of a single node grows exponentially with the number of parent nodes linked to it (Kumar *et al*., 2008).
- The explicit treatment of uncertainty means that important trends and differences can be obscured (Arancibia & Moriarty, 2003).
- BNs deal with variables in a discrete manner. If continuous variables are to be incorporated into a BN, some means must be found of optimally partitioning the values into sub-ranges which can then be treated as discrete categories (Kumar *et al*., 2008).
- BNs are static models, and as such do not include temporal dynamics or feedback loops. There has been some development of Dynamic Bayesian Networks (DBNs) to address this limitation (Kumar et al., 2008).

Applications of BNs in water-resource management include coastal lake management (Ticehurst *et al*., 2008), estuary eutrophication (Borsuk *et al*., 2004), and river flow allocations (Shenton *et al*., 2008), amongst others. Within NIWA, examples of BN use include fish farming studies (Giles, 2007, 2008), and sediment management (Hume *et al*., 2009).

There are also a number of software packages available for implementing BNs. These have not been further investigated here other than to note their existence.

Conceptualisation of how a BN may Potentially be Applied in UPSW

We envisage the primary use of one (or several) BNs within UPSW to be similar to that of Borsuk *et al*. (2004), where a BN was used as a synthesis model to represent eutrophication in the Neuse River, North Carolina, based on a collection of previously published submodels. In that instance, problems in the river were attributed to high nutrient loading, with nitrogen identified as the pollutant of primary concern. A set of attributes were determined for which decision-makers wished to see predictions. Influencing variables were then identified in a "bottom up" manner, working back to the model inputs which included nitrogen loading. The conditional probabilities describing the relationships between variables were determined using functional models, thus, the BN integrates these models into one cohesive network.

Under the current conceptualisation of the UPSW sDSS, the user would choose development scenarios which are associated with executive attributes. These executive attributes would then be used to determine values for the indicator attributes, which provide a basis for comparison between the scenarios. The executive attributes would be the input variables (or the parent nodes) in the BN. These would then be linked through intermediate attributes to the indicator attributes in a causal diagram. The conditional probabilities describing the relationships between variables would be determined by models such as C-CALM and the CLM, the Central Waitemata and South East Manukau harbour studies, the benthic health model and the SEV method. Other possible sources of information could also be included, such as observational data and expert opinion.

One key complication, which is discussed in Borsuk *et al*. (2004) and would also be relevant to UPSW, is that BNs use probabilistic rather than deterministic relationships between variables. Most ecological models, however, and indeed the models mentioned above, are deterministic. To overcome this issue and assign conditional probabilities, Borsuk et al. use the following approach: If variable Y is calculated by a functional relationship of the form

$$Y = f(X, p, \varepsilon),$$

where X represents the parent variables, p represents the set of additional parameters and ε is an error term, then probabilities are introduced by assuming the function arguments are random variables with associated probability distributions and performing a simulation procedure such as Monte Carlo analysis. It is worth noting, however, that in practice it may be difficult to specify the distributions of some parameters

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