Assessing the Resilience of Water Bodies to the Stormwater-Related Effects of Urban Development

Jonathan Moores[1], Chris Batstone[2], Malcolm Green[1]

[1]National Institute of Water and Atmospheric Research Ltd, Auckland, New Zealand

[2]Cawthron Institute, Nelson, New Zealand

Abstract

This paper proposes a conceptual framework for evaluating the resilience of urban water bodies to stormwater-related development effects. A pilot decision support system (DSS) has been developed which assesses urban impacts on ecosystem services provided by freshwater and estuarine waterbodies, reported as indicators of environmental, economic, social and cultural wellbeing. A goal of the further development of the DSS is to incorporate indicators of the resilience of those urban water bodies. A conceptual framework is derived from literature on the resilience of social–ecological systems (SESs) and resilience in urban planning. Urban development and stormwater management are conceived of as occurring within the setting of an 'urban aquatic SES'. System resilience is influenced by both the capacity of natural elements of the system, i.e. receiving water bodies, to provide ecosystem services, and the capacity of society to manage, adapt and potentially transform stormwater management to support the provision of ecosystem services. Natural capacity is assessed through the trajectories of key biophysical variables and their proximity to critical thresholds. Societal capacity is assessed through criteria such as diversity, redundancy and adaptability in stormwater management infrastructure and institutions. The research challenge is to develop methods for operationalizing this approach within the DSS.

Keywords

Resilience, urban development, stormwater management, social-ecological systems, decision support system, ecosystem services.

1 Introduction

Throughout the world, cities have been founded next to streams, rivers and harbours, but urban development has resulted in the degradation of these water bodies. Contaminants discharged in urban stormwater affect water quality and ecosystem health, with consequential impacts on the ways in which water bodies are used and valued by urban communities. This paper describes a conceptual framework for assessing the resilience of urban water bodies to these stormwater-related development effects. The context is a multi-disciplinary research project to develop a decision support system (DSS) for assessing the impacts of alternative urban development scenarios on ecosystem services provided by freshwater and estuarine waterbodies.

2 Overview of Pilot DSS

A pilot version of the DSS evaluates urban development outcomes by predicting impacts on the ecosystem services provided by receiving water bodies, reported under a sustainability assessment framework as indicators of environmental, economic and social wellbeing (Moores et al., 2013). Methods for assessing cultural wellbeing indicators which reflect the water-related values of New Zealand Māori are also under development. Users of the pilot DSS can compare alternative urban development scenarios by varying inputs representing land use change, stormwater management and related attributes (Figure 1). These inputs drive a suite of models which predict changes to biophysical attributes such as water and sediment quality and indicators of ecosystem health in rivers and estuaries. The Catchment Contaminant Annual Loads Model (C-CALM) estimates stormwater loads of sediments, copper, lead and zinc. Along with other inputs, these loads are used by: a Bayesian Belief Network (BBN) to predict seven indicators of stream ecosystem health; the Urban Stormwater Contaminants (USC) model to predict rates of estuary sediment and metal accumulation and grain size distribution; and the Benthic Health Model (BHM) to predict a benthic invertebrate community health indicator score.

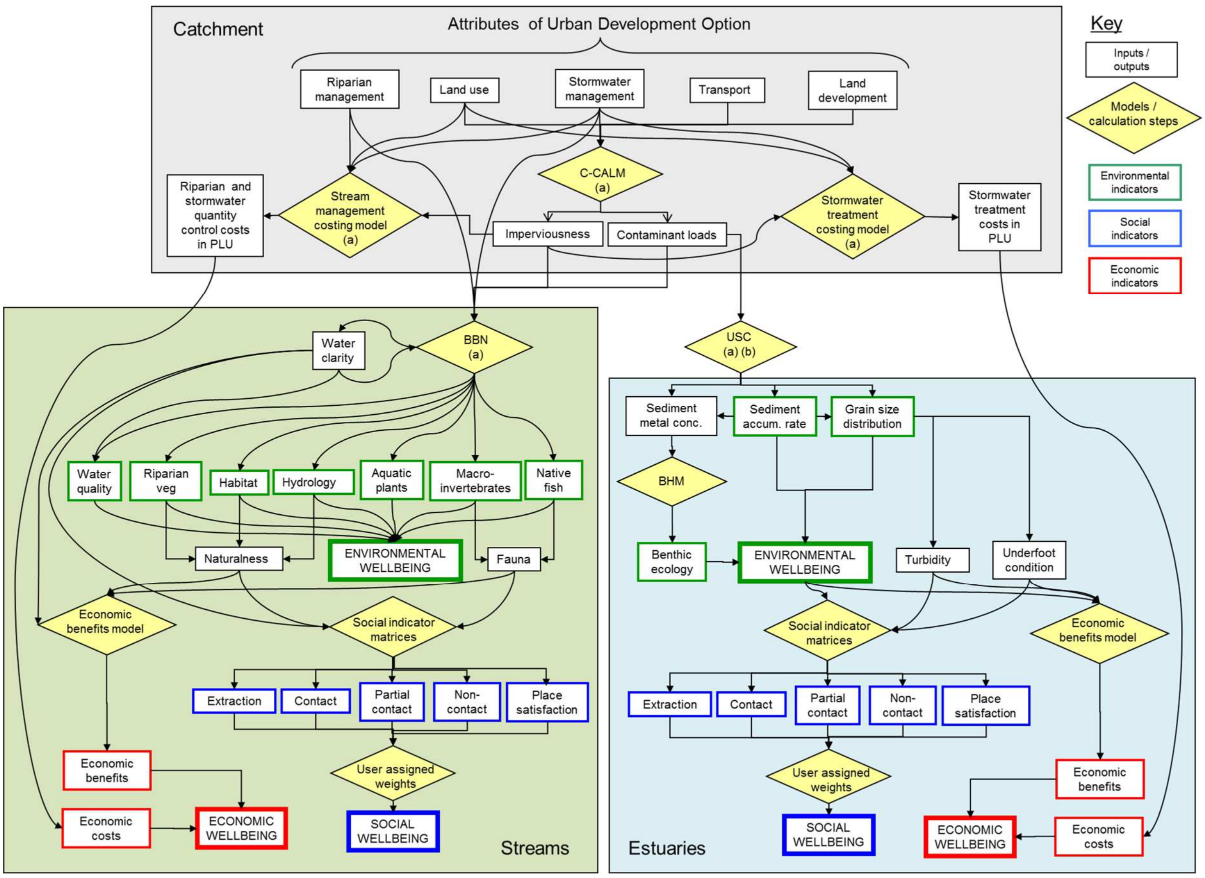

Figure 1: Overview of the pilot DSS.

The outputs of these biophysical models are in turn used to assess changes in a range of ecosystem services, reported as indicators of environmental, social and economic wellbeing. Put simply, ecosystem services are "the benefits people obtain from ecosystems" (MA, 2003), which can be goods, such as food, or services, such recreational opportunities. A set of social indicator matrices acts as a look-up table for the prediction of five types of relationship (extraction; contact, partial contact and non-contact recreation; and 'place satisfaction'), based on scores ascribed by workshop participants to combinations of biophysical attributes such as water clarity, underfoot condition and ecosystem health. These attributes are also used in the assessment of an indicator of economic benefits, based on the results of studies of household willingness-to-pay for stormwater improvements. Economic wellbeing is assessed by comparison of these benefits with costs, estimated from catchment-scale stormwater-treatment and stream-management costing models. While the pilot DSS reports numeric values (scores) of all indicators, it also assigns an indicator 'level' in the range 1 – 5, with 5 being 'best', in order to allow communication of predictions to technical and non-technical audiences, respectively (Figure 2).

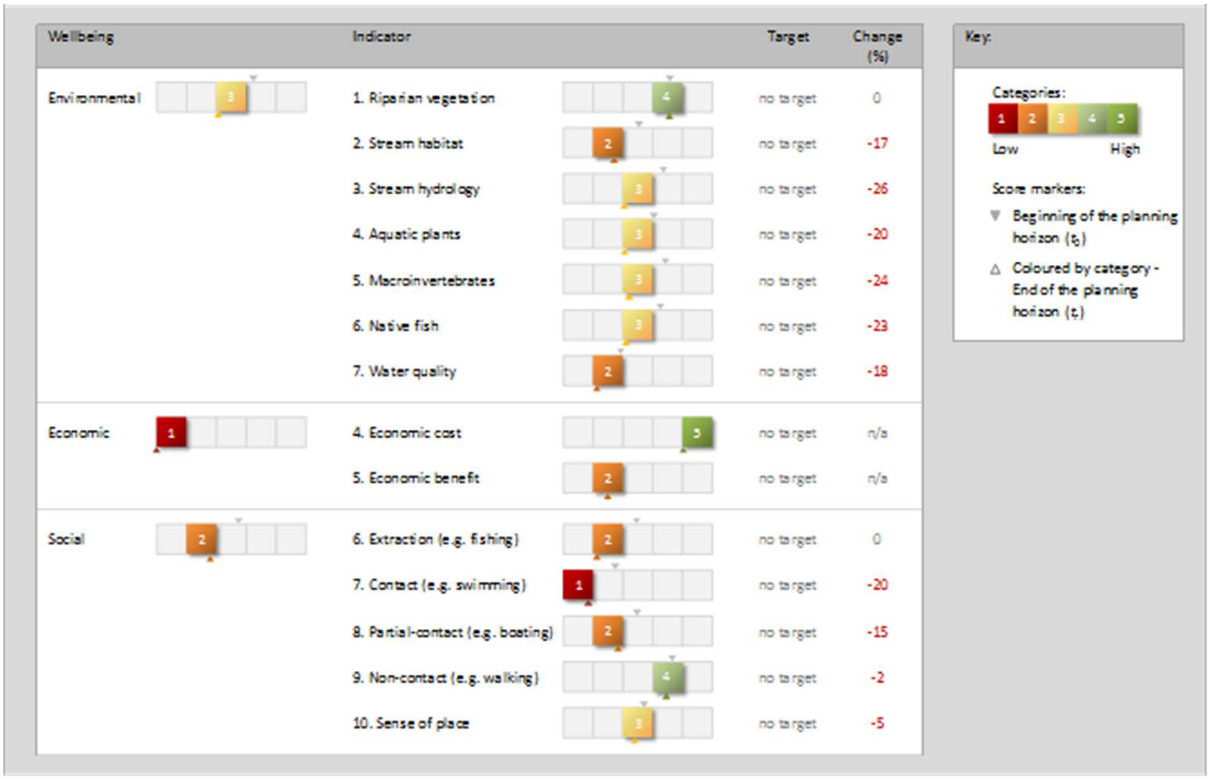

Figure 2: Example of indicator levels reported by the pilot DSS.

3 Resilience

3.1 Why Assess Resilience?

The wellbeing indicators described above characterize the state of the urban water body at a given point in time. Elsewhere, indicators developed for sustainability assessments have been criticized for their inability to express the likelihood of a system state being maintained or improved over time (Milman and Short, 2008). In contrast, indicators of resilience provide information on potential changes in the future state of a system, including changes which might impact the future provision of ecosystem services. In this research, a conceptual approach for assessing the resilience of urban water bodies has been derived from literature on the resilience of social–ecological systems and resilience in urban planning.

3.2 Resilience of Social-Ecological Systems

Folke et al. (2010) defined a social–ecological system (SES) as an "integrated system of ecosystems and human society with reciprocal feedback and interdependence." This definition reflects a recognition that the scale and impact of human activities in modern times make it "difficult and even irrational to continue to separate the ecological and social and to try to explain them independently" (Folke et al., 2010).

Resilience theory recognizes that SESs are subject to continuous disturbance. Walker et al. (2004) defined the resilience of an SES as the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks." An SES is in a state of flux, moving around within a 'basin of attraction' (Walker et al., 2004; Folke et al., 2010). Externally or internally-driven changes force movements within these basins or to alternate basins. Where a system lies close to the boundary between basins it is said to be characterized by high precariousness, and where a disturbance prompts a large response in the state of the system, it is said to have a low resistance.

Walker et al. (2012) described the behaviour of SESs in terms of the response of 'fast' variables to changes in the state of 'slow' variables. The latter, an example of which is soil organic matter, change slowly in response to external drivers, such as rainfall variations. An associated example of a fast variable is crop production. This is more dynamic, with the potential to change rapidly in response to disturbances. Fast variables are generally those that are of interest to humans, in other words the ecosystem services provided by an SES. As a slow variable approaches a threshold between stability domains (or 'regimes'), disturbances result in increasing fluctuation in fast variables, eventually pushing the system over a threshold and resulting in a change (usually reduction) in ecosystem service provision (Walker et al., 2012).

3.2 Resilience in Urban Planning

A resilience approach has been promoted as a means of improving the planning of urban development. Pickett et al. (2004) adopted the 'non-equilibrium' model of resilience to argue that the development of urban systems is not about "reaching or maintaining a certain end point or terminal condition, but [about] staying “in the game” ”. Ahern (2011) referred to resilient cities as being “safe-to-fail” rather than “fail-safe”, recognizing five types of strategy to build urban resilience capacity: practice multi-functionality; practice redundancy and modularization; promote (biological and social) diversity; build and restore multi-scale networks and connectivity; and practice adaptive planning and design. Redman (2011) observed that strategies such as these which encourage flexibility and adaptive capacity tend to be in conflict with traditional approaches which focus on optimization and efficiency. Building resilience into urban planning therefore requires a broad and long-term perspective to be taken, even when making short-term decisions.

4 Assessing the Resilience of Urban Water Bodies

4.1 Conceptual Framework

Despite the growth in the application of resilience concepts in recent years, assessments of resilience have generally been qualitative in nature (Birkmann et al., 2012). In its guidelines for assessing resilience in SESs, the Resilience Alliance (2007) recognized that progressing from concepts to measurement is the “difficult part of the process.” Given this challenge, a crucial first step is to define what resilience means in any given context. Folke et al. (2010) distinguished between ‘general’ and ‘specified’ resilience, the latter term referring to the response of particular attributes of a system to a specific set of disturbances, or as Carpenter et al. (2001) put it, the “resilience of what to what?”

The system of interest here can be termed an ‘urban aquatic SES,’ and conceptualized as comprising two sets of elements: (1) natural elements, being the receiving water bodies that provide ecosystem services; and (2) societal elements, which include both built elements (urban surfaces and stormwater management infrastructure that constitute stormwater source areas and conveyance, delivery and control systems) and non-built elements (governance frameworks, social capital and actors that influence the form of urban development and stormwater management). In this context, system resilience can be defined as the combined capacity of the natural and societal elements of an urban aquatic SES to provide the same, similar or a better level of aquatic ecosystem services in the face of the stormwater-related effects of urban development. This definition incorporates the potential for societal elements of the system to both moderate the effects of urban development and substitute for the provision of ecosystem services by natural elements. It also recognizes the potential for transformation of a system to some new state in which the provision of ecosystem services improves, for instance as a result of the rehabilitation of an urban water body.

Figure 3 provides a simplistic illustration of a framework for assessing the resilience of an urban aquatic SES based on the interaction of the natural capacity of the system to absorb the effects of urban development and societal capacity to moderate these effects. The key to operationalizing this approach is to develop methods for assessing natural and societal capacity, respectively, using information available from the pilot DSS (Figure 4).

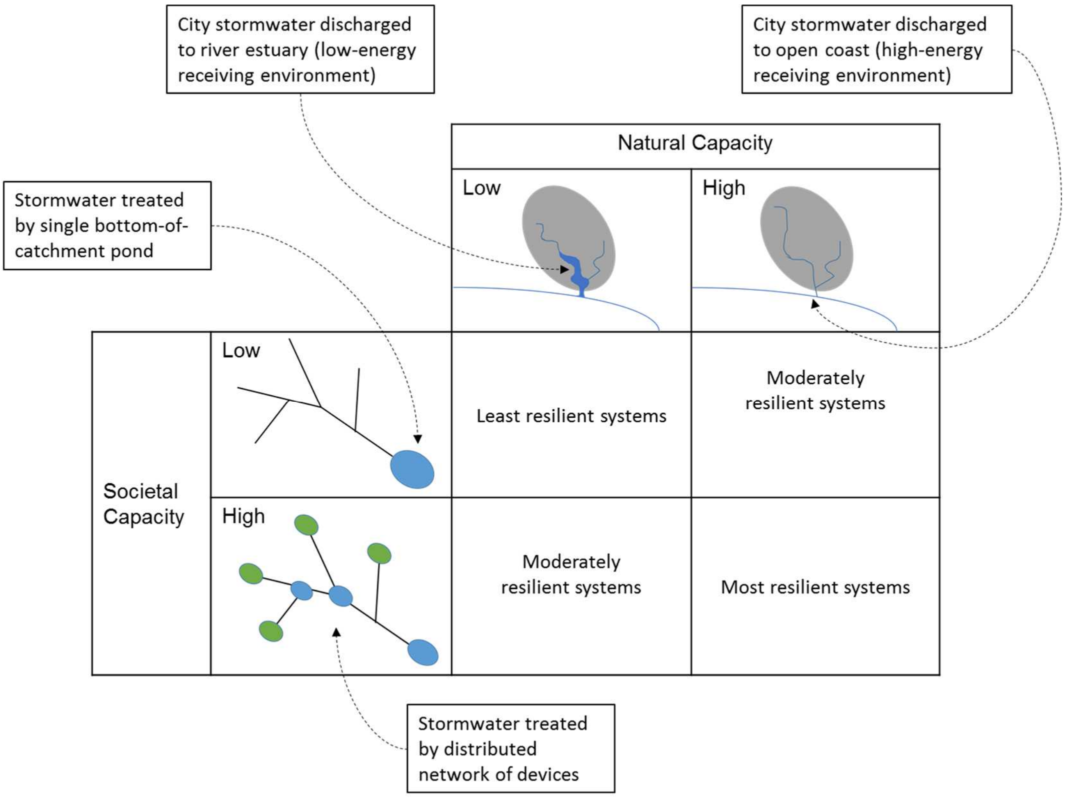

Figure 3: Illustration of the way in which the capacity of natural and societal elements intersect to influence the resilience of an urban aquatic SES.

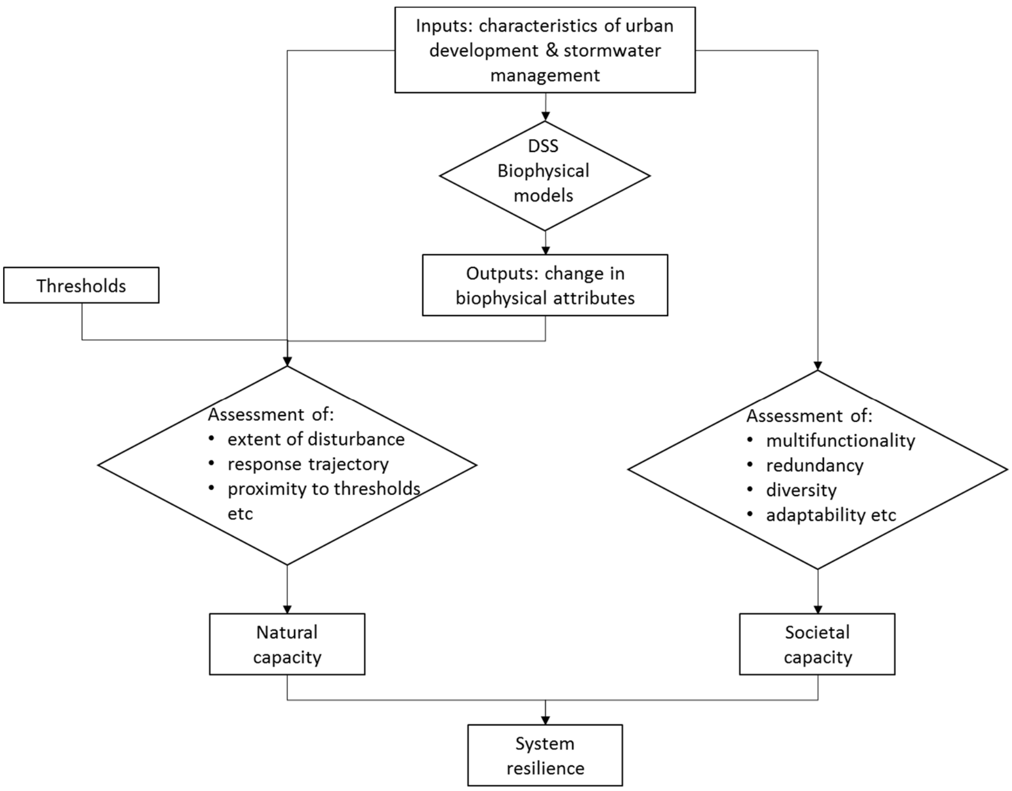

Figure 4: Overview of methods for assessing natural and societal capacity.

4.2 Assessing Natural Capacity

This task involves making predictions of the future level of ecosystem services provision, given knowledge of the current state of the system. It requires an assessment of the likelihood that one of more key biophysical attributes of the system will cross a threshold in the foreseeable future and, by crossing this threshold, that the level of ecosystem services delivered will change (probably decrease). Such an assessment is based on information on: (1) the characteristics of an urban development scenario (the system disturbance); (2) the response of biophysical variables predicted by the DSS (the 'slow' system response variables); and (3) thresholds for these biophysical attributes, for instance based on effects-based guideline values. The assessment of the capacity of the natural elements of the system to continue to provide ecosystem services involves establishing the relationship between the disturbance and the system response over the modelled time period and extrapolating forwards, relative to a threshold.

Figure 5 illustrates this approach by comparing system responses to an increase in the level of urban development between times t_0 (start of study timeframe) and t_r (time of reporting). Under scenario A, the system is assessed as having low natural capacity to support resilience because the state of the biophysical attribute is rapidly approaching a threshold. Under scenario B, the system is assessed as having high natural capacity to support resilience because the state of the biophysical attribute has hardly changed, despite the same increase in the level of urban development.

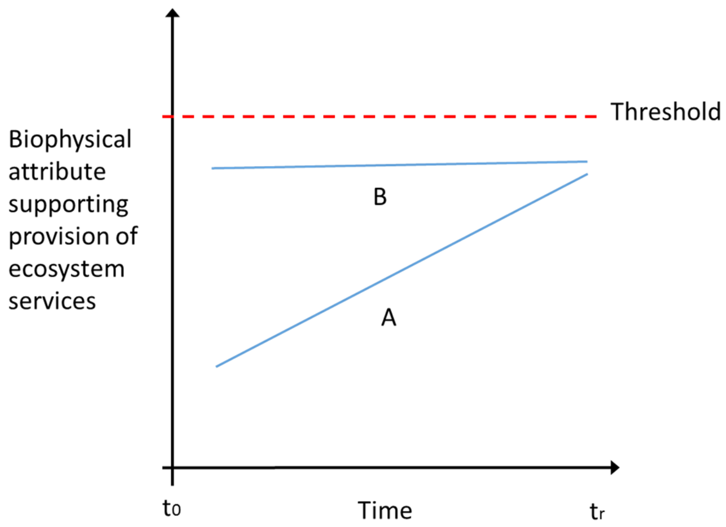

Figure 5: Illustrative responses of a biophysical attribute to urban development.

4.3 Assessing Societal Capacity

This task involves making an assessment of the way in which built and non-built societal elements of an urban development scenario can support the provision of ecosystem services by natural elements. It requires a multi-criteria assessment to examine the extent to which a given urban development scenario can be characterized by attributes such as those proposed by Ahern (2011). Table 1 provides an illustration of how these criteria might apply to the assessment of societal capacity in relation to the stormwater-related effects of urban development.

Table 1: Illustrative application of five criteria (after Ahern, 2011) as assessment criteria for societal capacity in the pilot DSS.

Criteria	**Application in relation to ecosystem services provision**	**Examples of urban development and stormwater management that score highly against this criteria**
Multi-functionality	Each element supports the provision of multiple ecosystem services.	Wetlands providing for contaminant removal (regulating service) and maintaining the quality of a receiving environment for fish (habitat and provisioning service) and swimming (cultural service).
Redundancy and modularization	Risks to ecosystem services are spread by multiple similar elements providing the same function.	Stormwater treatment distributed throughout the urban area each providing a small part of the total contaminant removal. The failure of one device has only a limited impact on the performance of the system as a whole.
Biological and social diversity	Each ecosystem service is provided by a range of elements, each with different tolerances to change.	Stormwater source control and treatment trains (e.g. permeable paving > swales > wetlands) providing for contaminant removal by different mechanisms (filtration, settling). A disturbance such as an extreme rainfall event that bypasses the capacity of the permeable paving and/or swale is able to be accommodated by the wetland.
Multi-scale networks and connectivity	Ecosystem services are supported by well-connected networks operating at a range of scales.	Retention and enhancement of urban stream networks linking headwaters to floodplains maintains drainage (regulating service) and provides green/blue corridors populated by native fish (habitat services) and used as walkways (cultural services).
Adaptive planning and design	Ecosystem services are supported through approaches that foster innovation, monitoring and learning.	Urban planning and stormwater management functions are delivered in an integrated fashion, using innovative approaches that are closely monitored, evaluated and, if necessary, revised. Communities are educated about urban water management issues, participate in planning and model behaviours that support the protection and enhancement of ecosystem services (e.g. stream clean-ups, riparian planting).

5 Conclusion

This paper proposes a conceptual framework for assessing the resilience of urban water bodies as part of research to develop a DSS for evaluating the stormwater-related effects of urban development. Urban development and stormwater management are conceived of as occurring within the setting of an urban aquatic SES. System resilience is influenced by both the capacity of natural elements, receiving water bodies, to provide ecosystem services, and the capacity of society to manage, adapt and potentially transform stormwater management to support or substitute for the provision of ecosystem services. Information entered into, and generated by, the DSS provides for an assessment of the natural and societal capacity associated with a given urban development scenario. The research challenge now is to develop the assessment methods and incorporate them within the DSS.

References

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape Urban Plan. 100: 341-343.

Birkmann, J.; Seng, D.; Abeling, T.; Huq, N.; Wolfertz, J.; Karanci, N.; İkizer, G., Kuhlicke, C.; Pelling, M.; Forrester, J.; Fordham, M.; Deeming, H.; Kruse, S.; Jülich, S. (2012) Systematization of Different Concepts, Quality Criteria, and Indicators. Deliverable 1.2. 7FP emBRACE project: Building resilience amongst communities in Europe.

Carpenter, S.; Walker, B.; Anderies, M.; Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? Ecosystems 4: 765-781.

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

Millennium Ecosystem Assessment, MA (2003). Ecosystems and human well-being. A framework for assessment. Island Press, Washington, DC.

Milman, A.; Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. Global Enviro. Chang. 16: 758-767.

Moores, J., Batstone, C., Gadd, J., Green, M., Harper, S., Semadeni-Davies, A. and Storey, R. (2013). A Tool for Evaluating Stormwater Management Across the Four Wellbeings. Water NZ 8th South Pacific Stormwater Conference, Auckland, 8-10 May 2013.

Pickett, S.; Cadenasso, M.; Grove, J.; (2004). Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. Landscape Urban Plan. 69: 369-384.

Redman. C. (2011). Social-Ecological Transformations in Urban Landscapes – A Historical Perspective. In Niemelä, J. (Ed.) (2011). Urban ecology: patterns, processes and applications. Oxford University Press, Oxford, UK. pp 206-212.

Resilience Alliance (2007). Assessing Resilience in Social-Ecological Systems – A Workbook for Scientists. Version 1.1 Draft for Testing and Evaluation.

Walker, B.; Holling, C.; Carpenter, S.; Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. Ecol. Soc. 9(2): 5.

Walker, B.; Carpenter, S.; Rockstrom, J.; Crépin, A.-S.; Peterson, G. (2012). Drivers, "slow" variables, "fast" variables, shocks, and resilience. Ecol. Soc. 17(3): 30.