ASSESSING RESILIENCE IN STORMWATER MANAGEMENT

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ABSTRACT

Resilience is a critical property of a liveable city. Urban communities aspire to live safe in the knowledge that life will go on 'as normal' in the face of extreme weather events or other natural disturbances. They also value high quality receiving environments that are not at risk of crossing ecological 'tipping points' as a result of the effects of the steady creep of urban development. Building resilience into stormwater management means adopting approaches that reduce vulnerability both to sudden natural shocks and to the potentially irreversible long-term environmental effects of urban development. But what are the characteristics of a more resilient approach to stormwater management? Firstly, there are a range of 'technical' characteristics relating to the way in which the built environment and stormwater infrastructure are designed and managed. For example, a resilient approach to stormwater quality management might incorporate a range of treatment device types, ensuring performance of the system as a whole under varying environmental conditions. It might also build in spare capacity to accommodate projected increases in contaminant runoff arising from infill development or in response to climate change. Secondly, more resilient approaches to stormwater management can also have a social dimension. Previous authors have found that resilience is fostered in situations where institutions, governance arrangements, social capital and community engagement support an inclusive and adaptive approach to stormwater management. Drawing on relevant literature, this paper describes a range of technical and social criteria for assessing resilience in relation to stormwater management. It also proposes the application of selected criteria as resilience indicators in a decision support system (DSS) for assessing stormwater-related outcomes associated with planning future liveable cities.

KEYWORDS

Resilience, vulnerability, technical capacity, social capacity, decision support system (DSS), indicators.

PRESENTER PROFILE

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1 INTRODUCTION

NIWA and Cawthron Institute are leading the development of a decision support system (DSS) to help assess the impacts of urban development on attributes such as water and sediment quality; ecosystem health; and cultural, amenity and recreation values. The project, Urban Planning that Sustains Waterbodies (UPSW), is part of the Resilient Urban Futures (RUF) research programme funded by the Ministry for Business, Innovation and Employment (MBIE). Progress to date has resulted in the development of a pilot version of the DSS (Moores et al., 2012) which is currently being tested and refined through its application in case studies (for instance, Moores et al., 2013). The goal of the continued development of the system is to deliver an operational tool for use in local government planning processes by September 2016.

A key objective of the current phase of the project is the development and incorporation of indicators of resilience in the DSS. At present, the system operates within a framework of the 'four well-beings' (environmental, economic, social and cultural), making predictions of a range of indicators in each case. These well-being indicators 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). The aim of extending the framework to incorporate indicators of resilience is to provide ways of assessing the future state of a water body, taking account of legacy effects of historic development and the forecasted future effects of further development.

2 RESILIENCE CONCEPTS

2.1 SOCIAL-ECOLOGICAL SYSTEMS

The approach adopted in this research is founded in concepts originating in the field of ecology and further developed in the study of social-ecological systems. Learning from those concepts, urban development and stormwater management is understood to occur within the setting of a social-ecological system, defined as an "integrated system of ecosystems and human society with reciprocal feedback and interdependence" (Folke et al., 2010). A key concept in social-ecological systems research is the notion that the biophysical elements of a system provide ecosystem services to people (Millennium Ecosystem Assessment, 2003; TEEB, 2010; Walker et al., 2009) and that the level of ecosystem service provision is influenced by societally-induced changes to the system. Put simply, ecosystem services are "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2003), which can be goods, such as food, or services, such as waste assimilation.

For this research, we have termed the system of interest as an "urban aquatic social-ecological system," which includes the following elements:

- Natural elements, being the receiving water bodies (streams, rivers and harbours) that provide ecosystem services; and
- Socio-technical (or non-natural) elements, which influence the level of ecosystem service provision and which can be further divided into:
    - Technical elements, or the urban built environment and stormwater management infrastructure that constitute stormwater source areas and the conveyance, delivery and control systems; and
    - Social elements, or the governance frameworks, social capital and actors that influence the form of urban development and stormwater management.

2.2 SYSTEM RESILIENCE

This research has developed the following definition of resilience:

> *"The combined capacity of the natural and socio-technical elements of an urban aquatic social-ecological system to provide the same, similar or a better level of aquatic ecosystem services in the face of the stormwater-related effects of urban development."*

Arising from the distinction made above between the natural and societal elements of urban aquatic social-ecological systems, the resilience of the system is a function of both:

- the capacity of the natural elements of the system to maintain the provision of aquatic ecosystem services; and
- the capacity of the socio-technical elements to moderate the effects of development and so support the provision of aquatic ecosystem services by the natural elements of the system

Figure 1 illustrates the way in which the natural and socio-technical elements of an urban aquatic social-ecological system might interact to influence system resilience. Resilience is highest when there is both a high natural capacity to absorb the effects of urban development and these effects are highly moderated by urban design and stormwater management interventions. An example of a system with high natural capacity is one in which stormwater is discharged from a relatively small catchment to an extensive high-energy receiving environment. At the other end of the spectrum, natural capacity is likely to be much lower where a receiving environment is small, depositional and receives stormwater from a relatively large and fully-urbanised catchment. An example of high socio-technical capacity is a catchment-wide distributed stormwater system. Low socio-technical capacity might exist in a city where stormwater management follows a 'drainage-focused' bottom-of-catchment treatment approach.

Assessment of the resilience of an urban aquatic social ecological system therefore needs to consider the characteristics of both natural and socio-technical elements of the system. In the case of natural elements, this involves consideration of the vulnerability of a water body to undergoing a change from its current state, or regime, to some less desirable state (Walker et al., 2004). It therefore requires an assessment of the likelihood that one or more key biophysical attributes of the system will cross a threshold in the foreseeable future and, that by crossing this threshold, the level of ecosystem services delivered will decrease markedly. While the development of methods for making this type of assessment are a key part of the current research, they are not the subject of this paper.

Instead, the remainder of this paper focuses of the development of methods for assessing the capacity of technical and social elements to support resilience in an urban aquatic social-ecological system. This involves, firstly, identifying relevant technical and social assessment criteria that can be expected to influence system resilience and, secondly, evaluating the potential for these criteria to be adopted as resilience indicators in the UPSW DSS.

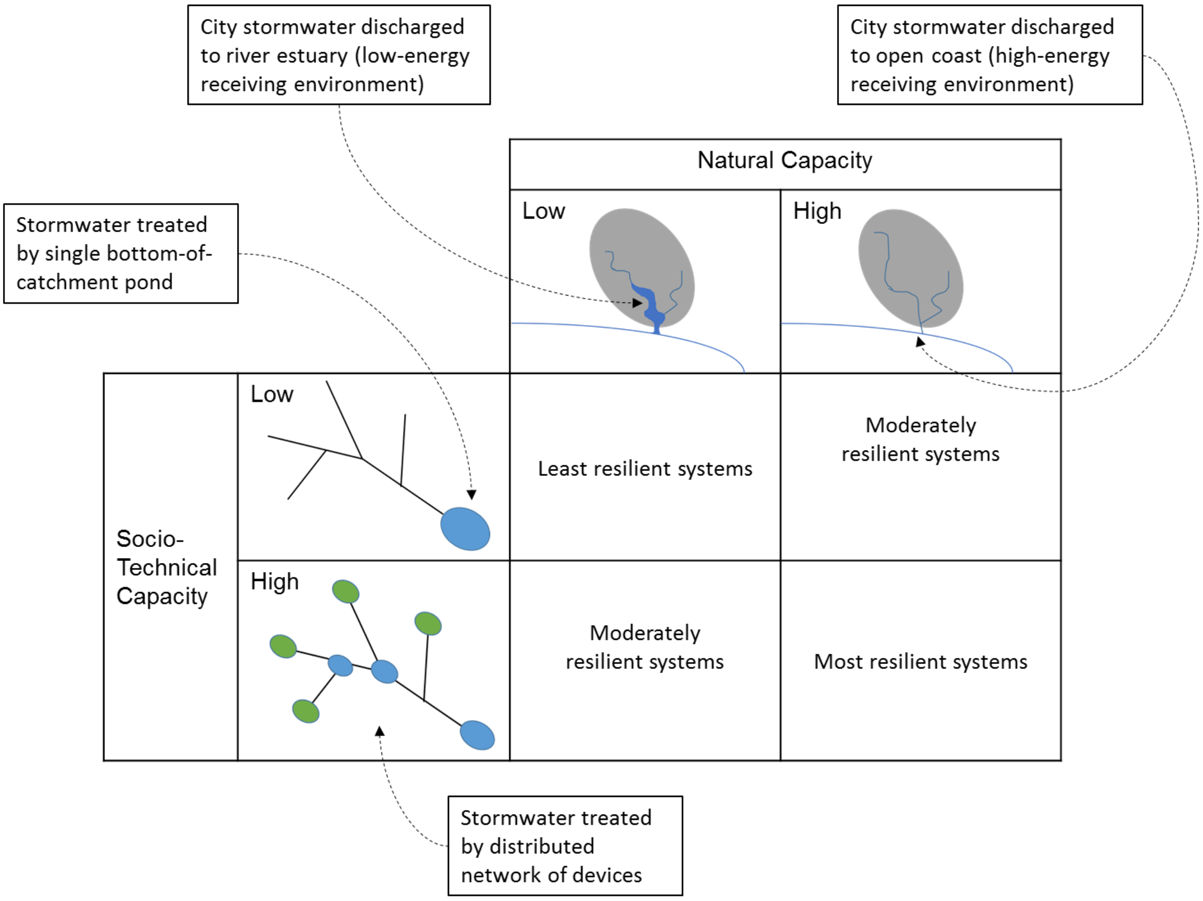


Figure 1: Illustration of the way in which the capacity of natural and societal elements intersect to influence the resilience of an urban aquatic social-ecological system.

3 RESILIENCE CRITERIA

3.1 INTRODUCTION

Over the last decade there has been a growing emphasis on the adoption of a resilience approach as a means of promoting better planning of urban development (Collier et al., 2013). This has included identifying characteristics which promote the resilience of urban systems. Ahern (2010; 2011; 2013) recognised five types of strategy to build urban resilience capacity:

- Practice multifunctionality, so that the functions of elements in the system are intertwined or combined, stacked in space or time-shifted;
- Practice redundancy and modularization, so that risk is spread across multiple elements that provide the same, similar or backup functions;
- Promote (bio and social) diversity, so that similar functions are provided by a range of elements of the system;
- Build and restore multi-scale networks and connectivity so that elements of the system are linked at multiple scales; and
- Practice adaptive planning and design so that urban planning innovates through experimentation with pilot designs, learns from monitoring and analysis and is continuously evolving.

Allan and Bryant (2011) found evidence of the inclusion of a similar set of resilience attributes or principles in urban design theory in relation to disaster recovery and vulnerability to climate change. In addition, they also observed three other related concepts previously described by Walker and Salt (2006):

- Tight feedbacks – the role of social networks in learning and responding to change;
- Overlap in governance – institutions that include redundancy in their governance structures; and
- Social capital – the capacity of people to respond together.

Albers and Deppisch (2012) identified eight principles for urban and regional resilience, again largely coinciding with those summarised above, but also including:

- Stabilizing and buffering factors – the ability to resist or absorb disturbances;
- Mobility – the ability of people to move freely; and
- Planning and foresight.

Based on the strategies, attributes and principles listed above, this section of the paper evaluates a range of criteria in terms of their relevance for assessing how stormwater management can contribute to the resilience of urban aquatic social-ecological systems. The evaluation draws on relevant literature and case studies and distinguishes between criteria that are relevant for assessing:

- the capacity of technical elements to contribute to system resilience, i.e. how the built environment is planned, designed and managed; and
- the capacity of social elements, including governance frameworks, social networks and capital, and individual actors, to contribute to system resilience.

3.2 TECHNICAL CRITERIA

3.2.1 MULTIFUNCTIONALITY

According to Ahern (2011), multifunctionality means that the functions of elements in a system are intertwined or combined, stacked in space or time-shifted. Spatial-stacking is the organising of functions to operate either independently or in a complementary manner in the same location or in close proximity. In the context of stormwater management, an example of this is the use of treatment devices such as wetlands which provide both water quality and quantity control functions at the same time in the same place. Time shifting refers to the separation of functions in time, for example, diurnally or seasonally. For example, playing fields also acting as emergency water storage facilities to prevent flooding following high intensity rainfall.

In the context of a social-ecological systems approach, multifunctionality can be understood as the ability of stormwater management systems or treatment devices to support the provision of a range of ecosystem services. This multifunctionality includes:

- Stormwater treatment (a regulating service) to remove or reduce concentrations of contaminants conveyed in stormwater.

- Flow control (a regulating service) to provide for stream baseflows and groundwater recharge while avoiding flooding, combined sewer overflows and stream erosion.

- Surface water conveyance (a regulating service) to the reticulated stormwater pipe network, other stormwater treatment devices or the receiving environment;

- Meeting water quality requirements in receiving waterbodies to support ecosystem health for aquatic, benthic and riparian communities, which in turn may support food gathering / te mahi kai (habitat, cultural and provisioning services);

- Habitat creation (a habitat service) for aquatic, benthic and riparian communities, e.g., wetlands;

- Rain-water harvesting (a regulating and supporting service);

- Micro-climate control (a regulating service) such as tree pits for street shading and open water for evaporative cooling (Spronken-Smith et al., 2000; Coutts et al., 2010);

- Amenity (cultural services) such as landscaping, delineating property boundaries and provision of public space for recreation and its aesthetic appeal;

- Connectivity (cultural and habitat services) or the creation of urban blue-green corridors for both people (e.g., cycle paths, walkways) and wild life (e.g., fish and bird passage).

An example of multifunctionality in stormwater design is the Potsdammer Platz urban renewal programme (Hoyer et al., 2011). The stormwater system was completed in 1998 as part of Germany’s post-unification redevelopment of Berlin. The elements in place include both hard and soft engineering solutions with cisterns (rainwater harvesting for use in buildings and irrigation of a park), proprietary and gravel filters (stormwater quality treatment), skimmers (stormwater quality treatment), canals (conveyance), a lake (water quality and quantity control, amenity, microclimate control), green roofs (water quantity control, microclimate control, bird habitat) and miniature wetlands / reed beds (habitat creation, landscaping).

3.2.2 MODULARITY AND REDUNDANCY

Modularity refers to the use of multiple replicated sub-systems which perform a similar function as each other within a larger system. Redundancy refers to the duplication of critical components or functions of a system with the intention of increasing the reliability of that system. Redundancy can also be thought of more generally as building excess or spare capacity into a system. In a stormwater system, for instance, incorporating spare capacity can help to mitigate the effects of future development on the drainage system (i.e. higher peak flows and contaminant loads associated with increased imperviousness). Together, modularity and redundancy are a means of spreading risk of failure over time and space so that the disturbance or failure of one element or module is contained and does not propagate, compared to centralised or overly connected systems which are more vulnerable to system-wide failure (Walker and Salt, 2006). However, it is important to note that, although complementary, modularity and redundancy are independent of each other. It is possible to have a modular stormwater system which has no spare capacity and, conversely, to have a stormwater system that has in-built redundancy, but which is not modular.

An example of modularity in stormwater design is the Chicago Green Alley programme which was initiated by the city's traffic department to reduce surface flooding on roads without the need for capital works on the sewer network (City of Chicago, 2010). The focus of the programme is the use of public lanes surfaced with of permeable paving. Each lane operates independently as a separate module and drains to the underlying combined sewer network. Green Alleys have also been adopted in other American cities including Los Angeles, Baltimore, Washington DC and Seattle.

In New Zealand, the promotion of Water Sensitive Design (WSD) concepts can be expected to promote a greater degree of modularity to reflect the sequential redevelopment of urban areas. Two Auckland examples are the redevelopment of the Wynyard Quarter and the New Lynn commercial precinct, both of which use modular raingardens to treat stormwater before it enters the reticulated stormwater network (Photograph 1).

Photograph 1: Raingardens along Jellicoe St, Auckland Waterfront, as an example of modular design, each raingarden serves a small section of road (Photo: Sharleen Yalden).

In relation to redundancy, a design requirement of reticulated drainage networks is that they have adequate internal capacity to avoid bottle-necking, backflow, surges, flooding or overflows (Butler and Davis, 2010). In cites around the world, existing reticulated networks are under increasing pressure due to aging and increased imperviousness resulting from intensification. While the installation of storage tanks and tunnels/interceptors is still standard practice, disconnection of stormwater from these networks in favour of surface water management is increasingly being adopted as an alternative method for introducing additional storage capacity into the reticulated drainage network. In the case of greenfield development, flexible stormwater systems can be designed and constructed in such a way that capacity can be increased as needs arise. This may involve installing devices which are off-line initially but can be plumbed in at a later stage, leaving space for future expansion or by re-engineering existing infrastructure as part of corrective maintenance. These sorts of incremental strategies have been advocated as applicable for climate change adaptation in the face of projected increases in the intensity of storm rainfalls (Semadeni-Davies, 2012; Semadeni-Davies et al., 2013).

3.2.3 DIVERSITY

Diversity means that a system contains a range of different elements capable of performing the same or similar tasks but which respond differently to disturbances, thereby increasing the ability of the system to function under changed circumstances. Systems that are managed with a "one-size-fits-all" approach are more vulnerable (i.e. less resilient) to the effects of both shocks and more gradual changes in external drivers (Walker and Salt, 2006).

A diverse stormwater system therefore consists of a number of devices each providing similar or complementary functions and having a different response to system drivers (e.g., high intensity rainfall, imperviousness). If one device fails, others are able to continue operation and maintain the target level of service. In the case of centralised reticulated drainage networks that are susceptible to underperforming during high-intensity storms, the provision of secondary flow paths and surface water drainage infrastructure reduces the risk of failure. In Augustenborg, Sweden, the drainage system was retrofitted in the late 1990s as a (modular) showcase that could be replicated within catchments experiencing water quantity pressures associated with urban development. Prior to the retrofit, the area experienced numerous instances of combined sewer overflows and basement flooding due to sewer backflows each year. By redesigning the surface drainage system as an interconnected system of green roofs, dry and wet ponds, open flow channels, infiltration surfaces, porous paving and rain gardens, the hydraulic performance of the system was improved, greatly reducing the frequency of combined sewer overflows (Villarreal et al., 2004).

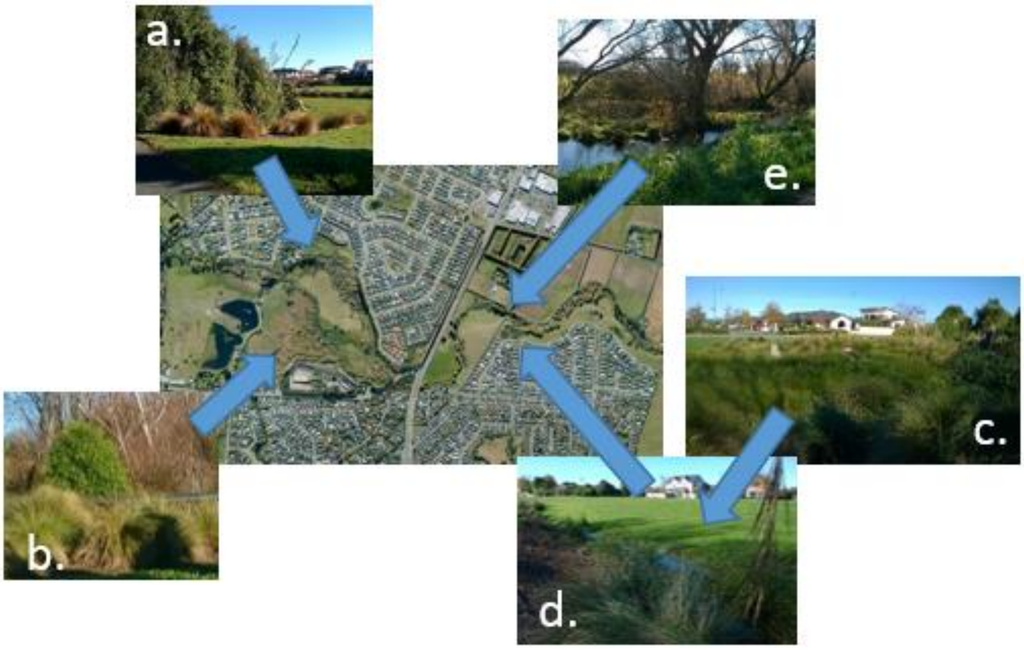
Devices arranged in a stormwater treatment train also provide functional and response diversity by utilising different processes for the removal of contaminants. Devices such as raingardens, which rely on filtration and bioretention for contaminant removal, can be preceded by settling forebays. Raingardens can also be designed to allow surface ponding, facilitating the removal of coarse sediments and gross pollutants. When linked to neighborhood and catchment scale devices, such as vegetated swales, wetlands and wet and dry ponds, the result is a sequence of devices with different sets of functions and responses, enhancing both water quality treatment and quantity control and reducing the risk of system failure at the catchment scale.

A local example incorporating diversity is the Housing New Zealand redevelopment of Talbot Park public housing estate in Glen Innes. This incorporates a variety of stormwater management devices in a diverse (and multifunctional) system (Bracey et al., 2008). Along with meeting a range of social and other environmental goals, diverse approaches were used to achieve stormwater management objectives. Flow reduction, for instance, was achieved by a combination of residential roof collection rain tanks, porous paving in drives and parking areas, and raingardens along roads.

3.2.4 MULTI-SCALE NETWORKS AND CONNECTIVITY

Networks support the provision of ecosystem services by enabling flows of energy, organisms and materials (Ahern, 2011). In a multi-scale network, the flows can occur across scales, either from the top-down or from the bottom-up. A stream network, for instance, flows from first order headwaters to the river mouth via increasingly larger, higher order channels fed by multiple tributaries, each connected to their own headwaters. Network connectivity in urban areas can be facilitated by the creation of blue-green corridors, also referred to as ecological networks, parkways, greenways and riverways. Blue-green corridors are a means of building resilience by maintaining or reconnecting the natural drainage and forest networks within the built environment (Meurk and Hall, 2006; Ahern, 2010; Lewis et al., 2013). Well-connected stream and riparian networks linking headwaters to floodplains support the provision of ecosystem services by maintaining drainage (a regulating service), allowing the free-movement of native fish (habitat services) and providing recreational walking routes (cultural services). Their creation can be achieved through the protection and restoration of natural stream channels, continuous riparian planting alongside stream banks, planting and protection of urban forest reserves, protection and reconstruction of natural wetlands, installation of open drainage channels and daylighting of buried streams. Blue-green corridors should be unbroken to avoid fragmentation of habitats and to encourage movement of animals (i.e., fish, birds, insects and other invertebrates) and people around the city.

There have been a number of urban stream restoration programmes in New Zealand which have been undertaken to improve, among other things, both ecological and amenity-based connectivity, including linking streams to coastal environments and providing access for walking and cycling. One of the most well-known and long-running programmes is Project Twin Streams in West Auckland (Gregory et al., 2008; Hall and Helsel, 2009). The programme aims to restore connectivity from the Waitakere Ranges to the Waitemata Harbour, largely through riparian planting and constructing walkways along the tributaries of Huruhuru Creek and Henderson Creek. Opportunities for restoring connectivity by day-lighting piped sections of urban streams in Auckland have also been investigated (Lewis, 2008). The La Rosa Reserve stream restoration programme in Green Bay, West Auckland, has day-lighted a 180 m section of the Waitahurangi and Parahiku Streams that had been piped as part of the stormwater drainage system (Lewis et al., 2014). In Christchurch, the Styx River restoration programme has among its objectives, the maintenance of a viable spring-fed river ecosystem and creation of a "source to sea" experience through construction of a continuous walkway and urban reserve along the river banks. A range of strategies have been adopted to achieve these objectives, including the use of 'green' stormwater management approaches which complement and link with protected and restored parts of river and its tributaries (Photograph 2).



Photograph 2: Maintaining connectivity along the northern rural-urban boundary of the Styx River, Christchurch. Centre – Google Earth image of the Styx River urban blue-green corridor; (a.) the Glen Oaks soakage and detention facility acts as a buffer to (b.)

the Styx Mill Conservation Reserve; (c.) the Redwoods wetlands/urban forest treats stormwater which is conveyed by (d.) a vegetated swale to the river; (e.) willow along the river is gradually being culled in favour of native riparian species. Photos a-e by A. Semadeni-Davies.

3.3 SOCIAL CRITERIA

3.3.1 INSTITUTIONS AND GOVERNANCE

A range of institutional and governance characteristics have been identified as promoting the resilience of social-ecological systems. These characteristics are relevant at different scales: from the whole system, through to organizations and the roles of individual actors in driving change. Walker & Salt (2006) identified an overlap in governance as being a key characteristic of the capacity of institutions to support resilience in social-ecological systems, giving a system many overlapping ways of responding to change. They argued that "messy" institutional structures that incorporate redundancy in roles will perform better during times of change than more efficient top-down governance structures which are unable to adapt to changed circumstances.

Rijke et al. (2013) investigated governance approaches that would support transformation to more resilient urban water management approaches in Australian cities, based on experiences of relevant agencies in dealing with drought. During early 'adaptation' and 'transition' stages, decentralised and informal governance structures were most effective, facilitating experimentation, learning and network formation. More formal and centralised structures became important to complete the transformation by mainstreaming and regulating the implementation of innovation. Focusing specifically on local government organisations, Brown (2008) identified five institutional characteristics influencing the transformation of urban water management practices in Sydney: organizational commitment and action; political capital; internal organizational expertise; organizational structure; and organizational culture. The most effective organizations were those that had progressed through a series of organizational phases culminating in the 'integrated phase.' In this phase, organizations place a high value on community governance and participation, have dedicated policies and resources for environmental protection, and value staff learning and involvement in research. Key to overcoming the institutional inertia which prevents transformation are loose networks of technical and political 'issues champions' from across government, academia, the community and the land development sectors (Brown & Clarke, 2007).

3.3.2 SOCIAL CAPITAL, NETWORKS AND COMMUNITY ENGAGEMENT

Walker & Salt (2006) identified social capital, including trust, strong networks and leadership, as important characteristics of a resilient social-ecological system. The level and characteristics of social capital influence the ability of people to respond together and effectively to change and disturbance. Social networks can arise as systems self-organize, with teams and actor groups drawing on various knowledge systems and experiences for the development of a common understanding and policies (Folke et al., 2005).

A number of authors have focused on the fundamental importance of engaging communities in order to mobilise social capital. According to Collier et al., (2013) "urban communities must be seen as the central stakeholders in transitioning objectives." The transition to resilient cities involves a fundamental shift in urban planning, with collaboration seeking "to stimulate processes that are citizen conceived and driven" to create and deliver projects that are facilitated by planning practitioners and a wider networks of stakeholders (Collier et al., 2013). In relation to the transition to sustainable urban water management, Brown (2008) found that the most effective local government organisations placed a high value on mobilising participation and, consequently, had the support of the community for sustainability initiatives. Shandas & Messer (2008) investigated the factors that foster effective community involvement in urban waterway restoration projects in Portland, Oregon. They found that programs encouraging the public to participate in environmental planning and stewardship need flexibility to allow innovation and accommodation in the planning process. Community stakeholders need to be involved early in programme development. Community partners have great success completing projects they themselves initiate, own and implement. Programmes that are designed correctly, produce tangible results and involve targeted technical expertise at the right point have the potential to increase citizen trust in government, improve the biophysical environment, and foster participants' ecological understanding (Shandas & Messer, 2008).

3.3.3 ADAPTABILITY AND ADAPTIVE PLANNING, DESIGN AND MANAGEMENT

The dynamics of social-ecological systems are strongly influenced by their adaptability and transformability (Walker et al., 2004). Adaptability is the capacity of the actors in the system (humans) to influence system resilience. It reflects the capacity of the system to "learn, combine experience and knowledge, adjust its responses … and continue developing" (Folke et al., 2010) so as to be able to manage system resilience. Transformability is the capacity to create a fundamentally new system when conditions make the existing system untenable (Walker et al, 2004). In a resilient world innovation is valued, there is an emphasis on learning and experimentation, and change is embraced (Walker & Salt, 2006).

The institutional, governance and social characteristics outlined in the preceding sections interact to influence the adaptability of social-ecological systems. More adaptive and, hence, resilient systems are likely to have mixed-model governance approaches, strong social networks and community-focused participatory processes. Adaptive urban planning and design draws on these characteristics to allow cities to respond rapidly in the face of incremental disturbances and shocks (Ahern, 2010; 2011). Plans and policies are developed and implemented in the face of imperfect knowledge and with in-built flexibility to address future uncertainty. Planning innovates through experimentation with pilot designs, learns from monitoring and analysis and is continuously evolving.

In relation to urban water management, Brown (2012) commented that uncertainty drives the need for solutions which incorporate the ability to learn to do things better. Ferguson et al. (2013) described the need to adopt an 'adaptive paradigm', embracing uncertainty and complexity, in order to foster the transition to a Water Sensitive City. Commenting on Melbourne's water system, the authors described a shift away from a traditional approach focused on controlling uncertainty to one which aims to build resilience by being "'prepared', 'adaptive' and 'flexible'". This could involve adopting strategies such as explorative scenario techniques for long-term planning and designing flexible and adaptable infrastructure that is not locked into current generations of technology (Ferguson et al., 2013).

4 DISCUSSION

The UPSW DSS provides for a multi-criteria assessment of alternative urban development and stormwater management scenarios by predicting scores for each of a range of environmental, economic, social and cultural well-being indicators. The scores are generated by a series of linked models based on inputs reflecting built and natural characteristics of the physical environment. These include: land use extent and type, land development erosion and sediment controls, stormwater management approaches, traffic volumes and stream management approaches. The extension of the DSS to allow for an assessment of resilience involves the incorporation of further indicators, the scores for which must also be able to be generated from this same set of inputs.

The previous sections of this paper have described a number of characteristics which have the potential to be adopted as criteria for the assessment of resilience. While most of these are 'technical' criteria, relating to how the planning, design and management of the built environment can support resilience, a number are 'social' criteria relating to the way in which institutions, governance, social capital and community engagement support an adaptive and resilient approach. Both sets of criteria have application in a stormwater management context: resilient stormwater systems can, for instance, incorporate redundancy both in a technical sense (spare capacity) and a social sense (overlap in governance).

However, within the context of the DSS (in which an urban aquatic social-ecological system is represented purely by its physical characteristics), only the technical criteria provide a realistic basis for distinguishing between alternative urban development and stormwater management scenarios. These criteria relate to the physical environment: the types of stormwater treatment device, how these are deployed and how development encroaches on natural waterbodies and their margins. Five technical criteria have therefore been adopted as the basis of the socio-technical component of the resilience indicators to be incorporated in the DSS. These are:

- Multifunctionality - the extent to which stormwater management supports the provision of multiple ecosystem services.

- Modularity - the extent to which stormwater management is delivered by multiple, similar elements across a range of scales in order to reduce the risks of system failure on the provision of ecosystem services.

- Redundancy - the extent to which stormwater management incorporates spare capacity to accommodate its future extension and so maintain the provision of ecosystem services in the face of a future increase in pressures on the system.

- Diversity - the extent to which stormwater management is delivered by multiple, different elements in order to perform across a range of environmental conditions and so reduce the risks of system failure on the provision of ecosystem services.

- Connectivity – the extent to which natural stream-to-estuary (in-stream and riparian) networks are maintained and support the provision of ecosystem services.

In contrast, social criteria reflect non-physical aspects of a stormwater management approach: the types of institutions and forms of governance; the extent of social capital and networks; the level of involvement of local communities; and the adaptive capacity of the system as a whole. The DSS does not attempt to represent these non-physical aspects of stormwater management. A whole range of other factors influence institutional arrangements and the level of involvement of communities in urban development planning and stormwater management, including: central and local government political processes; the state of the economy; population size, composition and education; freedom of information; and legacy effects, for instance. To attempt to take account of variations in these sorts of factors as part of the specification of scenarios in the DSS would be a significant undertaking, well beyond the intended scope of the tool. The fact that these factors are not represented by inputs to the DSS therefore leads to the conclusion that social criteria cannot be adopted as a way of distinguishing between urban development scenarios.

However, while the DSS is more suited to discriminating between scenarios based on technical criteria, use of the tool has the potential to promote (in the real world) some of the social characteristics identified above as being supportive of building resilience. For instance, use of the DSS can provide an opportunity to engage communities and facilitate cross-sectoral networking in planning processes around urban development and stormwater management. The ability of the tool to provide for comparison of multiple scenarios allows stakeholders and decision-makers to take account of outcomes under a range of alternative futures. This can help foster the adoption of adaptive approaches whereby decision-making allows for the possibility of a range of alternative forms of development and planning builds in the flexibility to respond to changing needs as development unfolds.

Two further points regarding the absence of social criteria in the indicators of socio-technical capacity are worth noting. Firstly, an 'indicator' is, by its very nature, a measure of some particular characteristic which is broadly representative of a wider range of characteristics. For instance, the DSS uses a benthic community health score as an indicator of the broader ecological status of estuaries. In similar fashion, the technical criteria adopted here can be considered to be representative more broadly of the way in which both the built and non-built aspects of stormwater management support system resilience. For instance, the inclusion of modularity, redundancy and diversity in the planning of stormwater treatment might be expected to be an outcome of a process which involves forward-thinking institutions, adopts adaptive planning, works across sectors and engages communities. As various authors (Brown, 2008; Rijke, 2013; Wong & Brown, 2008) have shown, where these social characteristics are not well developed, systems tend to remain locked into the delivery of (pre-WSD) traditional, less resilient forms of stormwater management. The technical criteria adopted for incorporation in the DSS can therefore be expected to perform reasonably well as surrogates for the social criteria which are not explicitly represented as indicators in their own right. The second point to note is that the absence of social criteria in the DSS reflects the scope and capabilities of the tool, rather than their wider relevance for assessing resilience. Where an assessment of the resilience of stormwater management employs some other method, it may be the case that both technical and social criteria can be adopted.

5 CONCLUSIONS

Building resilience into stormwater management means adopting approaches that reduce vulnerability, both to sudden shocks and to the potentially irreversible long-term environmental effects of urban development. This paper has described a series of criteria that can be used to assess the resilience of alternative stormwater management approaches.

Technical criteria relate to the way in which the built environment and stormwater infrastructure is designed and managed. They include multifunctionality, modularity, redundancy, diversity and network connectivity. A resilient stormwater network might incorporate a range of treatment device types, ensuring performance of the system as a whole under varying environmental conditions. It might also build in spare capacity to accommodate projected increases in contaminant runoff arising from infill development or in response to climate change.

Resilient approaches to stormwater management also have a social dimension. Previous authors have found that resilience is fostered in situations where institutions, governance arrangements, social capital and community engagement support an inclusive and adaptive approach to stormwater management.

Within the context of the UPSW DSS, in which urban development and stormwater management scenarios are represented by model inputs reflecting their physical characteristics, only the technical criteria provide a realistic basis for assessing system resilience. However, while the DSS is best-suited to discriminating between scenarios based on technical criteria, use of the tool has the potential to promote (in the real world) social characteristics consistent with a more resilient approach to the planning of urban development and stormwater management.

ACKNOWLEDGEMENTS

This research is part of the Resilient Urban Futures programme, led by the University of Otago and funded by the Ministry for Business, Innovation and Employment (MBIE) under contract UOOX1203.

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