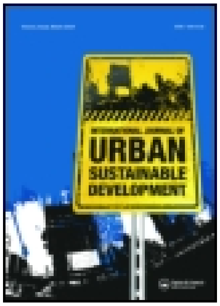

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A systems approach to meeting the challenges of urban climate change

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A systems approach to meeting the challenges of urban climate change

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This article identifies the future challenges that cities face in their ability to create well-being, particularly for urban poor communities, as a result of the compound effect generated by climate change – distinguishing between direct impacts, indirect effects and pre-existing vulnerability. This suggests that action to reduce exposure and improve the adaptive capacity of urban populations must therefore simultaneously address disaster risk reduction, urban poverty reduction and urban resilience (i.e. the ability of the city to maintain the functions that support the well-being of its citizens). Based on evidence and experience from 10 cities which form part of the Asian Cities Climate Change Resilience Network (www.acccrn.org), this article proposes that a simplified conceptual model and resilience characteristics be used to analyse urban systems, in parallel with spatial analysis, to target action at multiple levels to reduce exposure and improve the adaptive capacity of urban populations simultaneously.

Keywords: urban resilience; poverty; climate change; systems approach; urbanisation; governance

1. Introduction

The world's urban environments already host over half the global population – some 3.5 billion people – and it is anticipated that this number will increase up to 70% (or 6.4 billion people) by 2050. Urban areas in Asia are expected to see more than 60% of this increase, half of which will occur in cities with fewer than 500,000 inhabitants (United Nations 2000). In the face of such rapid urbanisation municipalities often lack the fiscal and institutional resources to ensure the socio-economic well-being of urban residents, while much existing infrastructure is rendered obsolete due to inadequate maintenance or limited capacity. Currently, one in three urban dwellers – one in every six people worldwide – lives in a slum, dealing with overcrowded conditions, inadequate access to water and sanitation, poor-quality shelter and lack of tenure (UN Millennium Project 2005). Overlaid on this is the future impact of climate change, which will exacerbate these existing vulnerabilities.

The role of cities in contributing to climate change mitigation is well established in academic, policy and practitioners' circles, driving significant action by municipal governments and city stakeholders to reduce emissions and introduce energy-efficient systems. Fewer efforts have been made to identify and implement adaptation measures that will increase the resilience of cities' to the local impacts of climate change (Satterthwaite *et al*. 2007; Bicknell *et al*. 2009; Bulkeley 2010; Bulkeley *et al*. 2011). Key challenges in this respect arise from the inherent uncertainties in climate change projections, and lack of evidence as to how resilience is achieved given the complexity of interactions within a city. Current debate recognises the limitations of uni-sectoral strategies and the need for integrated planning processes and

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policy-working across multiple scales and sectors (McEvoy *et al*. 2006; Hardoy and Pandiella 2009). Likewise, a balance between the quest for certainty of evidence and the need to make decisions and take action is required that enables decisions to be informed by climate change projections while allowing uncertainty to form a key aspect of the decision-making (Dawson *et al*. 2009; Carmin and Dodman forthcoming).

This article argues that traditional risk assessments founded on spatial analysis and climate projections fail to recognise uncertainty of climate change data or the complexity of cities. Instead, it is more useful to approach the problem from an urban systems perspective, founded on an understanding of how the city functions, its boundaries of control and influence and how it can continue to function in the face of a wide range of shocks and stresses. Resilience is understood as a desirable attribute of the urban system (Godschalk 2003). Resilience at a city scale cannot be measured directly, other than in terms of changing performance of systems in response to shocks and stresses. The socio-technical networks (such as infrastructure, institutions, ecosystems and knowledge) that make up city systems will, in a resilient city, demonstrate a number of key characteristics that can be used to measure progress.

This article draws on current discourse as well as Arup's[1] experience in numerous cities globally, but in particular the authors' experience working with stakeholders from 10 Asian cities as part of the Rockefeller Foundation's Asia Cities Climate Change Initiative Resilience Network (ACCCRN).[2] The 10 ACCCRN cities, from which the bulk of examples are drawn, are Da Nang, Quy Nhon and Can Tho (Vietnam); Surat, Indore and Gorakhpur (India); Bandar Lampung and Semarang (Indonesia) and Hat Yai and Chiang Rai (Thailand).

2. How climate change affects cities

While cities play a key role as generators of economic wealth, their role enabling the well-being for their populations is of equal or greater importance. In the context of climate change, both of these roles are threatened by a variety of *direct* and *indirect* impacts. The *direct* impacts of climate change take the dual form of shocks, sudden impacts such as storms, typhoons and heat waves, and stresses, impacts that build gradually over time such as sea level rise, general temperature increase and changes in rainfall patterns. Such events will in turn generate a cascade of *indirect* effects, eroding the city's capacity to adapt as a result of significant disruptions in the socio-technical networks essential for city functioning (Figure 1).

Notably, these impacts are felt most by vulnerable communities affected by widespread poverty, due to either their increased exposure to hazards

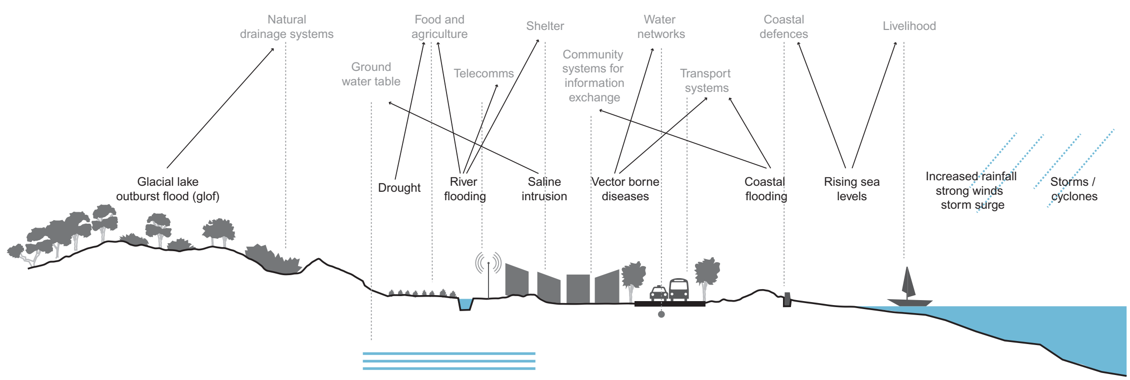

Figure 1. Climate change impacts could affect several key urban functions via direct and indirect effects.

or limitations in their ability to respond due to a low assets base (Satterthwaite *et al*. 2007; Bicknell *et al*. 2009). The compound effect of climate change, combining direct impacts, indirect impacts and pre-existing vulnerabilities is illustrated in Figure 2.

The notion of climate change adaptation refers to initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects (Intergovernmental Panel on Climate Change 2007). Figure 2 has been used consistently throughout the ACCCRN programme to explain that action to improve the adaptive capacity of vulnerable urban populations which focuses on disaster risk reduction (DRR) and urban poverty reduction is necessary, but insufficient. Specific action is also needed which enhances the ability of the city to continue to maintain the essential functions that support the well-being of its citizens and sustain its economy. Such action needs to consider climate change impacts in the context of how the city works (the 'urban system') and who is least able to respond to shocks and stresses ('vulnerable groups').

2.1. Pre-existing vulnerability

Several authors have highlighted the links between urban poverty, vulnerability and climate change, and the high level of risk of urban dwellers in low- and middle-income countries (Satterthwaite *et al*. 2007; Dodman and Sattherthwaite 2008; Bicknell *et al*. 2009; Moser and Satterthwaite 2010). A primary risk factor in such contexts is the high level of exposure to direct impacts. This is mostly related

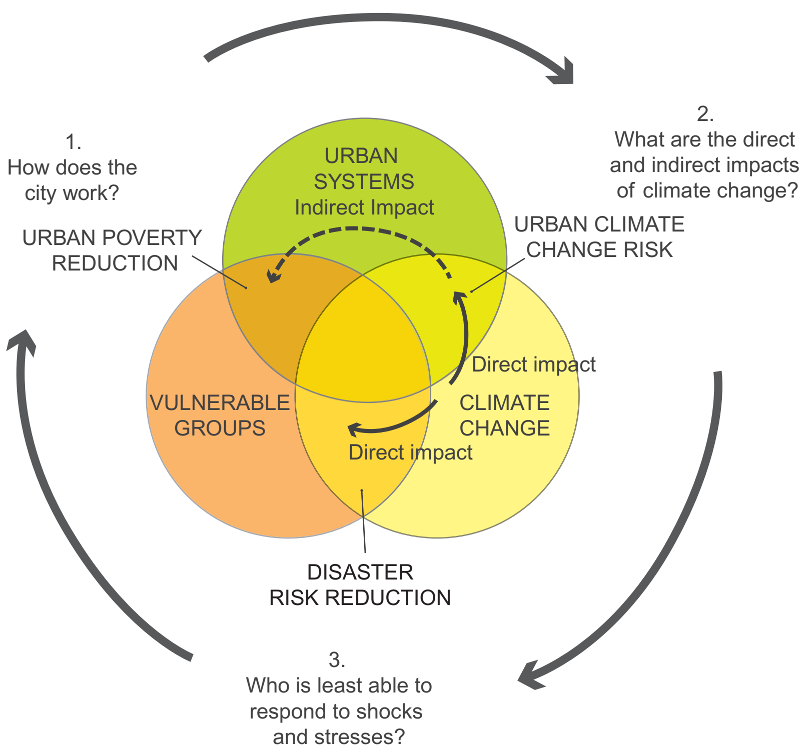

Figure 2. Climate impacts: a compound effect combining direct impacts, indirect impacts and pre-existing vulnerabilities.

to the location of settlements on high-risk areas such as flood plains, coastlines and inclined slopes susceptible to landslides, as well as poor-quality construction. This is a prevalent issue for many informal settlements, for example, in Semarang, Indonesia, where communities have settled on low-lying coastal areas or along the banks of rivers. This risk may also result from well-intentioned infrastructure, as in Da Nang, Vietnam, where widening of the coastal road has removed vegetation and dunes. The consequences of this exposure have been a significant increase in the impacts of storms, flooding and strong winds resulting in damage to the homes and property of adjacent communities (Brown and Kernaghan 2011).

The ability of such communities to cope or adapt is reduced by limited access to basic infrastructure and services (potable water, sanitation and drainage), lack of secure tenure, poor education and health care, and limited employment opportunities (Sanderson 2000; International Standards Organisation 2002; Corsellis and Vitale 2008). Non-responsive political systems and bureaucratic structures mean communities may have a limited voice or power to create change, and the absence of safety nets (e.g. insurance and savings) and lack of information limits their ability to adopt alternative strategies. While grass-root action at a community level are valuable, many of these challenges can only be overcome by actions and interventions at a city scale (Dodman and Mitlin 2011). These interventions are likely to be most effective when founded on strategies developed through multi-stakeholder engagement between government, non-government and civil society organisations, business and academia (Parker *et al*. 2012).

2.2. Urban systems failure

The *direct* impact of climate change on how the city works (the ‘urban system’) is significant as it has the potential to *indirectly* affect very large numbers of people, as well as impose additional burdens on communities who are least able to cope. At an urban scale, climate change will indirectly affect transport networks, power, potable water supply, food distribution networks, waste management facilities and telecommunication systems. This may be as a result of direct impacts from flooding, increased temperature affecting equipment, saline intrusion of an aquifer due to sea level rise or loss of life due to extreme events.

For example, in Semarang, Indonesia, flooding currently occurs in low-lying coastal areas that have been reclaimed. Groundwater extraction by coastal communities is contributing to significant land subsidence and the impacts of floods are likely to get much worse over the next decades. Sea level rise of 21 cm, predicted by 2050 as a result of climate change, is double the 11-cm-predicted subsidence over the same period and will affect coastal infrastructure including the port and train station. The indirect effects of the port or train station flooding include people being unable to travel to work, shortages of goods and failure of goods to reach market with far-reaching consequences (Technical Team for Climate Adaptation of Semarang City and City Working Group 2010).

This example from one of the ACCCRN cities illustrates that spatial analysis, although a useful tool for assessing the direct impact of climate change on individual urban communities or sectors, can be improved with a parallel approach focussed on systems. A traditional spatial analysis would have overlooked the interdependence of the infrastructure, institutions and individuals and the indirect impacts that coastal flooding might create. In reality, a city behaves as a complex system which is in constant flux as a result of many dynamic factors, reorganising and adapting to feedbacks across multiple scales temporally and spatially.

2.3. Overlaying climate change on existing challenges

Cities already face a range of dynamic factors including rapid urbanisation, urban renewal, immigration and economic cycles. Climate change represents an additional overlay on these existing challenges. The uncertainties surrounding climate change predictions, combined with the rapidly evolving urban context associated with these dynamic factors, are challenging traditional approaches to planning and engineering founded on a 'predict and prevent' paradigm (Brown and Kernaghan 2011). This is particularly important in cities in emerging economies facing rapid urbanisation, which are often characterised by poor planning, weak institutional structures, inadequate services (health care and emergency services) and large deficits in basic infrastructure (sewerage and drainage, water and energy) (Satterthwaite *et al*. 2007). Limited capacity, political will or resources to tackle climate change means that preventative action is only likely to be deemed relevant or viable if short-term improvements to quality of life are also evident.

In order to enable cities to better analyse their strengths and weaknesses and identify points for intervention to build resilience, we propose a simplified urban systems approach which complements the traditional spatial analysis. Rather than starting with climate science and attempting to predict future climate scenarios and plan accordingly, it is more useful to analyse a city in terms of the key *systems of provision* that underpin well-being and enable economic activity, so as to be able to understand how susceptible they are to the types of shocks and stresses that might arise as a result of climate change. This susceptibility is likely to be most significant where there are serious shortfalls in resources, or inadequate coverage and capacity that already compromise well-being, placing communities under stress even before climate impacts are considered. Interventions can then be identified, which address critical gaps or weaknesses in the system, thereby enhancing performance and catalysing alternative behaviours that build resilience. In the following sections, this simplified conceptual model of the urban system is tested, and explained as an approach which can be readily used by urban planners, decision-makers and their advisors as the basis for analysis and action.

3. Understanding cities as systems

The definition of 'urban' varies widely, developed from academic as well as practical perspectives. For the United Nations, an urban agglomeration is a 'built-up or densely populated area containing the city proper, suburbs and continuously settled commuter areas' (United Nations 2006). Key features associated with urban areas include increased levels of contact and interaction (Hillier 2007), a concentration of power and culture (Mumford 1961) and opportunities for wealth creation, resource distribution and efficient use of scarce natural resources (Davis 2002). Spatially, urban areas have been conceptualised socio-economically in terms of population density and/or administrative arrangements or in terms of land use (Hall 2009a). Such single-dimension definitions focus on specific aspects of urban living, but fail to capture the manifold nature of urban processes characterised by flows of goods, services and people, and the interdependency of infrastructure and socio-economic networks.

Systems thinking provides a platform for a more holistic approach in which urban areas, particularly cities, are considered as complex 'living' systems undergoing numerous dynamic exchanges at any given time, constantly evolving and responding to both internal interactions and the influence of external factors (Batty *et al*. 2006; Barnett and Bai 2007). Cities are adaptive, socio-technical systems comprising various elements which, when combined, have qualities that may not be present individually. Changes are systemic (i.e. changes in one element of the system may induce changes in another element), and dynamic (the result of feedback loops[3]) (Royal Academy of Engineering 2007). Therefore, a system's behaviour can only be understood by looking at the entire system and not its elements in isolation.

Extensive work has been previously done in approaching cities from a systems perspective. The field of urban ecology focuses on gaining a better understanding of the impacts and interactions between humans and natural systems (Grove and Burch 1997; Pickett and Burch 1997; Piracha and Marcotullio 2003). Other approaches have aimed to understand and model resource flows in cities as urban metabolisms, emphasising resource efficiency and optimisation (Newman 1999; Scheurer 2001; Girardet 2004; Marvin and Medd 2006;

Swyngedouw 2006; Fisk 2007; Keirstead 2007; Schulz 2009). More recently, applying a systems perspective to cities has also been used to understand the likely scenarios resulting from climate change impacts (Ruth and Coelho 2007; Dawson *et al*. 2009; Hall 2009b), and the implications of catastrophic failures in networked infrastructures (Bennett 2005; Marvin and Medd 2006; Graham and Thrift 2007; O'Rourke 2007; Graham 2010; Harris and Keil 2010; Sims 2010). The examination of failures in networked infrastructure has revealed the complex interdependencies of socio-technical networks in cities, highlighting the fragility of essential infrastructures and the importance of repair and maintenance to ensure urban resilience in restoring equilibrium (Summerton 1994; Graham and Thrift 2007). However, although the benefits of a systems approach are apparent, the challenge is in conceptualising the urban system in a way that does not require complex modelling and can be readily understood by city planners and key decision-makers. In a recent detailed review of urban resilience literature, Bahadur *et al*. (2010) concluded firstly that there is a lack of case studies which operationalise resilience concepts, and secondly that 'no part of the reviewed literature provides a substantial explanation of how this entity and its boundaries are defined'. The following sections aim to respond in past to these two identified gaps in existing literature.

3.1. Conceptualising the urban system

The ultimate objective of the urban system is to support the well-being of the urban population while generating wider socio-economic benefits (Table 1). Well-being encompasses basic human needs (food, water and shelter), access to goods and livelihood opportunity, security, health, social relations and freedom to act (Maslow 1971; Alcamo *et al*. 2003; Huitt 2004).

Key urban functions to secure well-being are underpinned by the natural resources and services provided by both local and remote *ecosystems*. *Ecosystems services* are 'the benefits people obtain from ecosystems' (Alcamo *et al*. 2003) which can be categorised as provisioning (e.g. food and water), regulating (e.g. flood control and air quality), supporting (e.g. soil formation and nutrient cycling) and cultural (e.g. recreational). Preservation and management of urban ecosystems are fundamental to urban resilience as they provide a local source of food, water and materials, as well as contributing cost-effectively to flood control, waste absorption and amenity (Roberts 2010).

In rural and semi-rural settings, there is a relatively direct relationship between ecosystems,

Table 1. The purpose of the urban system: well-being (Maslow 1971; Alcamo *et al*. 2003; Huitt 2004).

Well-being	
Basic needs for survival *biological and physiological needs*	Adequate livelihoods, sufficient nutritious food, access to water, sanitation and shelter, access to goods
Security *safety needs*	Personal safety, security from natural hazards and man-made hazards (terrorism, pandemics), secure resource access, order, law and stability
Health *Healthy body and mind*	Feeling well, access to clean air and water, access to health care
Good social relations and esteem *belongingness, love needs*	Social cohesion, mutual respect, ability to help others, family, personal relationships, achievement, status, responsibility and reputation
Freedom of choice and action *self-actualisation needs*	Opportunity to be able to achieve what an individual values doing and being, personal growth and fulfilment

the services they provide, and human well-being (Alcamo *et al*. 2003; Desakota Study Team 2008). In urban conditions, this relationship is expanded and requires mediation by various interconnected socio-technical networks, creating a shift in dependency from local to more remote ecosystems (Figure 3).

In this simplified model (Figure 3), we have identified three types of network: infrastructure, knowledge and institutions, in addition to the outcome of cities (well-being) and the resources upon which this is enabled (ecosystems). These three networks are considered as 'socio-technical networks' since they are composed of physical elements (e.g. technology and buildings) as well as social elements (e.g. regulatory structures and formal and informal practices) (Rip and Kemp 1998, cited in Geels 2004; Smith *et al*. 2005; Smith 2007; Monstadt 2009). For instance, water infrastructure may comprise boreholes and pipes as well as regulations and practices surrounding groundwater abstraction and both formal and informal water distribution.

- *Infrastructure networks* are considered to be the key physical and technological assets of cities. They define the experience of modern urban life, enable exchanges and dynamic relationships between different actors, and represent capital and knowledge embedded in the city (Graham and Marvin 2001). Networked infrastructure, which includes energy, water, sewerage, transport, waste and telecommunication systems, 'provides the technological links that make the very notion of a modern city possible' (Graham and Marvin 2001). Such networks enable access to essential resources (e.g. water, food and energy), provide education and health care facilities, buildings and services for government and business and access to markets and information.
- *Knowledge networks* refer to the structures and systems that regulate and enable access to information. Among them, educational organisations (schools, technological institutes and universities) play a key role. Access to information also happens on an everyday basis in more informal ways via various technological media (e.g. local radio stations and the Internet), as well as social networks acting from local to global scales (e.g. from neighbourhood interactions at community gathering spots to transnational professional networks). Information flows and technology development, alongside knowledge and learning, are critical to enabling the urban system to learn, evolve and adapt to changing circumstances or respond rapidly to extreme events.
- *Institutional networks* refer to the custodians of rules and practices supporting human interaction (e.g. justice, land tenure and markets). For example, governance systems allow for collective decision-making (by government, community or business associations, etc.); economic systems

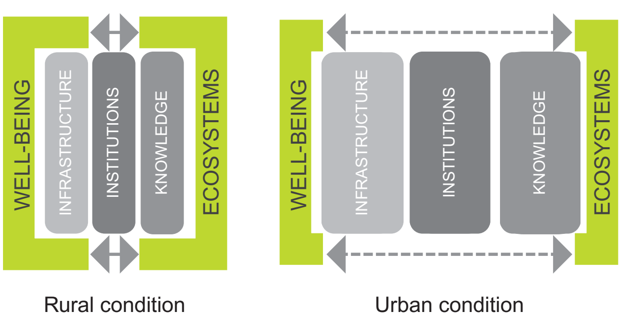

Figure 3. Relative ease of accessing resources and ecosystem services in rural and urban environments.

support and control financial exchange and production (via markets and funding mechanisms). No less important are the social systems and networks which underpin the hierarchy of relationships and basis of exchange, either reinforcing or preventing marginalisation and corruption. Finally, cultural codes and practices are responsible for providing frameworks for interpretation based on faith, myth, ethics and values, which influence social behaviour.

3.2. Urban system boundary

This model (Figure 3) describes the key elements within the urban system. For analytical purposes, it is also necessary to define the boundary of the system. Cities are characterised by a highly dense population; the needs of which exceed the carrying capacity of the local ecosystem. They rely on sources of food, energy, water and raw materials, human resources (e.g. labour and knowledge) and financial resources (e.g. trade and remittances), from outside the administrative boundary. There are similar flows of goods and services out of the city, and multifarious formal and informal linkages through regional, national and global networks (Barnett and Bai 2007). As such, cities are recognised functionally as open systems with ill-defined porous boundaries. A city's administrative boundary still provides a useful unit of analysis, however, as it identifies the reach of public policies, and enables assets within the control of the city authorities, businesses and inhabitants to be identified.[4] In the context of a city, the administrative municipal boundary tends to include both urban and suburban (or peri-urban) elements controlled by a single authority with a clearly defined governance structure. Large cities are typically divided into smaller administrative units described as boroughs (e.g. London and New York), districts (e.g. Shanghai and Lima), *delegaciones* (e.g. Mexico City), wards (e.g. Mumbai and Bangalore) (Burdett and Sudjic 2007).

The notion of an 'enabling environment' is used to account for the interactions and interdependencies beyond the administrative boundary. This term has been used previously in the context of resilient communities to define the wider institutional, policy and socio-economic factors that support resilience (Twigg 2007). In relation to a city, the enabling environment includes all the spatial and non-spatial dynamics essential for urban functioning which are located outside of the city boundaries. These could include surrounding and distant ecosystems, neighbouring settlements, industries and markets based in distant locations, as well as non-spatial socio-political dimensions such as regional and national policy, and national and global knowledge networks.[5] The distinction is that action and intervention within the administrative boundary is likely to be within the *control* of urban populations and decision-makers, while outside this boundary city actors are only able to *influence* activity in the wider enabling environment (see Figure 4).

4. Building resilience in urban systems

'Adaptive capacity' is considered to be the inherent capacity (financial, technological, knowledge or institutional) of a system or population to cope with climate impacts or climate change (Reid and Huq 2007; Smith *et al*. 2010). Interventions identified in the 10 cities engaged in the ACCCRN programme are beginning to illustrate the benefit of investment in a wide range of factors contributing to adaptive capacity including technological options, access to information, robust institutions, access to risk transfer and sharing mechanisms, ability of decision-makers to manage risks and information and public perception (Yohe and Tol 2002). The focus is typically on institutional and knowledge networks which offer relatively quick and cost-effective means to improve adaptive capacity compared to investment in major infrastructure.

4.1. Resilience

While the notion of adaptive capacity has emerged as part of the lexicon of climate change,

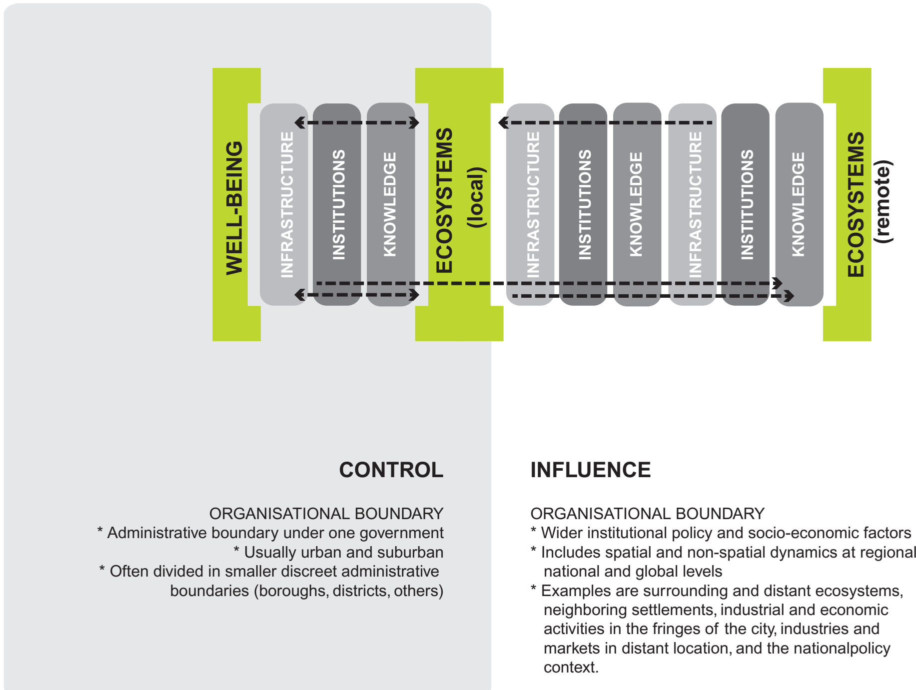

Figure 4. The city as an open system, interacting with its 'enabling environment'.

resilience is a broader concept which reflects the ability of a system to respond and reorganise or return to functional stability after a perturbation (Holling 1973; Pickett *et al*. 2004; Barnett and Bai 2007). Definitions of resilience vary slightly, but they all link the concept to the ability to recover and achieve a stable state, after physical shocks and stresses (Commonwealth Scientific and Industrial Research Organisation *et al.* 2007; O'Rourke 2007; Construction Industry Research and Information Association 2010). The Intergovernmental Panel on Climate Change defines resilience as 'the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change' (Intergovernmental Panel on Climate Change 2007). The emphasis here is on behavioural change and mobilising capacities within communities and systems, rather than addressing vulnerability to specific hazards, or individual/community needs in an emergency (Twigg 2007).

With the emergence of climate change and the lessons learned by the collapse of urban systems in New Orleans in the aftermath of Hurricane Katrina, resilience has increasingly been seen as a useful concept to approach risk, unpredictable change and the efforts to return to a balanced functioning state in an urban context. Although it has its foundations in the field of ecology, it is well suited to cities as its underlying premise is that humans and nature are strongly coupled and co-evolving, and should therefore be conceived of as one system (Folke 2006).

Some of the earlier work on understanding cities from a resilience perspective was aimed at bridging the fields of ecology, sociology, urban design and urban planning. Building on developments in the field of urban ecology in the 1980s and 1990s, it examined social systems using ecological frameworks (Grove and Burch 1997; Pickett and Burch 1997). This work emphasises resilience as a concept for dealing with change and learning in urban environments, rather than as system breakdown and return to stability (Musacchio and Wu 2004; Pickett *et al*. 2004). However, academics and practitioners in the fields of climate change science, DRR and infrastructure security have returned to the original emphasis of resilience as a behavioural attribute of the urban system, reflecting its ability to return to or maintain a stable state. Resilience in the context of cities has been defined as 'the degree to which cities are able to tolerate alteration before reorganising around a new set of structures and processes [which] can be measured by how well a city can simultaneously balance ecosystem and human functions' (Barnett and Bai 2007). It is argued that a resilient society, one that is able to adjust under uncertainty and surprise, is in a better position to take advantage of the positive opportunities that the future might bring (Barnett and Bai 2007).

4.2. Measuring resilience

With this understanding of the need for resilient urban systems, there is an understandable desire to articulate resilience so that it can be measured. Attempts to do so range from emphasising the human and social dimensions of resilience, understanding it as a function of the social fabric and community networks of a city (Campanella 2006; Hopkins 2009), focussing on the qualities of urban infrastructure: redundancy (presence of options); robustness (inherent strength); resourcefulness (capacity to mobilise resources) and rapidity (speed of recovery) (Bruneau *et al*. 2003; Godschalk 2003; O'Rourke 2007). Others have adopted a livelihoods approach focussing on the quantity and quality of assets (knowledge, labour, physical and financial capital, social relations and natural resources) and access to services, infrastructure, communications, credit markets, and emergency relief (Twigg 2007; World Bank 2008; International Federation of the Red Cross and Red Crescent Societies Arup 2011).

If resilience is considered as an attribute of the urban system's behaviour, it cannot be measured directly other than in terms of changing performance in response to shocks and stresses. Resilience, therefore, will only be achieved through the cumulative contribution of multiple interventions and actions over time, and the ability of individuals and institutions to internalise learning and experience to inform future behaviour. Hence, resilience cannot be attributed to a specific intervention. As an analytical and practical concept, resilience is only relevant in the context of a systemic approach, where the nature of the relationship among constituent elements plays the main role in determining the overall functioning of the system.

As a proxy for measuring resilience and in the context of the simplified systems model described earlier, we propose a preliminary list of *characteristics* that might be used to describe the various socio-technical networks and systems of provision that comprise a resilient city (see Figure 5). These characteristics define the desired network outcome (rather than output) arising from any intervention targeted at building urban resilience and provide a first step towards developing measurable network indicators. They draw on an extensive literature from the fields of urban infrastructure, international development and DRR, and have been developed in conjunction with the Institute of Social and Environmental Transition (ISET), as part of the ACCCRN programme (Moench and Tyler 2011):

(1) *Flexibility*: The ability to change, evolve and adopt alternative strategies (either in the short or longer term) in response to changing conditions. Flexibility implies recognising when it is not possible to return to the previous way things worked and finding new solutions and strategies (evolution). This favours 'soft' rather than 'hard' solutions.
(2) *Redundancy*: Superfluous or spare capacity to accommodate increasing demand or extreme pressures. Redundancy is about diversity and the ability to adopt alternative

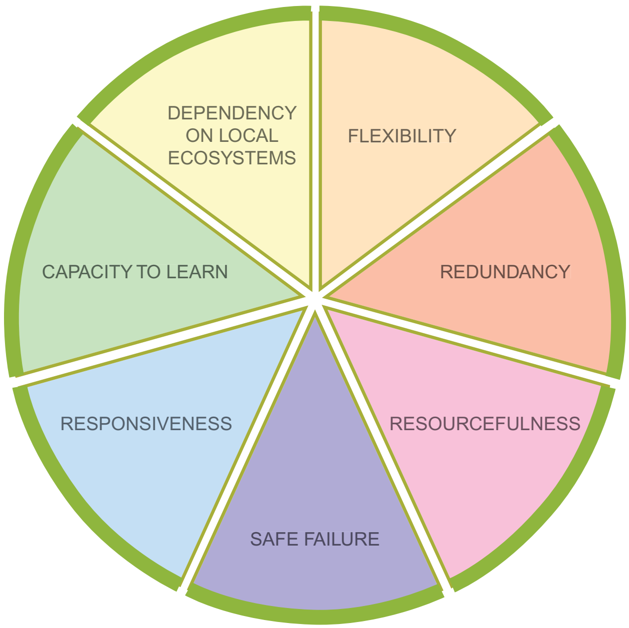

Figure 5. Characteristics of resilient urban systems.

strategies through the provision of multiple pathways and a variety of options. Some components of the urban system serve similar functions and can provide substitute services when another component is disrupted.

(3) *Resourcefulness*: The capacity to visualise and act, to identify problems, to establish priorities and mobilise resources when conditions exist that threaten to disrupt an element of the system. This capacity is related to the ability to mobilise assets (financial, physical, social, environmental, technology and information) and human resources to meet established priorities and achieve goals.

(4) *Safe failure*: Resilient network infrastructures are designed for safe failure.[6] This is related to their ability to absorb shocks and the cumulative effects of slow-onset challenges in ways that avoid catastrophic failure if thresholds are exceeded. When a part of the system fails, it does so progressively rather than suddenly, with minimal impact to other systems. Failure itself is accepted.

(5) *Responsiveness*: The ability to re-organise, to re-establish function and sense of order following a failure. Rapidity is a key part of responsiveness in order to contain losses and avoid further disruption. However, such rapidity of response should not impair the capacity to learn, and therefore, a balance between learning and rapidity should be achieved.

(6) *Capacity to learn*: Direct experience and failure plays a key role in triggering learning processes. Individuals and institutions should have the ability to internalise past experience and failures, and use such experience to avoid repeating past mistakes and exercise caution in future decisions.

(7) *Dependency on local ecosystems*: Resilient urban systems exercise a greater degree of control over the essential assets required to support well-being, securing access to and quality of such resources.[7] This involves recognising the value of the services

provided by local and surrounding ecosystems (often described as the city's green and blue infrastructure) and taking steps to increase their health and stability. These services (often undervalued) perform processes such as flood control, temperature regulation, pollutant filtration and local food production (Luque and Duff 2006; Hodson and Marvin 2009).

These characteristics of resilience can be used to group and conceptualise a set of systemic behaviours that avoid catastrophic outcomes or system breakdown, and enable recovery and stability after dramatic and unexpected events or gradual impacts that force change over time. Each of the characteristics is applicable to the infrastructure, institutional and knowledge networks that comprise the urban system, however characteristic (4) – safe failure – applies specifically to infrastructure, and (6) – dependency on local ecosystems – to ecosystems.

5. Applying the conceptual model and characteristics to emerging practice: the case of the ACCCRN

The urban systems model (Figure 4) can be used by city stakeholders to analyse a city (or part of a city depending on administrative boundaries), using the three systems of provision (infrastructure, institutions and knowledge networks) that enable the needs of the urban populace to be met. The focus of the analysis is to map the infrastructure, knowledge and institutional networks that mediate the relationship between the components of well-being (Table 1) and remote or local ecosystems, to provide a simplified model of the urban system. Based on this analysis, vulnerability of the urban system to the impacts of climate change can be better understood, creating the opportunity for interventions to be identified to enhance the performance of the system.

A number of case studies from ACCCRN cities have been analysed using this urban systems approach. The research to inform this analysis was undertaken in two key stages. Firstly, from 2008 to 2010, primary and secondary information were collected and reviewed to provide contextual background for each of the 10 ACCCRN cities. Primary research included field visits to many of the ACCCRN cities, semi-structured interviews and meetings with city actors and coordination with country and regional ACCCRN partners. This primary data were supplemented by a desk-based literature review of each of the City Resilience Strategies,[8] a city-wide planning document that brought together vulnerability assessments, sector studies and climate change projections into a holistic action plan for increasing resilience.

The second stage of research analysed a number of city intervention projects that are being funded by the Rockefeller Foundation through the ACCCRN programme. A desk-based review of the approved project proposals was undertaken from 2011 to 2012 to critically evaluate and test the urban systems approach.

The case studies detailed below describe a series of city intervention projects from the ACCCRN cities of Surat (India), Bandar Lampung (Indonesia), Quy Nhon (Vietnam), Chiang Rai (Thailand) and Indore (Indore). They have been selected based on their geographical and sectoral diversity, access to reliable data sources and timely availability of materials. The case studies act as a good illustration of the practical application of the urban systems approach and the resilience characteristics.

The city of Surat, located in the western Indian state of Gujarat, has a projected population of over 4.5 million and is the ninth largest city in India (TARU Leading Edge 2010b). The focus of the urban systems analysis is security relating to urban flood risk, both in terms of personal safety (particularly that of low-income communities located in vulnerable areas) and business continuity. Surat is a low-lying coastal city that is affected by tidal and fluvial flooding, notably from the Tapi River. Significant infrastructure exists already to mitigate this risk in the form of urban drainage systems, flood defences and a reservoir located outside the municipal boundary. Early warning systems and emergency preparedness plans also exist. However, the intensity of precipitation is currently increasing as a result of climate change, and flood risk will be amplified by sea level rise (TARU Leading Edge 2010b).

Figure 6 illustrates the urban systems analysis. It highlights the importance of city institutions' ability to respond effectively to flood emergencies and identifies the relationship between flood risk and operation of the reservoir which is outside the control of the city. Currently, dam management is a reactive process, responding to water levels in the reservoir, rather than being informed by wider catchment analysis and rainfall forecasting, or an understanding of the implications of dam release on the city of Surat. City stakeholders have identified the importance of knowledge networks (particularly information exchange between key institutions, notably rainfall forecasters, dam managers and Surat municipality), and decision-making founded on more comprehensive hydrological modelling. It was recognised that this modelling would only be effective if it was supported by improved institutional flood risk management (including improved management of water resources, early warning and emergency management plans) involving multiple stakeholders within the city as well as the Gujarat State Disaster Management Authority and the Narmada

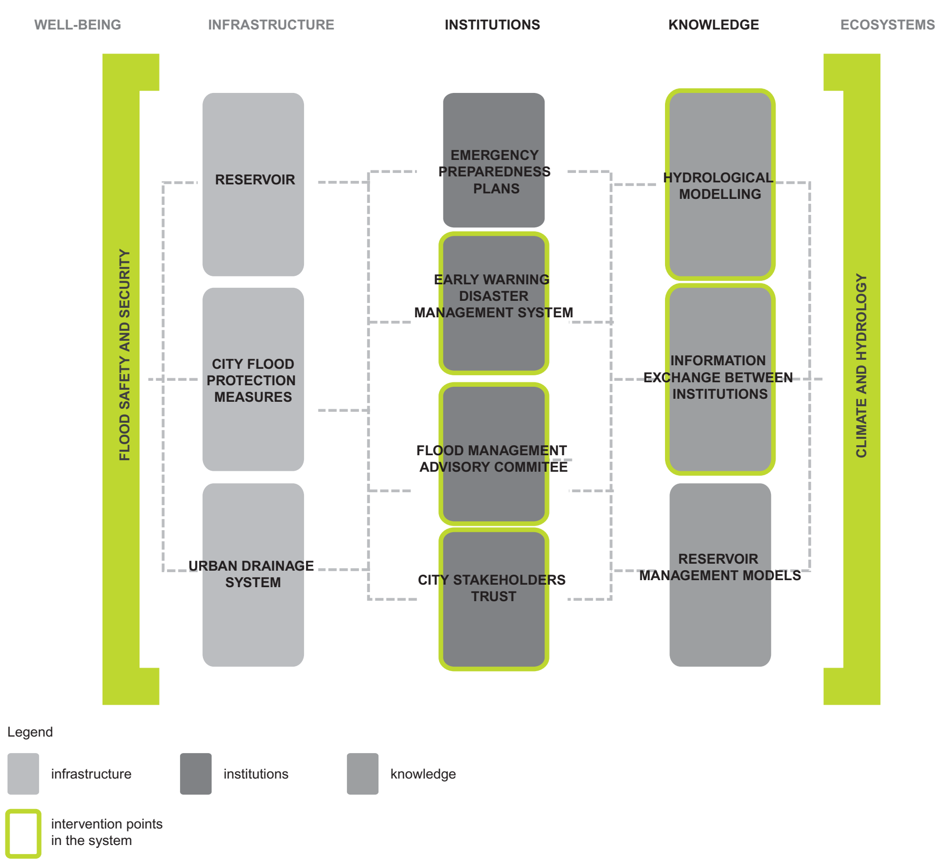

Figure 6. Systems analysis of flood safety and security, Surat, India.

Water Resources Water Supply and Kalpasar Department. In terms of resilience characteristics, the Surat example highlights efforts to improve the management and decision-makings around water storage and release at the Ukai Dam are focused on strengthening the relevant institutional and knowledge systems. These approaches demonstrate: *flexibility* – the improved management of the Ukai dam means that it will be able to function normally within a wider range of rainfall patterns; and *safe failure* – controlled release of water from the Ukai dam is a mechanism to manage the potential failure of the dam if its capacity is exceeded.

A similar analysis of flood safety and security in Bandar Lampung, Indonesia, identified that the effectiveness of the existing urban drainage system was severely compromised by unregulated dumping of waste in drainage channels, canals and rivers (infrastructure networks). This practice was causing freshwater contamination and disease (Institute for Social and Environmental Transition *et al*. 2010). As an intervention to the system, the city proposed the development of a city-wide integrated solid waste management plan in order to decrease the risk of flooding, as well as the generation and spread of vector and waterborne disease. In terms of resilience characteristics, research into current solid waste management conditions within the city, policy analysis and identification of national best practice shared through multi-stakeholder engagement increases *resourcefulness* – the capacity of internal agents to identify problems, prioritise actions and mobilise resources. Further, multi-sectoral working increases *responsiveness* – the capacity to organise the effective management urban systems such as solid waste management and water and sanitation infrastructure.

In Quy Nhon, Vietnam, flooding has always been a common occurrence as the city is prone to typhoons and storm surge (Huynh and DiGregorio 2010). Increased flooding has been attributed to changing rainfall patterns, but locally flooding is exacerbated by the uncontrolled urban expansion into the flood plain and sensitive coastal zones. Moreover, the impacts of flooding are now more intense, principally due to the funnelling of flood waters which in the past used to be undirected. These waters are now concentrated as a result of urban infrastructure which has raised the ground level to provide flood protection, and constructing man-made barriers (Brown and Kernaghan 2011). Flood waters build up around these barriers and create large-scale destruction when they eventually overflow. The city has recognised the need for institutional interventions and is looking into enhancing its understanding of the interaction between population growth, flooding and land use – creating the basis for improved urban planning practices. In terms of resilience characteristics, documentation of the 2009 floods, the creation of a shared flood and urban development model, and working as part of a multi-sectoral working group supports the *capacity to learn* – improved learning between stakeholders as working relationships are established.

Well-being in Chiang Rai, Thailand, is threatened by food and livelihood insecurity. The city is known for its relatively cool climate which allows significant urban agriculture on its periphery, particularly cultivation of fruit trees. Changing distribution of rainfall is now leading to droughts and water scarcity which is negatively affecting the agricultural sector. Temperature increases attributable to climate change have also altered growing seasons for some crops and brought increased exposure to disease carrying vectors so that dengue fever borne by mosquitoes has increased significantly. Reduced productivity has been linked to these health issues as well as higher temperatures which shorten the hours that farmers can work (Chiang Rai ACCCRN City Team and Thailand Environment Institute 2011). Raising the level of knowledge among urban poor on improved farming practices is recognised as critical to improving food and income security, and measures to introduce improved farming practices (inter-cropping and crop diversification) that utilise water more efficiently are being explored (see Figure 7). In terms of resilience characteristics, the Chiang Rai project includes rehabilitating the river, which will act as a reserve water

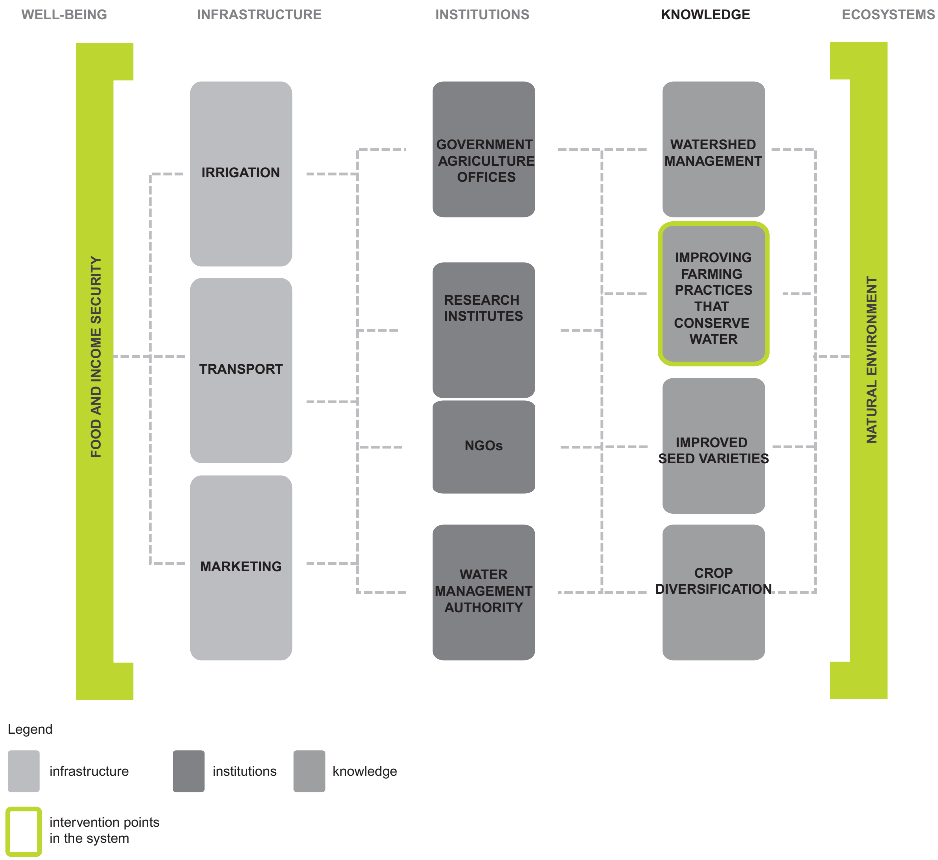

Figure 7. Systems analysis of food and income security, Chiang Rai, Thailand.

source building *redundancy* into the water supply system.

Households in Indore, India, face very severe water shortages due to limited local water supply which will become even more limited as a result of climate change, compounded by poor management and significant reliance on infrastructure. The local groundwater is increasingly polluted, and the city is reliant on water pumped from over 70 km away which is expensive and unreliable. The piped water distribution does not serve informal settlements which rely on wells and boreholes, limited rainwater harvesting and delivery by tankers. Water insecurity and the cost of water for these communities is significantly higher than in more affluent areas (TARU Leading Edge *et al*. 2010a). The analysis in Figure 8 demonstrates the opportunity for community-level interventions centred on improving knowledge of water resources, how to use water efficiently and improving water quality. These measures include water management at the household level, and introducing appropriate technologies to capture and treat water. In terms of resilience characteristics, the conjunctive water management project aims to demonstrate viable models for cost-effective, reliable, decentralised urban water management through community involvement. *Increasing reliance on local ecosystems* is core to this approach as remote water sources are unreliable. Through more flexible

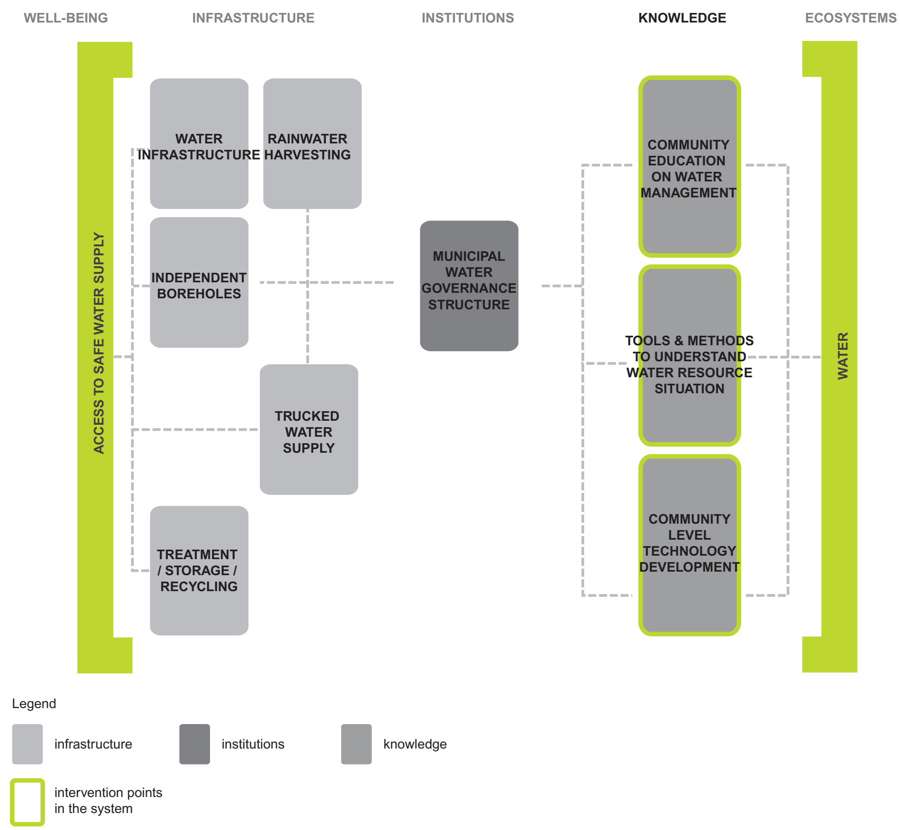

Figure 8. Systems analysis of water supply in Indore, India.

sources of water supply, institutions and infrastructure options – access to these local ecosystems is being improved.

There are currently over 25 projects that the 10 ACCCRN cities are implementing, demonstrating action at a range of levels, and providing early evidence that cities need to focus on their systems of provision, and increasing the resilience characteristics of those systems, in order to build resilience of cities to the impacts of climate change and others shocks and stresses. Further research to build an evidence base of what does (and does not) contribute to urban resilience, and the contexts in which specific interventions are applicable, is urgently needed. The interventions in 10 Asian cities in four countries as part of the ACCCRN programme of the Rockefeller Foundation are a notable effort towards meeting this need.

5. Conclusion

The well-being of more than half the world's population relies on a complex web of knowledge, institutions and infrastructure networks which mediate their dependency on natural resources. The ability of these networks to evolve and adapt to changing circumstances and extreme events as a result of climate change will determine the future of many cities; the alternative being progressive decay or catastrophic collapse of urban areas, housing 100,000s of people with wider economic implications.

This article identifies the future challenges cities face in their ability to provide well-being as a result of the compound effect generated by climate change, distinguishing between (1) direct impacts (e.g. due to temperature rise or flooding);

(2) indirect effects arising from disruption or loss of essential assets and networks that enable the city to function and (3) pre-existing vulnerability due to lack of services, infrastructure deficits, political voice and limited livelihood opportunity which compromises adaptive capacity. This suggests that action to reduce exposure and improve the adaptive capacity of urban populations must therefore simultaneously address DRR, urban poverty reduction and urban resilience (i.e. the ability of the city to maintain the functions that support the well-being of its citizens). In each of these three areas, action is required at multiple levels: within communities working through civil society organisations (e.g. NGOs and CBOs) and local government, as well as at a city-wide level integrated into formal planning processes and investment decisions and through national policy. Action which benefits large numbers of people and positively impacts the most vulnerable communities should be prioritised.

Whereas there is a strong evidence base of large- and small-scale interventions which positively contribute to DRR and poverty reduction, urban resilience is an emerging field. Cities are complex socio-technical systems, and as such it is difficult to predict their behaviour. Spatial analysis alone is insufficient as it does not recognise the flows of goods, services and people that enable a city to function. Equally, climate change impacts are based on uncertain projections, which challenge the 'predict and prevent' paradigm that has formed the basis of geo-hazard planning and engineering to date.

The examples from cities participating in the ACCCRN programme illustrate how a simplified conceptual model of the urban system can be used to analyse a city in terms of its key systems of provision (e.g. food, water and energy) and their relationships within and outside the city, to be able to understand how susceptible they are to the types of shocks and stresses that might arise as a result of climate change. This is likely to be most significant where there are serious shortfalls in resources, or inadequate coverage and capacity that already compromise well-being, placing communities under stress even before climate impacts are considered. Interventions can then be identified which address critical gaps or weaknesses in the system, and catalyse alternative behaviours that build resilience.

Action to build an evidence base of what does (and does not) contribute to resilience is urgently needed, not least to inform how resilience can be measured. As an attribute of the urban system's behaviour, resilience cannot be measured directly other than in terms of changing performance in response to shocks and stresses. Moreover, resilience will only be achieved through the cumulative contribution of multiple interventions and actions over time, and the ability of individuals and institutions to internalise learning and experience to inform future behaviour. The characteristics of the socio-technical networks that comprise a resilient city presented in this article can be used to define the desired network outcome (rather than output) arising from any intervention targeted at building urban resilience and are a first step towards developing measurable network indicators.

Acknowledgements

The authors are indebted to the wealth of experiences being generated by the ACCCRN partners and cities. This article grew out of the challenges that each city faces in attempting to build resilience to climate change and the search for conceptual clarity and practical responses.

Notes

1. Arup is an independent firm of built environment professionals (designers, planners and engineers) whose mission statement is to 'shape a better world'.
2. For further information, see http://www.acccrn.org
3. For a detailed description of system dynamics, refer to Forrester and Wright (1969), Clayton and Radcliffe (1996) and Coyle (1996).
4. For further examples, see 'Climate Action in Megacities: C40 Cities Baseline and Opportunities Version 1.0 June 2011' (http://arup.com/Publications/Climate_Action_in_Megacities.aspx). Based on a survey of member cities, it analyses the powers, actions and opportunities of the world's 40 premier cities to adapt to climate change.

5. The enabling environment described here, and its analogous use with the real functional boundary of a city, is not the same as the 'Functional Urban Area'. The 'Functional Urban Area' is in principle a spatial designation that recognises that several key dynamics of cities (e.g. employment and/or housing), occur outside the official administrative boundaries and in the fringe areas, forming an 'increasingly interwoven and interactive functional region' (Antikainen 2005).
6. The notion of safe failure is grounded in seismic design approaches. An alternative conceptualisation is provided by the notion of ductility. Safe failure should not be confused with 'fail safe', which refers to a system or mechanism that is guaranteed not to fail.
7. For example, in a bid to increase access to key resources, large cities in both developed and developing nations are implementing a new resource paradigm known as Secure Urbanism and Resilient Infrastructure (SURI) (Hodson and Marvin 2009). This approach is seen as a strategic response to issues of resource constraint, climate change and energy security and is designed to secure the key resources required for ecological and material reproduction, particularly those required to maintain and enhance economic growth.
8. The City Resilience Strategies for the ACCCRN cities are available to download from http://www.acccrn.org/resources

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