TOWARDS NATURE-BASED RESILIENCE IN INFRASTRUCTURE DEVELOPMENT AND ASSESSMENT: AN INTRODUCTORY GUIDE

Dr Michelle Audouin & Dr Nadia Sitas
Council for Scientific and Industrial Research (CSIR) 2019

Published in collaboration with the Centre for Complex Systems in Transition (CST), Stellenbosch University

Photo credit: Ryan McGuire

CSIR
our future through science

GRAID
At Stockholm Resilience Centre

CST Centre for Complex Systems in Transition

CONTENTS

LIST OF TABLES AND FIGURES

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support and funding provided for the production of this Guide, by the GRAID (Guidance for Resilience in the Anthropocene: Investments for Development) Programme. This programme is coordinated by the Stockholm Resilience Centre (SRC) at Stockholm University and funded by the Swedish International Development Cooperation Agency (Sida). This guide was published in collaboration with the Centre for Complex Systems in Transition (CST) at Stellenbosch University.

REVIEWERS

Thank you to the reviewers: Ms Susie Brownlie (de Villiers Brownlie and Associates cc) for providing comments on a working draft of the Guide; Mr Eoin Sinnot (previously Director, Valuing Nature Initiative, WWF-US), who provided a 'rapid review' of later draft; and to Prof. Nicholas King (Research Unit for Environmental Science and Management, North-West University, South Africa), Dr Jennifer Pope (Senior Lecturer, Edith Cowan University, Australia; Director, Integral Sustainability, Australia) and Dr Joshua Lewis (The ByWater Institute, Tulane University, United States), who all provided very useful comments on Version 1 of the Guide. The authors also wish to express their sincere gratitude to Prof. Reinette (Oonsie) Biggs (Stellenbosch University, Centre for Complex Systems in Transition) for undertaking the final review of the guide.

DISCLAIMER

Whilst every effort has been made to ensure that the information published in this work is accurate, the authors, editors, publishers and printers take no responsibility for any loss or damage suffered by any person as a result of the reliance upon the information and/ or recommendations contained herein.

DEFINITIONS

TERM	DEFINITION	REFERENCE
COMPLEX ADAPTIVE SYSTEMS	Complex adaptive systems are open systems that comprise many interacting components that individually and collectively adapt to change. These systems also exhibit behaviour that results from the interactions between system components, but which is not inherent to the characteristics of the individual components themselves (i.e. emergent behaviour). At least some of these interactions are non-linear, contributing to the dynamic and unpredictable nature of these systems. Examples of complex adaptive systems include the economy, the weather and more broadly, linked social-ecological systems.	Cilliers, 2008; Bohensky *et al.*, 2015; Stockholm Resilience Centre, n.d.
ENVIRONMENTAL IMPACT ASSESSMENT (EIA)	Environmental Impact Assessment (EIA) is a systematic process that involves the evaluation of the potential positive and negative effects of a proposed project (e.g. energy plant or a new road) on the natural, social and economic environment. Its purpose is to inform decision-makers on whether or not such projects should be approved and if so, under what conditions.	Wood, 2003.
FEEDBACK LOOPS WITHIN SOCIAL-ECOLOGICAL SYSTEMS	Feedback loops refer to instances where changes in a particular system variable result in interactions through the system, that eventually loop back to affect the original variable. These feedback loops can either reinforce existing system behaviour (i.e. positive feedbacks) or dampen/reduce this behaviour (i.e. negative feedbacks).	Biggs *et al.*, 2015.
GREEN INFRASTRUCTURE	Green infrastructure refers to "... the interconnected set of natural and man-made ecological systems, green spaces and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces and original grassland and woodlands, as well as possible building and street-level design interventions that incorporate vegetation, such as green roofs. Together these assets form an infrastructure network providing services and strategic functions in the same way as traditional 'hard' infrastructure".	Schaffler *et al.*, 2013: 3.
RESILIENCE OF SOCIAL-ECOLOGICAL SYSTEMS	"... the capacity of an SES (social-ecological system) to sustain human well-being in the face of disturbance and change, both by buffering shocks and by adapting or transforming in response to change" (parenthesis added).	Biggs *et al.*, 2015: 22.
RESILIENT INFRASTRUCTURE	The capacity of an infrastructural system or development "... to sustain human well-being in the face of change, both by buffering shocks but also through adapting or transforming in response to change".	Biggs *et al.*, 2015: 13.
SLOW AND FAST SYSTEM VARIABLES	Social-ecological systems comprise numerous variables that interact and change at different rates. 'Slow' variables (e.g. soil composition, erosion control, legal systems and traditions) typically determine the underlying structure of a social-ecological system, while its dynamics generally arise from interactions and feedbacks between 'fast' variables (e.g. crop production, water provision and harvesting of fish). It is important to note that the terms 'fast' and 'slow' are relative to one another in the context of a specific system.	Biggs *et al.*, 2015

SOCIAL-ECOLOGICAL SYSTEMS (SES)	"Social-ecological systems are linked systems of people and nature. The term emphasizes that humans must be seen as a part of, not apart from, nature — that the delineation between social and ecological systems is artificial and arbitrary." The term was coined by Fikret Berkes and Carl Folke in 1998 to give equal emphasis to the social and ecological dimensions.	Stockholm Resilience Centre, https://www.stockholmresilience.org/research/resilience-dictionary.html [2019, May 28].
SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT	The terms 'sustainability' and 'sustainable development' are used interchangeably in this guide to mean development that "… seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" as defined in the Brundtland Report.	World Commission on Environment and Development (WCED), 1987: Chapter 1, Part II (49)).
SUSTAINABILITY ASSESSMENT	Sustainability assessment - as it has emerged in the field of impact assessment - typically involves the evaluation of alternative project, plan or policy proposals against a set of contextually-derived sustainability objectives, targets and indicators. Sustainability assessment includes the selection and enhancement of a preferred project, plan or policy alternative; as well as monitoring and review (or follow-up) of the results of monitoring (Bond et al., 2015).	Bond and Morrison-Saunders, 2013; Bond *et al.*, 2015.
SUSTAINABILITY OBJECTIVES AS DEVELOPED WITHIN THE PROCESS OF SUSTAINABILITY ASSESSMENTS	Sustainability objectives (as defined within sustainability assessments) are aspirational statements of what a development project, plan or policy aims to achieve, specifically in terms of the general principles of sustainability (e.g. equity, developing within the biophysical limits of the environment etc.). While based on these general principles, such sustainability objectives are adapted specifically to the context of the assessment and should be defined by a range of stakeholders (e.g. representatives from local communities, government, business and academia). The objectives may include, for example, increasing access to health and education in a particular area and/or maintaining the quality and quantity of water in an important catchment. The potential positive and negative impacts of the project, plan or policy being considered are then evaluated against these objectives. This orientates the assessment beyond consideration of the effects of the proposed project, plan or policy on the current situation, towards aspirational possibilities for the future.	Therivel, *et al.*, 2009; Pope *et al.*, 2004.
SYSTEM CONNECTIVITY	Connectivity refers to the way in which parts of the SES interact with each other, primarily to transfer material, communicate and transform energy. The structure and strength of these interactions is included in the concept of system connectivity. Where green spaces are well connected within urban areas, for example, the movement of organisms from one area to another is facilitated, thereby increasing the resilience of the system to disturbances. However, limited connectivity can also enhance resilience through minimising the spread of disturbances such as fire and disease.	Biggs *et al.*, 2015.

SUMMARY

Infrastructure is critical to Africa's development and its ability to address poverty (African Development Bank (AfDB), 2018). Achieving Africa's development aspirations hinges on ensuring equitable access, not only to basic infrastructure such as water and sanitation systems, new electricity lines, roads and storm water drainage; but also to enhanced access to telecommunications and modern agricultural technologies for food security. However, the infrastructure deficit in Africa is well recognised and has been highlighted as one of the fundamental contributing factors hindering development in the region (World Wildlife Fund (WWF) and AfBD 2015; AfDB, 2017; African Union Commission (AUC), 2015). In response to this, the Programme for Infrastructure Development in Africa (PIDA), which has the support of all African countries, has been initiated.

The development of such infrastructure, however, needs to be undertaken in a way which is adaptable to a world of growing uncertainty and depleting resources. Africa is experiencing increasing demands on – and threats to – its natural resource base as a result of factors such as rapid urbanisation, land use change in the form of expanding agriculture, mining, illegal wildlife trade and the overharvesting of resources, among many other factors (WWF and AfBD 2015; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2018). Moreover, anthropocentric climate change is leading to warming across the continent and temperatures are expected to rise faster than the global average calculated for this century (International Panel on Climate Change (IPCC), 2014).

It is therefore critical that infrastructure is developed in a way that is resilient. Such resilience must be based on an understanding – and recognition of – the intrinsic systemic interdependencies between infrastructure projects, the broader social-ecological environment in which they are embedded, and the well-being of Africa's people (Biggs et al., 2015; WWF and AfBD, 2015; Folke et al., 2016). This approach to resilience includes, not only the ability of infrastructure to 'bounce back' from change and disasters, but also its ability to adapt and transform in response to changes in the broader social-ecological system of which it is a part, and on which it depends (Biggs et al., 2015; Gallego-Lopez and Essex, 2016). This social-ecological system may comprise, for example, an infrastructural project's sources of water, energy and building materials; as well as its employees, stakeholders, service providers and the communities that it serves, and their changing needs and values.

Drawing on a **de(nition of resilience** provided by Biggs et al. (2015: 13), 'resilient infrastructure' can therefore be understood as the capacity of an infrastructural system or development:

"… TO SUSTAIN HUMAN WELL-BEING IN THE FACE OF CHANGE, BOTH BY BUFFERING SHOCKS BUT ALSO THROUGH ADAPTING OR TRANSFORMING IN RESPONSE TO CHANGE"

In this context, 'sustaining human well-being' means promoting the sustainability of the social-ecological system of which infrastructure is a key part. The terms 'sustainability' and 'sustainable development' are used interchangeably in this guide to mean development that "… seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future", as defined in the Brundtland Report (World Commission on Environment and Development (WCED), 1987: Chapter 1, Part II (49)). More recently, United Nations (UN) Members States agreed in 2015 to a specific international agenda for sustainable development which is articulated in 17 goals that aim to end poverty, as well as promote economic growth, address climate change and preserve our natural environment (UN, n.d.(a)). Of particular relevance is Goal 9 which is to:

"BUILD RESILIENT INFRASTRUCTURE, PROMOTE INCLUSIVE AND SUSTAINABLE INDUSTRIALIZATION AND FOSTER INNOVATION (UN, n.d. (b))".

The purpose of this guide is to provide an introduction to resilience thinking as it applies to the environmental assessment of infrastructure projects in sub-Saharan Africa. The guide primarily aims to assist development and environmental management practitioners and governmental decision-makers, as well as development funding agencies which support infrastructure projects on the continent. The focus is on the energy, transport

and water sectors. It is important to note that there are very few documented case studies and limited other resources available that articulate experience and learning with the application of resilience thinking (as defined in this guide) to the assessment of infrastructure development, and even fewer that are of immediate relevance to sub-Saharan Africa. This guide is therefore partly exploratory in nature, and the recommendations included are presented to provide a point of departure for debate, testing and further development in this sphere.

THREE KEY TENETS for integrating resilience thinking into infrastructure development in sub-Saharan Africa are discussed in the guide. These tents are as follows (Harrison et al., 2014; Biggs et al., 2015; Pandit and Crittenden, 2015; Gallego-Lopez and Essex, 2016; Folke et al., 2016; Lloyds and Arup, 2017; Brownlie, Pers. Comm. 23/12/2017):

1. Develop infrastructure projects in a way that maintains (does not diminish) and enhances the sustainability of the social-ecological system in which they are embedded (e.g. promote local employment directly through job creation and indirectly through the use of local service providers);
2. Develop infrastructure projects to be adaptable to change and unexpected disturbances in a sustainable way (e.g. through ensuring diversity in renewable sources of energy and water supply); and
3. Ensure inclusivity in infrastructure planning, operation and maintenance (e.g. actively respond to the needs and values of local stakeholders, particularly traditionally marginalised communities).

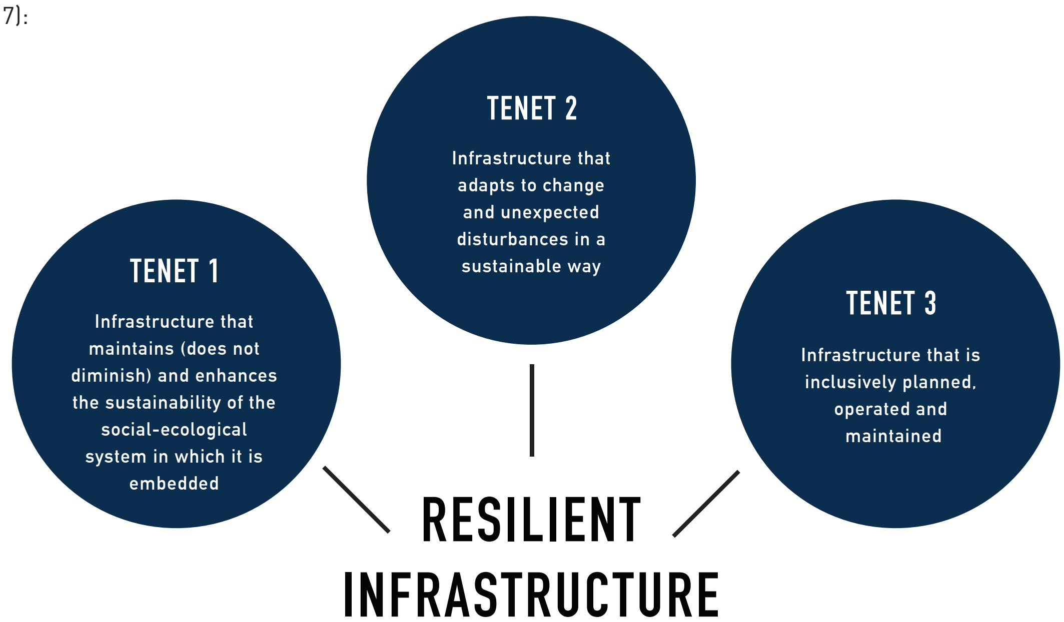


Figure 1: Integrating Resilience Thinking into Infrastructure Development: 3 Tenets

Based on these tenets, **recommendations** for the incorporation of resilience thinking into the design and assessment of proposed infrastructure projects are presented in the guide. In particular, these recommendations relate to Environmental Impact Assessment (EIA); and sustainability assessment (at the project-level of decision-making). However, it is important to note that the scope of these recommendations applies not only to the 'assessment' phase of project development, but also to determining its need and desirability. This task may be undertaken as part of other processes such as feasibility studies and/or the formulation of town planning applications (e.g. for rezoning). The recommendations are structured according to the following generic steps:

1. Identification of the need and desirability of the proposed infrastructure development;

2. Identification of sustainability objectives and targets;

3. Description of the social-ecological system;

4. Assessment of the proposed infrastructure development; and

5. Formulation of strategies and/or mitigation measures.

IMPORTANT NOTE: *The recommendations and lists provided in the guide are intended to support the integration of resilience principles in particular into the EIA and/or sustainability assessment process. They do not cover all aspects that should typically be considered in each of the phases of environmental/sustainability assessment processes. It is also acknowledged that EIA processes, in particular, are typically legislated and that in some instances implementing the actions recommended in this guide may require changes in such legislation. These recommendations are therefore provided as a guide to start exploring and testing as far as possible (and feasible), ways to integrate resilience thinking into assessment processes for infrastructure development in Africa.*

Figure 2 below provides a broad summary of the recommendations for integrating resilience principles into each stage of the assessment process. Each stage and the associated recommendations are discussed separately in further detail in the guide.

RECOMMENDATIONS FOR INTEGRATING RESILIENCE PRINCIPLES: SUMMARY

STAGE OF ASSESSMENT PROCESS

NEED AND DESIRABILITY OF THE PROPOSED PROJECT

WHEN DETERMINING THE NEED AND DESIRABILITY OF THE PROJECT INCLUDE WHETHER:

- Green infrastructure could replace and/or enhance the delivery of the services required;
- It will contribute to the resilience of the broader social-ecological system in a sustainable way;
- It will, itself, be able to sustainably adapt to constant change and unpredictable events;
- It responds to the needs and values of stakeholders, particularly from traditionally marginalised groups.

IDENTIFICATION OF SUSTAINABILITY OBJECTIVES AND TARGETS

WHEN IDENTIFYING OBJECTIVES:

- Maximise opportunities to sustainably contribute to the resilience of the broader social-ecological system (including linking to elements of green infrastructure);
- Ensure adaptability of the infrastructure itself to unpredictable events and disasters in a sustainable way;
- Maximise opportunities to directly respond to stakeholder needs andpriorities (particularly from traditionally marginalised groups) throughout the project lifecycle.

DESCRIPTION OF THE SOCIAL-ECOLOGICAL SYSTEM

Using a variety of tools, develop a conceptual framework which represents the social-ecological system to which the proposed infrastructure project is linked. As far as possible, represent and describe the links between social, ecological and economic elements, as well as characteristics that determine system resilience (e.g. diversity of the system) - see Supplementary Sheet 2. Include elements of the natural environment that can provide relevant infrastructural services (e.g. wetlands that contribute to water purification), as well as a description of the needs and priorities of various stakeholders.

ASSESSMENT OF THE PROPOSED INFRASTRUCTURE PROJECT

Include in the assessment of the proposed infrastructure project its effect on characteristics of the social-ecological system which influence its resilience (e.g. diversity and connectivity within the system) - see Supplementary Sheet 2. Include the extent to which the proposal has maximised opportunities to integrate natural features into the design; as well as to directly respond to stakeholder values and priorities, particularly those of traditionally marginalised groups. Evaluate the significance of these effects in light of the sustainability objectives identified earlier in the process.

DEVELOPMENT OF MITIGATION MEASURES & MANAGEMENT STRATEGIES

FORMULATE MANAGEMENT STRATEGIES AND/OR MITIGATION MEASURES, TOGETHER WITH KEY STAKEHOLDERS, IN ORDER TO, INTER ALIA:

- Mitigate the direct impacts of the project on the aspects of the social-ecological system that affect its resilience (and its ability to achieve sustainability goals) - see Supplementary Sheet 2;
- Weaken feedback loops that trap the system in unsustainable states (e.g. reliance on vehicles) and enhance feedback loops that promote system resilience for sustainability (e.g. use of renewable energy);
- Enhance the technical ability of the infrastructure project to be resilient in a sustainable way (e.g. diversify water sources to include recycled and/or desalinated water);
- Mitigate any potentially significant negative impacts on stakeholder groups, prioritising those that affect historically marginalised communities;
- Design management strategies and mitigation measures to enable their testing and evaluation in a process of continual learning.

Figure 2: Integrating Resilience Principles into Environmental Assessment (EIA and Sustainability Assessment): Summary

1. INTRODUCTION

1.1. BACKGROUND: RESILIENCE, SUSTAINABILITY AND INFRASTRUCTURE DEVELOPMENT IN AFRICA

Infrastructure is critical to Africa's development and its ability to address poverty (African Development Bank (AfDB), 2018). Achieving Africa's development aspirations hinges on ensuring equitable access, not only to basic infrastructure such as water and sanitation systems, new electricity lines, roads and storm water drainage; but also to enhanced access to telecommunications and modern agricultural technologies for food security. However, the infrastructure deficit in Africa is well recognised and has been highlighted as one of the fundamental contributing factors hindering development in the region (World Wildlife Fund (WWF) and AfBD 2015; AfDB, 2017; African Union Commission (AUC), 2015). The New Partnership for Africa's Development's (NEPAD) Planning and Coordinating Agency (NEPAD Agency, n.d.) reports that infrastructure inefficiencies on the continent are costing billions of dollars annually and constraining economic growth. In response to this, the Programme for Infrastructure Development in Africa (PIDA), which has the support of all African countries, has been initiated. This programme promotes regional cooperation through the development of infrastructure that is mutually beneficial and which enables increased trade and regional competitiveness (NEPAD Agency, n.d.). The focus of PIDA is on the four sectors of energy, transport, information and communication technology (ICT) and transboundary water.

The development of such infrastructure, however, needs to be undertaken in a way which is adaptable to a world of growing uncertainty and depleting resources. Africa is experiencing increasing demands on – and threats to – its natural resource base as a result of factors such as rapid urbanisation, land use change in the form of expanding agriculture, mining, illegal wildlife trade and the overharvesting of resources, among many other factors (WWF and AfBD 2015; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2018). Moreover, anthropocentric climate change is leading to warming across the continent and temperatures are expected to rise faster than the global average calculated for this century (International Panel on Climate Change (IPCC), 2014). Predicted changes in rainfall are more uncertain than those related to temperature, however climate change (together with drivers such as urbanisation and increased agriculture) is expected to exacerbate water shortages where these already exist, including in parts of southern Africa (IPCC, 2014). Climate change is also likely to increase food insecurity and vulnerabilities to disease, among other factors (IPCC, 2014) (Box 1).

BOX 1: POTENTIAL IMPACT OF CLIMATE CHANGE ON ROAD INFRASTRUCTURE IN AFRICA

Increases in temperature can lead to the "...softening and rutting of asphalt roads", while increased precipitation can reduce the carrying capacity and lifespan of roads, as well as, in severe cases, cause their)ooding and erosion (Cervigni et al, 2017: 28). The result includes increased maintenance costs, as well as disruption in the transport of people and goods. This reduction in connectivity can, in turn, have negative effects on food security in Africa, as well as signi(cant implications for the health of local, national and regional economies.

It is therefore critical that infrastructure is developed in a way which is resilient. Such resilience must be based on an understanding – and recognition of – the intrinsic systemic interdependencies between infrastructure projects, the broader social-ecological environment and the well-being of Africa's people (Biggs et al., 2015; WWF and AfBD, 2015; Folke et al., 2016). This approach to resilience includes not only the ability of infrastructure to 'bounce back' from change and disasters, but also its ability to adapt and transform in response to changes in the broader social-ecological system of which it is a part, and on which it depends (Biggs et al., 2015; Gallego-Lopez and Essex, 2016). This social-ecological system may comprise, for example, an infrastructural project's sources of water, energy and building materials; as well as its employees, stakeholders, service providers and the communities that it serves and their changing needs and values.

Drawing on a definition of resilience provided by Biggs et al. (2015: 13), 'resilient infrastructure' can therefore be understood as the capacity of an infrastructural system or development:

"... TO SUSTAIN HUMAN WELL-BEING IN THE FACE OF CHANGE, BOTH BY BUFFERING SHOCKS BUT ALSO THROUGH ADAPTING OR TRANSFORMING IN RESPONSE TO CHANGE"

(See Supplementary Sheet 1 for more information).

In this context, 'sustaining human well-being' means promoting the sustainability of the social-ecological system of which infrastructure is a key part. The terms 'sustainability' and 'sustainable development', in turn, are used interchangeably in this guide to mean development that "... seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" as defined in the Brundtland Report (World Commission on Environment and Development (WCED), 1987: Chapter 1, Part II (49)). More recently, United Nations (UN) Members States agreed in 2015 to a specific international agenda for sustainable development which is articulated in 17 goals that aim to end poverty, as well as promote economic growth, address climate change and preserve our natural environment (UN, n.d.(a)). Of particular relevance is Goal 9 which is to:

"BUILD RESILIENT INFRASTRUCTURE, PROMOTE INCLUSIVE AND SUSTAINABLE INDUSTRIALIZATION AND FOSTER INNOVATION (UN, n.d. (b))".

1.2. PURPOSE AND USE OF THIS GUIDE

The purpose of this guide is to provide an introduction to resilience thinking as it applies to the environmental assessment of infrastructure projects in sub-Saharan Africa. The guide primarily aims to assist development and environmental management practitioners and governmental decision-makers, as well as development funding agencies which support infrastructure projects on the continent. The focus is on the energy, transport and water sectors. It is important to note, however, that there are very few documented case studies and limited other resources available that articulate experience and learning with the application of resilience thinking (as defined in this guide) to the assessment of infrastructure development; and even fewer that are of immediate relevance to sub-Saharan Africa. This guide is therefore partly exploratory in nature, and the recommendations included are presented to provide a point of departure for debate, testing and further development in this sphere.

This introductory guide is based on understanding developed through consulting the literature on resilience; infrastructure development; sustainability and environmental assessment; and management. Importantly, it is also informed by participation in relevant global initiatives (e.g. IPBES); as well as involvement for many years in the environmental management sphere. This involvement includes the practice of environmental assessment, but focuses on research and the development of new innovations in this domain.

Following this introduction, the concept of 'resilience thinking' as it applies to this guide is outlined in Section 2, followed by its broad application to the context of infrastructure development in Section 3. In Section 4 recommendations are presented for the integration of resilience thinking into project-based environmental assessment (i.e. to Environmental Impact Assessment (EIA) and Sustainability Assessment). Following the conclusion in Section 5, the guide includes three 'supplementary sheets'. These sheets provide more detailed information to the reader on topics that are discussed in the guide (reference is made to them, where appropriate, throughout the main body of the text).

In the section that follows, 'resilience thinking' is described as the foundation for the discussion and recommendations regarding infrastructure development in Africa outlined in this guide.

Photo Credit: Ashraf Hendricks/GroundUp

2. RESILIENCE THINKING

Resilience thinking, as discussed in Section 1.1. above, acknowledges that humans are embedded in the biosphere, as part of social-ecological systems that, by nature, are subject to both ongoing and unpredictable changes (Biggs et al., 2015; Folke et al., 2016). In summary, the approach to resilience thinking adopted in this guide (Biggs et al., 2015; Folke et al., 2016):

- **Acknowledges the interdependent nature of social (including economic) and ecological aspects of reality** in which the well-being of human beings is inexorably connected to the state of the Earth's biosphere. The actions of people influence the biosphere (e.g. its ability to sustain itself); while natural elements (e.g. water and fertile soil) shape human activities and are a requirement for human health and well-being. Recognition of this interrelationship is reflected in the use of the term 'social-ecological systems'.

- **Recognises that social-ecological systems are complex and adaptive.** This means that such systems have the capacity to self-organise, learn and adapt in response to changing conditions in a way that is often unpredictable. This unpredictability results from numerous factors, including that elements within social-ecological systems (e.g. local communities, organisations, ecological processes) often interact in non-linear ways (i.e. small causes can have large effects and vice versa). Social-ecological systems also exhibit emergent properties, which are properties that cannot be attributed to any specific elements of the system (e.g. poverty and ecological sustainability can both be thought of as emergent properties that result from multiple interacting factors within the system). This unpredictability of complex systems is exacerbated by the fact that change, which is inherent to such systems, does not occur in a uniform way. Fast, unexpected change (e.g. new political leadership appointments and policies) can suddenly occur in a context where slow, gradual fluctuations (e.g. incremental changes and variations in political views among policy-makers) were predominant. The components or elements of social-ecological systems also interact at multiple temporal and spatial scales and across these scales. Changes that take place at a global scale, for example, can have significant implications for local dynamics and vice versa (e.g. global changes in the price of liquid natural gas (LNG), for example, can influence the viability of constructing a local LNG plant).

- **Focuses on the capacity of the system to adapt to continual change and unexpected shocks; as well as to transform in a way that sustains human well-being.** As discussed in Section 1.1. , the approach to resilience in this guide includes the ability of a system (in this case an infrastructure system or project), not only to 'bounce back' from unexpected disasters (e.g. fire, floods and earthquakes), but also to adapt and transform the way it operates in order to maintain and enhance the sustainability of the social-ecological system of which it is a part (e.g. through minimising water use, recycling waste and promoting local employment).

Photo Credit: Danie Nel Photography, Shutterstock

3. RESILIENCE THINKING AND INFRASTRUCTURE DEVELOPMENT IN SUB-SAHARAN AFRICA

In this section, key tenets for integrating resilience thinking into infrastructure development in sub-Saharan Africa are introduced. These tenets, which are based on fundamental notions inherent to the approach to resilience discussed in Section 2, are as follows (Harrison et al., 2014; Biggs et al., 2015; Pandit and Crittenden, 2015; Gallego-Lopez and Essex, 2016; Folke et al., 2016; S. Brownlie, personal communication (email, 23/12/2017); Lloyds and Arup, 2017):

1. Develop infrastructure projects in a way that maintains (does not diminish) and enhances the sustainability of the social-ecological system in which they are embedded;
2. Develop infrastructure projects to be adaptable to change and unexpected disturbances in a sustainable way; and
3. Ensure inclusivity in infrastructure planning, operation and maintenance.

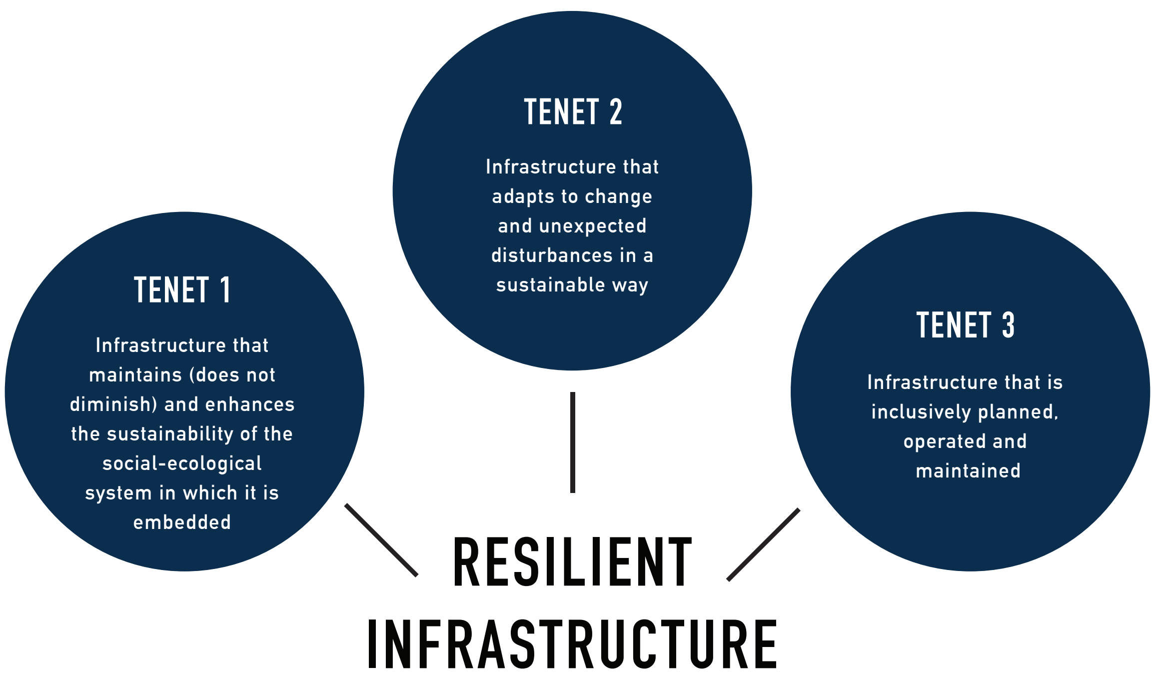


Figure 3: Integrating Resilience Thinking into Infrastructure Development: 3 Tenets

TENET 1: DEVELOP INFRASTRUCTURE PROJECTS IN A WAY THAT MAINTAINS AND ENHANCES THE SUSTAINABILITY OF THE SOCIAL-ECOLOGICAL SYSTEM IN WHICH THEY ARE EMBEDDED

Resilience brings to the fore the importance of recognising that infrastructure is an integral part of linked social-ecological systems (Biggs et al., 2015). Built infrastructure (e.g. dams) channels ecosystem service flows (e.g. clean water) enabling rural and urban development, while at the same time depending on provisioning services such as land, water and timber for its construction. Infrastructure development is critical to enable inclusive growth in Africa and to address poverty. However, if not undertaken in a sustainable way, it can also modify and/or degrade ecosystem services, limiting their ability to support development and local livelihoods (e.g. through the provision of food, water and clean air) (WWF and AfBD 2015). Such potential negative social and ecological impacts can, in turn, limit the ability of the social-ecological system as a whole to adapt to future change (e.g. global climate change).

It is therefore critical that infrastructure is developed in a way that actively maintains and/or enhances the social-ecological system in which it is embedded (as discussed in Section 2). The process of planning and assessing infrastructure projects should therefore begin with an understanding of the broader systemic context of the project. This includes, for example, its links to ecological (e.g. water and biodiversity), social (e.g. governance) and economic (e.g. livelihoods) components. A way of achieving this integrated understanding is to develop a conceptual framework of the social-ecological system (of which infrastructure is a part) at the outset of planning and assessment processes (Walker et al., 2002; Audouin and de Wet, 2010a; Tomich et al., 2010; Biggs et al., 2015). More information on the development of such conceptual frameworks is provided in Supplementary Sheet 2.

The construction, operation and implementation of infrastructure should be aligned with the achievement of sustainability goals and objectives, such as minimising the use of scarce resources (e.g. land and water), reducing and recycling waste, using renewable sources of energy; as well as promoting local economic development through the implementation of local procurement and employment practices. Such goals and objectives should not only be informed by targets defined at an international level (e.g. the SDGs), but also through national, regional and local development plans. It is also critical that they are informed by the views of stakeholders, including representatives from civil society, business, industry and research organisations (as discussed in Tenet 3).

When understanding infrastructure within its broader social-ecological context, resilience thinking also brings to the fore the importance of recognising the infrastructural services that can be provided by the natural environment (e.g. water regulation, flood protection, climate regulation and noise reduction) (Schäffler et al., 2013). These services, together with built/grey infrastructure, can significantly support human activities, thereby promoting the resilience of the social-ecological system (Elmqvist, 2015; Culwick and Bobbins, 2015). Internationally, the term 'green infrastructure' has emerged to refer to the harnessing of ecosystems and the services that they provide, in a way which addresses some of society's infrastructure needs (Culwick and Bobbins, 2015). Green infrastructure is: "... the interconnected set of natural and man-made ecological systems, green spaces and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces and original grassland and woodlands, as well as possible building and street-level design interventions that incorporate vegetation, such as green roofs. Together these assets form an infrastructure network providing services and strategic functions in the same way as traditional 'hard' infrastructure" (Schäffler et al., 2013: 3). When determining the need for new infrastructure projects, opportunities to use or enhance the services provided by green infrastructure - instead of extending grey infrastructure - should therefore be sought (e.g. rehabilitating a wetland could avoid, or reduce, the need for water infrastructure); as well as opportunities for the development of 'grey-green' infrastructure (e.g. attenuating storm water using vegetated swales, green roofs or permeable pavements) (Harrison et al., 2014; Maze and Driver, 2016). Further information on green infrastructure is provided in Supplementary Sheet 3.

TENET 2: DEVELOP INFRASTRUCTURE PROJECTS TO BE ADAPTABLE TO CHANGE AND UNEXPECTED DISTURBANCES IN A SUSTAINABLE WAY

Global trends such as climate change and unprecedented rates of environmental degradation (WWF and AfDB, 2012) significantly increase the uncertainty in our knowledge of the future dynamics of social-ecological systems. This uncertainty must be acknowledged and incorporated in current infrastructure development. If infrastructure development is to be resilient within this context of uncertainty, it is important that it is both robust and flexible (Lloyds and Arup, 2017; Gallego-Lopez and Essex, 2016).

Robust design includes the anticipation of potential system failures that may result from climate change impacts and scarcity in resource inputs (e.g. water and energy), among other factors (Lloyds and Arup, 2017). Increasing the diversity of infrastructure components (e.g. increasing the number of pipe connections providing water) and sources of supply (e.g. energy, water, building materials) contributes to the potential to adapt to such circumstances. If one aspect of a system fails, such diversity enables other components of the system to perform the same function and compensate for such failure (Lloyds and Arup, 2017; Pandit and Crittenden, 2015; Harrison et al., 2014). This is linked to the principle of redundancy which is typically identified as an important aspect of infrastructure resilience from an engineering perspective (United Kingdom (UK) Cabinet Office, 2011). Such redundancy within infrastructure can ensure continuity of supply and/or service to customers in the face of unexpected shocks and changes (UK Cabinet Office, 2011).

From a resilience perspective, however, opportunities should be sought to diversify in ways that are congruent with local, national and international sustainability goals and objectives. Energy supply, for example, may be diversified to include solar and/or wind energy;

while water sources are expanded to include rainwater harvesting, recycling and desalination. As far as possible, this should be achieved in ways that promote social goals, such as the generation of sustainable livelihoods. The development and maintenance of alternative pathways for water supply, energy supply, waste and transport, at a policy and planning level, is therefore critical (Harrison et al., 2014).

Developing alternative, diverse sources of supply for infrastructure projects increases their redundancy and therefore their robustness (Harrison et al., 2014; Pandit and Crittenden, 2015). However, when considering the use of natural resources, such as water and energy, it is important that a balance is obtained with efficiency (Lloyds and Arup, 2017; Kohler, 2014). Optimising the use of resources (e.g. water conservation, energy efficiency) within networks of infrastructure also has a role to play in reducing external dependencies, thereby reducing risks created by factors such as resource scarcity and climate change impacts, and increasing the resilience of towns and cities (Harrison et al., 2014).

The uncertainty inherent in our knowledge of social-ecological systems, the increasing risks posed by global environmental threats such as climate change and resource scarcity, and our continuously evolving understanding of new technologies, call for an approach to the management of infrastructure projects which is adaptive. Adaptive co-management - being based on an assumption of constant change - involves a continual learning process in which alternative pathways to achieve specific objectives (e.g. related to mitigating water and/or energy shortages) are designed, implemented, monitored, evaluated and revised, with the involvement of key stakeholders (Murray and Marmorek, 2003; Biggs et al., 2015). Effective monitoring systems are therefore central to adaptive co-management and should include not only technical indicators related to the infrastructure itself, but also critical elements of the social-ecological system to which the infrastructure is linked (e.g. water quality and supply). Adaptive co-management requires an ongoing process of identifying threats to (and opportunities to enhance) the resilience of infrastructure projects. The involvement of stakeholders, such as representatives from business, civil society organisations, government and local communities, in this process is important (Biggs et al., 2015), as discussed in the following section.

TENET 3: ENSURE INCLUSIVITY IN INFRASTRUCTURE PLANNING, OPERATION AND MAINTENANCE

Central to ensuring the resilience of infrastructure development is the inclusion of key stakeholders in its planning, implementation and monitoring (Lloyds and Arup, 2017; Gallego-Lopez and Essex, 2016). From an ethical perspective, respecting people's values and involving them in decision-making is fundamental to ensuring human well-being and the essential principles of democratic, accountable, equitable and legitimate governance (Folke et al., 2016; Folke et al., 2005). Moreover, infrastructure that is well-aligned with the needs of its beneficiaries is more likely to promote the resilience of the social-ecological system of which it is a part in a way that promotes local sustainability goals (as defined, for example, by the public, civil organisations, government, business, academia and others) (Lloyd's and Arup, 2017; Cilliers and Cilliers, 2016). It can be argued that such infrastructure is also more likely to receive societal buy-in and support for its growth, upgrading and maintenance. Although infrastructure users typically have different needs and priorities, it is important that these are raised and discussed as early as possible and influence infrastructure design, planning and operation.

Stakeholder involvement in the implementation and monitoring of infrastructure can also enable its continual adaptation to changing social-ecological conditions and assist in ensuring that projects continue to deliver the benefits for which they were developed. For example, feedback can be provided by local communities on whether green infrastructure that is linked to a built infrastructure project (e.g. a constructed wetland that is intended to purify water and provide recreational opportunities) is fulfilling its intended use. Moreover, including those that are responsible for facilitating recovery from disturbances and/or unforeseen events in the planning and design of infrastructure enhances the ability to recover from such events. For example, the needs of emergency services (e.g. for easy access) should be considered when locating energy plants and/or designing transport systems (Lloyds and Arup, 2017).

As infrastructure is critical in addressing poverty, it is particularly important that the concerns and priorities of traditionally marginalised groups are elicited and considered in the process of planning and design; so that the infrastructure developed assists in alleviating inequalities and promoting a good quality of life for all (Gallego-Lopez and Essex, 2016). Despite the importance of stakeholder engagement, however, Ravera et al. (2016) and Hankivsky (2014), as well as many others, assert that the inherent power asymmetries in governance decisions can mean that marginalised people and communities are often left out of decision-making processes. For example, the lack of adequate involvement of women in many stakeholder fora, or the silencing of their voices even if they are included, is common (United Nations Development Programme (UNDP), 2013; Gallego-Lopez and Essex, 2016). It is therefore important when co-designing stakeholder engagement processes that particular attention is given to how various stakeholder groups can be actively and explicitly included and how knowledge is mobilised and utilised to inform decisions (Tengö et al. 2014; 2017).

4. APPLICATION TO ENVIRONMENTAL ASSESSMENT AND MANAGEMENT PROCESSES

4.1. INTRODUCTION

This section presents ways in which resilience thinking can be incorporated into the design and assessment of proposed infrastructure projects.

General recommendations are provided for integration into processes such as Environmental Impact Assessment (EIA) and sustainability assessment (at the project-level of decision-making) (Box 2).

IT IS IMPORTANT TO NOTE THAT:

- The scope of these recommendations applies not only to the 'assessment' phase of project development; but also to determining its need and desirability. This task may be undertaken as part of other processes such as feasibility studies and/or the formulation of town planning applications (e.g. for rezoning);

- The recommendations made also relate to formulating proposals for - or changes to - the design, operation and maintenance of a proposed project in order to enhance its resilience. Some scope exists within EIA's and sustainability assessments to make such proposals (e.g. through identification of mitigation measures); however, in many instances, this may chiefly be the role of the project proponent (and his/her design and planning team) rather than the environmental/sustainability assessment practitioner;

- Standard, mainstream EIA's in particular, may not include some of the generic procedural elements referred to below (i.e. according to which the recommendations have been structured). For example, as EIA's usually focus on assessing the positive and negative impacts of a proposed development against baseline environmental conditions, the identification of sustainability objectives and targets against which to assess a proposed project is likely to be excluded (unless, of course, a sustainability assessment is integrated into the EIA). Some aspects, such as the development of a systemic view of the social-ecological environment - although typically not part of standard EIA's - can be included without significant changes to legislated procedures.

BOX 2: SUSTAINABILITY ASSESSMENT AND ENVIRONMENTAL IMPACT ASSESSMENT

SUSTAINABILITY ASSESSMENT

The purpose of sustainability assessment is to orientate development decision-making towards sustainability (Bond et al., 2012). A single, shared understanding of how sustainability assessment should be conducted does not exist and multiple different forms are practiced and proposed in the literature (Pope et al., 2017). It can be said, however, that sustainability assessment - as it has emerged from the (eld of impact assessment - typically involves the evaluation of alternative project, plan or policy proposals against a set of contextually-derived sustainability objectives, targets and indicators (Bond and Morrison-Saunders, 2013; Bond et al., 2015). The process includes the selection and enhancement (e.g. through proposing mitigation measures) of a preferred alternative; as well as monitoring or 'follow-up' (Bond et al., 2015). As the recommendations made in this section of the guide focus on the integration of resilience principles into project-level decision-making; it is sustainability assessment at the project scale that is of particular relevance in this section.

ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

Environmental Impact Assessment (EIA) is a systematic process that involves the evaluation of the potential positive and negative effects of a proposed project (e.g. energy plant or a new road) on the natural, social and economic environment (Wood, 2003). It also includes the identi(cation of mitigation measures to avoid, minimise or remedy any signi(cant negative impacts that are identi(ed (United Nations Environment Programme (UNEP), 2002). Its purpose is to inform decision-makers on whether or not such projects should be approved and if so, under what conditions (Wood, 2003). EIA, which is a widely adopted tool for environmental management globally, was (rst required in terms of the National Environmental Policy Act of 1969 (NEPA), promulgated in the United States (Wathern, 1988).

The recommendations presented in this section are based on the discussions and sources in Sections 1 to 3 above. However, they are also informed by practical experience within the field of environmental assessment and management, as well as current innovations and literature within this field that relate to systems and resilience thinking. Examples include social-ecological systems diagrams in sustainability assessment (e.g. Audouin et al., 2015), explorations around adaptive management (as listed in Hacking and Guthrie (2008) for instance), as well as attempts to expand sustainability assessment to include considerations of system resilience. Examples of literature in this regard, to which the reader is referred for more detail, include: Gibson, 2006; Audouin, 2009; Slootweg and Jones, 2011; Bond et al., 2013; Bond et al., 2015; Pope et al., 2015; Grace and Pope, 2015; Partidario and Pereia, 2015; Gaudreau and Gibson, 2015; Sala et al., 2015; Pope et al., 2017. Debate within the international impact assessment community has also explored the inclusion of resilience thinking into Strategic Environmental Assessment (SEA) (e.g. Slootweg and Jones; 2011).

The recommendations made below are organised in terms of generic procedural elements of assessing infrastructure projects – as well as making proposals for changes in its design, operation and maintenance – and are used as a basis for the proposals made. These procedural elements are as follows:

- Identification of the need and desirability of the proposed infrastructure development;
- Identification of sustainability objectives and targets;
- Description of the social-ecological system;
- Assessment of the proposed infrastructure development; and
- Formulation of strategies and/or mitigation measures.

IMPORTANT NOTE: *The recommendations and lists provided in this section are intended to support the integration of resilience principles in particular into the EIA and/or sustainability assessment process. They do not cover all aspects that should typically be considered in each of the phases of environmental/sustainability assessment processes. It is also acknowledged that EIA processes, in particular, are typically legislated and that in some instances, implementing the aspects recommended in this section may require changes in such legislation. These recommendations are therefore provided as a guide to start exploring and testing, as far as possible (and feasible), ways to integrate resilience thinking into assessment processes for infrastructure development in Africa.*

Figure 4 provides a broad summary of the recommendations for integrating resilience principles into each stage of the assessment process. Each stage, and the associated recommendations are then discussed separately, in further detail, in the sections that follow (Sections 4.2.1 – 4.2.5).

RECOMMENDATIONS FOR INTEGRATING RESILIENCE PRINCIPLES: SUMMARY

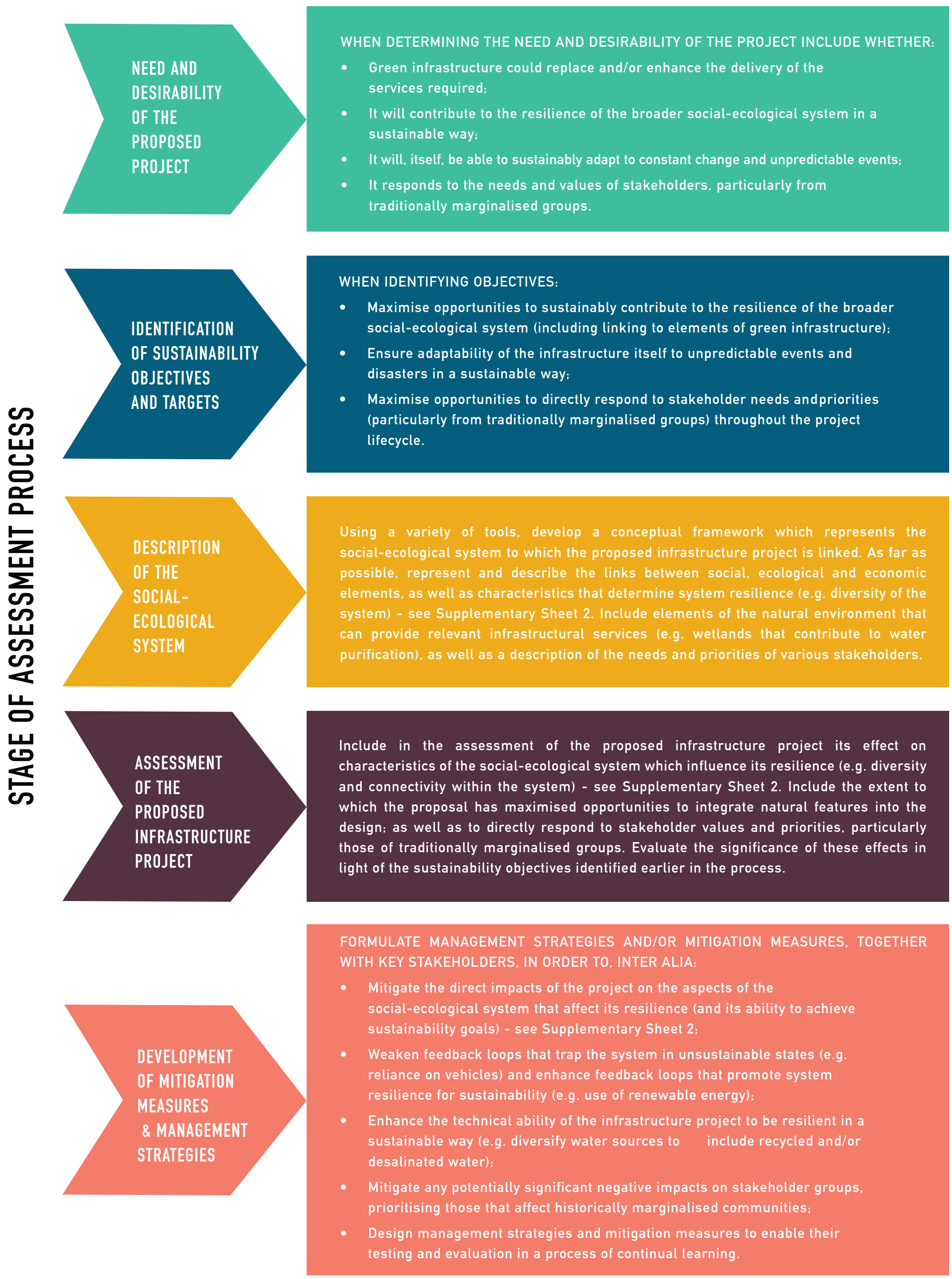


Figure 4: Recommendations for Integrating Resilience Principles into Environmental Assessment (EIA and Sustainability Assessment)

4.2.1. PHASE 1: NEED AND DESIRABILITY OF THE PROPOSED PROJECT

SUMMARY

When determining the need and desirability of the project include whether:

- Green infrastructure could replace and/or enhance the delivery of the services required?
- It will contribute to the resilience of the broader social-ecological system in a sustainable way?
- It will, itself, be able to sustainably adapt to constant change and unpredictable events?
- It responds to the needs and values of stakeholders, particularly from traditionally marginalised groups?

Understanding the need and desirability of the proposed infrastructure project, from a resilience perspective, requires an initial idea of the social-ecological system in which the project is embedded (as discussed in Section 3). This may involve outlining a draft causal-loop diagram (or systems diagram) and the consultation of maps and relevant policy and planning documents (e.g. strategic municipal land-use plans or previous Strategic Environmental Assessments (SEA's) that have been undertaken) (see Supplementary Sheet 2). Although this representation and description of the system will be 'fleshed out' and expanded in more detail later in the planning and/or assessment process, the focus here is on gaining a 'strategic' overview so that broad initial questions around project 'need and desirability' can be answered before detailed analysis is undertaken.

Examples of such questions are provided in this section. These questions are not meant to be answered in great detail at this early stage of the process. The aim is to guide practitioners in identifying any broad, significant concerns (or important opportunities) from a strategic perspective (i.e. from a general understanding of the proposed infrastructure and the system to which it will relate) that should be considered when determining the need and desirability of the project. Such concerns may include, for example, whether the project is responsive to the priorities expressed by key stakeholders and/or whether it is likely to diversify the energy sources available in a specific region.

GUIDING QUESTIONS FOR INTEGRATING RESILIENCE INTO THE 'NEED AND DESIRABILITY' PHASE

Integrating resilience considerations into this initial phase of a proposed project can be achieved by considering the following set of questions based on the three key tenets introduced in Section 3.

TENET 1: Develop infrastructure projects in a way that maintains and enhances the sustainability of the social-ecological system in which they are embedded

- Could green infrastructure replace and/or enhance the delivery of the services required?
- Does the proposed project present/include important opportunities to link built and green infrastructure, thereby enhancing the resilience of the system as a whole?
- Is the proposed infrastructure likely to exacerbate any forms of development or system linkages/relationships that are currently resulting in negative impacts? For example, will the configuration of a proposed transport corridor 'lock-in' dependency on individual cars rather than encourage a transition to more sustainable forms of mobility such as bicycles and public transport? Is the transport corridor likely to increase the emissions of pollutants that, in turn, have a negative effect on community health and well-being?
- Is the proposed infrastructure likely to enforce any system links that have a positive effect? For example, will it result in an increase in renewable energy supply that decreases dependencies on non-renewable sources and creates job opportunities in new, emerging sectors?
- Is the proposed infrastructure likely to have negative effects on beneficial connectivity within the social-ecological system? For example, will it decrease access to natural resources on which communities depend for their livelihoods such as a railway that 'cuts off' access to fishing grounds? Will it result in habitat fragmentation which negatively affects the migration routes of particular species?
- Could the proposed infrastructure enhance beneficial connectivity in the social-ecological system? For example, a transport route can connect people to previously inaccessible commercial areas and associated opportunities for livelihood creation.

TENET 2: Develop infrastructure projects to be adaptable to change and unexpected disturbances in a sustainable way

- Is the proposed infrastructure project likely to sustainably increase diversity and redundancy within the infrastructure system as a whole? For example, if an energy plant is being proposed, would it increase the variety and sustainability of energy sources available in a specific region, such as through introducing renewable sources, or simply increase reliance on non-renewable sources that are already available? Would it provide redundancy in the regional energy system by providing 'back-up' or alternative energy sources if existing sources such as coal-fired energy fail?
- Could the proposed infrastructure project contribute towards desired modularity in the system in a sustainable way? For example, could it provide a renewable power source that is not connected to the national grid, which could therefore supply power to an area in the event of a local disruption in electricity?
- Are the alternative sites and technology being considered for the project likely to promote the resilience of the infrastructure itself, particularly in the event of a disaster and/or unpredictable event? For example, could the proposed sites be vulnerable to the effects of sea-level rise in the future?

TENET 3: Ensure inclusivity in infrastructure planning, operation and maintenance

- Does the proposed infrastructure address the needs expressed by stakeholders (e.g. presented in local, regional or national development plans), particularly those of traditionally marginalised communities? For example, transport routes that provide easier access to employment opportunities for the poor.

4.2.2. PHASE 2: IDENTIFICATION OF SUSTAINABILITY OBJECTIVES AND TARGETS

SUMMARY

When identifying sustainability objectives and targets:

- Maximise opportunities for the project to sustainably contribute to the resilience of the broader social-ecological system (including linking to elements of green infrastructure);
- Ensure adaptability of the infrastructure itself to unpredictable events and disasters in a sustainable way;
- Maximise opportunities to directly respond to stakeholder needs and priorities (particularly from traditionally marginalised groups) throughout the project lifecycle.

The list of broad, general aspects presented in Table 1 below are intended as a 'starting point' or guide in the process of identifying context-specific objectives related to resilience within a particular sustainability assessment and/or EIA. This process should be informed by effective stakeholder engagement so that the objectives and targets that are formulated are responsive to the concerns of civil society, business, Non-Governmental Organisations (NGOs), the scientific community and the public, among others. It is assumed that the 'resilience objectives' identified would form part of a broader list of 'sustainability objectives' that are typically identified in sustainability assessments and sometimes in EIA's. Although a single, generic aspect for consideration is presented in the table below (related to each tenet), in practice multiple context-specific objectives may be formulated for each tenet.

TABLE 1: ASPECTS FOR CONSIDERATION WHEN IDENTIFYING SUSTAINABILITY OBJECTIVES AND TARGETS

TENETS	ASPECTS TO CONSIDER
TENET 1: DEVELOP INFRASTRUCTURE PROJECTS IN A WAY THAT MAINTAINS AND ENHANCES THE SUSTAINABILITY OF THE SOCIAL-ECOLOGICAL SYSTEM IN WHICH THEY ARE EMBEDDED	Maximising opportunities to develop and operate the infrastructure such that it enhances the resilience of the system to which it is linked; including the ability of that system to be sustainable (e.g. an objective may relate to livelihood creation through the use of local procurement, as far as possible, throughout the development and operation of the project). This includes opportunities to integrate the proposed built infrastructure with relevant green infrastructure and to include elements of green infrastructure (e.g. green roofs) in the design of the project.
TENET 2: DEVELOP INFRASTRUCTURE PROJECTS TO BE ADAPTABLE TO CHANGE AND UNEXPECTED DISTURBANCES IN A SUSTAINABLE WAY	Ensuring that the proposed project is adaptable to unpredictable events and disasters (e.g. droughts, floods and fires), while contributing to the achievement of sustainability goals. For instance, decreasing water consumption and diversifying sources of supply through reuse and recycling.

4.2.3. PHASE 3: DESCRIPTION OF THE SOCIAL-ECOLOGICAL SYSTEM

SUMMARY

Using a variety of tools, develop a conceptual framework which represents the social-ecological system to which the proposed infrastructure project is linked. As far as possible, represent and describe the links between social, ecological and economic elements; as well as characteristics that determine system resilience, such as the diversity of the system (see Supplementary Sheet 2). Include elements of the natural environment that can provide relevant infrastructural services (e.g. wetlands that contribute to water purification); as well as a description of the needs and priorities of various stakeholders.

It is important to remember the following when describing the social-ecological system (as discussed further in Supplementary Sheet 2):

- Key stakeholders should be effectively included in the process;
- There are multiple ways in which the system can be described depending, for example, on the boundaries selected, the issues that are considered and the stakeholders involved in the process. It is therefore critical that these choices and assumptions are made explicit;
- Multiple tools (e.g. systems diagrams, maps and narratives) and knowledge types (e.g. scientific and value-based knowledge) should be used; and
- The description should always be open to amendment should new information come to light.

ASPECTS TO CONSIDER IN DESCRIBING/MAPPING THE SOCIAL ECOLOGICAL SYSTEM

Key aspects to consider in describing or mapping the social-ecological system can again be informed by the three general tenets introduced in Section 2.

TENET 1: Develop infrastructure projects in a way that maintains and enhances the sustainability of the social-ecological system to which they are linked

Using a variety of tools, conceptualise the social-ecological system including, inter alia, the characteristics listed in Table 2 below. More detailed information around conceptualising the system and its characteristics is provided in Supplementary Sheet 3.

TABLE 2: DESCRIBING THE SOCIAL-ECOLOGICAL SYSTEM

SYSTEM CHARACTERISTICS (Biggs et al., 2015; Ryan n.d.)	EXAMPLES
1. LINKS/RELATIONSHIPS BETWEEN SYSTEM COMPONENTS	An infrastructure project (such as a dam) may increase water security, promoting the expansion of industry and associated job opportunities. However, the dam itself may decrease surrounding biodiversity, thereby diminishing livelihood opportunities based on the sustainable use of local plant species.
2. SYSTEM DIVERSITY	Diversity in, for example: ecological habitats; species; ecosystem services and landscapes; local skills; social infrastructure; community cultures, values and traditions; economic sectors and enterprises; opportunities for livelihood creation and options for energy and water supply. Include the location, nature and quality of green infrastructure within the social-ecological system in general, and in particular that which could enhance the functioning of the proposed infrastructure project (e.g. biodiversity within the catchment that can assist in water purification, thereby protecting a proposed dam from excess sedimentation).

3. THE CONNECTIVITY/MODULARITY WITHIN THE SOCIAL-ECOLOGICAL SYSTEM	Examples include: important ecological corridors (nodes and isolated patches); communication channels (or lack thereof) between organisations and communities; as well as flows of resources (e.g. transport routes that enable access to ports for trade) or restrictions in such flows.
4. CHANGES IN ANY SLOW VARIABLES OR FEEDBACKS THAT COULD SHIFT THE SYSTEM INTO A DIFFERENT STATE	Decreases in rainfall resulting from climate change, for example, can threaten water quantity and quality such that economic activities such as agriculture are no longer able to function sustainably.
5. ANY EXISTING FEEDBACKS THAT TRAP THE SYSTEM INTO UNDESIRABLE STATES	For instance transport routes that promote urban sprawl rather than more compact forms of development that minimise negative effects on natural areas and local ecotourism.
6. ANY EXISTING FEEDBACKS THAT PROMOTE THE RESILIENCE OF THE SOCIAL-ECOLOGICAL SYSTEM SUCH THAT SUSTAINABILITY GOALS ARE PROMOTED	An example is an energy plant that increases the supply of renewable energy; leading to decreases in its per unit cost. This, in turn, can increase the demand for renewable energy rather than non-renewable energy – decreasing the severity of pollution in a particular area.
7. INSTITUTIONAL AND POLICY LANDSCAPE	Sectors such as government, civil society, industry and business; as well as relevant laws and policies such as those related to land use planning, environmental management and local economic development.

TENET 2: Develop infrastructure projects to be adaptable to change and unexpected disturbances in a sustainable way

Identify the following based on the description of the social-ecological system (in particular the description of slow variables, feedbacks and the institutional landscape referred to in numbers 4-7 of Table 2):

- **Current and predicted changes and disturbances** (e.g. fires, floods, water shortages) in the social-ecological system that can significantly and directly threaten the effective functioning of the proposed infrastructure; and

- Elements of the social-ecological system (e.g. government policy and institutions, efficiency of emergency services, diversity in resource supply) that can significantly influence **the ability of the proposed infrastructure to respond - and adapt -** to change and/or unexpected events.

TENET 3: Ensure inclusivity in infrastructure planning, operation and maintenance

Identify the following based on the description of the social-ecological system (in particular the description of diversity and the institutional landscape referred to in number 2 and 7 of Table 2):

- The particular **values and preferences of stakeholders** within the social-ecological system that are likely to be affected by the planning, operation and maintenance of the proposed infrastructure. An emphasis should be placed on the needs and priorities of traditionally marginalised groups/communities.

GRAID INFRASTRUCTURE GUIDE_27 APRIL 2020_Print.indd 25 2020/04/27 19:45

4.2.4. PHASE 4: ASSESSMENT OF THE PROPOSED INFRASTRUCTURE PROJECT

SUMMARY

Include in the assessment of the proposed infrastructure project, its effect on characteristics of the social-ecological system which influence its resilience; for example diversity and connectivity within the system (see Supplementary Sheet 2). Include the extent to which the proposal has maximised opportunities to integrate natural features into the design; as well as to directly respond to stakeholder values and priorities, particularly those of traditionally marginalised groups. Evaluate the significance of these effects in light of the sustainability objectives identified earlier in the process.

The format in which the assessment is undertaken and the way impacts are described (e.g. in terms of nature, extent, reversibility, etc.) and assessed, should be determined by the country-specific procedures into which the criteria are integrated. Some of the criteria listed would already be included in typical sustainability assessments and EIA's. However, the purpose here is to highlight those aspects that are of particular importance from a resilience perspective.

The assessment stage should be informed by both scientific and value-based knowledge including, for example, specialist scientific studies, stakeholder views and local policies and plans. To ensure that stakeholder values are reflected, the proposed infrastructure should be assessed against the sustainability objectives (which include those relating to resilience) developed in the early stages of the process. In addition, stakeholder comment should be obtained on draft versions of the assessment. Ideally, this stage should include an assessment, as far as possible, of the proposed infrastructure under different social-ecological scenarios (e.g. changes in temperatures, resource availability and different economic factors such as pricing for services delivered etc.) and for alternative project descriptions (e.g. alternative sites, technologies).

INTEGRATING RESILIENCE PRINCIPLES INTO THE ASSESSMENT OF THE PROPOSED INFRASTRUCTURE PROJECT

The questions listed below provide an initial basis for the inclusion of 'resilience criteria' into project assessment.

TENET 1: Develop infrastructure projects in a way that maintains and enhances the sustainability of the social-ecological system in which they are embedded

Consider the following aspects in the assessment:

- **Diversity and redundancy in the social-ecological system** (for example, will the proposed project increase or decrease diversity in elements such as ecological habitats, community cultures and traditions, livelihood opportunities and/or resource supply such as energy and water sources?);
- **The extent of connectivity/modularity within the social-ecological system** (including, for example, important ecological corridors, the flow of resources such as raw materials for manufacturing, and important communication flows);
- **Changes in existing slow variables or feedbacks that could shift the system into a different state** (such as changes in sea surface temperatures that threaten to deplete fish stocks that support local livelihoods and food supply);
- **Feedback loops that trap the system into undesired states** (for example, transport routes that promote urban sprawl rather than more compact forms of development; making it more costly for people to travel to places of employment and decreasing income available to meet other needs);
- **Feedback loops that promote system resilience in a way that moves towards sustainability objectives** (for example, an energy plant that increases the supply of renewable energy; leading to decreases in its per unit cost. This, in turn, can increase the demand for renewable rather than non-renewable energy; decreasing the severity of pollution in a particular area); and
- **Institutional and policy landscape** (for example, the implications of the institutional and policy landscape for the effective and sustainable implementation of the project).

Include in the assessment whether (and to what extent) the proposed built infrastructure project:

- Incorporates the restoration of related green infrastructure which could benefit its functioning (e.g. a proposal for the construction of a dam which includes the restoration of catchment areas to decrease erosion and potential siltation);
- Optimises the services provided by green infrastructure (e.g. attenuating storm water through the construction of vegetated swales or green roofs); and
- Minimises and/or mitigates any potential, significant negative effects on green infrastructure within the social-ecological system.

TENET 2: Develop infrastructure projects to be adaptable to change and unexpected disturbances in a sustainable way

Assess **the extent to which the planned design, operation and maintenance of the proposed infrastructure project enables and/or constrains its adaptability** to current and predicted disturbances (e.g. fires, floods and water shortages) that occur in the social-ecological system; as well as to unpredictable events, using criteria such as:

- Its potential flexibility and robustness (e.g. incorporating multiple and diverse components that can perform a single function);
- The anticipated efficiency in the use of resources (e.g. water and building materials) in the construction, operation and maintenance of the proposed infrastructure; and
- The extent to which an adaptive approach will be adopted in which new, sustainable technologies, for example, will be tested, monitored and revised in a process aimed to increase infrastructure resilience and sustainability.

Assess **the extent to which the broader, linked social-ecological system enables and/or constraints the proposed infrastructure project's adaptability** to disturbances and unpredictable events in a sustainable way using criteria such as:

- The extent to which local skills and parts can support the maintenance and/or replacement of infrastructure components;
- The anticipated diversity in renewable sources of resource supply (e.g. water and energy) available in the system;
- The extent to which relevant local, regional and national government policies and legislation (and associated institutions) are likely to constrain/enable the project's adaptability; and
- The efficiency and effectiveness of emergency response services in the area.

TENET 3: Ensure inclusivity in infrastructure planning, operation and maintenance

Determine the extent to which the proposed project:

- Is actively responsive to the values and needs of key stakeholders, particularly traditionally marginalised groups/communities;
- Minimises and/or mitigates any significant negative effects that may be experienced by one or more stakeholder groups, in particular traditionally marginalised groups; and
- Is aligned to relevant sustainability goals, particularly at the local level (e.g. related to water recycling, the use of renewable energy, creating local employment and reducing income inequalities, among others).

4.2.5. PHASE 5: FORMULATION OF MANAGEMENT STRATEGIES AND/OR MITIGATION MEASURES

SUMMARY

Formulate management strategies and/or mitigation measures, together with key stakeholders, in order to, inter alia:

- Mitigate the direct impacts of the project on the aspects of the social-ecological system that affect its resilience; as well as its ability to achieve sustainability goals (see Supplementary Sheet 2);
- Weaken feedback loops that trap the system in unsustainable states (e.g. reliance on vehicles); and enhance feedback loops that promote system resilience for sustainability (e.g. use of renewable energy);
- Enhance the technical ability of the infrastructure project to be resilient in a sustainable way (e.g. diversify water sources to include recycled and/or desalinated water); and
- Mitigate any potentially significant negative impacts on stakeholder groups, prioritising those that affect historically marginalised communities.

The aim of the list below is to inform the identification of mitigation measures within a traditional EIA, or to inform management strategies within a sustainability assessment. The provision of detailed infrastructure design and operational guidance around each of the points listed is beyond the scope of this guide. It is important to note that the development of management strategies and/or associated mitigation measures and actions is highly contextual. The list below therefore represents a point of departure to guide the formation of strategies and actions that are important from a resilience perspective in the context of a particular project, but are not strategies or actions in themselves.

It is acknowledged that some of the points listed are often already included in EIA's and/or sustainability assessments. What is important from a resilience perspective is to:

- Develop the strategies and actions within the context of the social-ecological system conceptualised in the earlier stages; and

- Adopt an approach of adaptive co-management. This requires that the strategies and actions are:

    1. Co-designed between key stakeholder representatives, scientific specialists and policy-makers; and
    2. Developed in a way that enables their testing, monitoring and evaluation to include a process of continual learning about alternative pathways to achieve sustainability objectives and targets.

INTEGRATING RESILIENCE PRINCIPLES INTO THE FORMULATION OF MANAGEMENT STRATEGIES AND/OR MITIGATION MEASURES

Based on the tenets in Section 2, the following principles for including resilience in management strategies or mitigation measures can be identified:

TENET 1: Develop infrastructure projects in a way that maintains and enhances the sustainability of the social-ecological system to which they are linked

Develop management strategies and associated actions/mitigation measures that aim to:

- Restore and maintain any neighbouring ecosystem services that are (or can be) linked to the proposed infrastructure (e.g. a neighbouring wetland that purifies water for use in the operation of an energy plant) throughout the lifecycle of the project.

- Integrate natural features that can provide services into the infrastructure design (e.g. including green roofs and rain gardens that can assist in attenuating water) and plan for their ongoing maintenance and possible extension.

- Avoid (and where this is not possible, mitigate) any potential negative effects of the proposed infrastructure and its operation on diversity (and redundancy where applicable) within the social-ecological system, including on:

    1. Ecological habitats, species and ecosystem services;
    2. Landscapes and geology;
    3. Actors and institutions (e.g. civil society organisations);
    4. Sacred sites and valued cultural traditions;
    5. Opportunities for communities to meet their basic needs, such as those for housing, food and employment/livelihood creation; and
    6. Resource supply (e.g. options for energy and water supply).

- Weaken feedback loops that trap the social-ecological system (to which the infrastructure is linked) into undesired states that undermine the achievement of the sustainability objectives identified. For example, ensure that dam construction does not lead to land degradation that results in biodiversity loss with a negative effect on ecosystem services, such as water regulation, and the resultant need for further dam construction.

- Protect and enhance important feedback loops within the social-ecological system to which the infrastructure is linked, which promote system resilience in a way that moves towards the sustainability objectives identified. For example, develop and/or support initiatives that enhance the health and well-being of employees and other members of the local community; or invest in environmental programmes that promote the clearing of alien invasive plants and therefore enhance water supply to the area in general.

TENET 2: Develop infrastructure projects to be adaptable to change and unexpected disturbances in a sustainable way

Enhance the technical ability of the proposed infrastructure to respond to unpredictable events or disasters through, for example:

- Ensuring that it is robust and flexible, incorporating multiple components that can perform a single function;

- Diversifying sources of supply in a sustainable way (e.g. for water and energy), while simultaneously ensuring the efficient use of such resources in the operation of the proposed infrastructure;

- Increasing the diversity of components (e.g. number of pipe connections providing water);

- Ensuring that the components used in construction can be maintained using local skills; and

- Adopting an adaptive approach to management in which new procedures and technologies, for example, are tested, monitored and revised as circumstances change.

TENET 3: Ensure inclusivity in infrastructure planning, operation and maintenance

- Respond to the needs and values of stakeholders, prioritising those of historically marginalised groups. Aim, as far as possible, to mitigate any significant negative consequences that may be experienced by particular stakeholder groups.
- Contribute to the achievement of local sustainability objectives. For example, by creating opportunities for decent job and livelihood creation in the construction and operation of the infrastructure, particularly for traditionally marginalised groups (e.g. use local skills in the construction, monitoring and maintenance of the project).


Photo Credit: Pieter Uys, (Kaimara Studio)

5. CONCLUSION

Infrastructure is critical to Africa's development and addressing poverty on the continent (AfDB, 2018). Resilience thinking is an important lens through which such infrastructure can be developed in a way that not only allows the system to cope with and recover from disasters and unforeseen events; but also enables the achievement of Africa's developmental goals in a sustainable way. This document has provided an introduction to resilience thinking and shown how its principles can be applied to infrastructure development and assessment. A particular application of resilience thinking to environmental assessment has been presented to guide assessment practitioners. This guidance includes examples of key questions and criteria that can be asked at various stages of sustainability assessments and/or EIA's to integrate resilience considerations into these, and other (e.g. feasibility studies), development decision-making procedures. The future testing of the recommendations made (and guidance provided) in this document will be important if it is to facilitate continual learning and enhanced practice.

6. REFERENCES

African Development Bank (AfDB). 2017. African Economic Outlook 2017. Organisation for Economic Co-operation and Development, United Nations Development Programme.

African Development Bank Group (AfDB). 2018. Programme for Infrastructure Development in Africa (PIDA). Available : https://www.afdb.org/en/topics-and-sectors/initiatives-partnerships/programme-for-infrastructure-development-in-africa-pida/ [2018, February 9].

African Union Commission (AUC). 2015. "First Ten-Year Implementation Plan 2014-2023", Agenda 2063 The Africa We Want: A Shared Strategic Framework for Inclusive Growth and Sustainable Development. African Union Commission. Available : www.nepad.org/resource/agenda-2063-first-ten-year-implementation-plan-2014-2023-0 [2018, February 9].

Ahern, J. 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape and Urban Planning. 100 (4): 341 – 343.

Audouin, M. 2009. Modernism, Environmental Assessment and the Sustainability Argument: Moving towards a New Approach to Project-based Decision-making in South Africa. Unpublished Dissertation. Stellenbosch: Stellenbosch University.

Audouin, M. and de Wet, B. 2010a. Applied Integrative Sustainability Thinking: An Introductory Guide to Incorporating Sustainability Thinking into Environmental Assessment and Management. Pretoria: Council for Scientific and Industrial Research (CSIR).

Audouin, M. A., and B. de Wet. 2010b. Conceptualising social–ecological systems in environmental assessment and management. CSIR Report No. 8765. Stellenbosch: Council for Scientific and Industrial Research (CSIR).

Audouin, M. n.d. Conceptualising Social-Ecological Systems in Environmental Assessment and Management. Unpublished Information Sheet. Stellenbosch: Council for Scientific and Industrial Research (CSIR).

Audouin, M., Preiser, R., Nienaber, S., Downsborough, L., Lanz, J. and Mavengahama, S. 2013. Exploring the implications of critical complexity for the study of social-ecological systems. Ecology and Society. 18 (3): 12. Available: https://www.ecologyandsociety.org/vol18/iss3/art12/ [2018, February 8].

Audouin, M., Burns, M., Weaver, A., le Maitre, D., O'Farrell, P., du Toit, R. and Nel, J. 2015. An Introduction to Sustainability Science and its Links to Sustainability Assessment. In Handbook of Sustainability Assessment. A. Morrison-Saunders, J. Pope, and A. Bond, Eds. Cheltenham: Edward Elgar Publishing. 321 - 346.

Baró, F., Bugter, R., Gómez-Baggethun, E., Hauck, J., Kopperoinen, L., Liquete, C. and Potschin, M. 2016. Green Infrastructure. In OpenNESS Ecosystem Service Reference Book. EC FP7. M. Potschin, and K. Jax, Eds. Available : openness-project.eu/sites/default/files/SP_Green_Infrastructure.pdf [2018, February 8].

Benedict, M.A. and McMahon, E.T. n.d. Green Infrastructure: Smart Conservation for the 21st Century. Sprawl Watch Clearing House Monograph Series. Washington D.C: Sprawl Watch. Available: sprawlwatch.org [2018, February 8].

Berbés-Blázquez, M., González, J.A. and Pascual, U. 2016. Towards an ecosystem services approach that addresses social power relations. Current Opinion in Environmental Sustainability. 19: 134-143.

Biggs, R., Schlüter, M. and Schoon, M.L., Eds. 2015. Towards Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems. Cambridge: Cambridge University Press.

Binder, C.R., Hinkel, J., Bots, P.W.G. and Pahl-Wostl, C. 2013. Comparison of Frameworks for Analyzing Social-ecological systems. Ecology and Society. 18 (4): 26. Available : https://www.ecologyandsociety.org/vol20/iss4/art18/ [2018, February 8].

Bohensky, E.L., Evans, L.S., Anderies, J.M., Biggs, D. and Fabricius, C. Principle 4 - Foster Complex Adaptive Thinking. In Towards Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems. R. Biggs, M., Schlüter, and M.L. Schoon, Eds. 2015. Cambridge: Cambridge University Press. 142-173.

Boland, P. and Hunhammar, S. 1999. Ecosystem Services in Urban Areas. Ecological Economics. 29: 293-301.

Bond, A., Morrison-Saunders, A. and Pope, J. 2012. Sustainability assessment: the state of the art. Impact Assessment and Project Appraisal 30 (1): 53-62.

Bond, A. and Morrison-Saunders, A. 2013. Sustainability appraisal: jack of all trades, master of none? Impact Assessment and Project Appraisal. 27 (4): 321-329.

Bond, A., Pope, J. and Morrison-Saunders, A. 2015. Introducing the roots, evolution and effectiveness of sustainability assessment. In Handbook of Sustainability Assessment. A. Morrison-Saunders, J. Pope and A. Bond, Eds. Cheltenham: Edward Elgar Publishing. 3-19.

Cilliers, J. and Cilliers, S. 2016 . Planning for Green Infrastructure: Options for South African Cities. Johannesburg: South African Cities Network. Available : sacities.net [2018, February 8].

Cilliers, P. 2001. Boundaries, hierarchies and networks in complex systems. International Journal of Innovation Management. 5(2):135–147

Cilliers, P. 2005. Complexity, Deconstruction and Relativism. Theory, Culture and Society. 22(5): 255-267.

Cilliers, P. Complexity Theory as a General Framework for Sustainability Science. 2008. In Exploring Sustainability Science: A Southern African Perspective. M. Burns and A. Weaver, Eds. Council for Scientific and Industrial Research (CSIR). Stellenbosch: African Sun Media. 39-57.

Coyle, R.G. 1996. Systems Dynamics Modelling: A Practical Approach. London: Chapman and Hall.

Culwick, C. and Bobbins, K. 2015. Green infrastructure: a way to support development in Africa. UrbanAfrica.net. Cape Town: African Centre for Cities, University of Cape Town. Available: https://www.urbanafrica.net/urban-voices/green-infrastructure-a-way-to-support-development-in-africa/ [2017, December 11].

Davies, C., MacFarlane, R., McGloin, C. and Roe, M. 2013. Green Infrastructure Planning Guide: Version 1.1. Northumbria University, North East Community Forests, University of Newcastle Upon Tyne, The Countryside Agency: Landscape Access Recreation, English Nature, Forestry Commission, Groundwork. Available: greeninfrastructurenw.co.uk, [2018, February 8].

Elmqvist, T., Setala, H., Handel, S.N., van der Ploeg, S., Aronson, J., Blignaut, J., Gomez-Baggethun, E., Nowak, D.J., Kronenberg, J. and de Groot, R. 2015. Benefits of restoring ecosystem services in urban areas. Current Opinion in Environmental Sustainability. 14: 101-108.

Fabricius, C. Scholes, R. and Cundill, G. 2006. Mobilizing Knowledge of Integrated Ecosystem Assessments. In Bridging Scales and Knowledge Systems. W.V. Reid, F. Berkes, T. Wilbanks, D. Capistrano, Eds. World Resources Institute. Washington D.C.: Island Press. 165-184.

Flyvbjerg, B. 2004. Phronetic Planning Research: Theoretical and Methodological Reflections. Planning Theory and Practice. 5(3): 283 -306.

Folke, C., Biggs, R., Norström, A.V., Reyers, B. and Rockström, J. 2016. Social-ecological resilience and biosphere-based sustainability science. Ecology and Society. 21 (3): 41. Available: https://www.ecologyandsociety.org/vol21/iss3/art41/ [2019, May 16].

Folke, C., Hahn, T., Olsson, P and Norberg, J. 2005. Adaptive Governance of Social-Ecological Systems. Annual Review of Environment and Resources. 30: 441-473.

Gallego-Lopez, C. and Essex, J. (with input from the Department for International Development (DFID)). 2016. Introducing Infrastructure Resilience. United

Kingdom: Crown Copyright. Available : https://assets.publishing.service.gov.uk/media/57d6bc17e5274a34de000040/Introducing_Infrastructure_Resilience_25May16_rev_external.pd [2018, February 8].

Gaudreau, K. and Gibson, R.B. 2015. A sustainability assessment framework for energy systems: building an appropriate relationship with energy. In Handbook of Sustainability Assessment. A. Morrison-Saunders, J. Pope, and A. Bond, Eds. Cheltenham: Edward Elgar Publishing. 153-182.

Gibson, R.B. 2006. Sustainability assessment: basic components of a practical approach. Impact Assessment and Project Appraisal. 24 (3): 170-182.

Grace, W. and Pope, J. 2015. A systems approach to sustainability assessment. In Handbook of Sustainability Assessment. A. Morrison-Saunders, J. Pope, and A. Bond, Eds. Cheltenham: Edward Elgar Publishing. 285-320.

Gunderson, L. H., and Holling, C.S., Eds. 2002. Panarchy: understanding transformations in human and natural systems. Washington, D.C.: Island Press.

Hacking and Guthrie. 2008. A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. Environmental Impact Assessment Review. 28 (2008): 73-89.

Harrison, P., Bobbins, K., Culwick, C., Humby T-L., La Mantia, C., Todes, A. and Weakley, D. 2014. Urban Resilience Thinking for Municipalities. Johannesburg: University of the Witwatersrand, Gauteng City-Region Observatory. Available: wiredspace.wits.ac.za [2018, February 8].

Hankivsky, O. 2014. Intersectionality 101. The Institute for Intersectionality Research & Policy, SFU. Available : https://www.researchgate.net/profile/Olena_Hankivsky/publication/279293665_Intersectionality_101/links/56c35bda08ae602342508c7f/Intersectionality-101.pdf [2018, February 9].

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2018. Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for Africa of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. A. Archer, L.E. Dziba, K.J. Mulongoy, M.A. Maoela, M. Walters, R. Biggs, M-C. Cormier-Salem, F. DeClerck M.C. et al., Eds. Bonn: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. R.K. Pachauri and L.A. Meyer, Eds. Geneva: IPCC.

Kim, D. H. Introduction to Systems Thinking. Pegasus Communications Inc. Available: thesystemsthinker.com [2019, February 10].

Kithiia, J. and Lyth, A. 2011. Urban wildscapes and green spaces in Mombasa and their potential contribution to climate change adaptation and mitigation. International Institute for Environment and Development (IIED). Environment and Urbanization. 23 (1): 251-265. Available: journals.sagepub.com/doi/pdf/10.1177/0956247810396054 [2019, May 16].

Kohler, S. An Approach to Building Resilience through Infrastructure Development. Presentation at the Multi-year Expert Meeting on Transport, Trade Logistics and Trade Facilitation: Third Session: Small Island Developing States: Transport and Trade Logistics Challenges. 24-26 November 2014. UNOPS (United Nations Office for Project Services). Available: unctad.org [2019, February 10].

Lloyds and Arup. 2017. Future Cities: Building infrastructure resilience. Lloyds and Arup. Emerging Risk Report 2017: Society and Security. Available: file:///C:/Users/MAudouin/Downloads/Lloyds_Arup%20Future%20Cities%202017.pdf [2019, May 17].

Max-Neef, M. A. 2005. Commentary: Foundations of Transdisciplinarity. Ecological Economics.53: 5-16.

Maze, K. and Driver, A. 2016. Mainstreaming ecological infrastructure in planning and investment. In Greening the South African Economy: Scoping the Issues, Challenges and Opportunities. M. Swilling, J.K. Musango and J. Wakeford, Eds. Cape Town: University of Cape Town (UCT) Press. 273-289.

Murray, C. and Marmorek, D. 2003. Adaptive Management: A Science-based Approach to Managing Ecosystems in the Face of Uncertainty. Paper prepared for presentation at the Fifth International Conference on Science and Management of Protected Areas: Making Ecosystem Based Management Work. May 11-16, 2003. British Columbia. Available: https://www.researchgate.net/publication/237331389_ADAPTIVE_MANAGEMENT_A_SCIENCE-BASED_APPROACH_TO_MANAGING_ECOSYSTEMS_IN_THE_FACE_OF_UNCERTAINTY [2018 February 8].

National Association for Olmstead Parks. n.d. About the Olmsted Legacy. Available :http://www.olmsted.org/the-olmsted-legacy/about-the-olmsted-legacy[2017, December 10].

NEPAD (New Partnership for Africa's Development) Planning and Coordinating Agency (NPCA)). n.d. Programme for Infrastructure Development in Africa. Available: http://www.nepad.org/programme/programme-infrastructure-development-africa-pida, [2018, February 9].

Ostrom, E. 2008. Polycentric systems as one approach for solving collective-action problems. Available: dlc.dlib.indiana.edu. [2019, February 10].

Pandit, A. and Crittenden, J.C. 2015. Resilient Urban Ecosystems: Where we stand now and where we need to go. 24 April 2015. Originally published by Solutions Journal. Available [online]: resilience.org, accessed 8 February 2018.

Partidario, M.R. and Pereia, P. 2015. Cities and sustainability assessment: resilience and sustainability thinking about the future of cities. In: Morrison-Saunders, A., Pope, J. and Bond, A. (eds) 2015. Handbook of Sustainability Assessment. Edward Elgar Publishing, Cheltenham, UK. Pages 183-212.

Pope, J., Annandale, D. and Morrison-Saunders, A. 2004. Conceptualising sustainability assessment. Environmental Impact Assessment Review. 24 (6): 595-616.

Pope, J., Bond, A. and Morrison-Saunders, A. 2015. A conceptual framework for sustainability assessment. In: Handbook of Sustainability Assessment. A. Morrison-Saunders, J. Pope, and A. Bond, Eds. Cheltenham: Edward Elgar Publishing. 20-42.

Pope, J., Bond, A., Huge, J. and Morrison-Saunders. 2017. Reconceptualising sustainability assessment. Environmental Impact Assessment Review. 62: 205-215.

Ranjha, S. 2016. Green Infrastructure: planning for sustainable and resilient urban environment. Dresden Leibniz Graduate School - Leibniz Institute of Ecological Urban and Regional Development (IOER) - Technische Universität Dresden (TU Dresden). Available : https://sustainabledevelopment.un.org/content/documents/95599_Ranjha_Green%20infrastructure_planning%20for%20sustainable%20and%20resilient%20urban%20environment.pdf [2018, February 9].

Ravera, F., Iniesta-Arandia, I., Martín-López, B., Pascual, U. and Bose, P. 2016. Gender perspectives in resilience, vulnerability and adaptation to global environmental change. Ambio. 45(3): 235-247.

Resilience Alliance. 2010. Assessing Resilience in Social-ecological Systems: Workbook for Practitioners: Revised Version 2.0. Available : https://www.resalliance.org/files/ResilienceAssessmentV2_2.pdf [2018, February 8].

Ryan, P. n.d. (unpublished document). Minimum Requirements (for assessing projects through a resilience lens).

Sala, S., Ciuffo, B. and Nijkamp, P. 2015. A systemic framework for sustainability assessment. Ecological Economics. 119: 314-325.

SANBI (South African National Biodiversity Institute). 2017. 'Ecological Infrastructure' and 'Green Infrastructure'. Available : http://biodiversityadvisor.sanbi.org/industry-and-conservation/biodiversity-in-the-urban-economy/understand/success-stories-2/ [2017. December 9].

Schäffler, A., Christopher, N., Bobbins, K., Otto, E., Nhlozi, M.N., de Wit, M., van Zyl, H., Crookes, D., Gotz, G., Trangoš, G., Wray, C. and Phasha, P. 2013. State of Infrastructure in the Gauteng City-Region. Gauteng City-Region Observatory. Available : http://www.gcro.ac.za [2018, February 8].

Simonsen, S.H., Biggs, R., Schlüter, M., Schoon, M., Bohensky, E., Cundill, G., Dakos, V., Daw, T., Kotschy, K., Leitch, A., Quinlan, A., Petersen, G. and Moberg, F. n.d. Applying resilience thinking: Seven principles for building resilience in social-ecological systems. Stockholm Resilience Centre (SRC), Stockholm University. Produced in collaboration with the Resilience Alliance, the Global Institute of Sustainability (Arizona State University), the European Research Council and Society in Science. Available : stockholmresilience.org [2019. February 10].

Slootweg, R. and Jones, M. 2011. Resilience thinking improves SEA: a discussion paper. Impact Assessment and Project Appraisal. 29 (4): 263-276.

Stockholm Resilience Centre. n.d. Resilience Dictionary. Available : https://www.stockholmresilience.org/research/resilience-dictionary.html [2019, June 21].

Tengö, M., Brondizio, E.S., Elmqvist, T., Malmer, P. and Spierenburg, M. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. Ambio. 43(5): 579-591.

Tengö, M., Hill, R., Malmer, P., Raymond, C.M., Spierenburg, M., Danielsen, F., Elmqvist, T. and Folke, C. 2017. Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. Current Opinion in Environmental Sustainability. 26: 17-25.

Therivel, R., Christian, G., Craig, C., Grinham, R., Mackins, D., Smith, J., Sneller, T., Turner, R., Walker, D. and Yamane, M., 2009. Sustainability-focused impact assessment: English experiences. Impact Assessment and Project Appraisal. 27(2): 155-168.

Tomich, T.P., Argumedo, A., Baste, I., Camac, E., Filer,C., Garcia, K., Garbach, K., Geist, H. et al. 2010. Conceptual Frameworks for Ecosystem Assessment: Their Development, Ownership, and Use. In Ecosystems and Well-Being: A Manual for Assessment Practitioners. N. Ash, H. Blanco, C. Brown, K. Garcia, T. Henrichs, N. Lucas, C. Raudsepp-Hearne, R.D. Simpson et al., Eds. Ecosystems and Well-Being: A Manual for Assessment Practitioners. Washington: Island Press.

United Kingdom (UK) Cabinet Office. 2001. Keeping the Country Running: Natural Hazards and Infrastructure: A Guide to improving the resilience of critical infrastructure and essential services. Crown Copyright. Available : https://www.gov.uk/government/publications/keeping-the-country-running-natural-hazards-and-infrastructure [2018, February 8].

United Nations. 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations, Available: https://sustainabledevelopment.un.org/post2015/transformingourworld [2018, January 26].

United Nations. n.d. (a) Sustainable Development Goals. Sustainable Development Goals Knowledge Platform. Available: https://sustainabledevelopment.un.org/sdg9 [2019, February 7].

United Nations. n.d. (b) Sustainable Development Goal 9. Sustainable Development Goals Knowledge Platform. Available: https://sustainabledevelopment.un.org/sdg9 [2019, February 7].

United Nations Development Programme (UNDP). 2013. Women and Natural Resources: Unlocking the Peacebuilding Potential. United Nations Environment Programme, United Nations Entity for Gender Equality and the Empowerment of Women, United Nations Peacebuilding Support Office and United Nations Development Programme.

United Nations Environment Progamme (UNEP). 2002. Topic 7: Mitigation and Impact Management. Training Session Outline. EIA Training Resource Manual. Second Edition. Available [online]: https://unep.ch/etu/publications/EIA_2ed/EIA_E_top7_body.PDF, accessed 9 February 2018.

URBES (Urban Biodiversity and Ecosystem Services) Project. 2014. Green Infrastructure, a wealth for cities. Factsheet 6. Available: https://www.iucn.org/sites/dev/files/import/downloads/urbes_factsheet_06_web_1.pdf [2017, December 8].

Walker, B., Carpenter, S., Anderies, J. Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J. et al. 2002. Resilience Management in Social-ecological Systems: a Working Hypothesis for a Participatory Approach. Ecology and Society. 6(1): 14. Available : https://www.ecologyandsociety.org/vol6/iss1/art14/ [2018, February 8].

Wathern, P. 1988. An introductory guide to EIA. In Environmental Impact Assessment: Theory and Practice. P. Wathern, Ed. London: Unwin Hyman Ltd. 3-30.
Wood, C. 2003. Environmental Impact Assessment: A Comparative Review. 2nd edition. Harlow: Prentice Hall.

World Commission on Environment and Development (WCED). 1987. Report of the World Commission on Environment and Development: Our Common Future Our Common Future. Available : http://www.un-documents.net/our-common-future.pdf [2019, February 7].

World Wildlife Fund (WWF) and the African Development Bank (AfDB). 2012. Africa Ecological Footprint Report: Green Infrastructure for Africa's Ecological Security. WWF and AfDB. Available: wwf.panda.org [2018, February 8].

World Wildlife Fund (WWF) and the African Development Bank (AfDB). 2015. African ecological futures report 2015. World Wide Fund for Nature (WWF) and African Development Bank (AfDB). Available : http://wwf.panda.org/who_we_are/wwf_offices/regional_office_for_africa/african_ecological_futures/ [2018, February 8].

Wright, H. 2011. Understanding green infrastructure: the development of a contested concept in England. The International Journal of Justice and Sustainability.16 (10): 1003-1019.

SUPPLEMENTARY SHEET 1: PRINCIPLES FOR BUILDING RESILIENCE IN SOCIAL] ECOLOGICAL SYSTEMS

Biggs et al. (2015) outline seven principles that are important for building resilience in social-ecological systems, which are as follows:

- Maintain diversity and redundancy;
- Manage connectivity;
- Manage slow variables and feedbacks;
- Foster complex adaptive systems thinking;
- Encourage learning;
- Broaden participation; and
- Promote polycentric governance.

Each of these principles is briefly described in Box 1.1 below.

BOX 1.1: PRINCIPLES FOR BUILDING RESILIENCE IN SOCIAL-ECOLOGICAL SYSTEMS

(Biggs et al., 2015)

MAINTAIN DIVERSITY AND REDUNDANCY

The resilience of social-ecological systems is generally increased when the diversity of components, such as species, landscape types, actors and institutions, increases. This diversity ensures that a range of options are available within the system for responding to climate change and unpredictable events. Aspects of system diversity include variety (i.e. number of components present), balance (i.e. the relative abundance of the various types of components) and disparity (i.e. extent to which system components differ from one another). For example, livelihood diversity may comprise the number of livelihood options available (variety), the extent to which each is practiced (balance) and the degree of difference between them (disparity).

Associated with system diversity is the concept of redundancy, which provides 'insurance' for system functions and responses. For example, high functional diversity refers to the existence of multiple system components that can perform the same function (e.g. many different crops that can support food security). An example of 'response diversity' is the range of different responses each crop has to changes and/or disturbances such as drought or flooding. This redundancy in sources of food supply and their response to change increases the resilience of the social-ecological system to unpredictable events and changes, thereby increasing its ability to sustain food security.

MANAGE CONNECTIVITY

Connectivity refers to the way in which parts of the social-ecological system interact with each other, primarily to transfer material, communicate, and transform energy. The structure and strength of these interactions is included in the concept of system connectivity. Where green spaces are well connected within urban areas, for example, the movement of organisms from one area to another is facilitated, thereby increasing their survival and the resilience of the system to disturbances. However, limited connectivity can also enhance resilience through minimising the spread of disturbances such as fire and disease. As a further example, high levels of connectivity between social groups can increase the communication and trust required for collective action; while such connectivity can also hinder resilience if homogenisation of norms occurs. In the latter case, connected individuals and social groups can believe that they are moving in a sustainable direction, while the opposite may be true.

MANAGE SLOW VARIABLES AND FEEDBACKS

Social-ecological systems comprise numerous variables that interact and change at different rates. 'Slow' variables (e.g. soil composition, erosion control, legal systems and traditions) typically determine the underlying structure of a social-ecological system, while its overall dynamics generally arise from interactions and feedbacks between 'fast' variables (e.g. crop production, water provision and harvesting of fish). It is important to note that the terms 'fast' and 'slow' are relative to one another in the context of a specific system.

Feedbacks refer to instances where changes in a particular variable or process result in system interactions that eventually loop back to affect the original variable. Such feedbacks can either be reinforcing (i.e. positive feedbacks) if the effect of the 'loop' is more change of the same type; or dampening (i.e. negative feedbacks) if the effect is to reduce similar changes. For example, a reinforcing feedback exists if dam construction leads to land transformation that leads to biodiversity loss and the degradation of ecosystem services (e.g. water purification and regulation of run-off), which in turn results in a decrease in the supply of potable water and further dam construction. An example of a dampening or negative feedback is the formal or informal negative social sanctioning of the harvesting of threatened species.

As social-ecological systems are adaptive by nature, they can exist in different configurations or self-organising 'regimes' - each of which produces a different set of ecosystem services. Changes in slow variables (e.g. changes in temperature due to climate change) can result in certain thresholds being exceeded (e.g. amount of water available for agricultural production) that shift the social-ecological system into a different 'regime' or configuration, in which its structure, function and associated ecosystem services fundamentally changes (e.g. one in which agriculture is no longer the dominant economic activity and tourism and/or mineral exploitation becomes dominant). Although difficult in practice, identifying and managing slow variables and feedbacks is important in both maintaining ecosystem services and/or transforming the system into a new regime in which a different, desirable set of such services is produced.

FOSTER COMPLEX ADAPTIVE SYSTEMS THINKING

A 'complex adaptive systems (CAS) approach' is one in which the interconnectedness of the elements within social-ecological systems is recognised. Moreover, an understanding of complexity acknowledges the inherent uncertain and unpredictable nature of these systems. These characteristics are a result of the non-linear interactions within complex adaptive systems, as well as the existence of emergent properties which result from the interaction between system elements rather than the characteristics of any particular element itself (Cilliers, 2005). The interacting components of complex adaptive systems self-organise and evolve in a dynamic way, adapting to change. When such changes move beyond a certain critical point (also known as a threshold or 'tipping point'), 'regime shifts' can result. These are shifts between different system configurations or states (Resilience Alliance, 2010) that can lead, for example, to a different set of ecosystem services being delivered by the system.

In applying complex adaptive systems (CAS) thinking to resource management, it is therefore important to: conceptualise the social-ecological system under consideration to gain a shared understanding of the interdependencies; to expect and accommodate change and uncertainty; and to investigate and monitor critical thresholds, among other factors. CAS thinking also recognises that there are a multitude of perspectives that various actors within social-ecological systems hold, and that engaging with and understanding these perspectives is a critical element of effective resource management.

ENCOURAGE LEARNING

Our knowledge of social-ecological systems is always partial, due to the complexity of these systems and their dynamic nature. This highlights the importance of learning, including continually renewing existing knowledge, re-evaluating values and developing alternative understandings of the system. Such learning should be part of all efforts to ensure the resilience of social-ecological systems, particularly governmental policy and other decision-making processes. Three key approaches which explicitly integrate learning into the management of social-ecological systems are the following: adaptive management, adaptive co-management and adaptive governance. These approaches, which are based on recognition that knowledge is incomplete and that uncertainty is inevitable, are briefly described below:

ENCOURAGE LEARNING (CONTINUED)

- **Adaptive management:** is based on a scientific approach that involves the creation of alternative hypotheses, experimentation and evaluation. Management actions are explicitly viewed as large-scale experiments which are tested, monitored, evaluated and revised in a 'learning-by-doing' approach (e.g. testing the impact of allowing increased fishing quotas). Learning is considered one of the key outcomes of management.
- **Adaptive co-management**: integrates adaptive management's focus on learning through experimentation, monitoring and evaluation with learning through interactions and knowledge sharing among stakeholders. Collective actions as well as changes in values and norms are included in the outcomes of adaptive co-management.
- **Adaptive governance**: emphasises learning in the context of flexible and adaptive institutions at multiple levels of decision-making. It involves the exchange of knowledge across and between nested local, regional, national and international institutions. The discourse around adaptive governance tends to emphasise, inter alia, the development of social norms and the importance of bridging organisations in matching decision-making to the scale of the ecological processes under consideration.

PROMOTE POLYCENTRIC GOVERNANCE SYSTEMS

Polycentricity is "... a governance system in which multiple governing bodies interact to make and enforce rules within a specific policy arena or location, (and) is considered to be one of the best ways to achieve collective action in the face of disturbance and change" (parenthesis added) (Biggs et al., 2016). Governance in this context goes beyond formal governmental institutions to include civil society organisations, Non-Governmental Organisations (NGOs), the private sector and others. It involves multiple flexible, autonomous and nested institutions interacting at various scales (i.e. local, regional, national and international) both vertically (i.e. across scales) and horizontally (i.e. with institutions at the same scale) in order to develop and enforce norms and rules relating to a policy issue or geographical area. In particular, it aims to facilitate dynamic organisational collaboration to develop approaches to collective-action issues in a way that 'fits' the problem in nature, scale and timing.

This form of governance enables learning and experimentation, and enhances the ability of local individuals and organisations to participate in decision-making. Although highly decentralised, polycentric governance aims to find a balance between the assumption that local citizens and communities will always be able to address collective-action problems, and the assumption that top-down, centralised planning is necessarily a requirement for effective resource management and the provision of public services (Ostrom, 2008). However, the implementation of innovative ideas around polycentric governance is constrained by a lack of understanding of the best ways in which to operationalise it. Examples of cooperation exist, however, a clear set of principles around the effective implementation of polycentric governance do not.

SUPPLEMENTARY SHEET 2: CONCEPTUALISING SOCIAL-ECOLOGICAL SYSTEMS

At the outset of an assessment process, it is important to develop a shared understanding of the social-ecological system in which the proposed infrastructure project is embedded. This is because, once implemented, infrastructure projects become an integral part of the complex social-ecological system, and the assessment process should therefore evaluate the potential impacts of the project on this broader system. However, as Cilliers (2005) explains, complex systems are open systems and therefore to understand them comprehensively we need to understand the systems' complete environment, which is also complex (Cilliers, 2005). This is clearly an impossible task.

For this reason, boundaries need to be drawn which necessarily reduce the complexity of the system. Whether such boundaries are conceptual, spatial and/or temporal, they are needed for the generation of knowledge (Cilliers, 2001; Audouin et al., 2013). Typically, in a planning and/or assessment process for infrastructure development, such boundaries would relate, inter alia, to the physical boundaries of the study, the temporal boundaries (the period being considered, past and future), the key issues to be considered, the key social-ecological variables and the relationships between these, as well as cross-scale (i.e. local, regional, national and international) linkages to be included. It is these boundaries that comprise the 'conceptual framework' being referred to in this section (also see Box 2.1).

There is, however, no completely 'objective' way of drawing these boundaries for conceptualising the social-ecological system. There is no 'framework for frameworks' in which one can step outside of complexity (Cilliers, 2005: 259). The boundaries drawn for a social-ecological system are typically the result of the physical characteristics of the system (e.g. catchment boundaries, mountain ranges, the coast line) as well as strategic (e.g. considerations of expediency such as time and financial resources) and/or value-based choices (e.g. priorities raised by stakeholders) (Audouin and de Wet, 2010a). For this reason, our knowledge of any social-ecological system is always relative to the conceptual framework (including its boundaries) that has been drawn to describe it (Cilliers, 2005). It is therefore important that this conceptual framework is not only clearly delineated at the outset of a planning and/or assessment process; but that it is developed with the participation of relevant stakeholders (Audouin and de Wet, 2010b, Tomich et al., 2010). The involvement of stakeholders ensures that, inter alia, (Tomlich et al., 2010; Audouin, 2009):

- The 'value-based' choices made in defining the system reflect those that have an interest in - or are affected by - a proposed infrastructure development;

BOX 2.1: CONCEPTUAL FRAMEWORK OF THE SOCIAL-ECOLOGICAL SYSTEM: PURPOSE AND BENEFITS

In summary, formulating a conceptual framework of the social-ecological system to which a proposed infrastructure project and/or plan is linked can (Tomich et al., 2010; Audouin and de Wet, 2010b; Audouin 2009):

- **De(ne the system to which the study applies;**
- **Clarify underlying assumptions and values made in the planning and/or assessment process;**
- **Organise thinking and provide structure to the process, identifying inter alia: key issues/ relationships to be considered; physical boundaries; cross-scale linkages and period to which the study applies;**
- **Enable disciplinary specialists and stakeholders to gain an initial, shared understanding of the social-ecological system before its parts (e.g. social, ecological and economic) are analysed. This provides an important context for such analysis; and can enable easier integration of specialist studies later in the process;**
- **Highlight gaps in understanding.**

- Both the study team and stakeholders have some level of 'ownership' of the conceptual framework of the system which will guide the planning and/or assessment process going forward; and
- A range of knowledge types are included in defining the system, which are not limited to scientific understanding, but include personal experiences, values and cultural and historical knowledge, among others.

There are many ways of conceptualising the social-ecological system (of which infrastructure is a part). In the last decade significant progress has been made in the development of models and tools for this purpose (Binder et al., 2013), which includes the application of various types of systems dynamics modelling. The development of a causal-loop diagram - which often forms the foundation for systems dynamics modelling - can be a very useful tool in its own right for developing a shared understanding of the system (Audouin and de Wet, 2010b, Coyle, 1996). Causal-loop diagrams are particularly useful in a facilitated workshop setting where stakeholders, scientists and decision-makers can collectively develop their concept of the social-ecological system.

It is recommended, however, that as far as possible, a variety of tools should be used when describing the social-ecological system, including variations on at least the following broad categories: systems modelling (whether this is a computational model or simply a mind-map, network or causal-loop diagram); spatial mapping; and narrative/qualitative descriptions (Audouin and de Wet, 2010b). Using a range of tools is important from the perspective of resilience thinking, as it not only enables an improved description of the social-ecological system, but also allows for the inclusion of a variety of different knowledge types (e.g. spatial and non-spatial, codified and non-codified, and scientific and personal/ value-based). Each 'category of tools' mentioned above has its own strengths and weaknesses, examples of which are provided in Box 2.2. An example of a causal-loop diagram (included under 'systems modelling' in Box 2.2) is provided in Figure 2.1 (with an explanation of the conventions used shown in Box 2.3).

BOX 2.2: EXAMPLES OF ADVANTAGES AND DISADVANTAGES OF SYSTEMS MODELLING, SPATIAL MAPPING AND NARRATIVES WHEN DEPICTING SOCIAL-ECOLOGICAL SYSTEMS

(adapted from Audouin and de Wet, 2010b)

CATEGORY OF TOOLS	ADVANTAGES	DISADVANTAGES
SYSTEMS MODELLING (including the drafting of causal-loop diagrams to represent the social-ecological system)	• Effectively indicates cause-effect relationships – particularly based on variables that can be quantified (at least in a relative sense) – and the strength of these relationships. • Computational models have the ability to distinguish between fast and slow feedbacks. • Useful in depicting alternative scenarios and identifying system changes within each scenario. • Useful in developing and/or depicting a shared understanding of the social-ecological system among scientists, stakeholders and decision-makers. • Possible to link systems modelling to spatial mapping. • More easily include social dimension than traditional numerical models.	• Although not as quantitative as traditional numerical models, systems modelling has a bias towards information that can be quantified in some way (or converted into variables/ indicators that can be quantified, even if only in a relative way). • Can be difficult to represent (e.g. in causal-loop diagrams) spatially-specific information or information that relates to the nature (rather than extent) of a particular social-ecological linkage. • Can be time-consuming and resource intensive (e.g. data, funding and technology required). • Systems modelling is not ideal when aiming to optimise the functioning of a system or process (numerical models are better for this).
SPATIAL MAPPING	• Effective in representing the spatial extent of system variables, dynamics and flows in a visual way. • Assists scientists, stakeholders and decision-makers in visualising the nature of the social-ecological system. • Particularly useful in communicating a large amount of information in a way that is easy to understand and appealing.	• Although possible, it is demanding to represent changes over time and to distinguish between fast and slow variables. • Typically, two or three variables are included in a composite map, so depicting social-ecological system linkages can be challenging. • Can be time-consuming and resource intensive (e.g. data, funding and technology required), with difficulties being experienced in obtaining data of compatible scales. • Bias towards information that can be spatially depicted and/or converted into spatial variables/ indicators.
NARRATIVE DESCRIPTIONS	• Effective in communicating the value-based aspects of social-ecological systems (e.g. a diverse range of nuanced and possibly conflicting stakeholder priorities and concerns); and other aspects that are difficult to depict quantitatively or spatially (e.g. sense of place or nature of power relations). • Useful in explaining 'why' and 'how' things are happening; going beyond a description of 'what' is happening. • Effective in communicating the practical, lived experience of individuals and communities. • Particularly assists in conveying undocumented knowledge that is contained in local memory, customs and traditions and which is transferred orally (Fabricius et al., 2006).	• Narrative is a powerful tool that can be open to misuse if not skilfully interpreted (e.g. it is important to be aware that narratives reflect the perspective of the teller, which includes a level of inherent interpretation. What is left out in the telling of an event can be as important as what is included, as it can reflect the perspective of the teller). • When communicating, personal narratives require a beginning, middle and end in order to have coherence; however, this coherence does not necessarily exist in the events themselves, but rather in the way the teller explains the story.

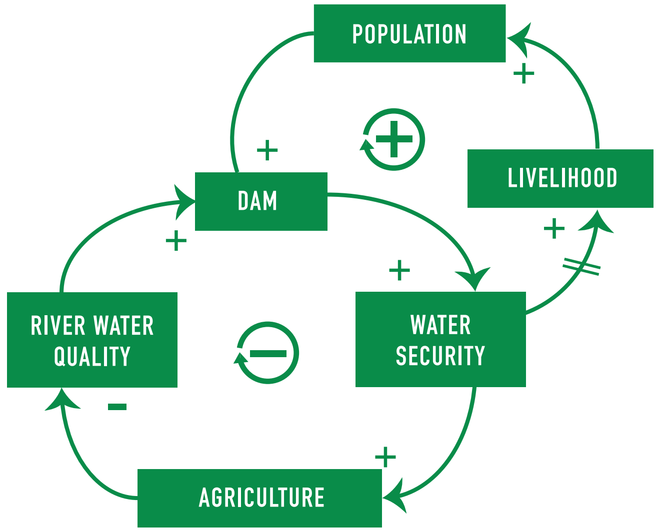
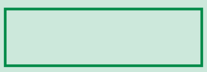


Figure 2.1 Hypothetical Causal-Loop Diagram for a Proposed Dam

BOX 2.3: BASIC CONVENTIONS FOR CAUSAL LOOP DIAGRAMS

(Coyle, 1996; Kim 1999; Audouin and de Wet 2010b)

CONVENTION	EXPLANATION AND EXAMPLES (RELATED TO FIGURE 2.1)
	Key variables that influence the system
	Flows indicating cause-effect relationships between key variables
Large D or // indicated on the flow	Significant delay in the flow. For example, the building of the dam will increase water security in the area, however it may be some time before this is converted into new opportunities for livelihood creation.
Plus sign (+)	A positive sign on the link indicates that if the variable at the tail of the arrow changes, the variable at the head also changes in the same direction. For example, if water security increases, so do the opportunities for livelihood creation.
Minus sign (-)	A negative sign on the link indicates that when the variable at the tail of the arrow changes, the variable at the head changes in the opposite direction. For example, as agriculture expands (and there is an increase in run-off and siltation), the river water quality decreases.
Positive feedback loop  Negative feedback loop 	Feedback loops exist when it's possible to follow the arrows from a particular starting variable, through the system, back to the original variable, without going through any of the system variables more than once. When a loop has an even number (including 0) of minus signs it is a positive (or reinforcing) loop. Positive feedback loops reinforce system change in a particular direction, with still further change that grows in the same direction. As Kim (1999:19) states they are "Also known as vicious cycles or virtuous cycles". When a loop has an odd number of minus signs, it is a negative (or balancing) loop. Negative feedback loops seek equilibrium in a 'balancing' dynamic that has a stabilising effect on the system.

Using a variety of tools (as described in Box 2.2), a number of aspects of the system should be described. From a resilience perspective, these include (Biggs et al., 2015; Ryan, n.d.):

- The existing links between the proposed infrastructure project and other parts of the system (e.g. between a proposed dam, the surrounding biodiversity and local livelihoods);
- The extent of connectivity in the system (e.g. habitat connectivity in the landscape);
- The diversity of the system (e.g. diversity in ecological habitats and species; cultural values and economic opportunities);
- The redundancy in the system (e.g. existence of 'back-up' energy supplies);
- Slow changes in the system that affect infrastructure development (e.g. climate change can lead to decreasing rainfall, which in turn, decreases water supply);
- How the social-ecological system has changed over time (e.g. changes in government policy, population structure and movements and weather patterns); and
- The institutional and policy landscape (e.g. the legal and policy framework and its influence on infrastructure development).

These elements are described in further detail in Box 2.4.

Box 2.4: DESCRIBING THE SYSTEM

(Biggs et al., 2015; Ryan, n.d.)

CHARACTERISTICS OF THE SOCIAL-ECOLOGICAL SYSTEM	DESCRIPTION IN THE CONTEXT OF INFRASTRUCTURE DEVELOPMENT
RELATIONSHIPS -OR LINKS[BETWEEN SYSTEM COMPONENTS TO WHICH THE PROPOSED INFRASTRUCTURE PROJECT IS LINKED	These links should relate to social (e.g. human well-being), ecological (e.g. biodiversity) and economic (e.g. effect on local businesses) factors. For example, the construction of a dam increases water security, thereby supporting the expansion of industry and the creation of livelihoods. However, the process of constructing the dam can also have a negative impact on biodiversity, which in turn can diminish the creation of local livelihoods that depend on the ecosystem services that such biodiversity provides.
DIVERSITY AND REDUNDANCY	This includes ecological, social and economic diversity. For example, diversity in ecological habitats and species should be explored, as well as in institutions, cultures (including traditional practices) and opportunities for employment and livelihood creation (from local-scale farming, craft-making and artisanal fishing, for example, to large-scale mining and other industrial activities). Moreover, it is recommended that 'value deliberation' is undertaken in which the diverse range of stakeholder values within the social-ecological system under consideration are broadly defined (Flyvbjerg, 2004). This assists in understanding who is likely to 'gain' as a result of changes in the social-ecological system and who will likely 'lose', from the perspective of what the stakeholders themselves value (Flyvbjerg, 2004). Such value deliberation should go beyond understanding the needs and preferences of such stakeholders (e.g. for food, housing etc.) to also identifying the underlying 'ethical principles' that are important (e.g. freedom of choice, identity and security). Redundancy may exist, for example, in the options available for increasing water supply, energy and food security within the social-ecological system. Water may be available from a variety of sources including aquifers, dams and desalination; while both renewable and non-renewable energy supplies may exist. Food supply may be secured by the cultivation of a range of different crops that respond differently to changes in climate and other disturbances.
SLOW VARIABLES AND FEEDBACKS	Relatively slow variables such as changes in government policy (Simonsen et al., n.d.) related to water, energy and transport can have a profound effect on infrastructure development. For example, the introduction of national policy that describes the national energy mix promoted and/or the signing of international environmental conventions, can influence: • The type of infrastructure that is enabled (e.g. renewable energy promoted through supporting government programmes); • The location of infrastructure (e.g. the potential corridor developments identified in the Programme for Infrastructure Development in Africa (PIDA)); and/or • The design of infrastructure systems (e.g. technologies required to reduce carbon emissions). Climate change is another example of a relatively slow variable that can significantly affect the need for infrastructure development, its location (e.g. through the effects of droughts, floods, sea-level rise and erosion); as well as its sustainability (e.g. scarcity of water resources), among other factors. A resilience perspective highlights the importance of understanding the key variables (e.g. water supply supporting energy development) and feedback processes (e.g. governance) that affect infrastructure development – as well as the impact of such development on these variables and feedbacks. The focus should be on those variables and feedbacks that could result in thresholds or 'tipping points' being exceeded that may lead the social-ecological system supporting the operation of infrastructure into an undesirable state (Biggs et al., 2015). For example, slow changes in climate can lead to decreasing rainfall levels, which in turn lead to decreases in water supply. This, together with increases in population numbers and slow changes in government policy and societal water-use behaviour, can lead to serious water shortages that 'tip' the system into a new state (e.g. changes in predominant economic activities from agriculture to other sectors such as tourism; and/or changes in water policy and long-term diversification of water supply sources).

CONNECTIVITY	Connectivity can have both positive and negative effects on the development and sustainable operation of infrastructure (Simonsen et al., n.d.). Effective communication and supportive relationships between different government departments and spheres of government; as well as between government and other stakeholders (e.g. local communities, business and Non-Governmental Organisations (NGOs)) can enable the integration and cooperation required for sustainable infrastructure development (Harrison et al., 2014). This applies not only to the planning of regional infrastructure, but also to specific infrastructure projects for which effective governmental coordination is typically required, for example, during the planning and approval processes, as well as for the monitoring of mitigation measures post-implementation. Good communication and engagement (throughout the project life-cycle) between developers of site-specific infrastructure projects and surrounding communities can also enhance resilience through increasing the development's responsiveness to local concerns and values (e.g. around potential positive and negative impacts on local livelihoods, noise and visual aspects and the rehabilitation of damaged landscapes, among many others). However, high levels of connectivity can also have a negative effect, if independent systems are not available in times of disaster (Lloyds and Arup, 2017). For example, from a technical, operational perspective it is desirable to create separate recovery systems (i.e. "skeleton systems") that have some level of independence from the overall connectivity within the infrastructure development (Lloyd's and Arup, 2017). For example, an independent back-up power supply can assist in recovering system operation, should the electricity received from the national grid be interrupted for some reason and/or affected by a natural disaster. Infrastructure development, in turn, can have both positive and negative effects on connectivity within the social-ecological system as a whole. For example, a newly built dam can increase the connectivity of human settlements to water supply; while its auxiliary infrastructure (i.e. its pipeline connections, roads etc.) fragments habitat connectivity within the landscape. This compromises the ability of such habitats to compensate for local species extinctions through the inflow of species from connected surroundings (Simonsen et al., n.d.). The principle of managing connectivity also highlights the importance of considering infrastructure developments at multiple scales. A renewable energy plant, for example, can have linkages that extend well beyond the local scale (e.g. neighbouring communities and local biodiversity), to include national (e.g. effects on national electricity supply) and international scales (e.g. effects of international markets for renewable energy on financial sustainability of the plant). Likewise, a new transportation strategy can have linkages to local (e.g. benefits to local businesses), national (e.g. increased domestic tourism) and international dynamics (e.g. increased cross-border trade).
PATTERNS OF SYSTEM EVOLUTION AND CYCLES, INCLUDING HISTORICAL DYNAMICS	Although social-ecological systems are dynamic and exhibit inherently unpredictable behaviour, there are patterns of change over time that can be identified (Ryan, n.d.). Exploring the historical profile of the system is revealing in terms of understanding its current dynamics (Walker et al., 2002). Ecosystems, for example, may change through four identifiable stages, which together have been called the 'adaptive cycle' (Gunderson and Holling, 2002; Resilience Alliance, 2010). Walker et al, 2002 explain that the first phase is the 'growth and exploitation phase' (r), which leads to the 'conservation phase' (K), both of which are fairly predictable. During the course of the K phase, the system becomes increasingly less flexible as resources are consumed in sustaining the structure of the system. This inevitably leads to collapse and release (Ω) followed by the reorganisation phase (ɑ̢) in which new opportunities arise. These last two phases are both inherently unpredictable. Other historical patterns which reveal how the system came to its current state include: changes in weather patterns, population structure and movements, income levels, urban expansion, technological innovations, economic activities and political policies, among many others.
THE INSTITUTIONAL AND POLICY LANDSCAPE	The institutional landscape is an important component of social-ecological systems, which influences the ability to respond to unexpected events and transform towards desired states. The flexibility and representativeness of multiple, autonomous and nested institutions that interact at multiple scales is likely to increase the resilience of the system; relative to more top-down, centralised forms of governance. Inclusivity in decision-making and its implementation, where stakeholders such as civil society, business and Non-Governmental Organisations (NGO's) actively participate in governance, is more likely to increase resilience. This is because such inclusivity enhances the legitimacy of decision-making, the extent of stakeholder 'buy-in' and the responsiveness of policies and plans to real stakeholder needs, among other factors. In studying the social-ecological system, it is also important to gain some understanding of the legal and policy landscape, both in terms of its ability to enable effective response to constant change and unpredictable events (and continual learning in this regard); as well as the ways in which stakeholders wish to transform the system (i.e. 'desired states' of the social-ecological system). Such 'desired states' are often expressed in local land use planning processes, for example; as well as in regional and national policies related to a variety of sectors. Moreover, international agreements that have been signed also provide an indication of the 'desired state'; an example being the Sustainable Development Goals (SDG's) which African countries have committed to achieving.

SUPPLEMENTARY SHEET 3: GREEN INFRASTRUCTURE

Green infrastructure is a way of understanding natural and man-made ecological elements as part of the infrastructure system that supports society (Schäffler et al., 2013). Schäffler et al. (2013) point out, however, that the consideration in strategic planning of ecological features and the connections between them is not new. Frederick Law Olmstead's 'parkways' concept (which aimed to promote a sense of community and tranquillity in urban areas in America in the late 19th century); and Ebenezer Howard's 20th century 'garden cities' in Britain, influenced green space planning in later decades (e.g. greenways movement of the 1990's) (National Association for Olmsted Parks, n.d.; Schäffler et al., 2013). However, the current dialogue around – and practice of – 'green infrastructure' development "... calls for a shift beyond conventional environmental protection and conservation, to a redefinition of green assets and ecological systems as part of the infrastructure that serves society" (Schäffler et al. (2013: 11).

The concept of 'green infrastructure' is a contested and evolving one, which is interpreted in a variety of ways depending on the context in which it is used (Wright (2011). For some, 'green infrastructure' refers to trees that provide ecological benefits in urban areas, while for others it means engineered structures (e.g. water treatment facilities) that are designed to have minimum impact on the natural environment (Benedict and McMahon (n.d.). The definition used in this document is presented in Box 3.1.

It is important to note that this definition goes beyond purely natural aspects to include man-made ecological elements that range from parks and planted vegetation, for example; to building interventions such as green roofs, among many others (URBES Project, 2014; Schäffler et al., 2013). It is also important to note that not all natural elements are considered 'green infrastructure'; only those that are part of a broad interconnected network that provides services in a similar way that built or grey infrastructure provides services (SANBI, 2017). Green infrastructure is, therefore, a new way of valuing natural and man-made ecological elements as a part of the infrastructure system supporting development (Schäffler et al., 2013).

BOX 3.1: GREEN INFRASTRUCTURE – DEFINITION

Green infrastructure refers to "... the interconnected set of natural and man-made ecological systems, green spaces and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces and original grassland and woodlands, as well as possible building and street-level design interventions that incorporate vegetation, such as green roofs. Together these assets form an infrastructure network providing services and strategic functions in the same way as traditional 'hard' infrastructure".

(Schäf)er et al., 2013: 3)

It is useful to view green and grey infrastructure as part of a continuum as shown in the diagram below (adapted from Davies et al.. 2013: 3):

Figure 3.1: Green Infrastructure; A green-gray continuum (adapted from Davies et al., 2013: 3)

The services that green infrastructure provides, which increases the resilience of the social-ecological system, include for example, the following (WWF and AfDB, 2012; Harrison et al., 2014; Elmqvist et al., 2015; Baró et al., 2016; Ranjha, 2016; Lloyds and Arup, 2017):

- Regulation of water run-off;
- Air quality improvement;
- Cooling heat islands;
- Noise reduction;
- Flood protection;
- Disaster risk mitigation (e.g. storm-surge protection);
- Pollution reduction and associated disease regulation; and
- Opportunities for outdoor recreation.

BOX 3.2: GREEN INFRASTRUCTURE FOR RESILIENT CITIES

"Natural and engineered green infrastructure solutions can create unprecedented opportunities for building resilient cities in the future."

(Harrison et al., 2014: 58)

Moreover, the integration of built infrastructure with relevant natural services provided by ecosystems can:

- Add flexibility to the infrastructure system as a whole, increasing its resilience through enhanced capacity to adapt to natural changes (Pandit and Crittenden 2015). The more dynamic nature of natural systems allows them to respond better than built infrastructure to gradual changes over extended periods of time (Pandit and Crittenden, 2015); and
- Enhance the diversity and redundancy within the infrastructure system through increasing the number of sources through which a single function is provided and spreading risks across geographical areas and systems (Ahern, 2011; Harrison et al., 2014). For example, water purification provided by built infrastructure can be assisted by green infrastructure in a catchment including wetlands and riparian areas, among other natural features (Cilliers and Cilliers, 2016).

Green infrastructure also has the advantage of being able to perform multiple functions simultaneously (e.g. flood alleviation, water filtration, carbon capture and places for people to recreate, among others); unlike built/grey infrastructure which is usually designed for a single purpose (Kithiia and Lyth, 2011; Schäffler et al., 2013; Harrison et al., 2014). As examples, Boland and Hunhammar (1999) point out that an urban forest can perform the functions of air filtering, micro-climate regulation, noise reduction, rainwater drainage and recreational opportunities; while wetlands can regulate micro-climate, drain rainwater, treat sewerage and provide recreational space. Further, a football field which is primarily developed to serve a recreational function, can also provide regulating services such as storm water reduction and softening of the effect of an urban heat island (Cilliers and Cilliers, 2016).

The concept of 'green infrastructure' has rapidly developed internationally, particularly in the United States and Europe (Barió et al., 2016). Kithiia and Lyth (2011) argue that while the role of green infrastructure in enhancing urban environmental quality and community health has been widely promoted in the African region, there is less emphasis on management approaches that recognise the full role of green infrastructure in climate change adaptation and mitigation. Drawing on examples from Mombasa (Kenya), Kithiia and Lyth (2011) illustrate the importance of the multi-functionality of green infrastructure, including its role in meeting direct social needs (e.g. enabling local urban communities to be close to nature), as well as its potential role in climate change mitigation and adaptation (e.g. cooling effect of Mombasa's Haller Park). Arguing for the use of green infrastructure in climate change mitigation and adaptation in Africa, Kithiia and Lyth (2011: 252) state that the "... combination of technological, financial, institutional and skills constraints...", as well as the shortage of data experienced in describing environmental conditions in low-income countries, is likely to constrain the implementation of "hard engineering" solutions, resulting in the need to consider 'alternative interventions'.

While acknowledging that green infrastructure is not a replacement for large-scale public built infrastructure, and that a diverse range of approaches to climate change adaptation and mitigation are needed, green infrastructure nevertheless has an important role to perform in African cities[1] (Box 3.3) (Kithiia and Lyth, 2011; Culwick and Bobbins, 2015). This is particularly since it can require less

[1]Green infrastructure also has a critical role to perform in rural areas, however, given the focus of this guide, the discussion centres on the role of green infrastructure in African cities.

capital budget expenditure than additional built infrastructure, while providing multiple benefits (Kithiia and Lyth, 2011; Culwick and Bobbins). Culwick and Bobbins (2015) point out that, "GI (green infrastructure) can provide infrastructure alternatives where the cost of traditional grey infrastructure is prohibitively high", using the example of Diepsloot informal settlement in Johannesburg, South Africa. Diepsloot does not have a formalised storm water infrastructure system due to its high cost, however a community-based organisation called Wassup (Water, Amenities, Sanitation Services Upgrading Programme), together with academics from the University of the Witwatersrand, are exploring opportunities to develop low-cost green infrastructure to address the risks of both standing water and flooding (Culwick and Bobbins, 2015). Initial findings indicate that such opportunities that use available resources and local skills exist (e.g. a pilot soak-away garden has been developed by Wassup to help in absorbing excess surface water) (Culwick and Bobbins, 2015).

BOX 3.3 RETHINKING INFRASTRUCTURE PROVISION IN AFRICA

"We believe that GI (green infrastructure) presents an opportunity to rethink the way infrastructure provision and development are envisaged in African cities, because it has the ability to deliver services using a)exible planning approach that can be tailored to address the speci(c challenges unique to African cities." (parenthesis added)

(Culwick and Bobbins, 20 October, 2015)

Effectively harnessing the benefits of ecosystem services within an integrated urban infrastructure system requires a number of proactive measures. These measures range in scale from those relevant to strategic urban and regional planning; to neighbourhood initiatives; to site-specific project-level design and assessment - and include the need to increase the value that is placed on green infrastructure at all scales (Harrison 2014; Maze and Driver, 2016; Cilliers and Cilliers, 2016). There are multiple guides and plans that have been developed internationally that provide recommendations around green infrastructure planning and design at these various scales. It is not within the scope of this discussion to provide detailed green infrastructure planning and design guidance (e.g. how to prioritise green infrastructure elements within plans for ensuring ecosystem connectivity in the landscape). However, to provide an initial idea of the type of broad actions that can be considered, examples are presented in Box 3.4 related to:

- Integrating green infrastructure into strategic urban and regional planning;
- Linking built infrastructure projects with relevant green infrastructure; and
- Developing the capacity needed to sustainably integrate relevant ecosystem services into the infrastructure system.

Box 3.4: INTEGRATING GREEN INFRASTRUCTURE INTO STRATEGIC DEVELOPMENT PLANNING AND INTO BUILT INFRASTRUCTURE PROJECTS

INTEGRATING GREEN INFRASTRUCTURE INTO STRATEGIC URBAN AND REGIONAL PLANNING

(Benedict and McMahon, n.d.; Harrison, 2014; Cilliers and Cilliers, 2016; Biggs et al., 2015; Maze and Driver, 2016)

- Identify high value green infrastructure assets (e.g. urban indigenous forest that provides space for recreation and mitigates the urban heat island effect) and include these in strategic planning for built infrastructure. The purpose is not only to protect such green assets directly, but to ensure that the services that they provide are recognised and integrated into a system of grey-green infrastructure.
- Plan for physical connectivity between elements of green infrastructure (i.e. across landscapes, scales and governmental jurisdictions) to enhance the sustainability of these ecosystems and the services they provide (e.g. the intactness of vegetation along the length of an urban river that crosses administrative boundaries affects the ability of such vegetation to control erosion, which in turn affects water quality in the river).
- Plan to maintain and enhance both the ecological integrity and the social amenity of existing urban and regional green networks, extending these where possible.
- Explicitly consider physical and functional connectivity of green-grey infrastructure within urban areas (e.g. providing easy pedestrian access to amenities through connecting urban parks, woodlots, streams and pedestrian walkways in an integrated system); as well as between rural and urban areas, and enhance these as far as possible.
- Ensure the effective management and maintenance (including formal protection, if appropriate) of strategic and irreplaceable natural assets (e.g. water source areas and wetlands); as well as the ecological processes that ensure the sustainability of these assets.

LINKING BUILT INFRASTRUCTURE PROJECTS WITH RELEVANT GREEN INFRASTRUCTURE

(Harrison et al, 2014; Maze and Driver, 2016)

- Include the restoration and/or maintenance of related green infrastructure in the planning and implementation of built infrastructure projects (e.g. restoration of catchment areas to decrease erosion when building a dam, thereby reducing potential sedimentation).
- Ensure that green infrastructure is not negatively affected by the construction of built infrastructure (e.g. avoid residential development within the protected area of an estuary and ensure that the migratory routes of highly valued species, on which tourism depends, are not fragmented by infrastructure development).
- Seek opportunities for the development of 'grey-green' infrastructure, for example:
  - Designing a park so that it serves both recreational and flood retention functions;
  - Attenuating storm water using, inter alia, vegetated swales, green roofs, vegetated curbs, rain gardens and permeable pavements; and
  - Developing green bridges to facilitate species movement.
- As far as possible, seek opportunities to use, maintain and enhance 'green infrastructure' instead of building and/or extending grey infrastructure (e.g. wetlands and restored catchments could avoid the need to construct water treatment infrastructure).

DEVELOPING THE CAPACITY NEEDED TO SUSTAINABLY INTEGRATE ECOSYSTEM SERVICES INTO THE INFRASTRUCTURE SYSTEM

(Harrison, 2014; Maze and Driver, 2016; URBES Project, 2014)

- Enable and promote awareness among a range of stakeholders (e.g. government decision-makers, civil society and business) of the functionality of ecosystems and their services and how they can contribute to supporting urban and rural infrastructure.
- Promote investment in green infrastructure and its maintenance at a local, provincial and national level.
- Invest in developing the range of skills needed for the development and maintenance of green infrastructure within multiple fields, including town and regional planning, hydrology, ecology, engineering, horticulture, and construction, among others.
- Undertake specific case studies to track and report on the benefits, as well as the costs, of developing and maintaining green infrastructure in a range of diverse contexts in Africa.