DESIGNING FOR INFRASTRUCTURE RESILIENCE

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1. INTRODUCTION

1.1 GUIDANCE, HANDBOOKS, MODELS AND APPROACHES FOR INFRASTRUCTURE DESIGN

There are many guidance documents and handbooks that set out ways in which infrastructure can be designed to be more resilient. However, these are most common for hazards that are not site specific, whose impact may be more directly related to infrastructure type/design. An example of this is earthquake loading, which can be considered as part of structural engineering design.

In contrast, where risks are not easily embedded in a standard or are site specific, such as climate or flooding risks, a different approach is needed that considers risks earlier, before a specific engineering solution is chosen. This is because such risks require further investigation to determine how they affect different infrastructure solutions[1]. This approach requires infrastructure to be considered within a wider, strategic planning context. Failing to do this could have significant impacts as highlighted by Benson, Twigg and Rossetto (2007) in their handbook, as set out below.

- In the Vietnamese city of Hue, expansion of infrastructure, including bridges, railway lines and roads, has created a barrier across the valley within which the city is located. As a result, excess rainfall can no longer soak away quickly and problems of flooding have become more severe.[1] Similar problems have occurred in several villages in Gujarat, India, following the construction of a donor-funded highway.
- Following widespread devastation caused by Hurricane Hugo in 1989, a new aid-funded hospital was built at the foot of a volcano in the Caribbean island of Montserrat. This hospital was subsequently destroyed by pyroclastic flows after the volcano began eruptive activity again in mid-1995.[2]
- Following the devastating 2004 Indian Ocean tsunami, some housing in Aceh, Indonesia, was reconstructed in flood-prone areas, leaving families vulnerable to future hazard events.

FIGURE 1 IGNORING HAZARDS HURTS. SOURCE: BENSON, TWIGG AND ROSSETTO, 2007.

Guidance provides recommendations in the form of guidelines, handbooks and toolkits as opposed to standards: which also means there is no legal requirement to comply with them. These guidance documents need to be used alongside risk information that accurately captures the level of risks in a given location (e.g. flood risk, drought impact on WASH/hydropower). For further information see the Understanding Risk and Resilient Infrastructure Investment resource (Gallego-Lopez and Essex, 2016b). As a result handbooks have tended to focus upon advising what to do if a disaster hits (e.g. post disaster relief or recovery efforts) or provide general design guidance. But this in itself assumes that the right type of infrastructure already exists in the right location in the first place, or that resilience can be addressed at the detailed design stage.

Approaches to assessing risks that require modelling data or analysis of some kind also tend to require specific expertise. This may change which professionals are required at the early stages of the feasibility and design process, along with greater investment in understanding an environment. To adequately address such risks, decision makers need to have access to the right data and models, as well as having the competency to understand what this data is telling them and to be able to make decisions with that information, which is just as critical as best practice type guidance (which will be highlighted through screening processes, again see the Understanding Risk and Resilient Infrastructure Investment resource (Gallego-Lopez and Essex, 2016)).

1 While guidance has been produced for climate and flooding risk this often just sets out general requirements rather than an appreciation of how design at specific locations is affected.

Therefore, the actual risks in a given situation may not be a straightforward choice between different infrastructure solutions. For example, re-afforestation upstream or re-planting of mangroves in a coastal delta may be more resilient than 'hard' engineering solutions. Different physical risks (e.g. sea-level rise and flooding) should also be considered alongside other considerations (e.g. long-term sustainability, livelihoods) so that resilience is not viewed as something that will affect the detailed design of a piece of infrastructure, but rather sets the context for how overall community/local economic resilience is delivered. Resilience therefore requires professionals to taking wider responsibility for factors not considered within current design manuals and at a much earlier stage in addressing infrastructure needs.

1.2 CURRENT APPROACH – INFRASTRUCTURE INVESTMENT IS NOT ALWAYS RESILIENT

This section provides examples of where infrastructure investment has failed to be resilient, before considering the sorts of processes and checklists that help avoid investment decisions which neglect or even undermine resilience.

The first example is historical, reflecting the way in which infrastructure has traditionally been provided to address a specific need, or more generally as a driver for economic growth. The central railway line of Tanzania was completed in 1914, traversing over 1250km from Dar es Salam to the capital Dodoma and on to the shore of Lake Tanganyika at Kigoma. But resilience was not considered when the railway was built and the alignment includes 55km through the wetlands of Malagarasi and Uvinza, which are now Ramsar registered wetlands. As a result the route has proven not to be resilient to flooding. Regular repairs are needed, including $11m of repairs following the 2009/2010 El Nino event (IRIN, 2010). This shows that while routes such as this are not designed for a hundred year design life, the investment decision, and the degree to which they are resilient will be felt far further into the future than was taken into account in initial planning.

More recently, the EBRD funded M06 Kiev-Chop Highway project in Ukraine aimed at improving economic growth through reduced journey times. However, the impact of the road on the urban environment, including road safety, was not considered as part of the road design (Ukrainian Road Safety Organisation, 2014).

Both of these projects might be assessed economically, and in terms of value-for-money, as being good investments if the assessment focussed on how they maximise value purely in terms of economic return on investment and in achieving specific stated development objectives (that is, to be economic, efficient and effective – see DFID, 2011). However, it is possible for such investment to still not be resilient, which can then require further investment, including due to climate, environmental and disaster risks, as seen with the investment in repair of the Tanzanian Central Line to *remain* efficient, effective and economic in the future.

Another example is how infrastructure studies (World Bank, 2011) and current spatial planning in Bangladesh does not sufficiently plan for climate resilience, as set out in Box 1.

Finally, the New Climate Economy Report (New Climate Economy, 2015) highlights how the G20 Global Infrastructure Initiative still largely ignores the close links between infrastructure investment and climate change, as do many national and local government planning processes. To change this, infrastructure planning and design needs to consider a much wider range of factors than are traditionally the responsibility of engineers and economists. The authors of the New Climate Economy report conclude that, "too often infrastructure and climate policies exist in separate silos. This creates potentially costly inconsistencies, sends mixed signals to investors, and heightens the risk of short-sighted infrastructure decisions."

BOX 1 THE NEED FOR STRATEGIC AND SPATIAL PLANNING OF INFRASTRUCTURE RESILIENCE IN BANGLADESH

Parvin and Shaw (2011) measurement of city resilience suggests poor to medium resilience in Dhaka, Bangladesh. For example, expansion of the built environment in Dhaka into its lowest lying area, which was previously set aside as flood plain for temporary storage of water (Haque, Grafakos and Huijsman, 2012) will increase future disaster risk.

The World Bank's assessment of the costs of adapting to extreme weather events in Bangladesh appears to focus predominantly on road transport impacts, although its scope is not identified as such (World Bank, 2011). While the World Bank analysis of rural climate change impacts in Bangladesh by 2050 suggests that $5.7 billion investment will be required, mainly to raise road infrastructure and strengthen polders, the EU's working paper on infrastructure strategy also considers energy generation, transmission, rail, aviation, shipping, construction and urban transport, as well as anticipating increased maintenance costs[2].

Source: Essex and Gallego-Lopez, 2014

Climate resilience, as well as DRR and ecosystem resilience, requires a different framing for investment that considers the risks and impacts of different resilience aspects from the outset, as illustrated in the figure below.

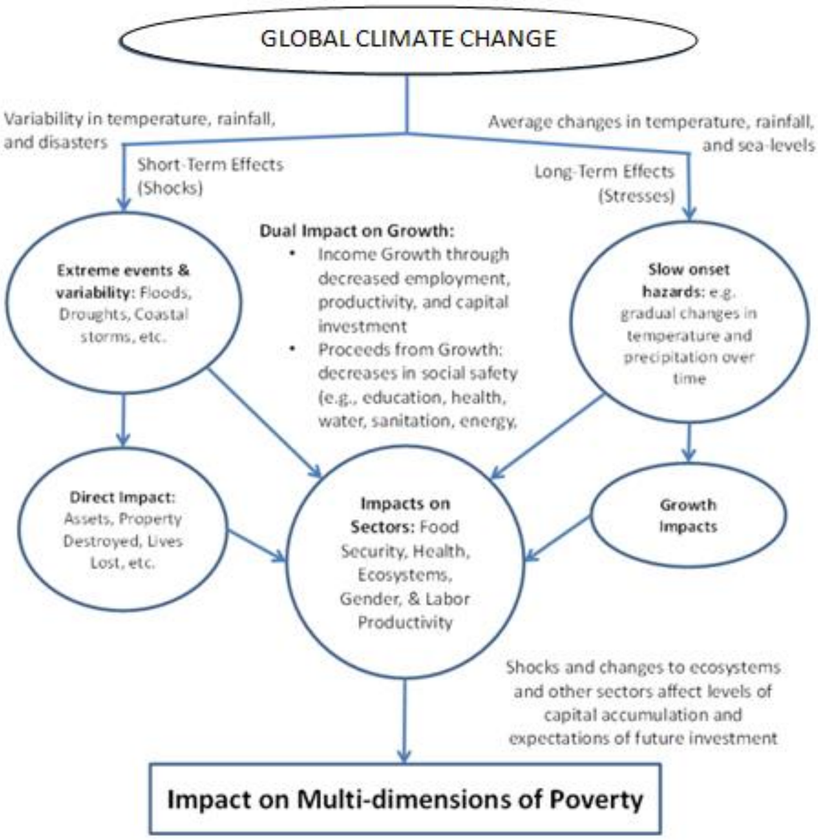


FIGURE 2 THE IMPACT OF CLIMATE CHANGE ON ECONOMIC GROWTH AND POVERTY AS DRIVERS OF DEVELOPMENT.

[2] The EU (2013) notes that for road infrastructure (the focus of the World Bank's Bangladesh study) around 30-40% of current road maintenance costs are due to 'weather stresses' and 10% of these due to extreme weather events alone. No increased maintenance costs or disaster rehabilitation were considered for Bangladesh.

Making the links between climate change (and disaster resilience) and the multiple dimensions of poverty requires sufficient consultation with intended users – in particular poor and excluded members of communities who lack voice, and women as well as men (see also Introducing Infrastructure Resilience resource; Gallego-Lopez and Essex, 2016a). This goes beyond consulting those most likely to be affected by climate change to taking different approaches that change which infrastructure solutions are selected and how they are designed. Examples include:

- International Alert's report looking at how to re-think gender in peacebuilding (Myrttinen et al, 2014) proposes that a 'gender-relational' approach is taken, that moves away from equating gender with women (and girls) while examining the interplay between gender and other identity markers, such as age, social class, sexuality, disability, ethnic or religious background, marital status or urban/rural setting. This approach requires more nuanced and better-researched interventions, which can enable more effective and sustainable targeting of programming.

- Similarly, UNDP highlight the vital importance in integrating a gender focus into disaster preparedness and post-disaster reconstruction, as set out in Box 2 below.

BOX 2. THE DIFFERENTIAL GENDER IMPACT OF HAZARDS.

Following the 1991 cyclone and flood in Bangladesh, women's death rate was almost five times higher than men's. Warning information was transmitted by men to men in public spaces, but was rarely communicated to the rest of the family. As many women are not allowed to leave the house without a male relative, they perished waiting for their relatives to return home and take them to a safe place.

Moreover, as in many other Asian countries, most Bengali women have never learned to swim, which significantly reduced their survival changes during the flood.

Source: Röhr (2006) cited in GCCA (2013).

A structure's climate resilience will affect what proves to be a good investment over the lifetime of the infrastructure. This could be considered in terms of a combination of different failure mechanisms for an individual piece of infrastructure (see infrastructure resilience proposed in the next section 3.2 below) and also for the overall resilience of infrastructure *systems* and the built environment and economy of local/sub-regional/city area (see similar principles presented in section 5.2 below). Failures in the infrastructure system may not be proportionally related to, or even the direct consequence, of an external shock and can be prompted by even small hazards that push one or more elements of the system over their functional limit (Moor et al, 2015).

Resilience in infrastructure is part of a wider sustainability and resilience road map. According to Ensuring new infrastructure is climate smart[3] (New Climate Report, 2015), integration of climate-smart principles into infrastructure decision-making needs to happen at all levels, for example; a) the design and alignment of overall strategy and policy, b) composition and balance of infrastructure plans and portfolios considered as a whole, and c) in relation to individual projects. Harmonization between government policies is crucial because inconsistencies can undermine intended outcomes, inhibit investment and perhaps raise the cost of capital.

3 2015.newclimateeconomy.report/wp-content/uploads/2015/10/Ensuring-infrastructure-is-climate-smart.pdf.

1.3 BETTER INFRASTRUCTURE: TWO APPROACHES TO RESILIENCE OF INFRASTRUCTURE

How infrastructure is designed to be disaster and climate resilient depends on the type of hazard addressed (and to a lesser extent, the type of infrastructure).

- At one extreme, infrastructure can be designed to be earthquake resilient through appropriate ***engineering standards***, with increased safety factors and appropriate details.
- At the other extreme, climate resilience requires climate modelling data to be translated (such as through hydrological modelling) into locally specific risks to inform infrastructure planning and design.[4] Although ***guidance and risk screening*** are useful here they are not sufficient. It is important that the wider risk context is understood and ***appropriate modelling results*** are used to inform infrastructure (and non-infrastructure) choices.

This means that making infrastructure resilient to disaster, environmental and climate risks is likely to require new approaches as well as new standards and regulations. However, **given climatic uncertainties, some current design codes and standards might not be applicable in the future, and this has implications for new and existing infrastructure.**

So, while resilience in infrastructure can sometimes be achieved through a ***standard design process (e.g. for earthquake risks)*** it increasingly requires a ***resilience-led approach (e.g. to address climate risks)***. These two approaches are contrasted in the table and the figure below.

In both cases, the way the infrastructure ***affects wider resilience*** of individuals, households and communities should also be considered, as set out in the Introducing Infrastructure Resilience resource (Gallego-Lopez and Essex, 2016a). Best practice can be drawn from both developed and developing countries, and in relation to both existing and new infrastructure.

Standards-led Infrastructure Delivery	Resilience-led Infrastructure Delivery
Based on standards and guidelines that prioritise meeting 'desires' of national government/return on investment. Decision making tends not to consider increasing risks due to … earthquake/ landslide, flood/storm surge, drought, heat, sea level rise etc. sufficiently or early enough to affect chosen engineering solutions. Risks are considered later (if at all) in infrastructure design and delivery. Resilience tends to be limited to that of individual infrastructure investments.	**An understanding of risk and resilience sets the context** for decision making with (risk and climate) modelling sufficiently interpreted to inform investment choices and selection of alternative solutions. Resilience of infrastructure, economic resilience, resilience of communities and sustainable livelihoods, wider service systems and economic resilience are considered together. Considering all of these requires risks to be perceived from the point of view of affected communities (including poor and other marginalised groups, men and women, old and young).

TABLE 1 CONTRASTING A STANDARDS-LED AND RESILIENCE-LED APPROACH

If governments/donors/IFIs want resilience-led design, greater investment is needed earlier so that alternative solutions (which may or may not require infrastructure) can be considered, and so that all relevant stakeholders can be engaged.

[4] This should address the increased uncertainty associated not just with individual hazards, but with the probability that different risks occur together. For example increased frequency, severity and variability of storm surge and flooding events can combine with sea-level rise to create a greater impact, which may furthermore be greater in the future, either within or beyond the design life of an infrastructure or wider infrastructure system.

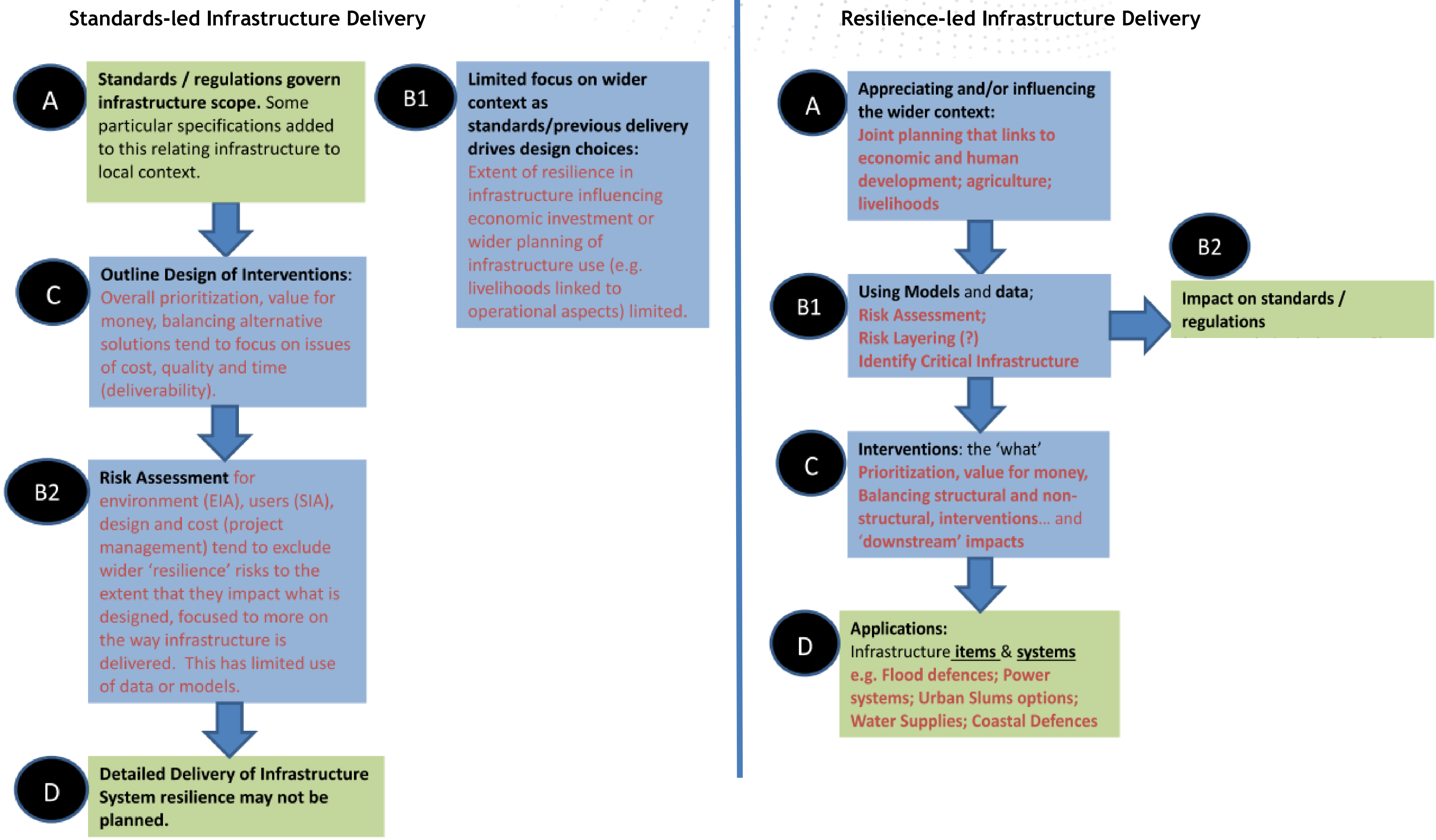


FIGURE 3 CONTRASTING A TRADITIONAL DESIGN APPROACH (LEFT) WITH A RESILIENCE-LED DESIGN APPROACH (RIGHT).

2. GUIDANCE AND TOOLS FOR CLIMATE AND DISASTER RESILIENT INFRASTRUCTURE

2.1 INTRODUCTION

The section above considered how an understanding of risk should inform the selection of infrastructure to improve resilience. This section explores the range of different options to improve the resilience of infrastructure.

This includes:

- building more robust (stronger, 'failsafe') structures;
- building in redundancy, by including sacrificial components that are 'designed to fail'; and
- ensuring that investment and design reflects as far as possible the ways in which risks are affected by the interconnections within and between infrastructure systems, and between infrastructure, communities, households and individuals.

The latter aspect, together with increasing climate risks, highlights the importance of strategic and spatial planning to improve the resilience of infrastructure and livelihoods together.

2.2 WIDER APPROACH NEEDED TO ADDRESS CLIMATE IMPACTS

OECD countries are increasingly referring to the need for climate resilience in their national infrastructure planning documents. However, there is not enough evidence that climate risks are being explicitly considered in infrastructure projects financed or commissioned by governments or infrastructure banks. The OECD report on The role of government in making infrastructure investment climate resilient: draft survey of current practices[5] (OECD, February 2016) investigates the ways in which OECD countries are supporting resilience in national infrastructure. The main findings) are:

- Climate resilience has been mainstreamed in some countries such as spatial planning, mainly through the Environmental Impact Assessment, as well as technical and economic regulation which influence infrastructure.
- About 30% of OECD countries are revising their national infrastructure standard(s).

The World Bank assessment of the climate impact on investment in infrastructure in Africa (Neumann and Cervigni, 2015) identified how to improve the analytical base for decision making. It concluded that:

a. Ignoring the large effects of climate change on infrastructure may lead to significant "regrets"; and

[5] www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/WPCID%282016%292&docLanguage=En

b. Despite uncertainty, it is possible to plan infrastructure development to reduce these regrets; and c) There will be cost increases and savings, but the benefits (in terms of reduced risk) are greater.

UNDP (2011) suggests that an overall climate resilient development strategy (sustainable in terms of climate change and resource use) should include a roadmap for how the infrastructure element will be climate resilient. This same approach is suggested by WRI (2010) who also describe this as a 'no regrets approach'.

However, resilience in infrastructure should take into account the **current** approach that cost of inaction is higher than the cost of action to climate change. "There have been several attempts to measure the costs of climate change globally and for specific regions. The Stern Review (2007) estimated the costs of inaction related to reducing risks of climate change at approximately five percent of global gross domestic product (GDP) per year, based on market impacts alone. When non-market impacts such as costs of health and environmental effects are incorporated into the analysis, the total average cost was estimated to be approximately 11% of global GDP. If the sensitivity of climate to carbon dioxide (CO_2) concentration is greater than baseline estimates, the projected losses were more than 14% of global GDP. Finally, accounting for distributional effects (based on the assumption that the impacts will be greater for developing countries), the total cost was estimated at approximately 20% of current per capita consumption" (cited in UNDP, 2009).

2.3 FRAMEWORKS FOR DISASTER AND CLIMATE RISK MANAGEMENT

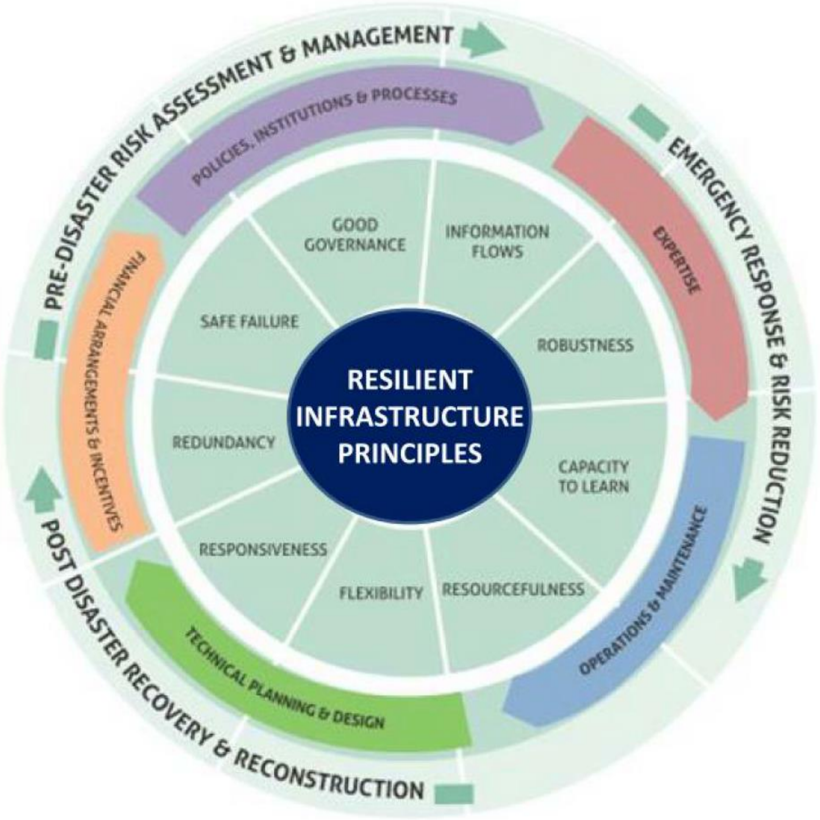
It is critical that the overall approach taken integrates both resilience (to both climate and disaster shocks) and sustainability (including climate change mitigation and the scale of resource-use and condition of ecosystem services). This will also impact on the decision making process and principles for climate proofing of existing infrastructure, including post disaster such as set out by UNDP (2011).

For some hazards (e.g. earthquake impacts, landslides) resilience can be achieved through a combination of best practice and updated engineering standards. However, to achieve wider disaster and climate resilience a different approach is needed, bringing a broader set of information and analyses into decision making. Two frameworks are presented on the next two pages, focused on disaster resilience and climate resilience respectively.

Firstly, principles for Disaster Risk Management in the transport sector (Moor et al, 2015 p.22-25) could inform a general analytical framework to mainstreaming resilience in infrastructure (see overleaf). This sets out an approach (and series of guidelines) on how different direct impacts of disasters (shocks) can be reflected in the technical 'solution-based' design approach.

Secondly, UNDP (2011) recommends an approach to decision-making on climate proofing infrastructure that integrates risk assessment based on climate modelling. This could also be considered for making infrastructure more resilient to disasters – this wider approach considers the context for infrastructure investment, and the role of the infrastructure professional as part of a wider multi-disciplinary team.

These examples set out the need for a wider, resilience-led, approach to the decision making (see figure that follows, drawn from discussions held in compiling this resources in February 2016). Such approaches are context-led, so resilience underpins not just the design of individual infrastructure elements but the planning through to operation of wider infrastructure systems.



Analytical framework to mainstreaming resilience in infrastructure

Source: Adapted from Moor et al, 2015

1. **Good Governance** involves defining roles and responsibilities so that organisations' functions do not overlap and there is not competition for limited financial and human resources. This also includes public, accountability, transparency and anti-corruption measures.
2. **Information Flows** between infrastructure system managers, staff and users as well as across multiple agencies and infrastructure systems. Efficient information flows must also exist to transmit back lessons after disasters and emergencies. Moreover, agents need reliable information derived from rigorous data collection and risk assessment processes in order to make strategic decisions regarding to infrastructure.
3. **Flexibility** to be able to change and evolve in response to changing conditions.
4. **Resourcefulness** is the ability to mobilise assets and resources to meet priorities and goals. This includes financial, social, physical, technological, information and environmental resources.
5. **Responsiveness** is the ability and motivation of agents to restore function and order rapidly after a failure.
6. **Capacity to Learn**: Engineers, emergency planners, transport operators, owners, regulators etc. are able to learn from experience and past failures. Processes encourage reflexivity and learning from past failures and events.
7. **Redundancy** is spare capacity and involves increasing the diversity of pathways and options so when one fails, others that serve a similar function can substitute and take their place.
8. **Safe Failure** involves designing infrastructure so that when one component fails it does this progressively with minimal disruption to other parts of the infrastructure and network.
9. **Robustness** is the ability of infrastructure assets and the network to withstand stresses and shocks to a level that is designated tolerable and cost effective (standards of tolerability and these design standards change over time).

FIGURE 4 DISASTER RISK MANAGEMENT FRAMEWORK. Adapted from Moor et al, 2015.

Decision Making Approach for Climate Proof Infrastructure

Step 1. Identify and Set Objectives: the area and time frame of analysis, the stakeholders and potential uses of infrastructure, acceptable risks and critical facilities. Focus on the objectives for climate-proofing exercise. CCA/DRM objectives should be balanced against overall economic, social, environmental, cultural objectives of the stakeholders.

Step 2. Establish Baseline: Recent experience with hazards and disasters. Vulnerability assessments including both quantitative (e.g. census data, household surveys) and qualitative assessments. DRM/CCA capacity assessment. Assessment of current standards, guidelines and enforcement.

Step 3. Climate Modelling and Assessment: Climate-proofing assessment together with the risk analysis, there should be an economic assessment of different climate-proofing options. Probabilistic risk modelling should be methodically conducted along with scenario testing since it brings together hazard, vulnerability and capacity assessments, which involve different types of data in different units of analysis. Reasonable alternatives should be assessed and prioritized.

Step 4. Inform Infrastructure Planning: Spatial-based climate-proofing plans: Combining stakeholders' objectives of the climate-proofing exercise and the results of the probabilistic risk modelling, it is possible to bring the CCA/DRM plans into the planning context at the appropriate level(s). Including disaster preparedness such as establishing Early Warning Systems.

Principles for Climate Proofing Infrastructure.

Principle 1. Climate Modelling Interpreted to Inform Risk Based Decision Making - A sophisticated array of information is needed to inform and guide long-term infrastructure investment as well as decisions on management. Integrating climate change risks into this process requires a probabilistic risk-based approach. Climate change models (alone) don't provide the granularity needed for the site-specific infrastructure design. Decision making tools should internalize climate change risks into infrastructure (e.g. enabling risk management at local, national and regional levels using a GIS-based platform. Engineering vulnerability/risk assessment must use (multi-disciplinary) professional judgement to assess uncertainties inherent in climate change projections.

Principle 2. Wider Solutions across the whole project cycle, as part of a Wider Approach - Soft solutions are sometimes as important, if not more, than hardware solutions. A risk-based approach can be linked to sustainable development by identifying risks to future generations.

Principle 3. Design to acceptable performance standards across the whole project cycle - Climate change must be considered in infrastructure planning, design, operation and maintenance. The performance response of infrastructure components that require estimation of climate change impacts include structural integrity, serviceability, functionality, operation and maintenance, emergency response, insurance, policies and procedures, economics, public health and safety, and environmental effects.

Principle 4. Locally Appropriate approach includes roles for innovation and private sector - Country-driven, localized efforts to internalise climate change risk considerations are essential. Top-down approaches are not successful. The government's role should be to facilitate market interventions to promote innovations in climate risk management. The resources, imagination and mobilizing power of the private sector are critical to support innovative and widespread risk management in a world of changing climate.

Step 5. Monitoring, Evaluation and Learning: This process is linked to a set of key principles for climate proofing infrastructure, as set out in the table (to the right).

FIGURE 5 CLIMATE RISK MANAGEMENT FRAMEWORK. Source: Simplified from UNDP, 2011.

3. EXAMPLES OF BETTER PRACTICES TO IMPROVE THE RESILIENCE OF INFRASTRUCTURE

3.1 DISASTER RESILIENCE: BUILDING CODES AND REGULATIONS

Building codes and standards should be designed or updated to ensure not just long-term robustness but also the flexibility for future adaptation (such as to address climate change) and to have safe failure mechanisms to reduce vulnerability in the event of a shock.

Designing infrastructure to be more 'robust' (meaning stronger) may be necessary, so it can withstand extreme events. For instance, bridges in the USA are designed to resist storms that have a probability of occurring one or two times every century (NRC 2008, p.153). GFDRR (2016) states that building codes and land-use regulations are proven effective tools to promote safety in cities and reduce risks from natural disasters.

But just 'raising design standards', that is to increase infrastructure robustness alone, is not always sufficient or the most cost efficient solution. Some developing countries do not adopt or enforce regulations, which makes infrastructure vulnerable to risk of collapse, flood or fire. Lack of regulations together with increasing migration to cities and unplanned urbanization are some of the main causes of disaster losses. Moreover, climate change is exacerbating these losses by more frequent and extreme droughts, cyclones and floods. To tackle this, the GFDRR just launched a global partnership and program to help to improve the implementation and compliance of building regulations in vulnerable countries (GFDRR, 2016a).

There are many examples where infrastructure in seismic zones is now better prepared for earthquakes as a result of updated building codes. Some specific examples are highlighted as follows:

- **Pakistan** has made some progress on this front when publishing its 2007 Building Code (BCP), which is the first nationwide policy for earthquake-resistant construction. Although the building code has been embraced and enforced, it only applies to new construction as stated in the Seismic design in Pakistan: building codes, bylaws and recommendations for earthquake risk reduction[6] (UNDP, 2015). Chapter 2 of the BCP quantifies the seismic hazard for design at a given building site, by mapping the country into five mapped zones and providing a table for parameters[7]. Chapter 3 addresses site selection. For important buildings this prohibits locations close to active fault traces and requires mitigation of liquefiable soils, however it does not define what an important building is.
- Another good practice is the Istanbul Seismic Mitigation and Emergency Preparedness Project[8] (ISMEP) in **Turkey** which aimed to evaluate, strengthen and reconstruct about 800 schools, hospitals and other buildings by 2013. Turkey is exposed to Earthquakes (about 70% of the population lives in seismically active areas; 66% of the country is located on active fault zones, 75% of damaged buildings in last 100 years were due to earthquakes),

6 www.pk.undp.org/content/dam/pakistan/docs/CPRU/Disaster%20Risk%20Management/Earthquake.pdf
7 Tehsil is an administrative division, generally an area of a city or town that serves as its administrative centre.
8 www.gfdrr.org/sites/gfdrr/files/publication/Istanbul.pdf

floods (which occur mostly in coastal plains, and are exacerbated by deforestation, erosion, and poorly planned development) and landslides (approximately 25% of the country is exposed to landslide hazard). Since the Marmara earthquake the country is now shifting from reactive approach to focus on disaster risk reduction and mitigation. The ISMEP forms part of this and focuses on 1) strengthening of emergency management, 2) seismic risk mitigation for priority public buildings and 3) enforcement of building codes. See figure below.

- Another example where seismic risks have been effectively addressed is in Concepcion, **Chile**. Existing building codes and appropriate enforcement have allowed buildings to sustain moderate damage during the 8.8 earthquake in 2010. (Arup, 2014).
- Utilities (e.g. water sector), particularly in developed countries, have developed plans to enhance the resilience of their infrastructure and services. For example, Wellington Water (2015) in **New Zealand** has considered the impact of a major earthquake on supply. Their analysis identified likely risks of damage to infrastructure and associated loss of service. Though Wellington Water state that they are actively addressing the risk, they also recognise that they do not currently have a whole system view on resilience that captures both the bulk water and reticulation networks and associated links with other utilities.
- The **Philippines** Forum on safe and resilient infrastructure[9] in 2013 (GFDRR et al, 2014b) is a good example of a national review of standards in relation to resilience. Its recommendations demonstrated that there is a need to take a wider approach going beyond earthquake risks, and also consider institutional changes at a national level.

3.2 CLIMATE RESILIENCE: ADDRESSING FLOODING THROUGH A RESILIENCE-LED APPROACH

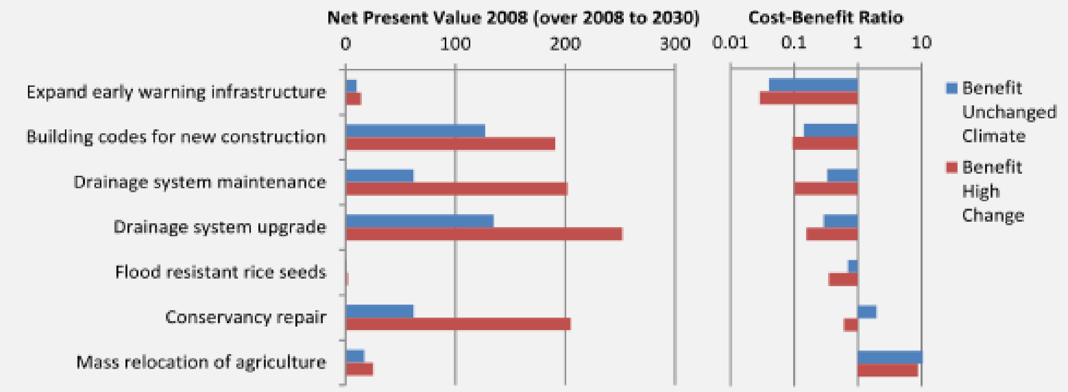
Though infrastructure standards and effective enforcement can be effective in earthquake-proofing, improving the resilience to flooding, including changing impacts due to climate change also requires local knowledge and data-modelling and forecasts to predict current and future flood events and return periods.

Climate change is changing established rainfall patterns, and hence the design of storm defences and surface run-off measures will need to change. Flood resilience of transport infrastructure for example, requires a design to be informed by (and follow on from interpretation of) climate modelling and hydrological modelling. An example of where this has informed an infrastructure programme design is the Belize Climate Resilient Infrastructure Project. Instead of designing a road first and then designing the most flood vulnerable sections during detailed design, the approach starts by considering what infrastructure types and locations are best in the long-term and how to improve not just the resilience of individual pieces of infrastructure but the overall infrastructure systems.

Ranger (2013) gives a further example (see Figure 9) where investment is planned to reduce the risk of flash floods in Guyana based on climate modelling outputs.

[9] www.gfdrr.org/sites/default/files/publication/WB%202014%20Philippines%20Forum%20on%20Safe%20and%20Resilient%20Infrastructure.pdf

Guyana's geography makes it prone to flooding. Much of the population and agricultural production lies in a narrow strip of land along the coast, which is prone to flash flooding from rainstorms. Guyana has high levels of poverty and a lack of flood protection. 'Moderate change' climate projections are for a reduction in rainfall of around 5%, though in a worst-case scenario ('high change'), rainfall could increase by 10% by 2030. Under this scenario, expected annual losses from flooding could rise from US$130 million (in a unchanged climate scenario) to US$200 million by 2030 due to climate change. A wide range of measures were found to be cost-beneficial under both a moderate change and a worst-case ('high change') scenario (see Figure below), including expanding early warning infrastructure, introducing building codes for new construction and upgrading the drainage system. The only measure where climate uncertainty is shown to have a material impact on cost-efficiency is repairs to Guyana's water conservancy (flood storage) system – this is found to be cost-beneficial only under the more pessimistic ('high change') climate scenario. Subsequent analysis by the World Bank suggests that if sea level rise is accounted for, upgrades to this system become cost-effective.



The benefit of a set of adaptation measures for flood risk management in Georgetown, Guyana, expressed in net present value (US$ million 2008), and the cost–benefit ratio, estimated for two climate change scenarios (unchanged and a 'high change' climate scenario).

Source: Economics of Climate Adaptation Working Group (2009)

Source: Ranger, 2013.

FIGURE 9 REDUCING THE RISKS FROM FLASH FLOODING IN GEORGETOWN, GUYANA.

However, there are still many examples where performance standards don't allow for the impacts of a changing climate. The following examples relate to flood risk:

- The Flood Estimation Handbook (FEH) is used for modelling surface water run-off in the UK. At the time of the last iteration in 1999, the approach used rainfall records up until the 1990s, which is already over fifteen years out of date, and concerning given the recent extreme weather in the UK over the last 5 years. Its approach to predicting how rivers will respond over the next 100-200 years as the climate changes is to apply a factor of safety, rather than based on modelling of UK rainfall patterns. In an attempt to address the continually changing climate, the FEH service now provides online databases, which are assumed to be updated regularly, based on recent data records.
- ADPC et al (2005) has provided the Handbook on design and construction of housing for flood-prone rural areas of Bangladesh[10] which include innovative and alternative methods for housing construction. However, this handbook does not mention infrastructure, and gives guidance only.
- WASH standards also need to consider the impacts of a changing climate. However, this is still largely absent, such as for the Tanzania Design Manual for Water Supply and

[10] http://www.adpc.net/igo/category/ID189/doc/2013-p74Wob-ADPC-handbook_complete-b.pdf

Sanitation (2009). This indicates that much more effort is needed to mainstream resilience into the performance specifications for infrastructure.

3.3 COMMUNITY INFRASTRUCTURE AND DECENTRALISED INFRASTRUCTURE SYSTEMS

New approaches are required for the resilience of small-scale community infrastructure as well. In some cases this type of infrastructure can be designed to enhance the resilience of communities, and countries as a whole, noting the need to differentiate the views of men and women, the poor and better off, and to obtain the views of potentially excluded groups such as the old and the young, and people with a disability – and ensuring that appropriate arrangements are put in place for information sharing, consultation and empowering users as informed decision makers.

The following examples are drawn from the energy and water sectors:

- **Community Energy Infrastructure.** Distributed systems (e.g. energy mini-grids) can result in more sustainable and resilient infrastructure (Biggs, Ryan and Wiseman, 2010). This move away from standard supply-side procurement specifications, to a more localised and flexible provision of infrastructure can reduce the overall capital expenditure needed to invest in new infrastructure.
- **Community Water Infrastructure.** Mawlamyine village in Myanmar can now access to potable water during even during severe floods thanks to an upgraded flood-proofed water pond[11] (BRACED, 2016). This is a great example of community participation in achieving resilient infrastructure.

The Myanmar Alliance has designed the BRACED Community Resilience Assessment and Action Handbook[12] to understand community resilience building on established vulnerability assessment methodologies. Additional tools for better understanding a wider set of resilience related issues covering climate change, natural disasters, environmental change, conflict and inclusion are integrated into the handbook.

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11 www.adpc.net/igo/category/ID189/doc/2013-p74Wob-ADPC-handbook_complete-b.pdf.

12 www.braced.org/resources/i/?id=127f0e24-a44a-4468-abca-96db853f6558&com.dotmarketing.htmlpage.language=1

4. KEY RECOMMENDATIONS TO ENHANCE THE RESILIENCE OF INFRASTRUCTURE

4.1 INTRODUCTION

This section sets out three key recommendations:

- Resilience-thinking should prioritise improving existing infrastructure (including infrastructure systems and links to community/livelihood resilience) first;
- There should be a shift from an approach that starts with pre-existing standard solutions to performance specifications aiming to maintain an acceptable level of service; and
- Capacity and skills need to be developed to deliver a participatory, resilience-led approach.

4.2 STRENGTHEN THE RESILIENCE OF EXISTING INFRASTRUCTURE

It is important that resilience is considered not just for new infrastructure, but also through a fresh look at infrastructure that already exists, and how this affects the resilience of communities and society. For example:

- The UK flood defences are becoming outdated and many have exceeded their intended lifespan, leading to ineffective protection in the face of the rising level of flood water, seen with recent storm events[13].
- The UK (HM Government, 2011) also has a strategy to ensure new and existing infrastructure is preparing for a changing climate. Infrastructure resilience requires investment decisions to take account of how climate change results in changing patterns of consumers demand - to ensure that infrastructure assets have greater flexibility so they can be modified in the future without incurring excessive cost and supporting this through infrastructure organisations and professionals with the right skills and capacity to manage that adaptation.
- Similarly, in Bangladesh many of the cyclone shelters built during the nineties or earlier were not used during recent cyclones, despite continued donor focus on funding these structures[14]. One option for mitigating this risk is to have dual purpose facilities that serve an everyday purpose, but can be used for alternative needs during an extreme event, for example building schools that also act as cyclone shelters in Bangladesh. However, while these might be 'resilient' and provide refuge from the most extreme disaster events it is not clear to what extent this enables continued resilience of livelihoods in these areas.

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13 www.theguardian.com/environment/2015/dec/27/floods-army-called-continue-devastate-northern-england

14 Early Recovery Assessment reports (see Kabir, 2010) have shown that only 12% of those surveyed reported using official cyclone shelters, despite 80% reporting that they knew that one existed, often less than a kilometre away. The majority of respondents (60%) either took shelter in a strong and well-built house in their village or stayed at home.

4.3 FOCUS ON MAINTAINING SERVICE – AND SHIFT TO PERFORMANCE SPECIFICATIONS

It is crucial that resilience is not just achieved in terms of the physical integrity of assets but to ensure that it is able to maintain service and operating performance. The Pitt Review (2008), which reviewed lessons from the widespread flooding in the UK in 2007, highlighted the importance of maintaining an appropriate level of service, even straight after a disaster event:

> *"Government should establish a systematic, co-ordinated cross sector campaign to reduce the disruption caused by natural hazards to critical infrastructure and essential services."*

This was considered further when the UK started its current review of its approach to infrastructure resilience[15], as highlighted in the box below.

BOX 3 OVERVIEW OF THE UK'S INFRASTRUCTURE STANDARDS

The UK Government has worked with regulators and industry to review the current levels of resilience of critical infrastructure design standards, service standards, performance standards, event standards and maximum recovery time standards. The UK's infrastructure is designed and built using a wide range of international and British engineering and design standards that are developed by industry and used to ensure infrastructure is fit for purpose and designed to operate in the range of conditions likely to be experienced in the UK (or worldwide). However, such standards are intended to protect the physical integrity of the asset, not necessarily the service. For example, an asset may not be destroyed by a flood event because of a good design standard, but it is nonetheless flooded and the service it provides may be lost for the duration of the event. *Therefore, whilst design standards contribute to ensuring resistance and reliability of infrastructure, they alone are not necessarily sufficient to provide resilience to essential services.*

Source: UK Cabinet Office, 2011.

Similarly in the US, the National Academy of Engineering (2009) found improving infrastructure resilience[16] requires a common platform (such as GIS) for information sharing and data integration. It recommended that resilience should be thought of in terms of infrastructure "services" to link physical damage to societal impacts, and efforts made to better understand this through a research centre and collaboration with end users.

The ADPC (2015, p36) proposed various measures for infrastructure design, reconstruction, retrofitting and maintenance. Building codes are designed to protect public health, safety and general welfare during construction and occupancy of structures. However, a traditional approach to building codes can lock-in risks (often through not properly evaluating them). A standards-led approach tends to be prescriptive so does not encourage the use of the latest risk information (e.g. climate and hydrology data) to inform infrastructure choices. For example, contrast:

- **Traditional building codes (prescriptive, standards based)** are generally easier easy to understand, follow and enforce. However, they can lock-in design characteristics that, though valid when the building code was written, do not necessarily allow for future changes in use, user characteristics or environmental risks; and
- **Performance-based codes (which do not direct design to standard solutions)** which define acceptable or tolerable risks for operation, health, safety, and public welfare and provide approved methods for demonstrating compliance. This explicitly evaluates performance under different conditions associated with potential hazard events. This

15 This includes the UK Collaboratorium for Research in Infrastructure & Cities (*UKCRIC*) – a new £138 million investment in UK infrastructure research coordinated by UCL. http://ukcric.co.uk/

16 https://www.nae.edu/Publications/Bridge/17281/17548.aspx

allows much greater flexibility in balancing system performance, with budget and risk management.

Defining an acceptable level of service is important. This allows a wider range of options than simply designing infrastructure to be more robust to address more extreme conditions. For example:

- The US National Academy of Engineering said that engineers have long tried to design infrastructure to withstand extreme events, but more recently they have addressed the need for infrastructure systems that are resilient. This entails analysis of interrelated dimensions to identify solutions that promote: lower probabilities of failure; less-severe negative consequences when failures do occur; and faster recovery from failures. Previous work on infrastructure in disasters aimed to understand the mechanics of how components of infrastructure systems perform when subjected to extreme conditions. However, alternative engineering solutions including different materials, technologies and strategies to retrofit existing infrastructure have been developed to improve infrastructure elements' ability to withstand natural hazards and climate change (Infrastructure Resilience to Disasters[17], NAE, 2009).
- Similarly, Glasser (2016) suggests a new science-based approach is needed, rather than rigid adherence to standards and guidelines which may only reflect the evidence of past (as opposed to future) risks. This will enable designs to address not just not vulnerability to shocks, but be better able to consider future risks and combine different risk elements, such as slow-onset and increasing climate and ecosystem related risks.
- Also, the African Development Bank (AfDB) proposes that performance standards are set through screening (or similar) processes at the early stages of project development. For example, the AfDB climate safeguard system requires risk assessments *before* projects are designed, which also enables appropriate adaptation components and measures that may be eligible for financial resources from climate funds to be identified. This focus on performance can lead to entirely different solutions[18]. For example, the promotion of urban water management by upgrading urban drainage to cope with severe and frequent floods in Yaounde in Cameroon, Nakuru in Kenya, and Harar in Ethiopia.

Setting functional or performance specifications for infrastructure is a good way to deliver resilience, however it should be recognised that this approach must be accompanied by an approved method for demonstrating compliance. Recognising the particular lack of accurate data in some contexts, establishing methods for designers to demonstrate compliance may be difficult.

One way to deliver this is through starting with an asset management framework that puts sustainable service delivery as central, rather than condition or resilience of a particular piece of infrastructure. One example of this is highlighted in Machedo (2015). Similar work has been carried out by the Institute of Public Works Engineering in Australia.

[17] https://www.nae.edu/Publications/Bridge/17281/17548.aspx

[18] Technical and advisory services to address climate change impacts and risks on energy projects under the Programme for Infrastructure Development for Africa (PIDA).

4.4 BUILD THE CAPACITY AND SKILLS NEEDED FOR A RESILIENCE-LED APPROACH

The link between tools and approaches and capacity is crucial. For example:

- In the past, opportunities to design and build infrastructure to reduce vulnerability to natural hazards were missed because of higher costs and lack of expertise.
- Similarly, land cost and availability is often the main driver in selecting locations for critical facilities, and expertise may not be present to analyse and articulate other locational features such as safety from potential hazards or environmental concerns.
- Often building codes exist but they are not correctly implemented due to lack of skilled professionals both to deliver and to effectively inspect and enforce construction against the codes.
- Poor governance and corruption can lead to abuse of land-use control and building codes, resulting in illegal expansion of buildings that can exacerbate damage caused by disasters (Benson, Twigg and Rossetto, 2007).

A key challenge is for sufficient in-country skills and resources to be available to deliver resilient infrastructure, and ensure it is properly maintained. This includes ensuring contractors, planners, engineers and operators all have the required skills. It will also include the skills to collect, model and interpret risk information (e.g. climate, hydrology related) so that it informs infrastructure investment choices and subsequent design.

This will also require skills to elicit and understand different user perceptions – differentiating between better off, poor, men and women, old and young, and those with a disability. This analysis will require traditional engineering skills for the provision of infrastructure (e.g. rural water supply) to be complemented by those of, for example, climate, economic social development specialists and means infrastructure investment should be part of an integrated development strategy (Schreiner and Naidoo, 1999).

To overcome the issues set out above, Benson, Twigg and Rossetto (2007) suggest an integrated and comprehensive approach that clearly establishes the design criteria including identifying the hazards, current risks, and socially acceptable levels of these risks, through:

- Consultation with engineers specialised in hazard-resistant construction from the initial stages of construction projects;
- Undertaking a multi-hazards appraisal to identify hazards, severity and occurrence;
- Evaluation of the current risk including identification of locations most likely to become unsafe such as areas prone to floods, landslides, etc.; assessing the land use and the ability of local construction to resist hazards identified;
- An additional survey of existing buildings and infrastructure can help to identify significant vulnerabilities prior to the occurrence of a hazardous event;
- Examination of local and national building codes, international legislation and good practice in order to determine the socially acceptable risk level. The level of socially acceptable risk will vary according to the use and importance of the facility and the desired post-natural hazard event performance. But if the level of current risk is greater than that which is socially acceptable, then the need for hazard-proofing (and/or re-siting) is

established, and the socially acceptable risk and identified hazards become the design criteria for the new construction or strengthening works; and

- Involvement of local stakeholders all the way through the project design and implementation. This is crucial for infrastructure to deliver wider development outcomes, and ensures that development is responding to user needs (see Deverill, 2002).

Thus involving local communities and other stakeholders is really important. UNDP (2011:p27) suggests that acceptable levels of risk should be determined by a wide range of stakeholders and key aspects should include sustainability of critical facilities in the short term such as in response to a hazard event as well as in the long term in response to climate change.

In addition to changing how infrastructure is provided to take account of resilience some infrastructure may be delivered specifically to enhance resilience of a given community/group of stakeholders. An example of this is planned investment in improved Integrated Water Resource Management set out below.

BOX 4 CASE STUDY: INFRASTRUCTURE INVESTMENT TO IMPROVE INTEGRATED WATER RESOURCE MANAGEMENT

An IWRM approach was used to tackle water constraints on increasing food production to increase agricultural resilience and food security.

In cooperation with the World Bank and Tanzanian Ministry of Water, Atkins prepared an IWRM and Development Plan for the Ruvuma River and Southern Coast Basin. The key objective of this project was to provide a blueprint for sustainable development and management of Tanzania's water resources considering current and future water demand.

Stakeholder workshops enabled a comprehensive cross-sector water demand assessment to be undertaken which informed the water allocation and development action plan for each sector at a basin scale. Guidelines for water management governance, policy and legal frameworks were developed to provide an effective regulatory structure including Urban Water and Sanitation Authorities and Water Users Associations. The final plan responded to population and economic growth and considered the needs of planned development projects like Mtwara Development Corridor and the oil and gas industry which are driving urbanisation as well as an increase in irrigated area for food crops and commercial farming for coffee and cashew nuts.

Source: Savage et al, 2016.

4.5 CONCLUSION

Resilience of infrastructure includes not just planning and designing infrastructure to be resilient itself, but considering how it interacts within an infrastructure system, and with other infrastructure types and how this overall impacts upon sustainability and resilience both at a community level, and for a national economy and society. This requires resilience and sustainability to set the context for selection and design, and to be informed by participation of those affected by the infrastructure, such as different groups and individuals; including the poor and vulnerable, women as well as men; in the local community. This is particularly important as major infrastructure investment, particularly of major (critical) infrastructure, can have both positive and negative impacts on the resilience of its surroundings.

There are many guidance documents and standards produced for designing resilience into infrastructure. However, for some risks, and certainly for climate change which has increasing future risks, resilience should be considered at a much earlier stage than design, when infrastructure investment decisions and strategic planning choices are made. Instead of a standards-led approach a process that links technical specification with climate and disaster impacts and local communities' capacities and vulnerabilities is needed. This is also reflected in the Understanding Risk and Resilient Infrastructure Investment resource (Gallego-Lopez and Essex, 2016b).

Finally, it is critically important to sustain and improve resilience of existing infrastructure as well as to ensure new infrastructure is resilient (and sustainable). This prioritisation of existing over new, and ensuring that all infrastructure can be sustainably managed affects the way budgets for capital expenditure (on new, major works) and revenue expenditure (to secure basic maintenance and operations) on infrastructure are balanced.

REFERENCES AND ACRONYMS

Please refer to the consolidated reference list for sources and acronyms used in the infrastructure resilience resources at http://dx.doi.org/10.12774/eod_tg.july2016.gallegolopezessex4