

Climate adaptation of interconnected infrastructures: a framework for supporting governance

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Abstract Infrastructures are critical for human society, but vulnerable to climate change. The current body of research on infrastructure adaptation does not adequately account for the interconnectedness of infrastructures, both internally and with one another. We take a step toward addressing this gap through the introduction of a framework for infrastructure adaptation that conceptualizes infrastructures as complex socio-technical “systems of systems” embedded in a changing natural environment. We demonstrate the use of this framework by structuring potential climate change impacts and identifying adaptation options for a preliminary set of cases—road, electricity and drinking water infrastructures. By helping to clarify the relationships between impacts at different levels, we find that the framework facilitates the identification of key nodes in the web of possible impacts and helps in the identification of particularly noxious weather conditions. We also explore how the framework may be applied more

comprehensively to facilitate adaptation governance. We suggest that it may help to ensure that the mental models of stakeholders and the quantitative models of researchers incorporate the essential aspects of interacting climate and infrastructure systems. Further research is necessary to test the framework in these contexts and to determine when and where its application may be most beneficial.

Keywords Climate change adaptation · Governance · Road · Electricity · Drinking water · Socio-technical systems · Systems of systems

Introduction

Infrastructures are capital-intensive, long-lived, large-scale systems that serve critical functions in support of human settlement and well-being. They are deeply embedded within their environment and are constructed to operate within particular ranges of environmental conditions. By affecting the “normal” range of environmental conditions and the frequency and severity of extremes, climate change poses a potential threat to these systems—from degrading their integrity and performance to inciting network-level failure.

The last decade has seen a shift in the research community from an exclusive focus on the role of infrastructures in climate change *mitigation* toward recognition of potential vulnerabilities and the need for *adaptation*. This shift is reflected in numerous studies focusing on various infrastructures, including water, electricity and transportation (e.g., Decicco and Mark 1998; Hor et al. 2005; Kirshen et al. 2008; Koetse and Rietveld 2009; Hunt and Watkiss 2011; van Vliet et al. 2012). Studies such as these represent an important step toward understanding the potential

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impacts of climate change on infrastructure and developing suitable strategies for dealing with them.

However, the current body of research is lacking in two key respects. First, it discounts the interconnectedness of infrastructure components. The existing literature tends to focus on the micro-level—the impacts on individual infrastructure components—and the macro/landscape level—the effects on the natural systems surrounding infrastructures (Chappin and van der Lei 2012). A void is left at the *meso*- or intermediate level—the level at which the technical and social elements of infrastructures interact with one another and at which component impacts may propagate into network-wide failures.

Second, much of the current scholarship disregards the interconnectedness of infrastructures with one another. With a few exceptions (e.g., Kirshen et al. 2008; Hunt and Watkiss 2011), the existing literature tends to explore impacts and adaptation strategies associated with different types of infrastructures separately. This approach disregards possible interconnections *between* infrastructures, in particular the potential for disruptions within one infrastructure system to spillover to others.

In this paper, we take a first step toward a more comprehensive approach—one that recognizes the *interconnectedness* of infrastructures, both internally and with one another. This first step takes the form of a *framework for infrastructure climate adaptation*, which we introduce in the next section. Following a description of this framework, we demonstrate its use in structuring potential climate change impacts and identifying adaptation options for a preliminary set of cases—road, electricity and drinking water infrastructures. After this, we discuss how the framework may be applied more comprehensively in support of adaptation

governance—in particular to facilitate the development of quantitative models and processes of stakeholder engagement. We conclude with a discussion and outlook.

Framework

The framework described in this section draws from two key theoretical traditions. First, we frame infrastructures as *complex socio-technical systems*—highly interconnected networks of interacting social and technical components that cannot easily be addressed independently from one another (Hughes 1987; Ottens et al. 2006; Simon 1973, 1962). Second, we frame infrastructures as *systems of systems*—sets of heterogeneous, distributed systems embedded in networks at multiple levels that evolve over time (Agusdinata and DeLaurentis 2008). Important with respect to climate change is that these heterogeneous, multilevel systems can furthermore be seen as embedded within and heavily linked with their environment (Cash et al. 2003; Gunderson and Holling 2002).

The proposed *framework for infrastructure climate adaptation* is illustrated in Fig. 1. At the core of this framework is a multilevel chain, beginning with *climate change*. Climate change translates into shifting extreme and mean values for weather variables, as well as changes in (sea) water levels, hydrological cycles, soil conditions, vegetation and other environmental conditions. It is a long-term phenomenon playing out over a scale of decades or even centuries, but its symptoms may be palpable on much shorter timescales—weeks, days, hours or even minutes. These symptoms are expressed in the form of *loads/events* such as droughts, heat waves, windstorms and floods (IPCC 2012).

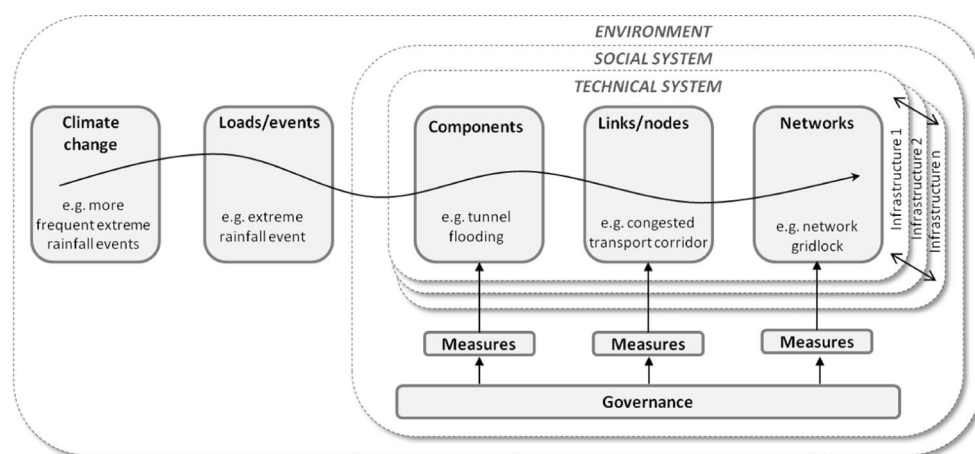


Fig. 1 The proposed framework for infrastructure climate adaptation. The framework captures several key aspects of climate–infrastructure interactions—the relationships between climate scenarios and loads/events and between loads/event and infrastructure components. It also captures the spread of impacts from the component level to the

network level within an infrastructure and the spillover of impacts between different infrastructures. The framework also highlights the relevance of the environmental, social and technical domains and the interactions between them

Component impacts arise when these loads and events encounter and affect the components of the socio-technical infrastructure—for example, a tunnel may flood, the cooling system of a thermal power plant may run short on cooling water, and people may suffer from extreme heat. Depending on various factors, these component-level impacts may affect the performance of the *link or node* within which a component is embedded (e.g., the transport corridor of which the tunnel is a part). Due to a breach in integrity, this link or a node may cease to function properly—traffic in a transport corridor may become congested, and a power plant may be forced to reduce output or shut down entirely.

From the level of a link or node, a disruption can propagate through the *network*. Depending on conditions, a single breach may lead to congestion elsewhere, overloading other links and eventually causing a network-level failure—for example, traffic gridlock, a cascading failure in the electricity grid. Such failures typically have substantial economic impacts (Laird et al. 2005). The magnitude of these impacts depends on the degree to which additional network effects occur, the sensitivity of the processes associated with network usage and the availability of options to use other networks.

In this context, it is important to keep in mind that any given infrastructure is not an isolated technical system—it is part of a system of infrastructure systems. Components of one infrastructure may be linked with components of another. Road signals require electricity; power plants need transport routes for fuel delivery; and rail systems depend on telecommunications. Disruptions at the component, link/node or network level in any single infrastructure system may propagate to other infrastructure systems.

This system of infrastructure systems is embedded within broader social, economic and political systems. Through processes of *governance*, these systems engender adaptation *measures*. These measures may be directed at various points in the chain of an infrastructure system. Measures can be directed at the component level—the points of interaction between environmental variables and infrastructures. They can also address the link/node level—preventing component impacts from affecting the performance of individual links or nodes (robustness). Or, they can be aimed at the network level, accepting that individual links or nodes may fail but ensuring that the network is able to accommodate these failures and continue functioning (resilience).

Example—flooding of the Botlek Tunnel

To further clarify the proposed *framework for infrastructure climate adaptation*, we use this framework to structure

the set of occurrences surrounding a particular *load/event*. On Tuesday August 7, 2008, a severe rainstorm struck the Botlek Tunnel, a key road tunnel in the Rotterdam harbor area of the Netherlands. The severity of this storm cannot be directly tied to climate change, but it is representative of the types of events that may occur with increasing frequency as a consequence of climate change.

The storm directly affected a component of the electricity infrastructure and quickly spread to a key component of the transport infrastructure. A lightning strike to electrical circuitry near the Botlek Tunnel cut power to a set of pumps that are normally used to drain excess water from the tunnel. Due to the failing of these pumps and the heavy rainfall—45 mm in a five-hour period—the water level in the tunnel rose to a height of one meter in some areas. These impacts at the component level spread throughout the network, causing a number of further impacts at various levels:

- At the *link level*, the incident resulted in traffic jams and subsequent vehicle loss hours on the A15 extending 15 km in both directions (Rosmuller et al. 2011).
- At the *network level*, the traffic jams on the A15 resulted in spillback effects in the form of increased traffic on the A4 (Benelux Tunnel) and extra travel time on other routes, including veer Rozenburg, Spijkenissebrug, N57, A29 (Heinenoord Tunnel) and A16 (Drecht Tunnel).
- In *other networks*, the incident resulted in extra travel time for travelers who shifted to other modes, as well as the diversion of inland ships from the Botlek Bridge.

Translated into economic terms, the combination of these phenomena resulted in costs for those delayed in traffic and for those forced to take other modes, as well as for those who decided to depart later or cancel their trips altogether. A rough estimate suggests that the economic cost of this incident was 367,500 euros (Rosmuller et al. 2011).

The impacts of this incident would have been larger were it not for several *measures* already in place. Two chief adaptation measures in this case were the deployment of mobile pumping units to the Botlek Tunnel and the closing of the Botlek Bridge to inland shipping so as to allow for greater volume of automobile traffic. Given the costs of the incident, the sufficiency of existing measures to deal with such *loads/events* was questioned and a *governance* process was initiated (Rijkswaterstaat 2009).

The governance process in this case was *reactive*—that is, initiated in reaction to the incident in question. In this paper, we suggest that the proposed framework can support the *proactive* identification of potential climate change impacts and adaptation options.

Application of the framework—structuring impacts and identifying adaptation options

In this section, we use the framework introduced above to facilitate the structuring of potential climate change impacts on three different infrastructures—road, electricity and drinking water. In each case, we present this structuring as a multilevel causal web and use it to facilitate the identification of possible adaptation measures.

Road infrastructure

Road networks are vulnerable to various types of disturbances—extreme wind, flooding, extreme temperatures and droughts. These types of events may affect the infrastructure in very different ways, some temporary and some extended (Snelder 2010). Extreme wind, for instance, may spread debris on roads, slowing traffic and reducing road capacity in the short term. Extreme temperatures, on the other hand, may cause rutting and melting of asphalt, resulting in longer-term issues and necessitating maintenance.

Structuring possible impacts

Using the proposed framework as a guide, Fig. 2 summarizes the impact chain of several extreme weather conditions. For example, heavy rain results in reduced vision and thus reduced speeds and reduced capacity. If demand is high enough, this will result in congestion on all affected links with high demand in the network. The situation may worsen because different links influence each other, causing congestion to spill back to other links and other parts of the network. The potential for serious disturbances is especially acute in densely populated regions where a single event can cascade easily through the network.

Identifying adaptation options

Drawing from the impacts web visualized in Fig. 2, we can identify possible adaptation measures at different levels. At the *component* or *link/node level*, important adaptation measures could include optimizing or redesigning components. In cases of extreme rain, options include increasing

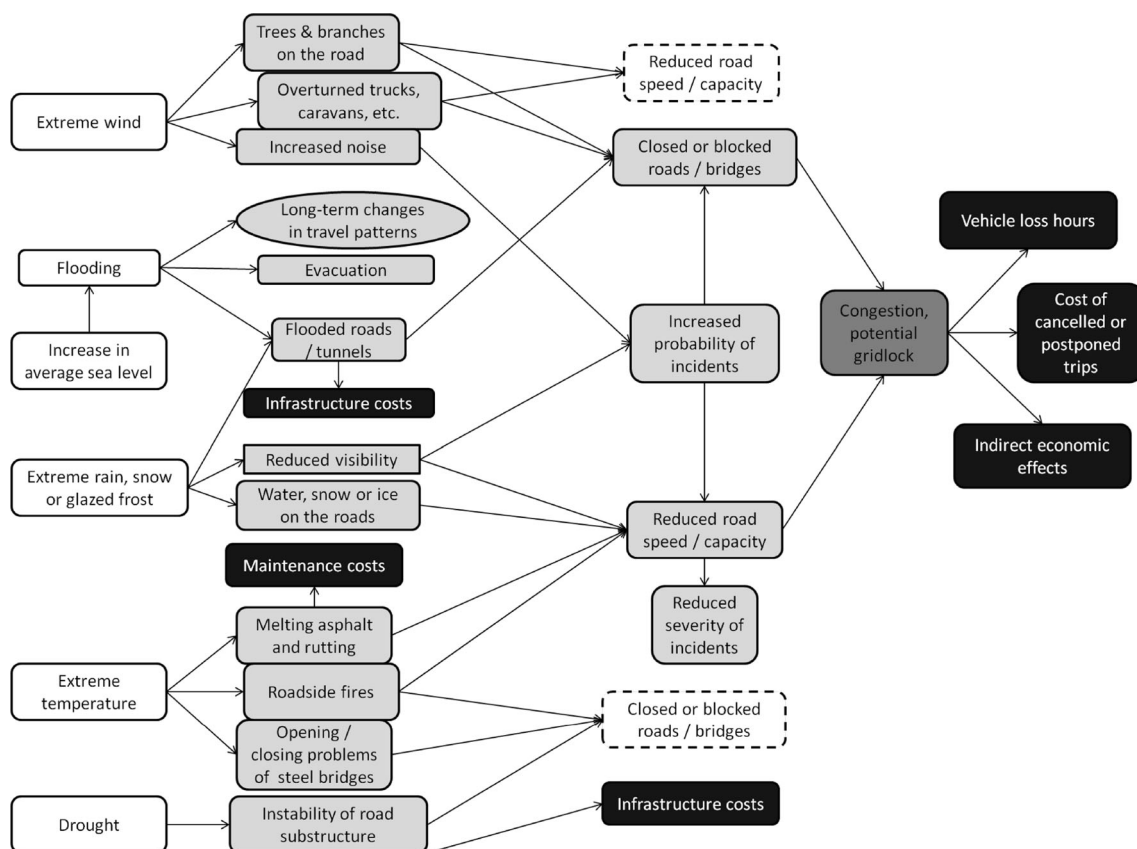


Fig. 2 Anticipated climate change impacts on road infrastructures (draws from research by Oostroom et al. 2008; Koetse and Rietveld 2009; SWOV 2009; TRB 2008). In line with the terminology of Fig. 1, white boxes represent climate events; light gray boxes represent component, node or link impacts; dark gray boxes represent

network impacts; and black boxes represent social and economic impacts. Boxes represent impacts on technical infrastructure components, and ovals represent impacts of climate events on infrastructure functions

the capacity of drainage and storage (pump cellars) and increasing the pump capacity to pump the water from the pump cellars out of the system. These measures could either be taken during maintenance or be included in new designs. Melting and rutting of asphalt during periods of extreme temperature could be addressed through the development and implementations of alternative road surfaces. Measures such as these could help to alleviate node-level issues such as closed or blocked roads and bridges and reduced speeds and road capacities.

At the *network level*, adaptation options entail both measures to improve the design of the road network and measures to improve the management of the road network under extreme conditions. As suggested by the structuring in Fig. 2, key network design measures could include creating more route alternatives (redundancy) so as to allow drivers to avoid closed, blocked or congested routes, as well as introducing buffers and unbundling. Network management measures could include weather alarms and the development of incident management scenarios for different extreme weather events.

Measures directed at the infrastructure's *environment* entail both the optimization of environmental conditions (e.g., modification of drainage patterns, subsoil compositions and vegetation) and location choice in network design. These types of measures could also be incorporated into spatial planning guidelines. Measures in this category could also incorporate strategies for enhancing cooperation/communication between traffic managers and other authorities, such as emergency services.

Drawing from Fig. 2, we can also see that no single category of load or event causes a disproportionate set of impacts—various types of loads/events are relevant. This suggests that adaptation strategies cannot be productively geared toward dealing with a particular type of event, but should be structured to deal with diverse types of events.

Electricity infrastructure

The supply, demand, transmission and distribution of electricity will be affected in myriad ways by a changing climate. With respect to electricity generation, increases in mean air and water temperatures and decreases in river flows are likely to affect the availability and efficiency of thermal generators, as well as the outputs of hydropower and other renewable energy generation technologies (Koch and Vogeles 2009; Linnerud et al. 2011; Mideksa and Kallbekken 2010). With respect to electricity demand, climate change is anticipated to result in reduced demand for electric heating and may increase demand for air-conditioning and refrigeration (Petrick et al. 2010). Furthermore, there is evidence that extreme weather events may induce the purchase of cooling devices and subsequent

long-term increases in peak electricity loads (Rothstein et al. 2008). With respect to electricity transmission and distribution, higher temperature extremes are expected to increase resistance and sag in overhead lines, and droughts may reduce the capacity of underground cables (Rade-maekers et al. 2011).

Structuring possible impacts

Using the proposed framework as a guide, Fig. 3 summarizes the impact chains of several extreme weather conditions.

Identifying adaptation options

Drawing from Fig. 3 and from available literature, we identify several relevant adaptation measures at different levels. At the *component* or *link/node level*, an important category of adaptation measures for electricity infrastructures could include modification of generator designs to improve performance under extreme conditions such as droughts and extreme wind speeds and temperatures. New thermal power plants can incorporate closed circuit cooling systems (Tzimas 2011), and old ones can be retrofitted with cooling towers. Furthermore, renewable installations such as hydropower dams and wind parks can be designed to take into account uncertainty concerning future climate conditions, such as more variable precipitation and altered wind patterns/speeds. In addition to design and retrofitting measures, adaptation may be directed at the management of individual nodes. For instance, power plant maintenance operations can be scheduled in the summer, or cooling water regulations can be relaxed during crises to avoid capacity shortages. Measures such as these can help to mitigate generation shortages, which can lead to blackouts and other disruptions at the network level.

At the *network level*, three distinct types of measures can be identified. First, *adaptability measures* can be used to improve the capacity of electricity infrastructures to actively respond to environmental changes. This category includes demand-side management—improving the responsiveness of loads to the availability of generation capacity—as well as dynamic rating (Tennet 2010), self-healing grid mechanisms and islanding techniques (Mili 2011). Second, *diversity measures* can improve the diversity of generation technologies in an infrastructure network. As illustrated in Fig. 3, different generation technologies have different vulnerabilities to climatic variables, so a technologically diverse generation portfolio can improve the likelihood that infrastructure is able to meet demand under abnormal circumstances. Third, *redundancy measures* can ensure sufficient slack and backup capacity, both in electricity generation and in the

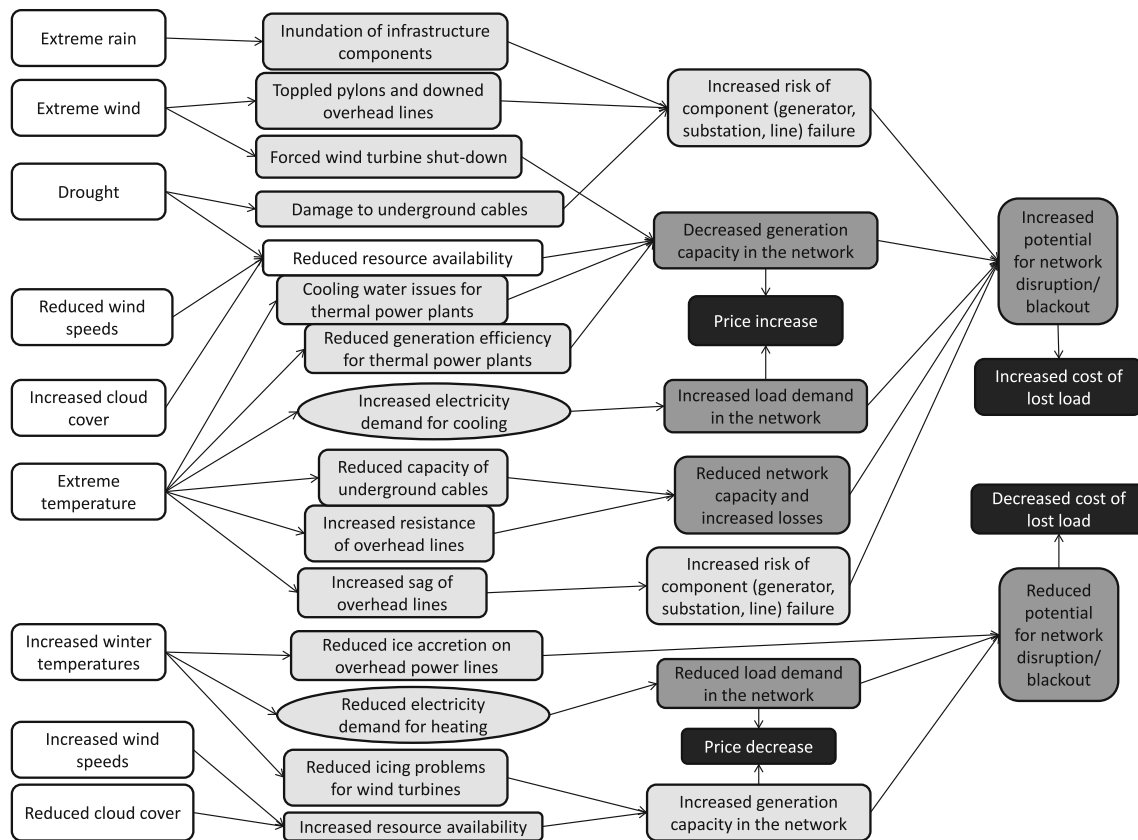


Fig. 3 Anticipated climate change impacts on electricity infrastructures (draws from research by Rothstein and Parey 2011; Rademaekers et al. 2011; Wilbanks et al. 2008; Mideksa and Kallbekken 2010;

Pryor et al. 2005; Pryor and Barthelmie 2010; De Groot et al. 2006; Rothstein et al. 2008)

electricity grid. Generation capacity mechanisms can include a variety of possible measures to incentivize capacity investments—capacity subscriptions, reliability contracts, capacity payments and strategic reserves (Finon and Pignon 2008).

Similar to the road infrastructure case, measures directed at the infrastructure's *environment* can include efforts to modify the environment or efforts relating to the placement of infrastructure components within the environment. Efforts to modify the environment might include measures to ensure the regular trimming of vegetation in the vicinity of overhead power lines or to enhance the flood defenses around substations or power plants. Measures concerning component placement might include legislation or guidelines to incentivize the construction of thermal power plants in locations with ample cooling water supply (e.g., coastal locations).

Like in the road infrastructure case, we can see that a diversity of loads/events may have impacts on the electricity infrastructure. However, in this case, we can also see the particular threat posed by extreme temperatures. This suggests that adaptation measures to shore up the

electricity infrastructure under cases of extreme temperatures may be especially important from a governance perspective.

Drinking water infrastructure

Climate change may impact the functionality of drinking water infrastructure indirectly by altering soil properties and soil movement. The deterioration of pipe systems results from failures in the materials and/or deterioration of the construction. Various types of climate change-related extreme weather conditions can affect these deterioration processes. Droughts and high temperatures can dry out and shrink the soil, causing an increase in pipe breakage rates (Newport 1981; Kleiner and Rajani 2001). Furthermore, high temperatures often result in higher water demand (Billings and Jones 2008), which can increase water pressure close to pumping stations and raise flow velocities. In turn, these effects can increase the risk of water hammer and associated damage to pipes. Higher soil temperatures may also affect drinking water temperature, which can adversely affect quality.

Structuring possible impacts

Figure 4 gives an overview of how climate events can impact drinking water distribution systems. All climate events may change the loads or strength of the pipe, which may result in pipe (or joint) failure. A small part of the network will then be cut off from the water supply for repairs. The resulting economic impacts include the costs associated with repairing both the distribution network and other impacted infrastructure in the surroundings of the burst, and interrupted water supply.

Identifying adaptation options

At the *component or link/node level*, important adaptation measures for drinking water infrastructures include the materials used for the construction of pipes and the types of joints applied between them. The centrality of increased pipe loadings in Fig. 4 suggests that a key adaptation may be the implementation of pipe materials with increased mechanical strength (e.g., steel pipes) or an increased flexibility to withstand differential settlements induced by climate change (e.g., PVC pipes). In areas expected to experience groundwater salinization due to sea-level rise, noncorroding materials have to be selected. Secondly, the types of joints between the pipes or the joint distance can

be altered to increase the structural flexibility of the network to withstand differential settlements.

At the *network level*, adaptation measures can address both the design of the network and management of the network. Even though currently most networks are looped on all levels, a branched network design for the tertiary network (neighborhood level, e.g., Vreeburg et al. 2009) offers benefits both for water quality (especially but not exclusively when soil temperatures increase) and, contrary to common belief, for continuity of supply in case of pipe bursts (Vreeburg et al. 2009). The number of connections affected by a pipe burst is determined by the size of sections which can be isolated, or in other words the valve density in a network (and of course also their locations). Either the valve density or the size of tertiary network branches can be adjusted to cope with possibly increasing failure rates.

Similar to the electricity infrastructure, demand-side management strategies can also be beneficial and can be executed using various technical, legal and economic mechanisms (Niemczynowicz 1999). However, in contrast to the electricity infrastructure, demand-side measures cannot be based on the price elasticity of the water (at least in developed countries), since costs of drinking water are low compared to those of energy. Effective short term demand-side measures are hosepipe bans as used in the UK

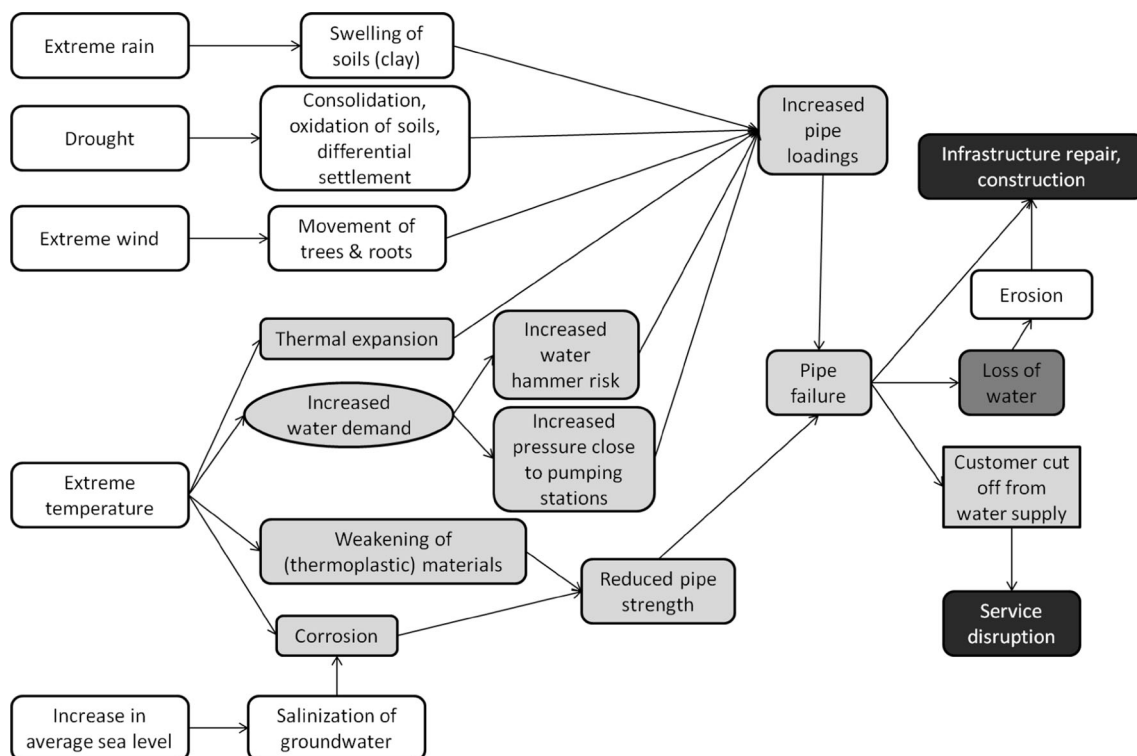


Fig. 4 Anticipated climate change impacts on drinking water infrastructures (draws from research by Hu and Hubble 2007; Newport 1981; Kleiner and Rajani 2001; Rajani and Tesfamariam 2004; Billings and Jones 2008; Rajani and Kleiner 2001; Van Daal et al. 2008)

and Australia during severe droughts. Improved monitoring of the infrastructure, for example, by estimating stresses on buried infrastructure due to soil movements using satellite observations (Dheenathayalan et al. 2011), can help to quickly locate and repair infrastructure damage.

Measures directed at the infrastructure's environment entail, most importantly, measures to mitigate risks to pipe integrity. For instance, the soil around a pipe can be modified to reduce soil differential settlements. Also, avoiding trees located near the pipes may reduce the chance of pipe bursts when a tree is uprooted by the wind.

Synthesis

In the previous sections, we have applied the proposed framework to facilitate the structuring of possible climate change impacts and the identification of adaptation impacts for three different infrastructures. The causal web diagrams illustrate that the impacts of climate change on infrastructures should not be seen in static terms—impacts at the level of components may radiate to higher levels, dynamically interact with other impacts and spread to other networks. These diagrams also help us to see several key impacts—impacts with a diversity of causes—as well as particularly noxious weather conditions—conditions with a diversity of impacts. In the case of both electricity and drinking water infrastructures, extreme temperatures appear to be an important threat. In the case of road infrastructure, the threats are more dispersed.

The causal webs point to several key adaptation strategies and illuminate strategies that may be applicable across different types of infrastructures. For instance, the centrality of increased pipe loadings in Fig. 4 points to increased pipe strength and flexibility as a potential key adaptation. Furthermore, the diversity of impacts caused by extreme temperatures in the case of both the electricity and drinking water infrastructures suggests that a diversity of measures may be appropriate under such circumstances. In the case of both infrastructures, this may include demand-side management combined with improved system monitoring. In addition to facilitating the identification of adaptation options, the proposed framework has provided us with a language for conceptualizing different types of infrastructures such that they become comparable and compatible with one another. This is a first step en route to governance processes that effectively address the interconnectedness of infrastructures.

Supporting adaptation governance

Our application of the framework has thus far disregarded several key aspects of adaptation governance—in particular

stakeholders and *quantitative models*. Adaptation governance may be seen as a process of stakeholders interacting with the best possible data while managing inherent uncertainties to determine specific measures for implementation. Models serve to inform these stakeholders about the behavior of the systems in question and possible consequences of various courses of action. While our focus here is on quantitative models, it is important also to point out the relevance of softer techniques (e.g., models using possible future scenarios without probabilities attached), which may also be combined with rigorous quantitative techniques. In either case, however, these models must be grounded in the particular geographies and socio-political realities within which the infrastructure in question is situated.

In this section, we explore the use of the proposed framework in adaptation governance in practice. In doing so, we take into account both the need for framing and analysis to ground the risks and possible responses, and the potential consequences of interconnections between different infrastructures. Insofar as it provides a coherent conceptualization of interacting climate and infrastructure systems, the proposed framework can facilitate both stakeholder engagement processes and the development of quantitative models. In particular, the framework highlights the essential aspects of interacting infrastructure and climate systems that should be considered in adaptation governance processes. These aspects are listed in Table 1.

Table 1 Key relationships highlighted by the proposed framework that should be captured in adaptation governance of infrastructures

Relationship	Description
Relationships between climate scenarios and loads/events	A range of climate change scenarios and their consequences on the assumed frequencies of various types of loads/events
Relationships between weather variables and infrastructure components	The (potentially numerous) relationships between weather variables and infrastructure components—for example, the relationship between precipitation and driver visibility/speed, or the relationship between temperature and electrical resistance in power lines
Relationships between the components, links and nodes of an infrastructure	Key interactions, both social and technical, that may cause disruptions to spread from the component level to the link/load and network levels
Relationships between different infrastructures	The interconnections between different infrastructure networks (e.g., road, rail and electricity) that may cause disruptions to spillover from one network to another

Supporting stakeholder engagement

A critical element of effective governance is involving a range of stakeholders with varying interests and perspectives (Functowicz and Ravetz 1993; National Research Council 2009). In a world of post-normal science, decision-makers and scientists become coproducers of knowledge (Functowicz and Ravetz 1993; Webb 2011). Stakeholder engagement done poorly can, however, lead to frustration, wasted time and resources, and ultimately project failure. Fortunately, there exists a wealth of knowledge on how stakeholder engagement can be done well. Best practices include using professional neutral facilitators; engaging the full breadth of stakeholders from both inside and outside of government; engaging stakeholders on an ongoing basis rather than only late in the game when key decisions are being made; and researching and exploring data together via *joint fact-finding* procedures (Innes and Booher 2010; Susskind and Crump 2009).

Stakeholder engagement is most effective when it is deeply entrenched in the institutional fiber of decision-making (Margerum 2011). This requires support and resources from higher levels of government, including legislative changes (Camacho 2009). Knowledge and decision-making around infrastructure management can no longer be treated as the reified domain of experts, but rather must be brokered between experts, policy makers and other stakeholders.

We argue that the proposed framework can facilitate processes of stakeholder engagement and interaction in adaptation governance. Each stakeholder enters such processes with a unique set of mental models—that is, mental representations of various situations and systems—and interests that form the basis for his or her argumentation and reasoning in decision-making (Susskind and Crump 2009). Application of the proposed framework can help to ensure that the mental models and interests of stakeholders incorporate the essential aspects of the system in question (Table 1) and subsequently that these aspects are incorporated into decisions that lead to the development of adaptation measures.

Several techniques can be used to support facilitated decision-making processes in complex environments. One of these is *systems thinking*. Systems thinking promotes a mind-set in which stakeholders challenge their mental models and explore the complex web of interactions in the relevant system(s) so that they may identify the most effective intervention points and anticipate the likely range of consequences (Meadows 1999). Models or diagrams are typically constructed to map the key elements of the system and how they relate (Stern 2000). Positive and negative feedback loops are given particular attention, as they drive stability and change in systems.

Systems models may be constructed solely by experts based on empirical research, collaboratively with stakeholders, using computer-driven agent-based modeling, or via some combination of these approaches (Costanza and Ruth 1998; Janssen and Ostrom 2006). Collaborative approaches allow for a broader range of insights and perspectives. Users must appreciate that their models are inherently simplifications and can overlook key elements because their importance is not appreciated, is misunderstood or miscalculated or is not apparent at the time of model construction. This may be particularly problematic when considering climate change, given the significant uncertainty.

Another relevant technique is *collaborative adaptive management*. Adaptive management presupposes that, because of uncertainty and changing conditions like those associated with climate change, no plan or project will be optimal from the outset and remains so throughout its life cycle. Instead, ongoing monitoring and evaluation is conducted, and both designs and management systems are left flexible so that new information can be used to iteratively hone practice (Doremus et al. 2011; Gunderson and Holling 2002; Susskind and Crump 2009; Williams et al. 2009).

Experts may conduct adaptive management technocratically, but the presence of irreconcilable uncertainties and value-based decisions make it more effective when managed by multistakeholder groups—that is, as collaborative adaptive management (Williams et al. 2009; Innes and Booher 2010). Adaptive management can appear expensive up front compared to traditional decision-making, but often results in much more efficient, cost-effective and successful management over the long term (Doremus et al. 2011). Given the dynamic and uncertain nature of climate change, this may be all the more true. Adaptive management provides a way forward while acknowledging that we are most likely to get our forecasts wrong and thus must continue to monitor, evaluate and adapt as we proceed.

Supporting the development of quantitative models

Infrastructures are complex socio-technical systems of systems. As demonstrated above, the impacts of extreme weather events may cascade through different levels of an infrastructure network, affecting the myriad decisions made by various actors and spilling over to other infrastructures. Together with the massive uncertainties associated with climate change, the complex sets of interactions triggered by such events challenge our cognitive capabilities and complicate the selection of effective adaptation measures. Modeling and simulation techniques can help stakeholders to navigate this complexity, playing a key role in facilitating the identification of effective adaptation measures (Claussen et al. 2001; Larsen et al. 2007; Stern 2007).

The proposed framework highlights the essential aspects of interacting infrastructure and climate systems that should be considered in developing models to support adaptation governance. Many models capturing the individual relationships listed in Table 1 already exist. Models of traffic and road congestion are widespread, and power flow models are commonly used to anticipate congestion in electricity grids (e.g., Bando et al. 1995; Lobato et al. 2004). Numerous global climate models (GCMs) exist, and some have been, or are in the process of being, downscaled to provide regional-level results (e.g., Frei et al. 2006; Giorgi et al. 1993). The vulnerability of road networks has been evaluated using risk assessments through which the probability of unwanted events and related consequences are assessed (Baarse et al. 2008; Bles et al. 2010). Considerable work has also been done in elaborating the component-level impacts of weather events (e.g., Rade-maekers et al. 2011; Koetse and Rietveld 2009).

While models such as these can provide valuable insights to support adaptation governance, they are insufficient for isolation. Some progress has been made in the development of *integrative models*—computational models that, via direct or indirect linkage, allow for studying multiple systems as an integrated whole. An example here is a model developed by Van Vliet et al. (2012), which combines a hydrological model with an electricity production model and GCM outputs to arrive at conclusions concerning the vulnerability of regional electricity supplies to climate change. Such models are increasingly feasible from a computational standpoint, but are difficult to develop given the degree of coordination necessary to accurately capture the interactions, even in the form of static outputs. Moreover, such models still offer only a partial view of the system in question. The model of Van Vliet et al. (2012), for instance, does not capture the spread of node-level impacts to the network level (meso-level interactions) and ignores interactions between different types of infrastructures. Models incorporating multiple, interacting infrastructure systems exist, but are in their nascence (Haimes and Jiang 2001; Panzieri et al. 2004; Pederson et al. 2006; Carreras et al. 2007; Rosato et al. 2008). Such models are nonexistent in adaptation literature.

The development of integrative computation models is not the only approach to addressing inherent complexity in the interactions between infrastructure and climate systems. An alternative approach involves the participation of stakeholders in the integration of model results. For cases in which two models are not directly compatible due to different assumptions, system boundaries, etc., stakeholders may use their collective knowledge and mediated perspectives to facilitate the translation of the results of one model for use in another. Alternatively, stakeholders may be exposed to the results of multiple models with different

system boundaries and/or underlying assumptions and asked to discern an acceptable course of action in discussion with one another. While such approaches inevitably introduce added subjectivity into the governance process (although real objectivity is never possible in such situations), they may also help to more fully incorporate the complexity of the system in question into governance processes, in particular the consequences of interconnections between infrastructures.

Synthesis

By highlighting the essential aspects of interacting infrastructure and climate systems, we suggest that the proposed framework can facilitate both stakeholder engagement processes and the development of quantitative models in support of adaptation governance. Quantitative models are an important ingredient in helping stakeholders to understand interacting infrastructure and climate systems, and much progress has been made in the development of models to inform adaptation processes.

However, quantitative models alone are not sufficient. Interacting climate and infrastructure systems are characterized by persistent uncertainty, fragmented knowledge and locus of control, and the inherently subjective nature of many decisions. Adaptation is thus most effective and efficient when multiple stakeholders are engaged such that they can advocate for their interest and explore the implications of the various decisions across networks. Used in concert with the proposed framework, a variety of techniques can make facilitated multistakeholder planning processes more effective.

Conclusions

The adaptation of infrastructures is a key challenge posed by our changing climate. In addressing this challenge, it is essential that governance processes adequately account for the *interconnectedness* of infrastructures, both internally and with one another. With the aim of supporting this, we have introduced a *framework for infrastructure climate adaptation*, which captures the key relationships of interacting climate and infrastructure systems.

We have demonstrated how this framework can be applied to different types of infrastructures, and how it can facilitate the structuring of possible impacts and the identification of adaptation options. By helping to clarify the relationships between impacts at different levels, the framework can facilitate the identification of key nodes in the web of possible impacts—for example, increased pipe loadings in the drinking water infrastructure. It can also help to identify particularly noxious weather conditions,

for instance extreme temperatures in the case of the electricity infrastructure and the drinking water infrastructure. Insights such as these can support the identification of key adaptation measures—for example, construction of drinking water pipes with stronger and/or more flexible materials—and adaptation measures that may apply across multiple infrastructures.

Our application of the framework in the first part of this paper leaves out several key aspects of adaptation governance in practice and largely disregards the role of interconnections between infrastructures. In the second part of the paper, we have explored how the framework may be applied more comprehensively to facilitate the development of quantitative models and processes of stakeholder engagement in a context of interacting infrastructures. We argue that the proposed framework can help to ensure that the mental models and interests of stakeholders incorporate the essential aspects of interacting climate and infrastructure systems. Techniques such as systems thinking and collaborative adaptive management can facilitate this. With respect to quantitative models, we similarly suggest that the proposed framework can help to ensure the inclusion of the essential aspects of interacting infrastructure and climate systems. Some progress has been made in the development of integrative models capturing several of these aspects, but more work is necessary—in particular in the development of models capturing interactions between different infrastructures.

In the preceding sections, we have pointed to a path for addressing the interconnectedness of infrastructures in climate change adaptation. Much is left to do. We have suggested how the proposed framework can be useful in the context of facilitating governance processes, but it is not clear when and where its application may be most beneficial. We have mentioned the limitations of quantitative modeling in capturing all the aspects of the proposed framework. But we do not know exactly how these models can best facilitate governance processes that *must* consider all of these aspects in combination. A key tenet of complexity theory is that we cannot fully know the path before us until we have walked it. The best we can do is to make sure we have the tools we might need along the way.

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