Chapter 19
Advances in Climate Adaptation Modeling of Infrastructure Networks

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Abstract As the adverse effects of climate change are increasingly becoming unavoidable, calls for improving climate adaptation assessments have gathered interest at the global scale. Infrastructure policymakers and practitioners are now interested in understanding climate vulnerabilities and risks that capture the systemic nature of failure propagation seen across interconnected networks. This would help inform adaptation planning objectives meant to improve systemic resilience. This paper presents recent technical methodological and tool-based advances made in climate vulnerability, risk, and adaptation modeling of large-scale infrastructure networks. These methodologies adopt a bottom-up approach that focuses on creating data-rich representations of infrastructure network attributes, resource flows, and socio-economic indicators that are all used for quantifying direct and indirect risks to network assets exposed to extreme climate hazards at multiple scales. Insights from different case studies are presented to show how such methodologies have been used in practice for informing different policy needs. The paper concludes by identifying the existing gaps and future opportunities for such bottom-up infrastructure network vulnerability, risk, and adaptation assessment methodologies.

Keywords Infrastructure networks · Climate change · Vulnerability · Risks · Adaptation

Introduction

There is increasing evidence that climate change will increase variability of weather patterns, magnifying the severity of short-term shock events such as flooding, storms, heatwaves, while also extending long-term shock events such as droughts (Wang et al. 2017). While mitigation efforts to limit the increase in global average temperature to 1.5 °C above pre-industrial levels remain a primary focus of policymakers (Christoff 2016), there is also increasing awareness that climate change adaptation action is

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needed with some urgency (Global Commission on Adaptation 2019). As stated by the European Commission (2014) "Adaptation means anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause or taking advantage of opportunities that may arise". Among others, climate adaptation is becoming an important focus of national and global infrastructure system planners, investors, and decision-makers who are faced with new challenges of embedding adaptation planning into objectives of managing sustainable development, economic prosperity, and demands of growing population. In particular, climate adaptation of economic infrastructures, which include large-scale spatially distributed networks of energy, transport, water, waste, telecommunications, is now a key topic of interest because such networks are recognized as lifelines of modern societies (Hallegatte et al. 2019).

The focus of this paper is on building data-driven decision-making models and tools for evaluating the costs and benefits of climate adaptation of infrastructure networks at different spatial scales. There has been an increasing demand for such tools from policymakers and practitioners interested in improving their decision-making for monitoring and evaluating adaptation options (European Commission 2014). When it comes to infrastructures, some questions relevant to informing climate adaptation include: (1) What are the key network locations and assets exposed to current and future climate-change driven hazards? (2) How do asset vulnerabilities and risks cascade across infrastructure networks? (3) What are the indirect consequences of network failures in terms socio-economic impacts felt beyond the initiating infrastructures? (4) What are some key climate adaptation investments and strategies for reducing network risks? (5) Where and what are the key infrastructure network locations prioritized for climate adaptation measures to reduce systemic network risks? This paper discusses how the above questions are being answered with generalized methodologies supported by data-driven case studies in different countries and at the global scale. These methodologies and case studies are all from the experiences and examples of work done in the Infrastructure Transition Research Consortium (ITRC 2020), which aims to build data-driven models for the identification of spatial network vulnerabilities and risks to support decision-making. Through these studies, the paper highlights the specific issues, recent advances, and further opportunities in creating technical knowledge to improve the information of climate adaptation modeling of infrastructure networks.

Methodologies for Evaluating Network Vulnerabilities, Risks, and Adaptation

A generalized methodology or framework for climate vulnerability, risk, and adaptation assessments would be difficult to conceive, as it is nearly impossible to account

for every context-specific issue. Nonetheless, some broad principles of such a framework would include, among others: (1) identifying current and future climate vulnerabilities and risks under different climate hazard scenarios; (2) integrating climate risks within the decision-making process; and (3) identifying options and prioritizing responses based on the benefits of implementing such options. Most approaches that incorporate these steps apply a top-down modeling philosophy, where the identification of vulnerabilities and risks is mainly done by quantifying the direct physical impacts induced by exposures to external hazard shocks and any uncertainty in estimates is purely a function of the variability of climate model outputs (Conway et al. 2019). An example of such an approach is a global-scale assessment of lengths (in kilometers) and losses in asset damage costs (in US$) estimated for roads and railway assets exposed to multi-hazard risks (Koks et al. 2019).

More relevant for infrastructure network vulnerability, risk, and adaptation assessments are methodologies that also take a bottom-up modeling approach, which incorporates information at finer geographic scales with underlying physical, operational, social, and economic aspects associated with systems (Conway et al. 2019). Infrastructures operate as a "system-of-systems" of interdependent networks that are increasingly reliant on each other for services under normal working conditions, but which also create failure cascades from an originating asset toward the rest of the system-of-systems (Hall et al. 2019). Most climate vulnerability, risk, and adaptation analysis studies fail to capture the sensitivities of cascading failure mechanisms across infrastructure networks along with the sensitivities associated with weather and climate extremes. The methodological steps toward a hybrid top-down and bottom-up climate vulnerability, risk, and adaptation assessment of infrastructure networks involve combining (Hall et al. 2019; Pant et al. 2020): (1) Climate hazard information that includes spatially correlated probabilities, magnitudes, and extents of hazard events under current and future climate scenarios; (2) spatial representations of network point and line assets to evaluate their exposures to various climate hazards; (3) direct vulnerability measures of the exposed network assets that quantifies the sensitivity of the assets to be damaged by varying severities of climate hazards; (4) network connectivity effects that capture how failures cascade from the directly damaged assets toward other assets either physically or through the flow of resources (goods, information, etc.); (5) indirect vulnerability measures that quantify the socio-economic effects resulting from disruptions of infrastructure network services in terms of numbers and monetary values attached to household and business customers; (6) further indirect vulnerability measures of impacts to the regional economic flows that quantify the effects of production and labour disruptions on the outputs of macroeconomic sectors; (7) measurements of risks as the product of the probabilities, exposures and direct and indirect vulnerabilities summed over all possible hazard and network failure and disruption scenarios; (8) quantifiable options for building resilience (to climate or any shock event) of individual assets and the networks that include, but are not limited to, upgrading existing design standards of assets to withstand more extreme shocks, incorporating backup options to substitute for disruptions of services provided from one network to another (e.g. electricity backup generators at railway stations), increasing network redundancy and rerouting

options to maintain resource flows, speeding up the recovery of damaged assets to bring back the networks to normal levels of service.

The effectiveness of different resilience options (mentioned in Step 8 above) is evaluated in terms of their costs and the benefits of avoiding direct and indirect risks of failures. Climate adaptation assessment involves the consideration of changing costs and benefits (avoided risks) over the life cycle of asset and network management. The costs over the lifetime include (Oh et al. 2019; Pant et al. 2019): (1) Initial investment costs of adaptation which are the one-time costs of a resilience option when it is implemented and (2) costs of routine maintenance (assumed to apply every year) and periodic maintenance (assumed to apply every few years) over the life cycle of the asset. To inform decision-makers on how to prioritize investment decisions for adaptation planning, a cost–benefit analysis is done to estimate network asset and location-specific benefit–cost ratios (BCR) that help identify for which options the avoided asset risks would be worth implementing (BCR ≥ 1) and which options would be more expensive than the avoided risks (BCR < 1).

The purpose of the methodology outlined above is to create an effective high-level screening whereby the efficacy of different types of adaptation options can be compared and locations and assets with high (or low) adaptation benefits can be narrowed down for further investigation. At a country scale, where it is not possible to invest in every asset to make it climate resilient, such information is useful for narrowing down the locations of risks, which should be followed by detailed site-specific investigations of, among others, local conditions of hazards and assets risks.

A few case study examples are presented next to highlight how the described methodology has been implemented in practice to inform decision-makers about quantifiable vulnerabilities and risks to infrastructure networks at the national scale.

Case Studies of Infrastructure Vulnerability, Risk, and Adaptation Assessments

To understand the cascading nature of network failures, a recent study of interdependent energy, water, waste, telecommunications, and transportation network failures in New Zealand, to inform Civil Defence Emergency Management, showed that from all simulated failure events, nearly half (46%) of the total disruptions could be attributed to network propagation effects instead of disruptions attributed to the directly failed assets (Zorn et al. 2020). Also, recent analysis on infrastructure resilience in Great Britain, done for the National Infrastructure Commission, looked at interdependent electricity and telecom networks with dependent water, rail, and road networks (Pant et al. 2020). The study showed that if failures were initiated in the electricity network, then about 40% of failure events led to further disruptions to telecoms and at least one of rail and water networks, which set up another sequence of failures where 20% of failure events led to further electricity failures, and 5.7% to another order of telecoms failures. But if failures were initiated in the telecom network, then only about 7.8%

of failure events led to electricity and at least one of the rail and water disruptions, with 1.8% events leading to further sequence of telecom failures. The study also explored different resilience combinations of installing backup electricity supply for limited durations and increasing network redundancies, which on average reduced the worst-case socio-economic disruptions of network failures by 89%–94%. While they do not include any climate hazards and risks, these studies have proved effective in informing stakeholders how interdependencies influence failure cascades, especially creating feedbacks that lead to further disruptions in the networks where the failures originate. The analyses highlighted the regularity with which failures in networks like electricity could lead to several orders of cascading failures, which was not demonstrated previously in these countries.

Studies done with the World Bank in Tanzania (Pant et al. 2018), Vietnam (Oh et al. 2019), and Argentina (Pant et al. 2019) on multi-modal transport networks have estimated risks due to failures of key network links exposed to one or more climate hazards (e.g. floods, cyclones, landslides). These studies have helped inform transport investors and policymakers in these countries about the locations of their critical transport assets and routes, by estimating and comparing the ranges of magnitudes of freight tonnage disruptions and macroeconomic losses incurred from asset failures. By incorporating the sensitivities of climate models and scenarios with transport and economic growth forecasts, the studies have informed stakeholders about the changing risks in the future. For example, the Tanzania analysis estimated that the worst-case transport asset failure would result in US$ 1.4 million/day economic losses in 2018 due to supply chain disruptions and by 2030, the same failure scenario would create as high as US$ 2.5 million/day economic losses under a 6%–7% GDP growth forecast (Pant et al. 2018).

The studies in Vietnam and Argentina also incorporated adaptation options of upgrading roads and bridges to higher climate resilience designs and assessed the BCRs of such adaptation options. Both studies highlighted that the transport networks in these countries were increasingly exposed to more severe and frequent extreme hazards, and their respective road networks would require significant investments to upgrade to higher climate-resilient design standards. In Vietnam estimates, it was suggested that adaptation investment costs of upgrading the 20 worst-impacted national roads would be high, but the cumulative benefits over 35 years of such investments were substantial, where for every 1 US$ invested in enhancing climate resilience, the benefits of avoiding risks would be equivalent to safeguarding US$ 7–23 of economic value associated with freight supply chains (Oh et al. 2019). Similarly, in Argentina, for building resilience to flood risks, the costs of investments could be high, but the benefits of avoiding damages and disruption losses would outweigh the investment costs (Pant et al. 2019). Furthermore, the case for investing in climate resilience became stronger as the durations of disruptive impacts increased, which in turn meant that investing in reducing the duration of disruption should be a priority of adaptation planners in Argentina (Pant et al. 2019). These studies are proving useful in providing scientific evidence to the transport ministries to develop a national strategy for climate-resilient transport and plans, as part of the transport sector's contribution to the Nationally Determined Contributions, to meet the Paris Climate Agreement

targets (Oh et al. 2019). The results of the analyses are also being provided as web-based tools for data inquiry and detailed network-scale climate risks and adaptation outcomes, which are integrated into the data analytic systems being used by the Ministry of Transport in Argentina (Pant et al. 2019).

Tools Developed Through Case Studies

In the process of implementing the case studies discussed above, several open-source Python programming-based tools have been created. We discuss three Python resources from the transport risk and adaptation analysis studies done in Vietnam and Argentina.

For the Vietnam study, the GitHub repository (https://github.com/oi-analytics/vietnam-transport) was created to host the Python codebase for Vietnam-specific analysis. A similar Python codebase was also developed for the transport analysis in Argentina, available at (https://github.com/oi-analytics/argentina-transport). Both these codebase repositories allow the user with information to install a set of functions for creating spatial analysis functions of processing hazard datasets, create networks, perform transport network flow and failure analysis, and do the adaptation analysis. For the Argentina analysis, a web-based risk visualization platform, available at https://github.com/oi-analytics/oi-risk-vis, was also developed as a results inquiry tool to help stakeholders identify and zoom in on the locations of the most vulnerable transport network assets in the country. The tool also helps identify locations of the roads and bridges where adaptation investments should be prioritized based on their BCRs, as shown in Fig. 19.1.

Conclusions and Recommendations

The hybrid top-down and bottom-up methodologies, for quantifying climate vulnerabilities, risks, and adaptation for infrastructure networks, discussed in this paper, are being increasingly required in making policy decisions. While policymakers and investors make infrastructure planning decisions at the asset scale, they lack knowledge on spatial network vulnerabilities and risks, resulting in investments being often not prioritized with the aim of building systemic resilience. But this gap is being filled as such network analyses are becoming more prevalent and achievable because more data on spatial hazards, spatial assets and network topologies, customer and economic usage are becoming available. Improving these methodologies and their uptake worldwide has been highlighted as one of the greatest adaptation opportunities (Hall et al. 2019).

The key gaps and opportunities lie in enhancing data collection to reduce the uncertainties in model estimates and improve confidence in the outputs of such analyses.
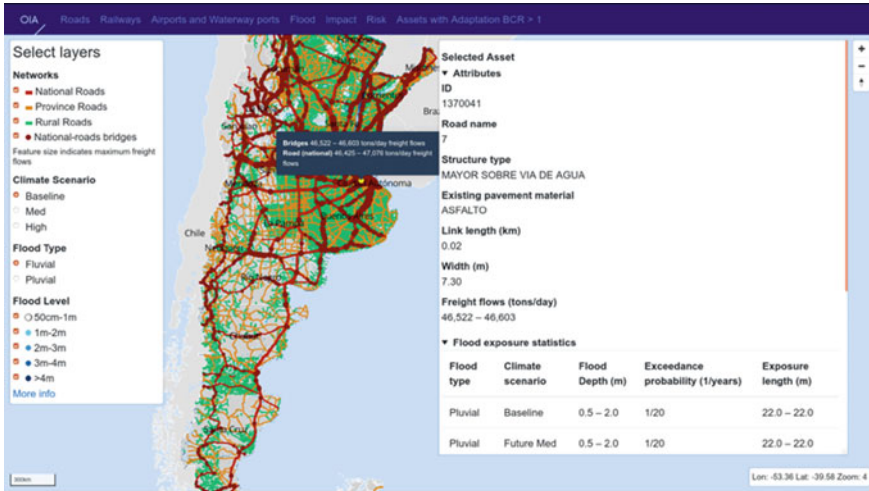
(a)
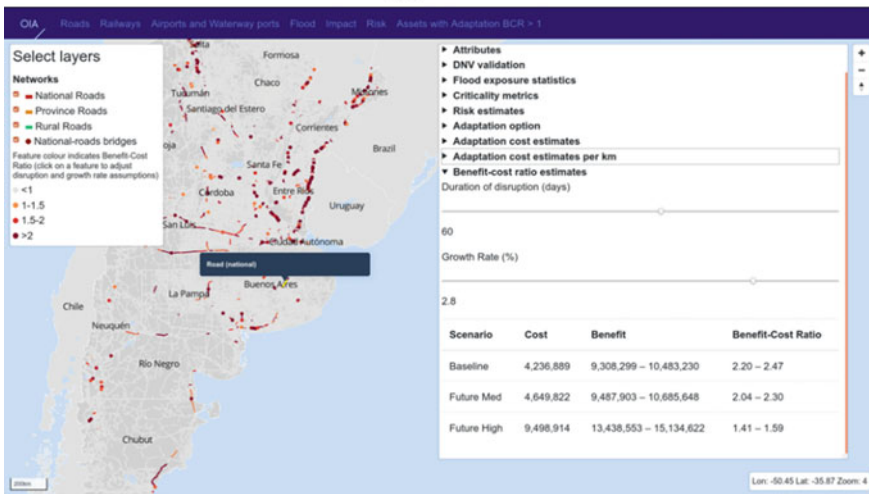
(b)

Fig. 19.1 Risk Visualization tool outputs at asset level for Argentina transport analysis study showing: **a** Characteristics and level of flood exposures of a road and **b** Road asset highlighted and identified by the BCRs of investing in climate adaptation

A lot of focus is given in improving hazard modeling, as it has been widely acknowledged that most climate hazard models are based on Global Climate Model scenarios at very coarse spatial scales, which lack regional climate information and show a lot of variability in their estimates, and fail to satisfactory represent some effects such as sea-level rise (Conway et al. 2019). Relatively less focus has been given on data collection on the impact assessment elements of the analyses, where a lot of opportunities for improvement lie. Hence, based on the experiences from different

case studies, a key recommendation of this paper is to focus on, among others: (1) better data creation and sharing of asset locations, network connectivity, structural and conditions of assets, operational rules of networks; (2) empirical evidence of cascading mechanisms seen during network failures and their resulting disruptive impacts; (3) data on indirect economic losses that are less understood and validated in practice, as most risk assessments and investment decisions are being made based on direct damage losses; (4) empirical evidence on the timelines and patterns of infrastructure asset, network, and socio-economic recovery for disruptions; and (5) local knowledge on adaptation options and their costs.

All the above requires multi-sectoral and multi-organizational commitment as it is a system-of-system problem. There is now a global call for integrating adaptation needs in the infrastructure decision-making process from the outset of national infrastructure planning and sustainable development (Global Commission of Adaptation 2019; Hall et al. 2019), which shows that there would be increased uptake for such methodologies supported by better data analytics and tools to inform climate risk and adaptation decision-making.

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