CLIMATE CHANGE AND EARTHQUAKE EXPOSURE IN ASIA AND THE PACIFIC

ASSESSMENT OF ENERGY AND TRANSPORT INFRASTRUCTURE

DECEMBER 2022

ASIAN DEVELOPMENT BANK

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Notes:
(i) In this publication, "$" refers to United States dollars and "CNY" refers to yuan.
(ii) In this publication, tables, figures, and maps without explicit sources are those of the authors.
(iii) ADB recognizes "China" as the People's Republic of China, "Russia" as the Russian Federation, and "Vietnam" as Viet Nam.

Cover design by Joe Mark Ganaban.

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FOREWORD

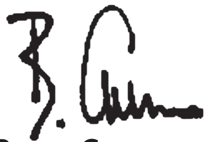
The negative impacts of climate change are already being felt throughout the Asia and Pacific region. As a result, severe effects are expected on societies and economic systems, on the built environment, and on the environment throughout the region. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) finds that adaptation efforts today are still largely incremental, reactive, and small-scale, due in part to a lack of information on exposure to climate impacts. The IPCC estimates that adaptation needs for developing countries alone will reach $127 billion and $295 billion per year by 2030 and 2050, respectively.[a] According to an Asian Development Bank (ADB) report, infrastructure investments of up to $26.2 trillion will be needed in the Asia and Pacific region over the 2016–2030 period to maintain economic growth, eradicate poverty, and respond to climate change.

The unabated rise in atmospheric concentration of greenhouse gases—despite the hiatus caused by the coronavirus disease (COVID-19) pandemic—highlights the increasing urgency to assess the resilience of the built environment to withstand projected climate change and, more generally, natural hazards. The first step is to identify and assess the exposure of infrastructure assets to these hazards. For assets that are deemed highly exposed to climate change and natural hazards, the second step will be to assess vulnerability, taking into account their age, material composition, and construction type, among other factors. Furthermore, it is important to understand the interconnectedness between infrastructure assets within and across sectors to assess the vulnerability of the systems they support.

This report employs an innovative methodology to examine the exposure of more than 30,000 energy and transport assets in the Asia and Pacific region to climate change and earthquake hazards. The results of the analysis show that transport and energy assets in the region are exposed to significant climate change and earthquake hazards. A significant portion of assets assessed in the report show high levels of exposure to two or more hazards. Given that infrastructure in these key economic sectors often lasts for several decades, the analysis emphasizes the critical need for multi-hazard assessment and for systematically integrating an understanding of the potential impacts of these hazards into the planning, design, and financing of infrastructure upgrades and maintenance.

[a] IPCC. 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

As Asia and the Pacific's climate bank, ADB is scaling up support to its developing member countries to help them manage increasing levels of climate and disaster risk. This requires planning, financing, and investments to be based on robust understanding of risk so that all decisions can steer development in a resilient direction. In the context of its Strategy 2030, ADB aims to ensure that climate change, disaster risk, and environmental considerations are fully mainstreamed into its operational strategies, country programming, and project design. The ongoing crisis brought about by the COVID-19 pandemic presents additional significant human, fiscal, and economic challenges for the whole region. Continued collaboration between ADB and its developing member countries will further deepen the overall understanding of infrastructure exposure and potential risk and guide the planning of investments and improvement of systems to manage these risks. In many ways, the response to these challenges will determine the extent to which a prosperous, inclusive, and climate-resilient region is achieved.



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ABBREVIATIONS

ADB	–	Asian Development Bank
CMIP5	–	Coupled Model Intercomparison Project Phase 5
IPCC	–	Intergovernmental Panel on Climate Change
km	–	kilometer
NASA	–	National Aeronautics and Space Administration
PNG	–	Papua New Guinea
PRC	–	People’s Republic of China
RCP	–	representative concentration pathway

EXECUTIVE SUMMARY

This report employs an innovative methodology that geolocates more than 30,000 transport and energy infrastructure assets in the Asia and Pacific region and then individually evaluates them for the degree and characteristics of existing and future exposure to extreme heat, water stress, floods, extreme precipitation, sea level rise, cyclones, and earthquakes. It aims to contribute to a better understanding of the region's exposure to climate change and earthquake hazards and to raise awareness of the need to consider resilience measures in infrastructure planning.

This report is not intended to be a comprehensive analysis of climate change and earthquake hazards in the region. The distribution of assets across the region and economies together with limitations in the data available constrain the comparability of the results. Despite these limitations, the report makes an important contribution to understanding the extent of the exposure of the region's infrastructure to these hazards. In addition, an exposure assessment such as the one presented here is only a first step in understanding the risk to these assets. With appropriate additional information that can be obtained at the national and local levels, a vulnerability assessment should be conducted to complement the exposure assessment. Together, these assessments will help guide efforts to build resilience in the region.

The report provides two central messages that are relevant to policy makers in the Asia and Pacific region. First, transport and energy infrastructure in the region is exposed to significant climate change and earthquake hazards. About 62% and 44% of transport assets included in the study are rated *red flag* or *high* (the two highest exposure categories in this report) for floods and extreme heat, respectively. Water stress accounts for the largest proportion of energy assets evaluated that are rated *red flag* or *high* (45.1%). A significant share of assets included in this analysis are exposed to earthquakes (72.4%), cyclones (22.4%), and sea level rise (8.3%). The seemingly low share of assets exposed to sea level rise and cyclones does not imply that sea level rise and cyclones are not significant hazards in the region. The results are influenced by the nature of these hazards; sea level rise and cyclones are only relevant to a subset of assets in coastal areas. Projected sea level rise and the increases in intense tropical cyclones will have severe effects on some subregions of the Asia and Pacific region. Of the assets included in the study, 2.5% are rated *red flag* (none are rated *high*) for exposure to sea level rise and 2.2% are rated *red flag* or *high* for exposure to cyclones. Of the regions studied, the Pacific region has the highest share of assets exposed to sea level rise at 39.8%, followed by Southeast Asia at 17.5%. At the same time, exposure to cyclones is most significant in South Asia, Southeast Asia, and the Pacific with more than 50% of analyzed assets exposed.

The report's second key message concerns the importance of a multi-hazard approach to building infrastructure resilience, as three-quarters of the assets included in the analysis are exposed to four or more hazards. In addition, one in three assets evaluated are rated *red flag* or *high* in two or more hazards. The proportion varies by region and is particularly high in the Pacific (55.8%), South Asia (48.4%), and Southeast Asia (41.7%).

These findings underscore the importance of considering adequate climate and earthquake information in infrastructure planning. To go beyond climate proofing, upstream infrastructure planning must focus on the resilience of individual assets and identify investment opportunities that strengthen the resilience of a wide range of systems. A holistic approach to building infrastructure resilience considers the benefits of the services provided by the infrastructure and the exposure of infrastructure systems to multi-hazards, and assesses underlying vulnerabilities more broadly. This is necessary to enable risk-informed investment planning, make concrete investment decisions, and ensure that national priorities are translated and communicated to the project level and investment pipelines.

1

INTRODUCTION

Infrastructure plays a critical role in development. Ensuring the long-term viability of infrastructure requires an understanding of how existing infrastructure is exposed to climate change and earthquake hazards that can not only reduce their performance but even disrupt the critical services they provide. In 2017, the Asian Development Bank (ADB) (2017a) published a landmark report describing climate change risks to the Asia and Pacific region and their impacts on economic and human systems. ADB (2017b) estimated that, factoring in climate adaptation, required infrastructure investments in developing Asia increased by 16% between 2016 and 2030, from $22.6 trillion to $26.2 trillion. In 2018, the G20 principles for quality infrastructure investments acknowledged the importance of infrastructure resilience, taking into account long-term adaptability and building infrastructure resilience to risks under the principles on “Building Resilience against Natural Disasters and Other Risks” (G20 2018). A more recent publication by McKinsey Global Institute (2020) identifies infrastructure services as a key area on which future climate change will have substantial impact, thereby affecting socioeconomic development in the region.

However, there is no systematic analysis of the exposure of critical infrastructure assets to climate change and other hazards in Asia and the Pacific. Exposure of infrastructure to multiple hazards can lead to the disruption of the critical services they provide, with potentially severe economic and human impacts. Therefore, it is not only important to follow a development pathway that addresses climate and disaster-risk to ensure the resilience of infrastructure assets, but also to maintain the resilience of the people in the region. This report conducts the first extensive multi-hazard exposure assessment of critical transport and energy infrastructure in Asia and the Pacific. While a number of studies have assessed the exposure of a specific hazard (Asada and Li 2020), to our knowledge, such a multi-hazard assessment has not yet been conducted.

This report uses an innovative methodology to assess the exposure of more than 30,000 existing energy and transport infrastructure in the Asia and Pacific region to climate change and earthquake hazards. The transport and energy assets are first geolocated to a precise latitude and longitude and then individually evaluated for the degree and characteristics of existing and modeled future exposure to sea level rise and coastal floods, extreme heat, water stress, inland floods, and extreme precipitation. Each infrastructure asset is also assessed for its exposure to cyclones and earthquakes, leveraging databases of the location and severity of historical occurrences. Although earthquakes are a geologic hazard with no direct relationship to climate change forcings, they are included here because they have a high level of potential impact and partly because earthquakes increase the vulnerability of structures and make them more susceptible to damage from future climate hazards. Earthquakes need to be considered as part of a multi-hazard analysis to provide a more holistic perspective and inform measures to reduce potential risk to infrastructure.

There are two central messages in this report that are relevant to policy makers in the Asia and Pacific region. First, transport and energy infrastructure in the region is significantly exposed to climate change and earthquake hazards. About 62% and 44% of transport assets included in the study are rated *red flag* or *high* (the two highest exposure categories in this report) for floods and extreme heat, respectively. Water stress accounts for the largest proportion of energy assets evaluated that are rated *red flag* or *high* (45.1%). A significant share of assets included in this analysis are exposed to earthquakes (72.4%), cyclones (22.4%), and sea level rise (8.3%). Second, the analysis emphasizes the importance of a multi-hazard approach to building infrastructure resilience. Nearly 75% of all assets in this study are exposed to four or more hazards, while more than one in three are rated *red flag* or *high* for two or more hazards. The share varies by region and is particularly high in the Pacific (55.8%). These findings underscore the critical need to systematically integrate an understanding of the potential impacts of these hazards into the planning, design, and financing of infrastructure upgrade and maintenance.

Although this report is not intended to be a comprehensive analysis of climate change and earthquake hazards faced by the region, it makes an important contribution to understanding the extent of the region's exposure to these hazards. The findings are best used as additional information to the limited but growing knowledge about the varying degrees to which the region's infrastructure may be exposed to climate change and earthquake hazards. Further efforts using locally available information on the physical characteristics of the assets (such as age, material composition, and construction type) should then guide the preparation of a vulnerability assessment. Ongoing collaboration between ADB and its developing member countries will take this understanding further and inform governments and other development partners in identifying, assessing, and managing exposure to these hazards. These efforts support ADB's commitment to scale up its investments in climate and disaster resilience in line with its long-term corporate strategy (ADB 2018) and its aspiration to be Asia and the Pacific's climate bank.

The rest of the report is organized as follows. Section 2 provides a brief overview of existing and future climate change and earthquake hazards in the Asia and Pacific region. The scope of the analysis, methodology, and limitations are described in section 3. The overall results are presented in section 4. Section 5 provides a brief conclusion and three steps for building resilience.

2

CLIMATE CHANGE AND EARTHQUAKES IN ASIA AND THE PACIFIC

As reviewed extensively in ADB (2017a), the climate in the Asia and Pacific region will continue to experience significant changes. In addition, the region is among the world's most active seismically.

2.1 Extreme Heat

Due to anthropogenic climate change, heat extremes are projected to become more frequent and severe over the century. Under a high emissions scenario,[1] global mean temperature is projected to rise more than 4°C above pre-industrial levels by the end of the century. In some areas of the region, a 7°C warming will result in wet-bulb temperatures[2] in excess of 35°C, surpassing the biophysical heat dissipation thresholds for humans and other terrestrial animals without adaptation measures (Sherwood and Huber 2010). While natural variability varies across the region, temperature changes in the Asia and Pacific region are projected to exceed natural variability more frequently and the temperature range to which populations are acclimated. Many affected areas will experience temperature increases of more than six standard deviations above the mean—an unprecedented warming relative to the historical baseline (ADB 2017a). These extreme temperature changes will place enormous stress not only on human health, but also on the region's infrastructure.

Under a high emissions scenario, extreme summer temperatures are expected to occur primarily in the People's Republic of China (PRC), India (southern region), Indonesia, Mongolia, the Philippines, and Sri Lanka, where maximum temperatures are estimated to be more than five standard deviations above the historical mean. The absolute temperature increase will be more prominent at higher latitudes. The PRC (northern and western regions), Kazakhstan, Mongolia, Pakistan, and Tajikistan are projected to have the largest absolute temperature changes (ADB 2017a; IPCC 2013). In other parts of Asia, most land areas are expected to face mean summer temperatures of three standard deviations above the historical baseline in half of all years.

Rising temperatures can lead to surges in energy demand and put additional stress on existing power grids. Thermal-powered generation infrastructure—such as coal- and natural gas-fired power plants—is sensitive to extreme heat, especially during periods of peak demand. Extreme heat can also reduce transmission capacity and lead to higher losses in the transmission system.

1 In this report, a high emissions scenario refers to representative concentration pathway (RCP) 8.5. The main characteristics of this pathway are described in Riahi et al. (2011).

2 The wet-bulb temperature is the temperature reading of a thermometer covered in water-soaked cloth over which air is passed. At 100% relative humidity, the wet-bulb temperature is equal to the air temperature.

In the transportation sector, extreme heat can lead to rapid deterioration of paved roads and runways and significantly higher maintenance costs. Dry conditions also exacerbate the occurrence of wildfires, which destroy the ecosystem and make roads near burning areas hazardous to traffic.

2.2 Extreme Precipitation and Inland Flooding

Changes in average precipitation will show considerable spatial variation, with increases in some regions and decreases in others. There is high confidence that the difference between annual mean precipitation in dry and wet regions and the difference between wet and dry seasons will increase as temperatures increase (Collins et al. 2013). In Central Asia, Kazakhstan is projected to experience an increase in precipitation across all seasons, with the largest increase occurring in the dry season. The nature of precipitation changes in other parts of the region is less certain, as projections vary considerably among climate models. Uncertainty is greatest in southeastern PRC, where models disagree on annual, summer, and winter precipitation changes. In Southeast Asia, the direction of changes in mean annual and summer precipitation is also highly uncertain due to model disagreement (ADB 2017a).

The precipitation regime in many parts of Asia is governed by the seasonal monsoon. However, monsoon projections are constrained by the inability of climate models to capture the complex spatial patterns associated with shifting monsoon patterns.[3] Nonetheless, Asian monsoon regions are expected to face intensified precipitation, with heavier and more extreme rainfall resulting from increased evaporation and subsequent moisture convergence driving the wet season changes (ADB 2017a). Average rainfall during the rainy season is projected to increase in southern India and western PRC, but uncertainty is high in most parts of the region (Rajeevan, Bhate, and Jaswal 2008; Sen Roy 2009). In the PRC, particularly in the Yangtze basin, higher rainfall is expected to increase the risk to floods and landslides (Kundzewicz et al. 2013).

In South Asia, observations indicate an increasing trend and intensification of rainfall associated with the South Asian monsoon (Lehmann, Coumou, and Frieler 2015). Projections show a rise in the frequency and intensity of extreme precipitation events in the region (Sillmann et al. 2013). Despite a potential weakening of the overall monsoon circulations, the wet season in South Asia is expected to bring heavier and more extreme rainfall due to higher evaporation and subsequent moisture convergence.[4] In India, dry and wet spells are expected to intensify and monsoon rainfall is expected to become more variable as the climate warms (Chou, Tu, and Tan 2007; Menon et al. 2013). In Bangladesh, greater moisture convergence is anticipated to cause more frequent and severe flooding (Kamiguchi et al. 2006).

Glaciers feed many of Asia's major rivers, including the Brahmaputra, Ganges, Indus, Mekong, Yellow, and Yangtze rivers. A rise in precipitation extremes combined with increased melting of alpine glaciers due to warmer temperatures will result in greater river discharge, which could increase the risk of riverine flooding in the short term (ADB 2017a). The wider Tibetan Plateau is expected

3 At the time of analysis, the CMIP5 models were used as the basis for the analysis. More recent generations of global models (i.e., CMIP6) have shown increasing skill in simulating the Asian monsoons.

4 See Allen and Ingram (2002); Held and Soden (2006); Pall, Allen, and Stone (2007); and Westra et al. (2014).

to experience elevated risk of flooding due to increased meltwater from glaciers (Milly et al. 2002). As the rainy season and the melt season coincide in the Himalayas, river discharge is likely to be higher, leading to more flooding in warm and wet years.

As temperatures continue to rise, a greater percentage of precipitation is likely to fall as rain rather than snow as the snowfall line moves upward, increasing the risk of flooding, as already seen in the Hindu Kush and Himalayas (Shrestha et al. 2015). Once glaciers have retreated significantly, rainfall and spring temperatures will be the only remaining modes of variability influencing river discharge (Chaturvedi et al. 2014).

2.3 Sea Level Rise and Coastal Flooding

The Asian coastal region is highly exposed to sea level rise, with urban areas heavily concentrated in low-lying coastal regions and river deltas, putting large numbers of people and infrastructure at risk. More people are exposed to sea level rise in the Asia and Pacific region than in any other region of the world, with Asian port cities facing nearly 65% of global exposure to 1-in-100-year coastal flooding (Hanson et al. 2011). Dasgupta et al. (2009) found that among 84 developing countries of the world (excluding Pacific island countries), people in Brunei Darussalam, Cambodia, the PRC, Indonesia, the Republic of Korea, Malaysia, Myanmar, Papua New Guinea (PNG), the Philippines, Thailand, and Viet Nam face the greatest exposure (as a percentage of their respective national populations). In Indonesia, approximately 5.9 million people are most exposed to sea level rise of 0.45 meters, assuming middle-of-the-road projections by the end of the century and no adaptation measures is taken (Mcleod et al. 2010).

In the region, sea level rise is driven by several factors, and the estimates are well above global averages. Several coastal cities in Asia are subsiding as a result of overextraction of groundwater resources, exacerbating the effects of sea level rise. Small island states in the Pacific are experiencing greater regional sea level rise, largely due to gravitational effects from the loss of ice mass, which concentrates in the tropics as a result of effects from both hemispheres (ADB 2017a).

Sea level rise is expected to contribute to increased flooding in certain parts of the region. A number of coastal Asian cities, particularly in eastern PRC, Southeast Asia, and India, could suffer significant economic losses due to coastal flooding associated with sea level rise if adaptation measures are not taken.

In recent years, global sea level rise projections have trended higher, in part due to better modeling and understanding of ice sheet processes and glacial dynamics in polar regions. Kopp et al. (2014) estimate that, taking into account the potential for ice cliff failure and hydrofracturing (rain- and meltwater-enhanced crevassing and calving) in the Antarctic ice sheets, the median projected 21st century global mean sea level could rise by 1.1 to 1.9 meters under a high emissions scenario. Although more research is needed in this area, Bamber et al. (2019) estimate that global sea level could rise by more than 2 meters by the end of the century under a high emissions scenario, regardless of the future trajectory of greenhouse gas emissions (DeConto and Pollard 2016; and Tollefson 2016).

2.4 Tropical Cyclones

In Asia, most landfall storms originate in the western Pacific, southern Pacific, and northern Indian oceans, and to a lesser extent in the southern Indian Ocean. The western Pacific Ocean generally produces more tropical cyclones per year than any other ocean basin. These cyclones affect small island states in the Pacific, the coasts of Southeast Asia, the Philippines, and southern PRC. Global observations indicate an increase in the destructive power of tropical cyclones related to an increase in sea surface temperature, which is an important driver of tropical cyclone formation and intensification (Elsner, Kossin, and Jagger 2008; Emanuel 2005). One study projected that cyclone-related economic losses will double by 2100 due to climate and population changes (Mendelsohn et al. 2012), with the largest absolute losses expected in the PRC and the highest losses relative to gross domestic product (GDP) in Pacific island countries (ADB 2017a).

Precipitation associated with tropical cyclones is projected to increase by up to 20% over the same period (Christensen et al. 2013). In addition, projections indicate a likely increase in intense tropical cyclones, such as those reaching Category 3 intensity or higher, and a decrease in overall frequency (Holland and Bruyère 2014). However, their intensity is expected to rise in all basins except the western Pacific Ocean (Kossin, Emanuel, and Camargo 2016). A study that examined basins in the Asia and Pacific region estimated that by the end of the century, the frequency of intense tropical cyclones and the intensity of the strongest storms in 2100 would escalate by up to 25% and 5%, respectively, compared to 2000–2019.

Some studies indicate that rising sea surface temperatures at higher latitudes will shift maximum intensity to areas less accustomed to strong tropical cyclones, suggesting more frequent and possibly more intense tropical cyclones at subtropical and mid-latitude locations (Kossin, Emanuel, and Vecchi 2014; Kossin, Emanuel, and Camargo 2016). In the western Pacific Ocean, this suggests more intense storms, leading to greater exposure of the central eastern PRC and eastern Japan. However, the frequency and path of tropical cyclones in the future remain uncertain.

2.5 Water Stress

Climate-induced water stress is linked in multiple ways to increased poverty, migration, and water insecurity caused by diminishing water supplies, increasing competition for freshwater, and more frequently occurring extreme weather events (Stoler et al. 2021). Greater demand for freshwater coupled with climate-induced water shortages is accelerating the degree of water stress and increasing its spatial extent across Asia (Dai 2021). Terrestrial water storage appears to be declining across Asia, particularly in regions dependent on retreating glaciers (Maurer et al. 2019) and where groundwater withdrawal exceeds the replenishment rate (Rodell, Velicogna, and Famiglietti 2009).

Around 800 million people rely on meltwater from the Himalayan glaciers (Pritchard 2017). The water towers of South Asia have long protected the region from droughts, but this major source of water supply could lose two-thirds of its glaciers by the end of the century (Wester et al. 2018). Other Asian glaciers outside the Himalayan region are facing a similar development. Glacier melt is expected to initially increase river basin discharge rates as glaciers retreat, but eventually snow and glacier water will ultimately wane (Lutz et al. 2014). The water from the retreating glaciers and snowpack is currently being used for irrigation, power generation, industry, and many other uses. A lower supply will increase stress on the systems that depend on it. As a result, the reliance on precipitation to replenish water sources is anticipated to increase (Immerzeel, van Beek, and Bierkens 2010).

Toward the end of the century, hot and dry years are expected to lead to a much lower river discharge as ice storage, which is critical to regional water security, can no longer serve as a buffer during periods of drought. The upper Indus, upper Ganges, and Brahmaputra rivers are expected to experience significant declines in discharge within the next 20 to 30 years (Koirala et al. 2014).

Northern India relies heavily on groundwater for irrigation and drinking water supplies, but unsustainable withdrawal rates have significantly depleted water tables, despite a 1% increase in precipitation since 1979 (Rodell et al. 2018). A downward trend in groundwater reserves has also been observed in eastern India, Bangladesh, Myanmar, and southern PRC over the same period, due to irrigation demand combined with declines in monsoon rainfall.

While projected climate changes will contribute to water shortages in the long term, increasing water demand due to rapid population and economic growth will also exacerbate water stress in Asia. Water stress is likely to reduce hydropower generation in South Asia and may affect biomass and geothermal generation. Extreme heat can also substantially reduce water cycle efficiency in coal and oil refineries in the region. Finally, water stress can lead to low river levels that make ports unusable.

2.6 Earthquakes

Many parts of Asia and the Pacific are at high risk for earthquakes due to several tectonic plate boundaries in the region as well as the Pacific Ring of Fire and associated subduction faults. The faults between the Indo-Australian Plate and the Burma, Sunda, and Andaman subplates run through several countries in Southeast Asia. Earthquakes particularly affect the PRC, India, Indonesia, Nepal, the Philippines, and the small island states of Oceania. Earthquakes can also trigger tsunamis, which can cause extreme damage, as seen during the 2004 tsunami that devastated Sumatra (Wang and Liu 2006) and the 2011 Great East Japan Earthquake and tsunami that caused damage beyond the nuclear power plant (Mimura et al. 2011).

In addition, earthquakes caused by the collision of the Indian Plate with the Eurasian Plate and the Arabian Plate contribute to the seismic risk in the Himalayan region and in Pakistan and western India. Faults along the Pacific Plate and the Australian and Burma Plates result in strong seismicity in the Philippines, Indonesia, PNG, and the small island states of Oceania (Denham and Smith 1993).

Earthquakes are the only geophysical hazard assessed in this study. Although earthquakes are not related to climate change, they are a major hazard in the region and can increase the vulnerability of structures, making them more susceptible to adverse impacts from climate hazards. Earthquakes also need to be considered as part of a multi-hazard analysis to provide a more holistic perspective and inform measures to reduce potential risk to infrastructure.

3

SCOPE, METHODOLOGY, AND LIMITATIONS OF STUDY

This report uses an innovative approach to assess the exposure of infrastructure assets to climate change and earthquake hazards. Exposure is defined as the presence of infrastructure assets in locations and settings that could be adversely affected. More than 30,000 infrastructure assets in Asia and the Pacific are individually geolocated to a precise latitude and longitude. Infrastructure locations are derived from public data sources or a combination of Open Street Mapping software and satellite imagery (see Appendix for list of infrastructure data sources). These assets are then individually evaluated for the degree and characteristics of existing and future exposure to sea level rise and coastal floods, extreme heat, water stress, inland floods, and extreme precipitation. Each infrastructure asset is also screened for exposure to cyclones and earthquakes, leveraging databases of the location and severity of historical occurrences. This report does not carry out a vulnerability assessment, i.e., the propensity of assets to be adversely affected and the adaptive capacity are not examined (Box 3.1).

Box 3.1: Exposure, Vulnerability, and Risk

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) provides the following definition:

Exposure: The presence of people, livelihoods, species, or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Risk: The potential for consequences when something of value is at stake and the outcome is uncertain, recognizing the diversity of values. Risk is often presented as the probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if those events or trends occur. In this report, the term risk is often used to refer to the potential for adverse consequences to life, livelihoods, health, ecosystems, and species; economic, social, and cultural assets; and services (including environmental services) and infrastructure when the outcome is uncertain.

This report focuses on exposure assessment.

Source: Mach, K. J., S. Planton, and C. von Stechow, eds. 2014. Annex II: Glossary. In Pachauri, R. K. and L. A. Meyer, eds. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC. pp. 117–130.

3.1 Scope of Analysis

In 2017, ADB published a landmark report estimating infrastructure investment needs in Asia for the period 2016–2030 (ADB 2017b). The report focuses on four investment sectors (transport, energy, telecommunications, and water and sanitation) and estimates Asia's investment needs at $22.6 trillion ($1.5 trillion per year) which increases to $26 trillion ($1.7 trillion per year), if we take into account climate change mitigation and adaptation costs (Table 3.1).

Table 3.1: Estimated Infrastructure Investment Needs by Sector, 2016–2030
($ billion in 2015 prices)

Sector	Baseline Estimates		Climate-Adjusted Estimates	
	Total Investment Needs	Annual Average	Total Investment Needs	Annual Average
Energy	11,689	779	14,731	982
Transport	7,796	520	8,353	557
Telecommunications	2,279	152	2,279	152
Water and sanitation	787	52	802	53
Total	**22,551**	**1,503**	**26,166**	**1,744**

Source: ADB. 2017b. *Meeting Asia's Infrastructure Needs*. Manila.

The report shows that the energy and transport sectors have by far the highest investment needs—the energy sector alone accounts for more than 55% ($14.7 trillion) of the climate-adjusted estimates, and the transport sector accounts for more than 30% ($8.4 trillion). Transport infrastructure facilitates the flow of people and commodities, allowing the concentration and specialization of economic activities in different regions, while energy infrastructure is essential for production and quality of life (ADB 2017b). For this reason, this report focuses on the energy and transport sectors. The selection of these two sectors in no way undermines the need for similar hazard exposure assessments in other sectors such as agriculture, water, telecommunications, and health.[5]

Of the 30,946 assets evaluated for climate change and earthquake hazards exposure, 61.3% are in the energy sector and 38.7% are in the transport sector. The analysis includes five subsectors within the energy sector, consisting of generation and transmission infrastructure, while the transport subsectors included in the study consist of rail and air transport, multimodal logistics, bridges and highways, and road construction. Within these sectors, electricity transmission and transport (bridges) represent the bulk of assets included in the analysis (77.1%) (Table 3.2). These subsectors are based on the sector and subsector classification system used by ADB.

5 At the time of writing, the effects of the ongoing COVID-19 pandemic highlighted the importance of ensuring the resilience of infrastructure assets in the health and telecommunication sectors as well.

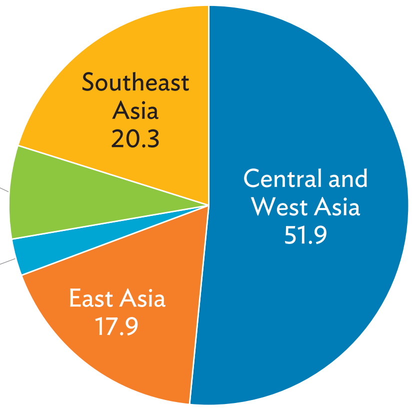
Table 3.2: Number of Assets Evaluated by Subsector and Subregion

Sector	Subsector	Central and West Asia	East Asia	Pacific	South Asia	Southeast Asia	Total
Energy	Conventional energy generation	59	1,179	10	356	181	1,785
	Hydropower generation	64	647	9	243	269	1,232
	Renewable energy generation[a]	9	587	5	285	170	1,056
	Oil and gas transmission	36	573	1	97	212	919
	Electricity transmission	9,982	1,614	19	1,060	1,305	13,980
	Total	**10,150**	**4,600**	**44**	**2,041**	**2,137**	**18,972**
Transport	Air transport	257	79	548	258	424	1,566
	Rail transport[b]	0	13	0	0	0	13
	Multimodal logistics[c]	16	139	42	45	198	440
	Transport (bridges)	5,651	447	287	0	3,497	9,882
	Highway and street construction[d]	0	60	0	1	12	73
	Total	**5,924**	**738**	**877**	**304**	**4,131**	**11,974**
Total all sectors		**16,074**	**5,538**	**923**	**2,343**	**6,268**	**30,946**

[a] Renewable energy generation includes solar, wind, small hydropower, geothermal, biomass, and waste.
[b] Only nonurban rail transport is included.
[c] Multimodal logistics include coastal and inland logistics hub such as ports, deep sea freight transportation (domestic), deep-sea passenger transportation, marine cargo handling, trucking, storage, and transportation equipment and supplies.
[d] Includes highway and steel construction except elevated highways.
Source: ADB estimates.

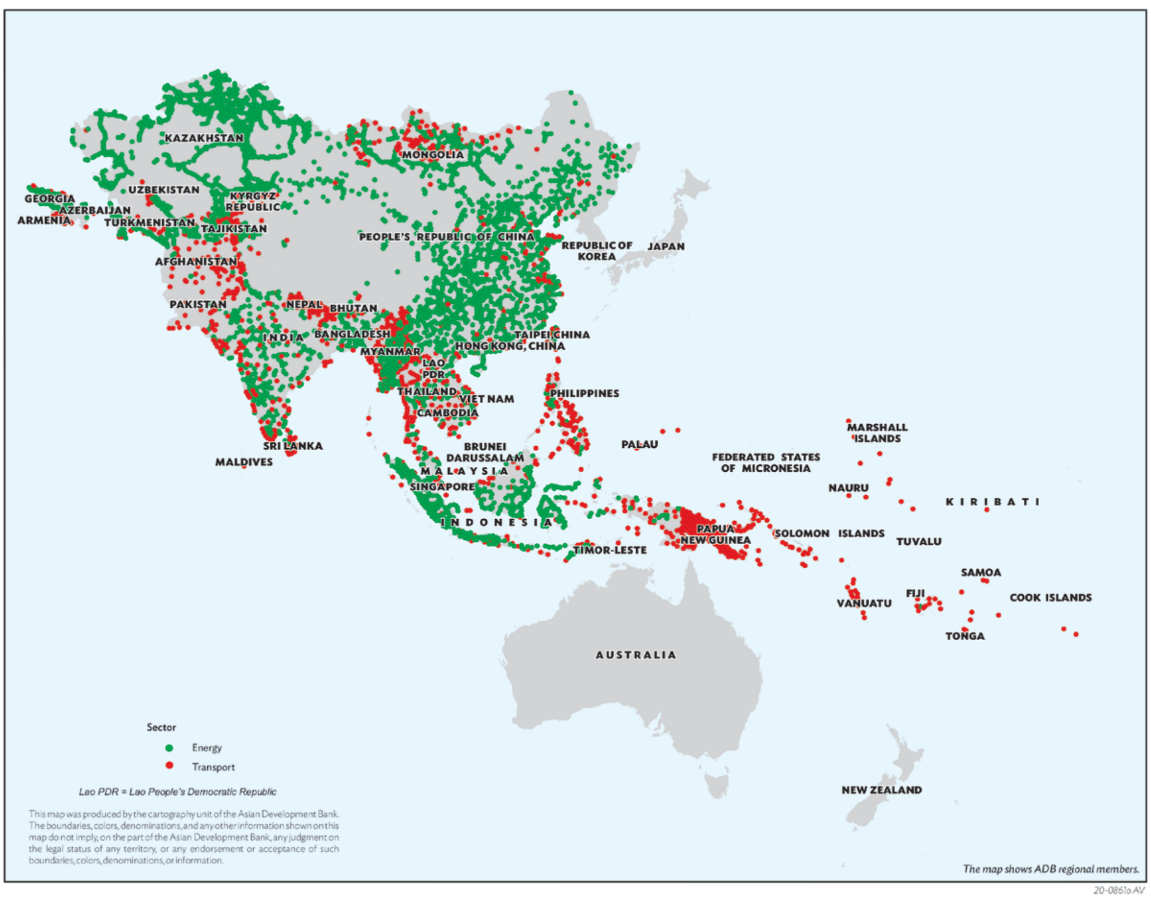
In terms of geographic scope, the analysis focuses on the Asia and Pacific region, which includes ADB's five subregions: Central and West Asia, East Asia, the Pacific, South Asia, and Southeast Asia. As discussed earlier, the analysis is based on available data and is not representative of the size of the subregion or economy or the total number of infrastructure assets in the subregion or economy. Figure 3.1 and Map 3.1 show the geographic coverage of the analysis by sector. Central and West Asia dominate the analysis with about 52% of assets, followed by Southeast Asia with 20.3% and East Asia with 17.9%.

Figure 3.1: Distribution of Analyzed Assets by Subregion
(%)



Source: ADB estimates.

Map 3.1: Assets Included in the Analysis



Source: ADB estimates.

3.2 Hazard Rating Methodology

This section describes the methodology used for the analysis, along with the thresholds used to determine the extent of exposure to the infrastructure assets by hazard. As discussed earlier, the 30,946 assets are geolocated to a precise latitude and longitude and individually evaluated for the degree and characteristics of existing and future exposure to sea level rise and coastal floods, heat and water stress, inland floods, and extreme precipitation. Each infrastructure asset is also examined for exposure to cyclones and earthquakes,[6] leveraging databases of the location and severity of historical occurrences.

For temperature- and precipitation-based indicators, definitions developed by the joint CCI/CLIVAR/JCOMiM Expert Team on Climate Change Detection and Indices (Sillmann 2013) are used. Values for a high emissions scenario and for the 2030–2040 period[7] are derived from five statistically downscaled climate models,[8] which perform modestly well across the Asia and Pacific region.[9] To address the varying performance of the models, a multi-model mean is used to evaluate precipitation and temperature metrics across the region. Climate model outputs are statistically downscaled to approximately 25 kilometers (km) x 25 km resolution from Earth Exchange Downscaled Climate Projections data set of the United States National Aeronautics and Space Administration (NASA-NEX) and downloaded and processed via Amazon Web Services using custom-built modules capable of processing terabytes of climate data for the specific time period and locations of interest.

Given the nature of the hazards in this analysis, supplemental models and environmental hazard data sets are used to evaluate past extremes such as cyclones. While climate models are useful for evaluating the character and magnitude of changes in precipitation and temperature, these models provide a limited view into more complex phenomena such as floods, water stress, and cyclones. Understanding the impacts of these events requires input from terrain models, two-dimensional hydrodynamic flood models, satellite-derived elevation data, population growth models, and historical occurrence data sets.

Raw indicator values are converted to dimensionless scores from 0 to 100 so that indicators with different units can be evaluated and aggregated on a common scale. For example, degrees Celsius and millimeters of rainfall are on different numerical scales before normalization.[10] These climate scores correspond to the exposure thresholds described in Table 3.3. The thresholds are based on

6 Although earthquakes are a geologic hazard with no direct relationship to climate change forcings, they have been included here because they have a high level of potential impact and because earthquakes increase vulnerability of structures and make them more susceptible to adverse effects from future climate hazards.

7 For the climate change projections that serve as inputs to our analysis of extreme heat and extreme rainfall patterns, we measure the direction and magnitude of change by using a 1975–2005 historical baseline as a benchmark, with points of measure at 2030–2040 under the high emissions scenario (RCP 8.5). Comparing the 2030–2040 projections to the historical baseline provides a basis for how climate is expected to shift over time in a given location. For this time frame and scenario, five statistically downscaled global climate models are averaged together.

8 These models are ACCESS1-0, CCSM4, CNRM-CM5, GFDL-ESM2M, and MPI-ESM-MR. All global climate models have inherent biases that result in varying levels of skill in representing climate indices across specific regions of the world. Because of myriad model configurations, each model performs more or less skillfully for a given variable in a specific region of the world relative to a multi-model ensemble. Some of these biases can be reduced through statistical or dynamic downscaling, which more accurately captures smaller-scale processes and features, such as those related to coastlines.

9 The analysis was derived from Coupled Model Intercomparison Project Phase 5 (CMIP5) models and therefore may present a number of the same biases. Several studies have sought to evaluate the performance of individual CMIP5 models in the region. See, for example, McSweeney et al. (2015); Sperber et al. (2013); and Gao, Wang, and Jiang (2015).

10 A min-max method is used to convert indicator values to a score between 0 and 100. The distribution for rescaling is based on the Four Twenty Seven Facility Database, which includes over 1.1 million sites around the world.

either statistical thresholds, specific to the ADB members included in this analysis[11] or absolute thresholds for floods, cyclones, sea level rise, and earthquakes. Absolute thresholds are used in relation to this latter category of exposure, as an asset may or may not be exposed to flooding due to its elevation or proximity to waterways.

Extreme heat is measured by the relative change in frequency and severity of hot days and average temperature over time. Locations that are projected to experience large changes relative to the recent historical mean will most likely be affected by higher temperatures, even if those locations are not projected to experience the absolute warmest temperatures. These increases may in turn affect energy demand and costs, labor productivity, grid reliability, and human health. Extreme heat data are sourced from the Intergovernmental Panel on Climate Change (IPCC) and NASA-NEX data set.[12] Because all extreme heat indicators are derived from downscaled global climate models, they exhibit some of the same uncertainties observed in the Coupled Model Intercomparison Project Phase 5 (CMIP5) models.[13] Table 3.3 summarizes the exposure criteria and specific thresholds used to classify risk levels. For extreme heat, infrastructure assets are assigned risk classifications using a statistical percentile relative to all other infrastructure included in this analysis.

Water stress measures were derived and downloaded from the World Resources Institute's Aqueduct Water Risk Atlas.[14] These measures capture current (Gassert et al. 2014) and projected (Luck, Landis, and Gassert 2015) water stress at a watershed level. Water stress variables focus on physical water scarcity and include absolute and relative percentages of change in water supply and demand between the current period and 2040, as well as recent evaluations of water stress and interannual variability. The analysis uses a high emissions scenario for the water supply and demand projections.

Water stress estimates focus on physical water scarcity and do not capture other indicators of water risk, such as governance, water quality, and associated regulatory risks. All water stress indicators are derived from the watershed(s) that directly surround the infrastructure asset, even if the primary water source is outside the immediate basin—which may be the case for water users in urban areas. For water stress, a statistical percentile is used to assign risk classifications to infrastructure assets relative to all other infrastructure included in this analysis (Table 3.3).

Floods measure the severity and frequency of historical pluvial and fluvial flooding, the frequency of future heavy rainfall events, and the intensity of prolonged periods of heavy rainfall in the future. Flood-related data are from the IPCC, NASA-NEX, and Fathom, and flood frequency and severity indicators are based on a simulated 1,000-year history extrapolated from an observational history (1985–2011).

11 Percentiles are generated using infrastructure scores from ADB members only.
12 Full details can be found at the NASA Center for Climate Simulation. Climate Data Services. https://cds.nccs.nasa.gov/wp-content/uploads/2015/06/NEX-GDDP_Tech_Note_v1_08June2015.pdf.
13 CMIP5 is a project that provides a framework for coordinated climate change experiments across 20 climate modeling groups with an aim—among others—to give a better understanding of the determinants of the variations in climate change projections across models.
14 World Resources Institute. Aqueduct Water Risk Atlas. https://www.wri.org/resources/maps/aqueduct-water-risk-atlas.

Table 3.3: Hazard Thresholds by Exposure Level

	Basis for Exposure Level	Red Flag	High	Medium	Low	None
Extreme heat	Statistical percentile[a]	> = 95%; Exposed to some of the most severe changes in global heat extremes	67%–94%; Relatively high changes in heat extremes compared with regional average	34%–66%; Warming, though changes in heat extremes are within range of regional average	1%–33%; Warming, but changes in extremes are relatively less severe than regional average	<1%
Water stress	Statistical percentile[a]	> = 95%; Competition for water resources is extreme, and future water supply failure is possible	67%–94%; Current water stress is high, and future water supplies are projected to fall	34%–66%; Water supply and/or demand changes are likely to increase competition for water resources	1%–33%; Water supply and/or demand changes are relatively small	<1%
Floods	Absolute score	> = 75; Susceptible to high frequency and/or severe rainfall or riverine flooding during a 1-in-100-year flood event	50–74; Susceptible to some degree of flooding and inundation during rainfall or riverine flood events	28–49; Susceptibility to flooding based on historical record or future rainfall intensification	1–27; Site likely not susceptible to inundation	<1
Cyclones	Absolute score	> = 80; Situated in the regular path of cyclones, and severe cyclones are common	60–79; Situated in the regular path of cyclones	40–59; Exposed to frequent and/or severe cyclone activity based on historical record	25–39; Cyclone activity possible, but frequency or severity of past storms have been relatively minimal	0–24; No known historical occurrence
Sea level rise	Absolute score	> = 70; Frequent floods and/or significant increase in the frequency of flooding in the future	60–69; Susceptible to some degree of coastal flooding in the future, and changes in flood frequency are small	50–59; Assets located under 10 meters above sea level	40–49; Assets located over 10 meters above sea level	0–39; Not coastal or near waterways connected to the sea
Earthquakes	Absolute score	> = 80; Large damage to most buildings likely	70–79; Buildings likely to suffer some damage	50–69; Few instances of building damage	1–49; Damage to buildings is unlikely	No earthquake

[a] Percentiles are derived from the distribution of scores relative to other infrastructure evaluated in this analysis.
Source: ADB estimates.

To analyze the level and spatial extent of potential pluvial and fluvial flooding, several land-use variables and historical observations were used to simulate overland flooding over several return periods ranging from 1-in-5-year to 1-in-1,000-year events. The spatial extent of flooding was adjusted to reflect high-resolution elevation data and flood infrastructure. While the flood models used to estimate historical flood frequency and severity include terrain surface details, they do not capture site-level details (e.g., flood gates, drainage, bioswells) that may improve or worsen flood conditions on site.

Projection-based rainfall indicators capture changing precipitation patterns to indicate the relative change in rainfall intensification during future extreme rainfall events. These indicators include the percent change in total maximum volume of rainfall in a 5-day period in an average year over the projection period, the absolute number of days in a year that daily rainfall volume exceeds the baseline period, the local 95th percentile, and the additional number of days in a year when the daily rainfall volume exceeds 10 millimeters.

The flood hazard rating is based on the susceptibility of the site to flooding and changing climate conditions. If the asset is not susceptible to flooding, even in the event of a rare but severe 1-in-1,000-year flood, then the asset is assigned a *low* or *no hazard* rating. A score of *medium* indicates that the asset is susceptible to some flooding based on historical records or future rainfall intensification, but inundation and frequency of flooding are moderate. Assets that are exposed to a *high* hazard or assigned a *red flag* are susceptible to high frequency of and/or severe rainfall or riverine flooding.[15]

Sea level rise estimates the absolute and relative increases in the frequency of coastal flooding. Estimates of exposure to sea level rise capture the frequency of inundation due to a combination of sea level rise, storm surge, and high tides, as well as changes in the frequency of inundation between historical and projected periods. The estimates leverage global high-resolution digital elevation model data and local storm surge and sea level rise estimates from 2017 and 2040. This analysis incorporates local flood risk statistics from proximate tide gauges, site elevation data at about 30-meter horizontal resolution and about 1-meter vertical resolution (NASA 2013), and local median sea level rise projections under a high emissions scenario.

These measures do not capture coastal flooding in areas more than 5 km inland from the coast. Similarly, sea level rise indicators do not capture subsurface hydrologic impacts such as salination or groundwater flooding. This limitation may lead to an underestimation of exposure risk in coastal-adjacent, low-lying areas that extend far inland (e.g., Ganges–Brahmaputra Delta).

Sea level rise hazards are not only a function of location and elevation, but also of how often the asset is expected to flood and the relative change in flooding frequency over the 2017–2040 period. Assets that are not located on the coast or near coastal waterways are assigned a *no risk* rating. Assets that are located near the coast but more than 10 meters above sea level and not directly exposed to coastal flooding receive a *low hazard* rating. Assets located at elevations less than 10 meters yet not directly exposed to coastal floodwaters are given a *medium hazard* rating.

15 The change in extreme precipitation was used as a proxy for flooding. It is noted that other details must be considered (such as changes in average and seasonal precipitation, or whether the heavy rain falls in a dry or wet period) to determine whether increased rainfall will result in a potential flood exposure. This does not translate directly into flooding.

Assets that are susceptible to some degree of coastal flooding in the future are classified as *high hazard*, while assets where both future flooding and relative changes in flood frequency are high, fall into the *red flag* category (Table 3.3).

Tropical cyclones are a measure of geographic exposure to these events. The indicator is based on data from the World Meteorological Organization and reflects both the severity of storms with the highest maximum winds and the frequency with which an area experienced a recorded number of cyclones during the period 1980–2016. Tornadoes and inland windstorms are not included, and only historical data are used—global projection data are not available because it is highly uncertain how climate change will affect the formation, intensity, and location paths of tropical cyclones. Historical data provide a reasonable indication of where tropical cyclones may form and how severe they are likely to be. The scores do not capture the damage caused by tornadoes or intense and prolonged rainfall, storm surge, or flooding associated with tropical cyclones. Hazard ratings are assigned based on the frequency and severity of past cyclones, and assets are assigned hazard classifications according to their exposure using statistical percentiles, relative to all other infrastructure included in this analysis (Table 3.3).

The ***earthquake*** indicator reflects the maximum shaking intensity experienced by the site and surrounding area and should be considered a high-level measure of geographic exposure to earthquakes. The earthquake indicator relies on the United States Geologic Survey's Shakemap archive from 1950 to 2018 to determine potential maximum shaking intensity.

This measure does not consider the frequency with which earthquakes occur or make predictions about where they will occur in the future. The earthquake indicator may underestimate hazards in areas that have not experienced large, destructive earthquakes during the analysis period and does not explicitly incorporate related hazards such as liquefaction or tsunamis.

For earthquakes, assets are classified into hazard levels based on the Modified Mercalli Intensity Scale, which attributes a level to the expected damage to built structures. There are 10 levels, defined in this analysis as follows: levels 1 through 5 are considered *low hazard*; levels 5 through 7 are considered *medium hazard* where some building damage is possible; levels 7 through 9 are considered *high hazard* where damage to poorly constructed buildings is expected; and levels 9 through 10 are considered *red flag* when damage is expected to most buildings.

3.3 Limitations of the Study

The results presented in the following sections should be interpreted and contextualized based on these limitations and the nature of the analysis.

First, as noted earlier, this report assesses the exposure of infrastructure assets to climate change and earthquake hazards. It does not assess how sensitive the assets are to the hazards or the extent to which the risks can be readily adapted.

Second, while the report examines more than 30,000 infrastructure assets in the energy and transport sectors, it is not intended to be a comprehensive analysis of climate change and earthquake hazards in the region. The distribution of assets across the region and the availability of data inherently constrains the comparability of results within the region. As discussed in section 3.1, the assets covered by the study are not evenly distributed across regions, economies, and sectors. Therefore, any analysis at the regional level is bound to be influenced by the distribution of assets across the region.

Third, at the time of writing, the Sixth Assessment Report of the IPCC and the Coupled Model Intercomparison Project (CMIP) Phase 6 had not yet been published. CMIP5 was used for the assessment. While the key messages remained unchanged, the latest generation of global climate models, i.e., CMIP6, was found to have demonstrated increasing skill in simulating climate impacts compared with CMIP5.

Fourth, due to the challenges associated with mapping spatially complex and distributed infrastructure, this analysis focuses on examining the largest known networks and key nodes within those networks. For example, rather than mapping every kilometer of road in the Asia and Pacific region, important nodes such as bridges and inland dry ports are mapped for economies where transportation is a priority.

Furthermore, due to data limitations on the criticality and interdependence of individual assets, all infrastructure is evaluated equally; consequently, this analysis may underestimate the implications of the failure of critical or interdependent infrastructure networks that serve many people or are part of larger national or transnational systems. Similarly, infrastructure exposure is based on the degree to which assets are exposed to climate risks and does not take into account asset-specific design and construction.

For infrastructure assets such as utilities that are spatially complex and encompass multiple underlying points of analysis, the assessment is based on the point with the highest score to capture potential network-wide failures. As a result, summary findings are based on the scores for the most exposed point in the distributed network.

Finally, any comparison of the level of exposure between different hazards is influenced by the nature of the hazards. Some hazards, such as extreme heat, may affect all assets, while hazards such as sea level rise, cyclones, and earthquakes are more location specific. Sea level rise is purely a coastal phenomenon that affects only assets near the coast, while exposure to cyclones and earthquakes is generally limited to coastal areas and tectonic fold lines, respectively.

The results of this analysis should be interpreted with caution and with these limitations in mind. These findings are best used as additional information to the limited but growing knowledge about the varying degrees to which the region's infrastructure may be exposed to climate change and earthquake hazards. Further efforts using locally available information on the physical characteristics of the assets (such as age, material composition, and construction type) should then guide the preparation of a vulnerability assessment. Ongoing collaboration between ADB and its developing member countries will take this understanding further and help inform governments and other development partners in identifying, assessing, and managing exposure to these hazards. These efforts support ADB's commitment to scale up its investments in climate and disaster resilience in line with its long-term corporate strategy (ADB 2018).

4

RESULTS AND DISCUSSION

The results of the analysis show that the transport and energy infrastructure in the region is exposed to significant climate change and earthquake hazards. Nearly three-quarters of the assets included in the analysis are exposed to four or more hazards. The assessment shows that Pacific developing member countries are particularly exposed to multiple hazards (Table 4.1). In addition, one in three assets in the region is rated *red flag* or *high* for two or more hazards. The proportion varies across regions and is particularly high in the Pacific (55.8%), South Asia (48.4%), and Southeast Asia (41.7%) (Figure 4.1). This finding emphasizes the importance of a multi-hazard approach to building resilient infrastructure.

Table 4.1: Exposure of Energy and Transport Sectors to Multiple Hazards in ADB Members

Economy	Number of Assets Analyzed			Percent of Assets Exposed to					
	Total	Energy	Transport	1 hazard	2 hazards	3 hazards	4 hazards	5 hazards	6 hazards
Afghanistan[a]	104	22	82	0.0	0.0	0.0	100.0	0.0	0.0
Armenia	23	12	11	0.0	0.0	0.0	100.0	0.0	0.0
Azerbaijan	56	38	18	0.0	0.0	0.0	89.3	10.7	0.0
Bangladesh	1,124	1,101	23	0.0	0.0	0.0	10.1	83.9	6.0
Bhutan	11	6	5	0.0	0.0	0.0	100.0	0.0	0.0
Cambodia	26	11	15	0.0	0.0	23.1	65.4	11.5	0.0
China, People's Republic of	3,205	2,963	242	0.0	0.2	10.4	56.8	26.3	6.4
Cook Islands	4	0	4	0.0	0.0	0.0	100.0	0.0	0.0
Fiji	29	10	19	0.0	0.0	0.0	17.2	58.6	24.1
Georgia	3,881	847	3,034	0.0	0.0	0.0	89.4	10.6	0.0
Hong Kong, China	15	5	10	0.0	0.0	0.0	0.0	86.7	13.3
India	1,060	880	180	0.0	0.0	10.6	61.2	22.1	6.1
Indonesia	1,086	799	287	0.0	1.2	4.5	62.0	29.4	2.9
Kazakhstan	7,273	7,233	40	0.0	0.5	81.2	18.3	0.0	0.0
Kiribati	7	0	7	0.0	0.0	85.7	14.3	0.0	0.0
Kyrgyz Republic	143	104	39	0.0	0.0	0.0	100.0	0.0	0.0
Lao PDR	30	18	12	0.0	0.0	16.7	20.0	63.3	0.0

continued on next page

Table 4.1 *continued*

Economy	Number of Assets Analyzed			Percent of Assets Exposed to					
	Total	Energy	Transport	1 hazard	2 hazards	3 hazards	4 hazards	5 hazards	6 hazards
Malaysia	116	77	39	0.0	1.7	6.0	37.1	34.5	20.7
Maldives	2	0	2	0.0	0.0	0.0	100.0	0.0	0.0
Marshall Islands	4	0	4	0.0	0.0	0.0	100.0	0.0	0.0
Micronesia, Federated States of	2	0	2	0.0	0.0	0.0	0.0	100.0	0.0
Mongolia	2,057	1,599	458	0.0	0.0	43.4	56.6	0.0	0.0
Myanmar[b]	4,261	748	3,513	0.0	0.0	4.0	58.7	35.5	1.8
Nauru	3	0	3	0.0	0.0	0.0	100.0	0.0	0.0
Nepal	88	10	78	0.0	0.0	0.0	100.0	0.0	0.0
Niue	1	0	1	0.0	0.0	0.0	0.0	100.0	0.0
Pakistan	122	56	66	0.0	0.0	1.6	72.1	17.2	9.0
Palau	2	0	2	0.0	0.0	0.0	0.0	100.0	0.0
Papua New Guinea	494	15	479	0.0	0.0	48.0	28.1	19.0	4.9
Philippines	238	103	135	0.0	0.0	0.0	0.4	33.2	66.4
Samoa	4	0	4	0.0	0.0	0.0	0.0	100.0	0.0
Solomon Islands	23	0	23	0.0	0.0	0.0	0.0	39.1	60.9
Sri Lanka	60	44	16	0.0	0.0	6.7	65.0	28.3	0.0
Taipei,China	61	33	28	0.0	0.0	0.0	42.6	29.5	27.9
Tajikistan	2,022	604	1,418	0.0	0.0	0.0	100.0	0.0	0.0
Thailand	292	206	86	0.0	0.0	4.1	67.8	16.1	12.0
Timor-Leste	314	19	295	0.0	0.0	0.0	0.0	47.5	52.5
Tonga	8	0	8	0.0	0.0	0.0	0.0	100.0	0.0
Turkmenistan	2,263	1,075	1,188	0.0	2.9	16.4	75.7	5.0	0.0
Tuvalu	0	0	0	na	na	na	na	na	na
Uzbekistan	187	159	28	0.0	0.0	5.3	94.7	0.0	0.0
Vanuatu	26	0	26	0.0	0.0	0.0	0.0	0.0	100.0
Viet Nam	219	175	44	0.0	0.0	0.0	60.3	37.9	1.8
Total	**30,946**	**18,972**	**11,974**	**0.0**	**0.4**	**26.3**	**54.2**	**16.2**	**3.0**

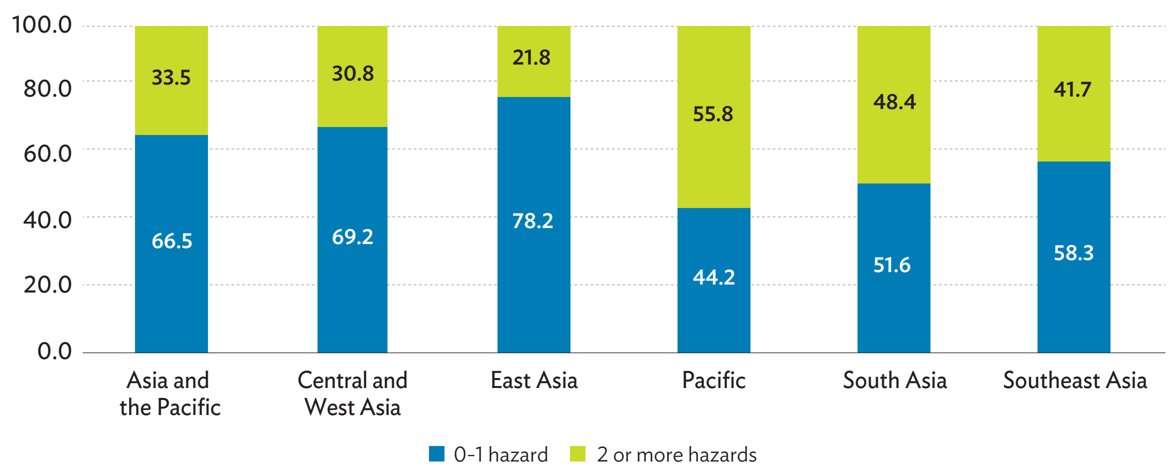
ADB = Asian Development Bank, Lao PDR = Lao People's Democratic Republic, na = not applicable.

[a] ADB placed on hold its assistance in Afghanistan effective 15 August 2021. See ADB (2021). This report was prepared based on information available for Afghanistan as of 31 July 2021.

[b] ADB has placed a hold on sovereign project disbursements and new contracts in Myanmar effective 1 February 2021. This report was prepared based on information available for Myanmar as of 31 January 2021.

Source: ADB estimates.

Figure 4.1: Percent of Assets Rated *Red Flag* or *High* in More Than One Hazard
(%)

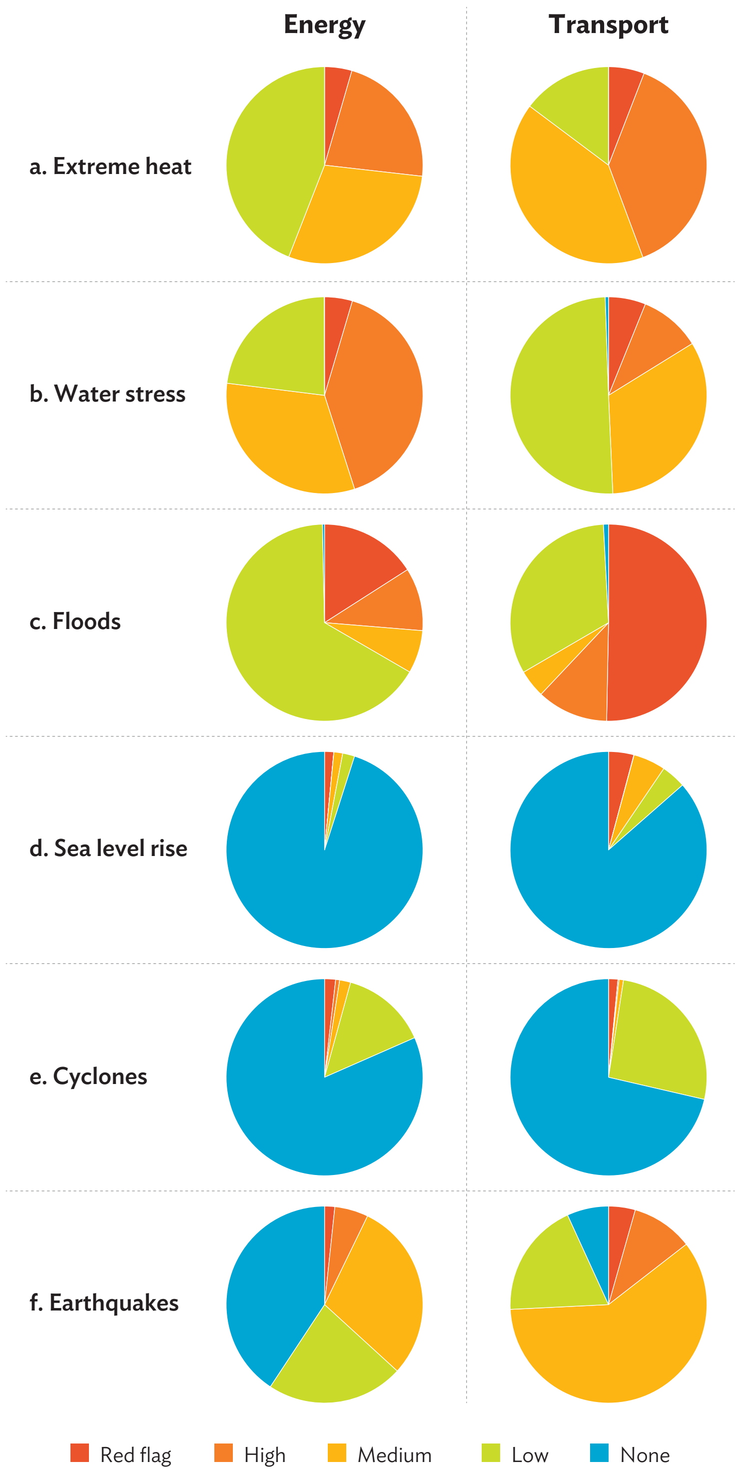


Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Figure 4.2 provides a snapshot of the exposure of energy and transport assets to climate change and earthquake hazards. As temperatures are projected to rise across the region, more infrastructure assets will be exposed to extreme heat. Within the transport sector, 44.3% of the assets included in the analysis are rated *red flag* or *high* for extreme heat (Table 4.2). Air transport is particularly exposed, with 72.5% of assets rated *red flag* or *high* (Table 4.3). Higher temperatures, often exceeding engineering design thresholds, can soften paved roads and runways, making them more prone to damage from vehicle traffic and thus requiring more frequent maintenance. Underwood et al. (2017) estimated that projected temperature increases would increase infrastructure construction and maintenance costs in the United States by about 3%–9% over a 30-year period. In many developing countries in the region, if similar increases were to apply to these countries, these additional costs would imply a significant reallocation of resources.

In the energy sector, 26.8% of the assets analyzed are rated *red flag* or *high* for extreme heat (Table 4.2). This increase in temperature is likely to drive up energy demand and put additional stress on existing power grids, especially those serving large and growing megacities. Increased use of air conditioning in these cities will likely save lives but also threaten the reliability of local grid systems. In addition, extreme heat can lead to electricity brownouts and blackouts, especially where grid expansion has not kept pace with climatic changes and rising demand, as seen in Almaty, Kazakhstan, in the summer of 2019. Thermal-powered generation infrastructure—such as coal- and natural gas-fired power plants, which are prevalent in the higher-latitude regions projected to experience greater temperature increases (i.e., the northern and western PRC, Kazakhstan, Mongolia, Tajikistan, and the Himalayan regions of India and Pakistan)—is sensitive to extreme heat, especially at times of peak demand (Cradden et al. 2010). Transmission and distribution lines are also sensitive to extreme heat and have lower capacity during periods of extreme heat (Bartos et al. 2016).

Figure 4.2: Exposure of Energy and Transport Assets to Climate Change and Earthquake Hazards by Rating



Source: ADB estimates.

Table 4.2: Percent of Assets Exposed to Climate Change and Earthquake Hazards by Rating

Sector	Red Flag	High	Medium	Low	None
	Extreme heat				
Energy	4.5	22.3	29.1	44.1	0.0
Transport	5.9	38.4	40.9	14.8	0.0
Total	**5.0**	**28.5**	**33.7**	**32.7**	**0.0**
	Water stress				
Energy	4.6	40.5	31.9	23.0	0.0
Transport	6.1	10.1	33.1	50.2	0.5
Total	**5.2**	**28.7**	**32.4**	**33.5**	**0.2**
	Floods				
Energy	16.0	10.3	7.1	66.3	0.3
Transport	50.3	11.7	4.6	32.6	0.8
Total	**29.2**	**10.9**	**6.1**	**53.2**	**0.5**
	Sea level rise				
Energy	1.5	0.0	1.4	2.0	95.1
Transport	4.2	0.0	5.3	4.0	86.5
Total	**2.5**	**0.0**	**2.9**	**2.8**	**91.7**
	Cyclones				
Energy	1.8	0.6	1.8	14.2	81.6
Transport	1.5	0.2	0.7	26.2	71.4
Total	**1.7**	**0.5**	**1.4**	**18.8**	**77.6**
	Earthquakes				
Energy	1.7	5.5	29.6	22.5	40.7
Transport	4.4	10.1	59.7	18.9	6.8
Total	**2.7**	**7.3**	**41.2**	**21.1**	**27.6**

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Table 4.3: Percent of Assets Exposed to Extreme Heat in the Transport Sector

	Subsector	Red Flag	High	Medium	Low	None
Extreme heat	Air transport	30.3	42.2	19.5	7.9	0.0
	Rail transport (non-urban)	0.0	0.0	15.4	84.6	0.0
	Multimodal logistics	29.3	35.7	15.0	20.0	0.0
	Roadway bridges	1.0	38.1	45.6	15.3	0.0
	Highway and street construction	0.0	19.2	31.5	49.3	0.0

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

In addition, the region faces increasing water demand due to socioeconomic development, with agriculture being the largest water user. Water supplies are expected to decline in much of the Asia and Pacific region due to changing precipitation patterns, higher temperatures, and lack of glacial water supplies. Overall, water stress accounts for the largest percentage of energy assets analyzed that are rated *red flag* or *high* (45.1%) (Table 4.2). This percentage reaches 59.9% for renewable energy generation (Table 4.4). Water stress can lead to poor performance of energy assets in the hydroelectric power subsector as well as in the conventional power generation subsector, where a large amount of water is needed for cooling purposes.

Table 4.4: Percent of Assets Exposed to Water Stress in the Energy Sector

	Subsector	Red Flag	High	Medium	Low	None
Water stress	Conventional energy generation	12.6	35.4	25.4	25.5	1.1
	Hydropower generation	2.2	17.5	23.5	54.6	2.3
	Renewable energy generation	4.5	55.4	28.5	10.6	0.9
	Oil and gas transmission	10.8	25.6	24.9	37.8	1.0
	Electricity transmission	3.4	43.0	34.2	17.3	2.1

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Changing precipitation patterns combined with increased melting of alpine glaciers due to warmer temperatures will result in greater river discharge, potentially elevating the risk of riverine flooding in the short term. Within the transport sector, 62.0% of the 11,974 individual assets evaluated are rated *red flag* or *high* for exposure to floods, which is the highest for the transport sector, while 66.9% of roadway bridges are rated *high* or *red flag* (Table 4.5). Exposure to flooding has also been noted in recent papers such as such as that of Koks et al. (2019), who estimate that even without climate change, about 73% of the world's expected annual damage to transport infrastructure is caused by surface and river flooding, followed by coastal flooding (15.5%), earthquakes (7.3%), and cyclones (3.8%). Across all the criteria, Koks et al. (2019) show that the Asia and Pacific region is the most affected.

Table 4.5: Percent of Assets Exposed to Floods in the Transport Sector

	Subsector	Red Flag	High	Medium	Low	None
Floods	Air transport	28.5	10.2	4.0	55.4	1.9
	Rail transport	30.8	30.8	0.0	38.5	0.0
	Multimodal logistics	33.9	8.4	1.6	54.3	1.8
	Roadway bridges	54.8	12.1	4.8	27.7	0.6
	Highway and street construction	16.4	13.7	4.1	65.8	0.0

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Of the assets included in the study, 10.0% are rated *red flag* or *high*, while another 41.2% are rated *medium* for earthquake exposure. Exposure to earthquakes is more acute in the transport sector, where 74.2% of the analyzed assets are rated *red flag, high*, or *medium*. Air transport and multimodal logistics have the highest percentage of assets within the transport sector rated *red flag* or *high*, at 27.3% and 24.5%, respectively (Table 4.6).

Table 4.6: Percent of Assets Exposed to Earthquakes in the Transport Sector

	Subsector	Red Flag	High	Medium	Low	None
Earthquakes	Air transport	8.6	18.6	46.0	17.7	9.0
	Rail transport (nonurban)	7.7	7.7	30.8	53.8	0.0
	Multimodal logistics	9.3	15.2	39.8	20.0	15.7
	Roadway bridges	3.5	8.6	62.9	19.0	6.1
	Highway and street construction	1.4	6.8	46.6	31.5	13.7

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Sea level rise and increases in intense tropical cyclones are projected to have severe effects on some subregions in the Asia and Pacific region. Similar to earthquake hazards, interpretation of these results must be contextualized based on the nature and scope of the analysis. First, as discussed before, unlike heat and water stress, sea level rise is a purely coastal phenomenon that affects only assets that lie close to the coast, while exposure to cyclones is mostly limited to coastal areas. Second, infrastructure assets are not evenly distributed across regions, economies, and sectors. Any analysis at the regional level is bound to be influenced by the distribution of assets in the region. This difficulty in conducting regional analysis is exacerbated by the availability of data on subregions, economies, and sectors. For example, more than 50% of all assets included in the analysis are located in the Central and West Asia region, where sea level rise and cyclones do not pose a significant risk (Figure 3.1).

Of the assets included in the study, 2.5% are rated *red flag* (none are rated *high*) for exposure to sea level rise, and 2.2% are rated *red flag* or *high* for exposure to cyclones (Table 4.2). Despite the seemingly low exposure of assets in Asia and the Pacific to sea level rise, the Pacific stands out with a 39.8% share of assets exposed to sea level rise, followed by Southeast Asia with 17.5%, while exposure to cyclones is highest in South Asia, Southeast Asia, and the Pacific with more than 50% of assets analyzed. In affected areas, sea level rise may cause permanent disruptions while contributing to higher floods that lead to temporary disruption of low-lying transport and energy infrastructure. This will likely threaten connectivity of remote coastal areas and islands whose economic growth depends on maintaining connections to major growth centers in the region. While sea level rise is a more permanent threat, tropical cyclones can be far more destructive in the short term. They can cause significant destruction of infrastructure due to high wind speeds and increased flooding due to heavy rainfall.

The rest of this section presents results for each of the five subregions of Asia and the Pacific.

4.1 Central and West Asia

The study includes 16,074 assets from Central and West Asia, representing about 52% of the assets included in the study. A majority of these assets are in two subsectors—9,982 assets in energy transmission and 5,651 assets in roadway bridges. The study includes assets from all countries in the subregion, but Kazakhstan dominates the analysis with 7,273 assets, of which 7,208 are in electricity transmission (Table 4.1). The analysis of the electricity transmission subsector in Kazakhstan shows that 99.5% of the assets analyzed are exposed to extreme heat, water stress, and flooding. Further details are given in Box 4.1.

Box 4.1: Electricity Transmission in Kazakhstan

In its 2018 annual report, the Kazakhstan Electricity Grid Operating Company cited 272 emergency grid outages, 53% of which were attributed to natural hazards (KEGOC 2019).

Climate change-driven extreme rainfall risk in Kazakhstan varies by geography, with energy infrastructure in Turkistan, Zhambyl, Almaty, East Kazakhstan, and Akmola projected to experience the largest increase in extreme rainfall by 2040 relative to 1975–2005. Transmission infrastructure in these regions is most likely to be impacted by flooding and

Map 4.1: Electricity Transmission Assets Rated *Red Flag* or *High* in Kazakhstan

Source: ADB estimates.

continued on next page

Box 4.1 *continued*

increased extreme rainfall. A cluster of energy transmission lines near the refinery in Atyrau in western Kazakhstan, particularly lines that run adjacent to the Ural River, are exposed to flooding at various return periods, including a frequency of 1-in-5 years.

Temperatures are projected to increase throughout Kazakhstan, but the largest relative increases in annual maximum temperatures are in the north near Akmola and in eastern Kazakhstan, where temperatures are projected to increase by about 7% and 8%, respectively, relative to 1975–2005. The increase in extreme heat days is greatest in the south near Almaty and Shymkent and in Mangystau province near the Caspian Sea. High temperatures can affect the performance of transmission equipment, for example, by causing disconnections, which ultimately reduces network capacity and efficiency. Greater frequency of extreme heat events can lead to chronic disruptions.

Climate hazards can also indirectly affect electricity transmission by increasing energy demand, such as through increased use of air conditioning during heat waves. Near Almaty, Shymkent, and Mangystau Province, cooling degree days are expected to increase by 260 to 270 days relative to the historical baseline. The potential impact is illustrated by the heat wave in Almaty on 15 July 2019, when temperatures above 35°C caused a surge in electricity demand and eventually a power outage.

Sources: Asian Development Bank (ADB). 2012. *Climate Risk and Adaptation in the Electric Power Sector*. Manila; Kazakhstan Electricity Grid Operating Company (KEGOC). 2019. *KEGOC Annual Report 2018*. Astana; and United Nations Development Programme (UNDP). 2018. National Adaptation Plans in Focus: Lessons from the Republic of Kazakhstan. National Adaptation Plan Global Support Programme. NAP-GSP.

Overall, extreme heat and water stress are the most significant hazards in the subregion, with all evaluated assets exposed to both hazards to some degree. For extreme heat, 26.3% of analyzed assets are rated *red flag* or *high*, while the share for water stress is 45.8% (Table 4.7). At the country level, Azerbaijan and Turkmenistan are most exposed to extreme heat, with 82.1% and 76.8% of evaluated assets, respectively, rating *red flag* or *high*, while the Kyrgyz Republic and Kazakhstan are most exposed to water stress, with 99.3% and 68.1% of evaluated assets, respectively, rated *red flag* or *high*.

Table 4.7: Percent of Assets Exposed to Climate Change and Earthquake Hazards in Central and West Asia

Sector	Red Flag	High	Medium	Low	None
	Extreme heat				
Energy	0.1	17.2	34.1	48.7	0.0
Transport	0.2	41.7	41.8	16.3	0.0
Total	**0.1**	**26.2**	**36.9**	**36.7**	**0.0**
	Water stress				
Energy	5.0	54.7	35.1	5.2	0.0
Transport	11.5	10.5	52.6	25.4	0.0
Total	**7.4**	**38.4**	**41.6**	**12.7**	**0.0**

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Table 4.7 *continued*

Sector	Red Flag	High	Medium	Low	None
	Floods				
Energy	8.6	11.3	9.1	70.6	0.5
Transport	49.1	13.5	7.3	29.1	1.1
Total	**23.5**	**12.1**	**8.4**	**55.3**	**0.7**
	Sea level rise				
Energy	1.3	0.0	0.1	0.6	98.1
Transport	2.6	0.0	2.0	2.0	93.4
Total	**1.8**	**0.0**	**0.8**	**1.1**	**96.3**
	Cyclones				
Energy	0.0	0.0	0.0	0.2	99.8
Transport	0.0	0.0	0.0	0.3	99.7
Total	**0.0**	**0.0**	**0.0**	**0.2**	**99.8**
	Earthquakes				
Energy	0.7	5.9	21.6	12.8	59.0
Transport	5.1	9.5	63.1	15.3	7.1
Total	**2.3**	**7.2**	**36.9**	**13.7**	**39.9**

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Extreme heat is a significant hazard to the transport sector, with 41.9% of assets rated *red flag* or *high*. Within the transport sector, multimodal transport is most exposed to extreme heat, with 56.3% of assets rated *red flag* or *high*. Roadway bridges and air transport are also highly exposed to extreme heat, with 41.9% and 40.5% of analyzed assets rated *red flag* or *high*, respectively (Table 4.8).

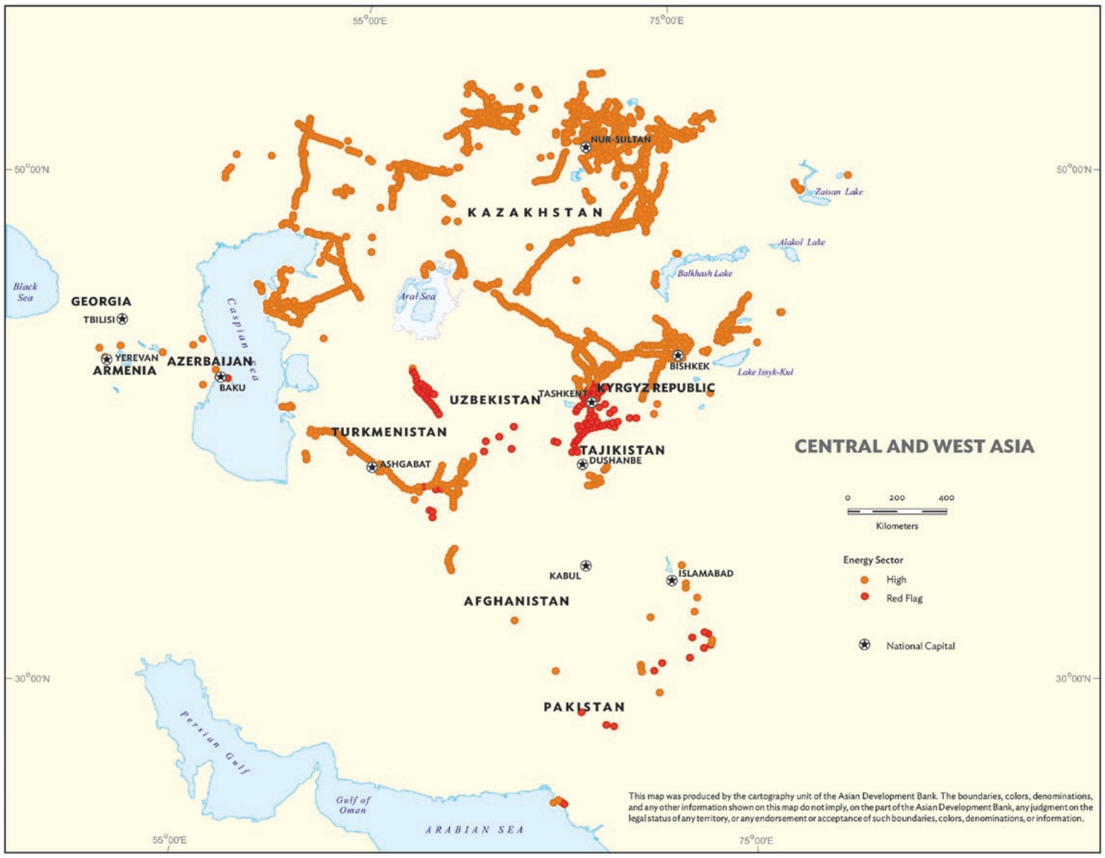
Table 4.8: Percent of Transport Assets Exposed to Extreme Heat in Central and West Asia

	Subsector	Red Flag	High	Medium	Low	None
Extreme heat	Air transport	3.9	36.6	40.9	18.7	0.0
	Multimodal transport	12.5	43.8	18.8	25.0	0.0
	Roadway bridges	0.0	41.9	41.9	16.2	0.0

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Water stress is a significant hazard in the energy sector, with 59.6% of assets included in the study rated *red flag* or *high* (Map 4.2). Energy generation assets are the most exposed, as water stress can lead to poor performance of hydropower generation as well as conventional power generation, which requires a large amount of water for cooling purposes.

Map 4.2: Energy Assets Rated *Red Flag* or *High* for Water Stress in Central and West Asia



Note: This report was prepared based on information available for Afghanistan as of 31 July 2021.
Source: ADB estimates.

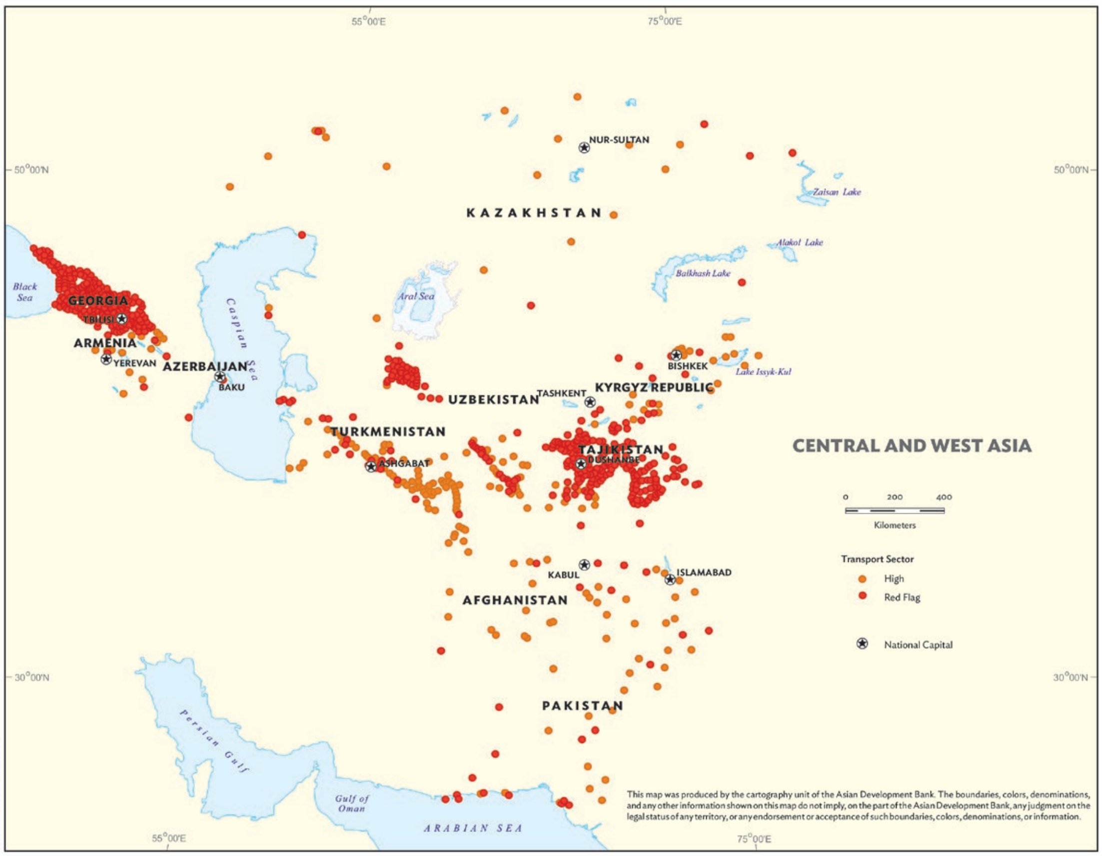
In addition, the analysis shows that flooding is a significant hazard in the region, especially in the transport sector, where 62.5% of analyzed assets rated *red flag* or *high*. Within the transport sector, ports and roadway bridges are particularly exposed, with 75.0% and 63.7% of assets included in the study rated *red flag* or *high*, respectively (Table 4.9 and Map 4.3).

Table 4.9: Percent of Transport Assets Exposed to Flood in Central and West Asia

	Subsector	Red Flag	High	Medium	Low	None
Floods	Air transport	16.7	19.8	11.3	51.4	0.8
	Ports	68.8	6.3	0.0	25.0	0.0
	Roadway bridges	50.5	13.2	7.2	28.1	1.1

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Map 4.3: Roadway Bridges Rated *Red Flag* or *High* for Flood in Central and West Asia



Note: This report was prepared based on information available for Afghanistan as of 31 July 2021.
Source: ADB estimates.

In terms of exposure to earthquakes, 60.1% of the analyzed transport and energy assets are exposed, with 9.5% rated *red flag* or *high*. At the country level, Armenia and the Kyrgyz Republic are particularly exposed. In Armenia, 100% of the analyzed assets in conventional energy generation, oil and gas transmission, and electricity transmission are rated *red flag* or *high*; while in the Kyrgyz Republic, of the assets included in the study, 90.5% in electricity transmission and 66.7% in energy generation (conventional and hydropower) are rated *red flag* or *high*. In both countries, earthquakes also pose a significant hazard to air transport infrastructure, with 63.6% of assets analyzed in Armenia and 58.3% of the assets analyzed in the Kyrgyz Republic rated *red flag* or *high*.

Furthermore, the analysis shows that assets in all economies assessed have significant exposure to more than one hazard. Over 60% of all analyzed assets in the subregion are exposed to more than three hazards. In Georgia, a significant percentage of the evaluated assets are rated *red flag* or *high* for extreme heat, floods, and earthquakes. In the transport sector, the *red flag* and *high* ratings are given to 45.9% of assets for extreme heat, 73.0% of assets for floods, and 26.2% of assets for earthquakes. In the energy sector, the *red flag* and *high* ratings are given to 59.3% of assets for extreme heat, 29.4% assets for floods, and 28.0% of assets for earthquakes. More details on the exposure of Georgia's energy sector to multiple hazards are provided in Box 4.2.

Box 4.2: Hazards to the Energy Sector in Georgia

In Georgia, energy transmission infrastructure runs along major riverways and is highly exposed to flooding—the sections along the Rioni River (and the country's main "east-to-west" highway) are particularly at risk. North of the Rioni river, the city of Kutaisi—one of Georgia's main economic hubs—is primarily electrified by large hydroelectric dams, which are exposed to potentially damaging earthquakes, registering 8 out of 10 on the Modified Mercalli Intensity Scale. In the east, near the capital city (Tbilisi), water supply is projected to decline by about 24% by 2040 under a business-as-usual scenario, which in turn could affect hydropower productivity.

At a national level, Georgia generates about 75%–90% of its electricity from hydropower, and more projects are planned as the country pursues alternatives to fossil fuel imports (IHA 2016). Of the 100 new hydropower plants planned, nearly 25 are in Upper Svaneti, including a potential Asian Development Bank-funded project, the Nenskra hydropower plant (280 megawatts). The area is seismically active, and several areas are located in regions that have an earthquake susceptibility ranking 60 to 70 on the Modified Mercalli Scale.

Much of the inflow for hydropower comes from upland glaciers and snowmelt in the Greater Caucasus Mountains, where runoff is expected to decrease by 13% by 2100. In the short term, ongoing glacial melt could lead to an increase in runoff (Shahgedanova et al. 2014). Georgia's reliance on glacier melt makes runoff levels highly sensitive to air temperatures and increases the probability and length of flood periods. In the upland portions of the Nenskra River, for example, runoff is expected to decrease by 20% by 2040 (Luck, Landis, and Gassert 2015), and warmer spring temperatures could exacerbate the dangers of landslides and flooding for downstream communities. During the 2000 drought, high spring temperatures melted much of the country's snowpack. Many cities had no electricity, and the capital, Tbilisi, had only 2 hours of electricity on some days. The threat of drought and unreliable runoff levels could also spell trouble for the agriculture sector, which accounts for much of the country's production and 52% of its jobs (FAO 2019).

Sources: Luck, M., M. Landis, and F. Gassert. 2015. Aqueduct Water Stress Projections: Decadal Projections of Water Supply and Demand Using CMIP5 GCMs. Washington, DC: World Resources Institute; and Food and Agriculture Organization (FAO). 2019. Georgia at a Glance. FAO: Tbilisi.

4.2 East Asia

Of the 5,262 assets included in the analysis in the East Asia region, 4,562 assets are in the energy sector and 700 assets are in the transport sector. At the economy level, 2,057 assets are in Mongolia and 3,205 assets are in the People's Republic of China (PRC). The analysis shows that 76.6% of assets in East Asia are exposed to more than three hazards, while the proportion in the PRC rises to 89.5% (Table 4.1).

Water stress is a significant hazard in East Asia, with 42.2% of evaluated assets rated *red flag* or *high*. This is particularly true in the transport sector, where 45.5% of assets are rated *red flag* or *high* (Table 4.10). In the PRC, most of these assets are located in the northern part of the country.

Table 4.10: Percent of Assets Exposed to Climate Change and Earthquake Hazards in East Asia

Sector	Red Flag	High	Medium	Low	None
	Extreme heat				
Energy	0.0	6.3	19.7	74.0	0.0
Transport	0.0	4.7	10.4	84.9	0.0
Total	**0.0**	**6.1**	**18.5**	**75.4**	**0.0**
	Water stress				
Energy	6.9	34.8	37.9	20.4	0.0
Transport	4.6	40.9	42.1	12.4	0.0
Total	**6.6**	**35.6**	**38.5**	**19.3**	**0.0**
	Floods				
Energy	16.9	10.3	5.6	66.8	0.4
Transport	46.7	18.0	6.4	28.9	0.0
Total	**20.9**	**11.3**	**5.7**	**61.7**	**0.3**
	Sea level rise				
Energy	1.6	0.0	1.4	1.6	95.4
Transport	3.1	0.1	1.9	2.4	92.4
Total	**1.8**	**0.0**	**1.5**	**1.7**	**95.0**
	Cyclones				
Energy	4.4	1.1	3.1	16.1	75.3
Transport	4.4	0.7	4.0	12.4	78.4
Total	**4.4**	**1.1**	**3.2**	**15.6**	**75.8**
	Earthquakes				
Energy	1.9	3.1	26.1	41.6	27.3
Transport	1.4	2.6	28.6	33.3	34.1
Total	**1.9**	**3.0**	**26.4**	**40.5**	**28.2**

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Water stress is particularly significant for the renewable energy generation subsector, with hazard ratings of *red flag* or *high* for approximately 72.9% of the assets evaluated (Table 4.11).

Table 4.11: Percent of Energy Assets Exposed to Water Stress in East Asia

	Subsector	Red Flag	High	Medium	Low	None
Water stress	Conventional energy generation	16.5	39.7	20.4	23.4	0.0
	Hydropower generation	0.9	15.2	20.5	63.3	0.0
	Renewable energy generation	6.5	66.3	16.8	10.3	0.0
	Oil and gas transmission	14.2	32.4	21.5	31.9	0.0
	Electricity transmission	0.0	28.5	70.8	0.7	0.0

Source: ADB estimates.

Flooding is another significant hazard in East Asia. This is especially true in the transport sector, where 64.7% of analyzed assets rated *red flag* or *high*. Within the transport sector, roadway bridges in particular are highly exposed, with 60.9% of assets rated *red flag* and another 22.6% rated *high*. Rail transport is also highly exposed, with 61.6% of assets rated *red flag* or *high* (Table 4.12).

Table 4.12: Percent of Transport Assets Exposed to Floods in East Asia

	Subsector	Red Flag	High	Medium	Low	None
Floods	Air transport	12.1	1.5	13.6	72.7	0.0
	Rail transport (nonurban)	30.8	30.8	0.0	38.5	0.0
	Multimodal logistics	29.3	10.3	3.4	56.9	0.0
	Roadway bridges	60.9	22.6	6.5	10.1	0.0
	Highway and street construction	15.5	13.8	5.2	65.5	0.0

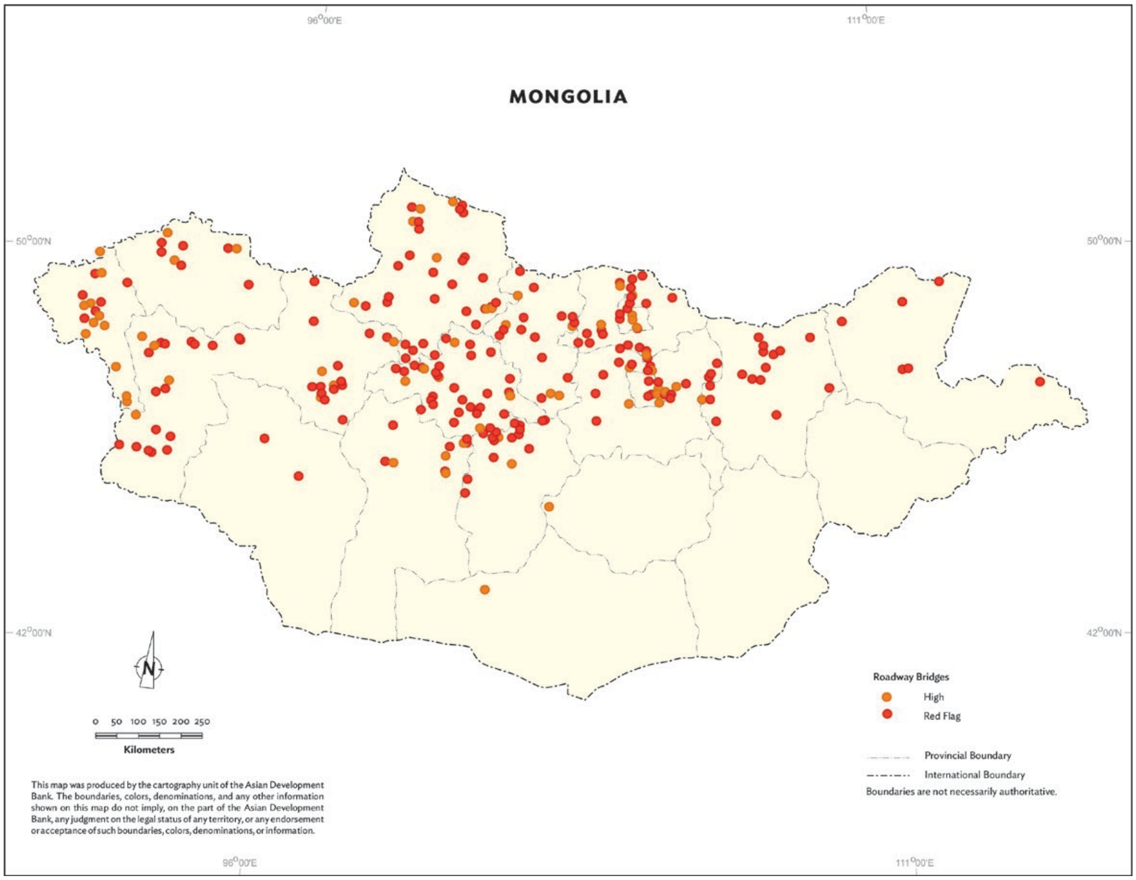
Source: ADB estimates.

At the economy level, of the assets evaluated, 36.8% of transport assets in the PRC and 79.5% of transport assets in Mongolia are rated *red flag* or *high* for flood exposure. More details on the importance of transport infrastructure to Mongolia's economic development and its exposure are provided in Box 4.3.

Box 4.3: Exposure of Transport Infrastructure in Mongolia

The exposure of the transport sector to climate change hazards is particularly challenging in Mongolia, a landlocked country. A few road and rail connections to the People's Republic of China serve as important corridors for the movement of goods and people. Important mines are distributed throughout the country, and rail connectivity between mines and border-crossing points is limited, with only copper and iron ore mines in the north–central part of the country linked to border-crossing points by rail. Since mine-to-border rail connectivity is inadequate, most mineral exports are transported by road.

Map 4.4: Bridges Rated *Red Flag* or *High* in Mongolia



Source: ADB estimates.

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Box 4.3 *continued*

However, the road network is underdeveloped, and many of the roads leading to the border-crossing points are not paved. The road and rail assets that support the movement of international freight suffer from deterioration, limited investment, and inefficiencies that contribute to higher costs and longer transport times, ultimately undermining the competitiveness of Mongolian exports.

Although the impact on these transport systems is not well documented, extreme events have destroyed, damaged, and/or blocked roads in Mongolia, with snow and dust storms, flooding, and strong winds posing particular threats. Increasing intensity and incidence of permafrost melting, warmer soil temperatures, and more frequent storms can cause roads to collapse, while stronger storm intensity can cause the overflow of road drainage assets and nearby drainage systems (ADB 2017d). This report shows that bridges are significantly exposed to floods—83.4% of assets are rated *red flag* or *high*. In addition, the unpaved nature of roadways connecting to border-crossing points makes them particularly susceptible to flood impacts. For railways, heavy rains and flooding can inundate railways, as illustrated by the example of the 2018 inundation of the southern section of the rail line near the People's Republic of China border, which resulted in the derailment of a passenger train (Unurzul 2018).

Source: Authors.

In Mongolia, none of the assessed assets are exposed to sea level rise or cyclones. In the PRC, 39.8% of all evaluated assets are exposed to cyclones, and 8.2% of assets are exposed to sea level rise. The assessment shows that in the transport sector, 62.4% of the assets included in the study are exposed to cyclones and 21.9% are exposed to sea level rise. Some low-lying areas are particularly exposed, such as the Pearl River Delta, where 60 of the 100 energy production and logistics hubs evaluated are susceptible to rising sea levels, cyclones, and extreme rainfall events, as explained in Box 4.4.

Box 4.4: Transport Assets in the Pearl River Delta—Exposure to Multiple Climate Hazards

The Pearl River Delta region, an economic center that features prominently in the economy of the People's Republic of China (PRC), is a critical component of global and regional supply chains. The region includes industrial and financial hubs such as Hong Kong, China; Macau, China; Guangzhou; Foshan; and Shenzhen. The establishment of the Shenzhen and Zhuhai special economic zones in 1980 led to unprecedented growth and development in the Pearl River Delta region. The rapid development and urbanization that accompanied a soaring population and booming economy led to the removal of natural barriers and defenses such as mangroves and coastal wetlands and their replacement with landfills and concrete in this low-lying region (Kimmelman 2017).

This region is projected to experience an increase in intense precipitation, as measured by the maximum precipitation over 5 days per year, of about 116% by 2040 relative to the 1975–2005 baseline period. This change suggests that the Pearl River Delta is likely to experience a rise in extreme rainfall-induced flooding. The low-lying region is also considered one of the most vulnerable to sea level rise in the PRC (Canfei and Yang 2011).

Of the 14 ports evaluated in the Pearl River Delta region, 6 are already exposed to coastal flooding associated with sea level rise, tidal surges, and storm surges, with site-level inundation occurring at least 1-in-10 years, or 10% chance per year. The entire region is low-lying, so flooding from extreme rainfall and storm surge is a major

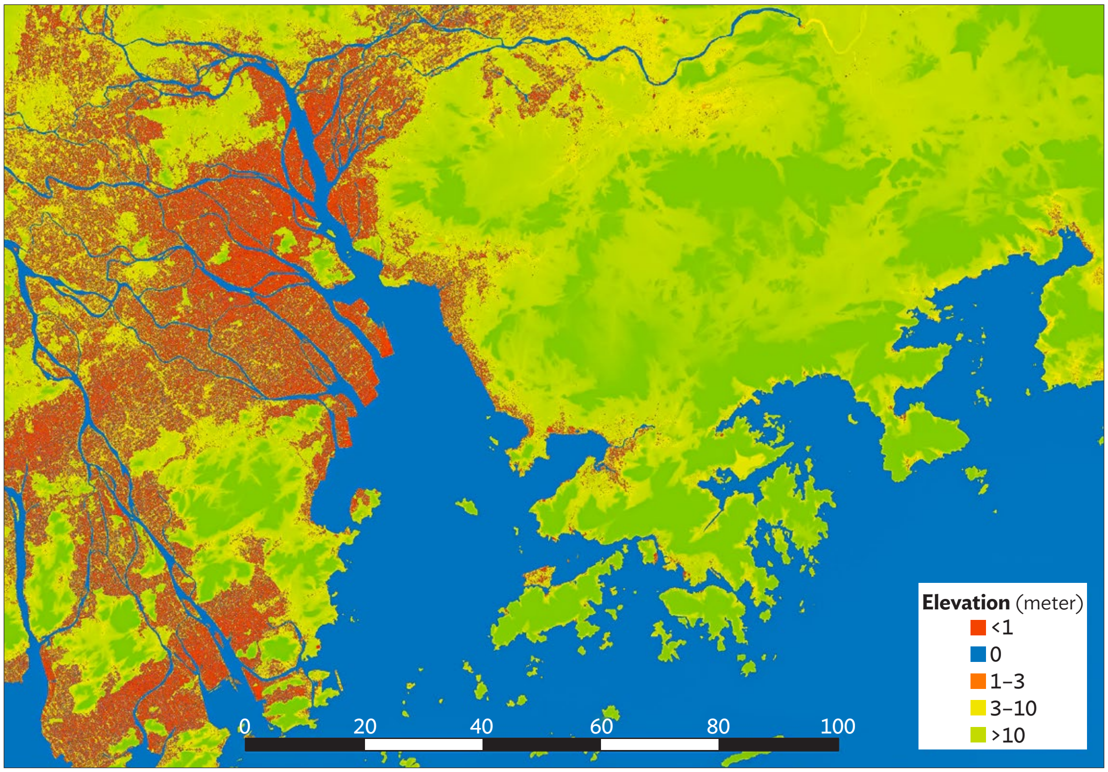
continued on next page

Box 4.4 *continued*

concern. One study estimates that sea level rise will rise 0.29 meters from 1990 levels by 2030, taking into account all factors including ground subsidence (Huang, Zong, and Zhang 2004). With a sea level rise of only 0.3 meters, more than 1,100 square kilometers of land in the delta region is expected to be inundated at high tide (Canfei and Yang 2011). By the end of the century, sea level rise in the delta region will range from 0.71 meters under representative concentration pathway (RCP) 4.5 to 1 meter under RCP8.5, the high emissions scenario. When factoring in land subsidence, the approximate extent of sea level rise under the high emissions scenario will be about 1.5 meters by 2100 (Xia et al. 2015), covering much of the red area in the map. Even in the best-case scenario, sea level will rise enough to threaten many low-lying transport infrastructure and disrupt regional and global supply chains. While there are numerous alternate transport routes and types, movement throughout the region will likely be impeded if multiple key transport modes and corridors are affected.

The delta is also highly exposed to cyclones, with at least 42 tropical cyclones recorded between 1980 and 2016. Cyclones such as Typhoon Hato in August 2017 and Typhoon Mangkhut in September 2018 caused costly and extensive damage in the region. In Guangdong province, Typhoon Mangkhut affected 458 townships in 14 cities and caused CNY2.37 billion ($337 million) in storm-surge related damages (Xia et al. 2015) and CNY4.25 billion ($604 million) in direct economic losses (China National Emergency Broadcasting 2018). The intensity of typhoons affecting land in this region has increased by 12%–15% since the 1970s, with Category 4 and 5 typhoons making landfall much more frequently (Mei and Xie 2016). The increase in water vapor associated with a warmer atmosphere

Map 4.5: Elevation of the Red River Delta



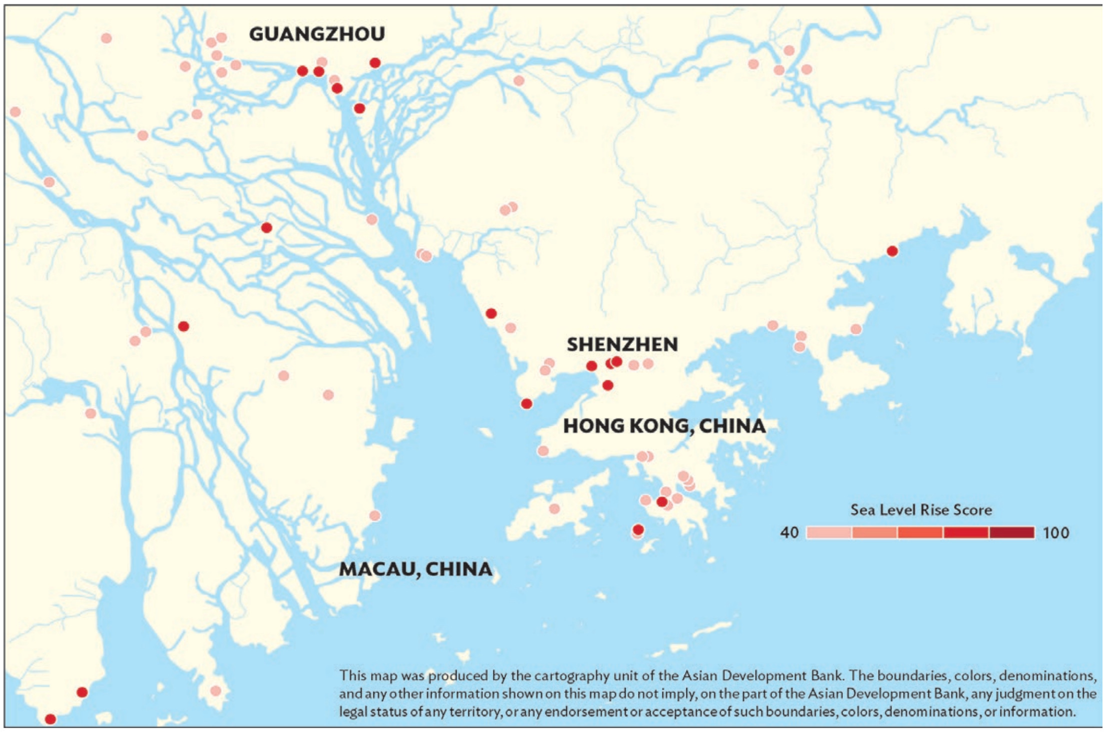
Source: ADB estimates.

continued on next page

Box 4.4 *continued*

is expected to lead to tropical cyclones with higher wind speeds, bringing more intense precipitation and increased flood risk. While some studies suggest that tropical cyclone paths in the western Pacific Ocean may shift northward on average, resulting in lower overall frequency in the future (Kossin, Emanuel, and Camargo 2016), projected changes in tropical cyclone tracks are the subject of ongoing research and remain highly uncertain.

Map 4.6: Sea Level Rise Exposure of Transport Assets



Source: ADB estimates.

Source: Authors.

4.3 The Pacific

The hazard exposure analysis for the Pacific included 921 infrastructure assets: 877 in the transport sector and 44 in the energy sector. The three largest Pacific developing member countries, Papua New Guinea (PNG), Timor-Leste,[16] and Fiji, dominated the analysis with 494, 314, and 29 assets, respectively, while 84 assets from the 12 smaller island countries were included (Table 4.1).

The analysis shows that the Pacific subregion has one of the highest levels of exposure to multiple hazards in the region, with 73.6% of the assets analyzed exposed to more than three hazards and more than a quarter of the assets exposed to six hazards (Table 4.1). Compared with other regions in Asia and the Pacific, a significant proportion of assets in the Pacific are exposed[17] to sea level rise (39.8% compared with 7.3% in the rest of the region). Sea level rise poses a greater threat to the transport sector than to the energy sector, with 5.5% of assets rated *red flag* (Table 4.13). One reason for this is that some transport infrastructure, such as seaports, is located near the coast.

Table 4.13: Percent of Transport Assets Exposed to Climate Change and Earthquake Hazards in the Pacific

Sector	Red Flag	High	Medium	Low	None
	Extreme heat				
Energy	20.5	36.4	34.1	9.1	0.0
Transport	33.5	30.8	16.0	19.7	0.0
Total	**32.9**	**31.1**	**16.8**	**19.2**	**0.0**
	Water stress				
Energy	0.0	34.1	11.4	54.5	0.0
Transport	0.0	14.6	27.4	57.9	0.0
Total	**0.0**	**15.5**	**26.6**	**57.8**	**0.0**
	Floods				
Energy	25.0	4.5	0.0	68.2	2.3
Transport	41.2	8.6	1.8	44.4	4.1
Total	**40.4**	**8.4**	**1.7**	**45.5**	**4.0**
	Sea level rise				
Energy	0.0	0.0	9.1	52.3	38.6
Transport	5.5	0.0	12.4	20.9	61.2
Total	**5.2**	**0.0**	**12.3**	**22.4**	**60.2**
	Cyclones				
Energy	0.0	0.0	0.0	59.1	40.9
Transport	0.1	0.1	1.5	48.6	49.7
Total	**0.1**	**0.1**	**1.4**	**49.1**	**49.3**
	Earthquakes				
Energy	6.8	6.8	68.2	18.2	0.0
Transport	9.6	21.7	59.2	7.4	2.2
Total	**9.4**	**21.0**	**59.6**	**7.9**	**2.1**

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

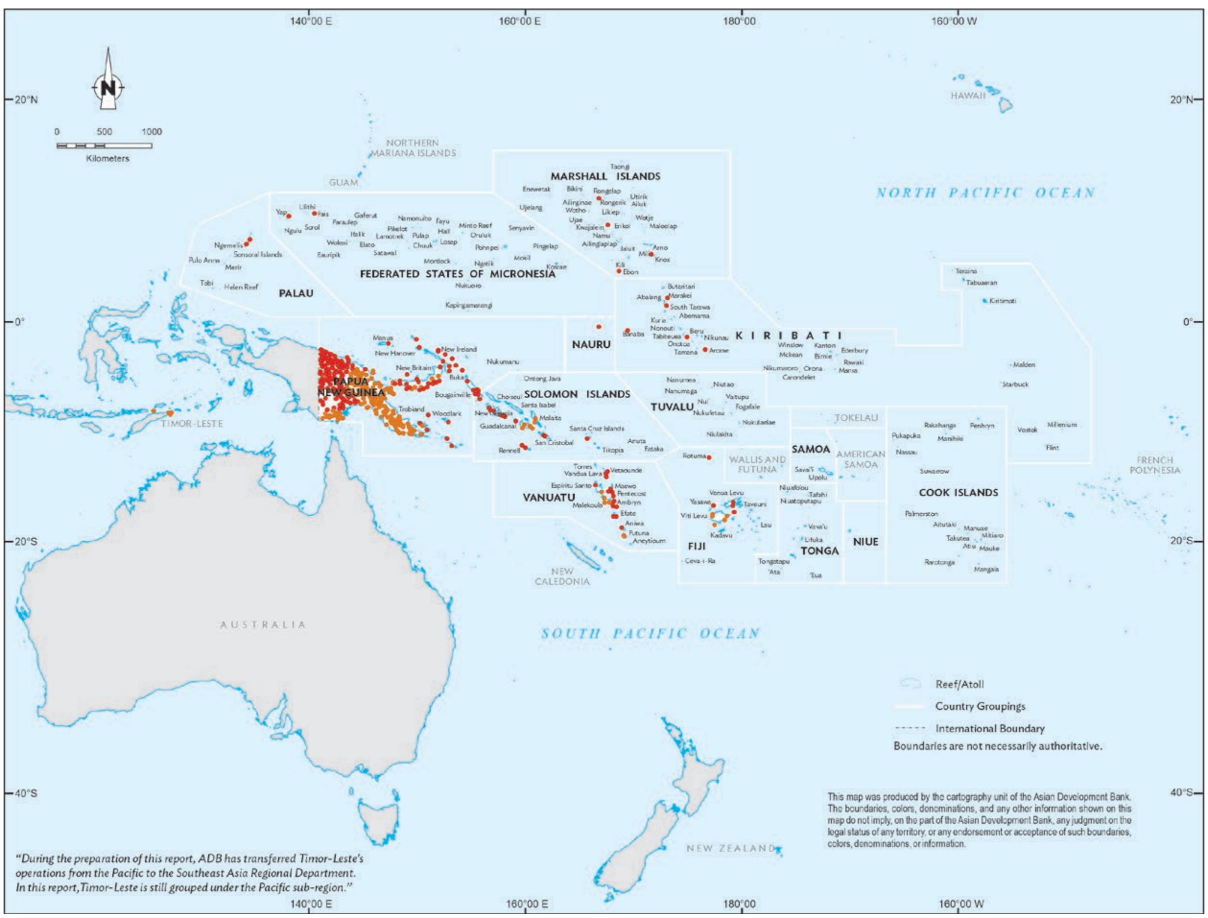
16 At the time of writing, ADB had moved its Timor-Leste operations to the Southeast Asia Department; however, in this report, Timor-Leste's results are included under the Pacific subregion.

17 Rating of *red flag*, *high*, *medium*, or *low*.

In the small Pacific island states, 100.0% of the assets analyzed are exposed to sea level rise, compared to 33.8% in the three larger states. This shows how severe sea level rise is for small Pacific island states. This can be partly explained by the limited land mass of these states, which forces many assets to be built near the coast, as sea level rise is only relevant for assets located near the coast (for this analysis < 5 km).

The analysis shows that extreme heat is a significant hazard in the subregion, with 64.3% of the evaluated assets in the transport sector (Map 4.7) and 56.8% of evaluated assets in the energy sector rated *red flag* or *high* (Table 4.13). In addition, in 12 of the 14 Pacific countries analyzed, extreme heat is rated *red flag* or *high* for more than 95% of the assets evaluated in the transport sector. For example, of the 479 evaluated transport assets in PNG, 221 are rated *red flag*, and 235 are rated *high*. Extreme heat could lead to rapid depreciation of paved roads and runways and significantly higher maintenance costs. In many Pacific island countries, runways are an important link for access to external resources.

Map 4.7: Transport Assets Rated *Red Flag* or *High* for Extreme Heat in the Pacific



Source: ADB estimates.

In addition, flooding is a major hazard in the Pacific. In the transport sector, 41.2% of evaluated assets are rated *red flag*, while in the energy sector the share is 25.0%. Each type of flooding considered in this analysis—riverine, rainfall, cyclone, and coastal—could render a transport node unusable during an event, or chronic in the case of sea level rise, which could bring the entire network to a halt if few or no alternative trade and commute routes exist. Table 4.14 shows that 59.9% of the roadway bridges are rated *red flag* and another 13.2% are rated *high* for floods. The high exposure of road infrastructure and air and maritime ports to flooding and sea level rise in Fiji and PNG may create a potential risk, as economic growth in these countries depends on maintaining links to major growth centers in the rest of the Asia and Pacific region (Box 4.5).

Table 4.14: Percent of Transport Assets Exposed to Floods in the Pacific

	Subsector	Red Flag	High	Medium	Low	None
Floods	Air transport	33.2	6.4	0.2	55.1	5.1
	Multimodal logistics	16.7	4.8	0.0	59.5	19.0
	Roadway bridges	59.9	13.2	5.2	21.6	0.0

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Box 4.5: Inland and Coastal Flooding Risk for the Ports of Papua New Guinea

Airports, small airstrips, and maritime ports across Papua New Guinea (PNG) enable movement within the country and connectivity to the rest of the region and the world. PNG's transport infrastructure is primarily exposed to coastal hazards, earthquakes, and accelerated changes in extreme rainfall intensity. Flooding from extreme precipitation events poses the greatest risk, particularly to airports.

Airports throughout PNG provide access to the many small, isolated islands of the Bismarck Archipelago and to remote areas of the country, especially given the limited coverage of the road network. However, moderate to heavy precipitation could saturate the ground of the often unpaved runways or stretches of cleared forest, making landings and takeoffs difficult, especially for heavier aircraft. The most extreme flooding events could inundate the runways of more developed airports, causing delays or infrastructure damage. Of the 464 airports and airstrips assessed in PNG, 162 fall into the high-risk category for floods, and of the 15 ports evaluated, 5 are categorized as *red flag*. This analysis indicates that they are already regularly exposed to flooding from extreme precipitation and are likely to be at heightened risk by 2040. These facilities are located in low-lying areas, which amplifies the risk of flooding during heavy precipitation events.

Sea level rise is another concern, particularly for PNG's maritime ports. Three ports on New Guinea (Wewak, Salamaua, and Oro Bay), two on New Britain Island (Rabual and Kimbe), and one on Bougainville Island (Kieta) were regularly subjected to 1-in-10-year coastal flooding events during the historical baseline period of 1975–2005, and are expected to face continued exposure in the coming decades. Increased inundation will have considerable impact on surrounding infrastructure such as terminals and access roadways, and potentially disrupt port operations.

Source: Authors.

The Pacific subregion has the highest exposure of evaluated assets to earthquakes—31.2% of transport assets analyzed in this study and 13.6% of energy assets analyzed are rated *red flag* or *high*. Overall, the analysis shows that in the three larger states, almost all analyzed assets are exposed to earthquake hazard (99.9%), while in the smaller countries, 78.6% of analyzed assets are exposed.

4.4 South Asia

The analysis includes 2,345 assets from the South Asia region, of which 2,041 are in the energy sector and 304 in the transport sector. Bangladesh and India dominate the analysis with 1,124 and 1,060 assets, respectively. The analysis shows that 95.1% of the analyzed assets in the region are exposed to more than three hazards. In particular, 89.9% of the assets in Bangladesh are exposed to five or more hazards (Table 4.1).

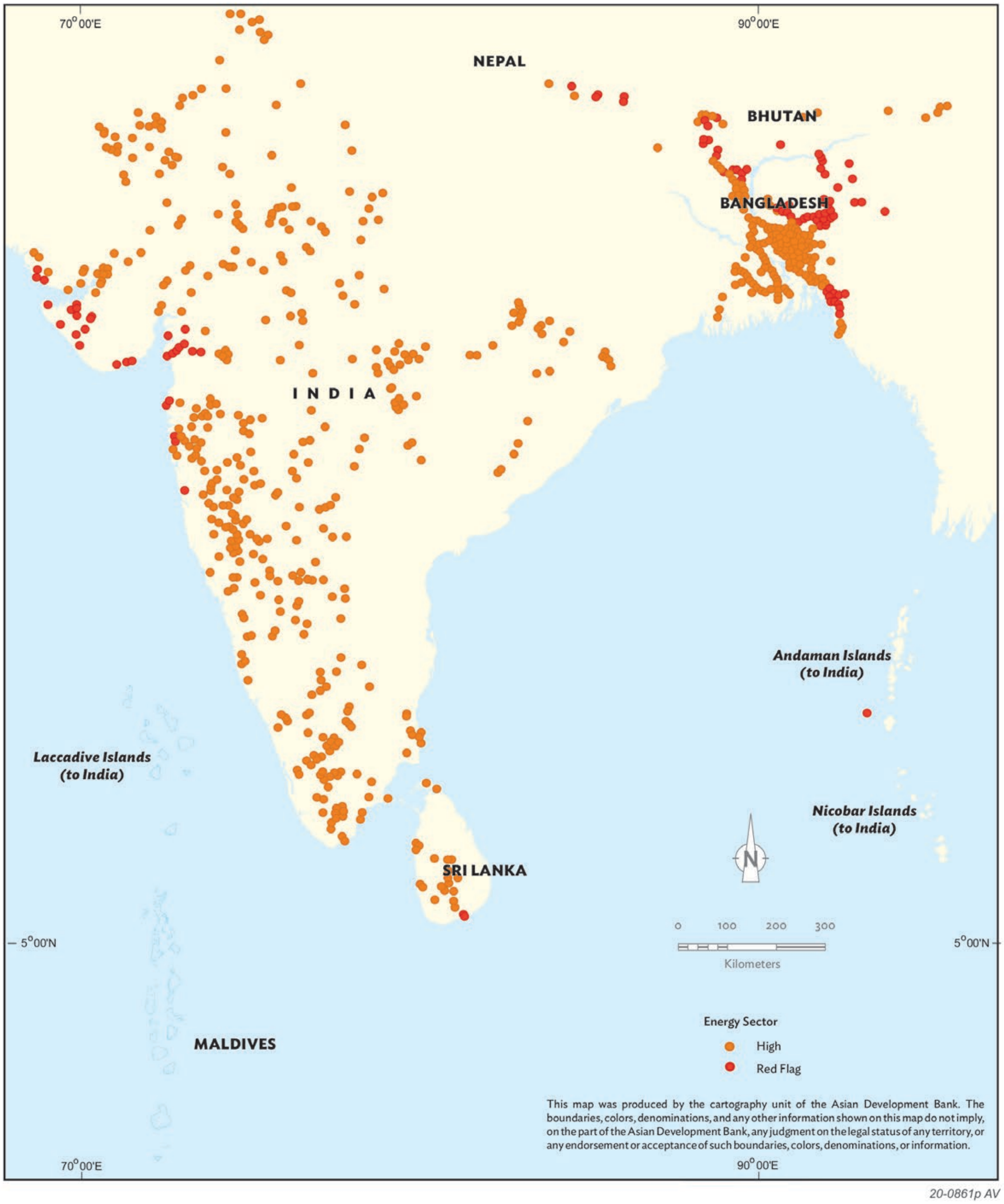
The analysis shows that extreme heat is a significant hazard in the subregion, with 72.3% of the analyzed assets rated *red flag* or *high* (Table 4.15). While a significant share of assets in both sectors are exposed to extreme heat, the share of energy assets is particularly high at 73.7% (Map 4.8).

Table 4.15: Percent of Assets Exposed to Sources of Hazards

Sector	Red Flag	High	Medium	Low	None
	Extreme heat				
Energy	12.6	61.0	24.9	1.4	0.0
Transport	13.5	49.7	32.6	4.3	0.0
Total	**12.8**	**59.6**	**25.9**	**1.8**	**0.0**
	Water stress				
Energy	2.1	19.2	15.0	63.5	0.0
Transport	4.3	28.6	22.4	44.4	0.0
Total	**2.3**	**20.4**	**15.9**	**61.0**	**0.0**
	Floods				
Energy	27.8	8.7	6.4	57.1	0.0
Transport	18.4	10.5	6.6	64.5	0.0
Total	**26.6**	**9.0**	**6.4**	**58.0**	**0.0**
	Sea level rise				
Energy	1.6	0.0	3.9	1.5	93.0
Transport	8.6	0.0	7.2	3.3	80.9
Total	**2.5**	**0.0**	**4.3**	**1.7**	**91.5**
	Cyclones				
Energy	0.0	0.0	6.3	60.7	33.0
Transport	0.0	0.0	2.0	32.6	65.5
Total	**0.0**	**0.0**	**5.7**	**57.1**	**37.2**
	Earthquakes				
Energy	2.4	4.4	58.2	22.1	13.0
Transport	7.9	13.8	53.9	5.9	18.4
Total	**3.1**	**5.6**	**57.6**	**20.0**	**13.7**

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

Map 4.8: Energy Assets Rated *Red Flag* or *High* for Extreme Heat in South Asia



Source: ADB estimates.

A closer look at the energy sector shows that extreme heat is a significant source of hazard in all major subsectors (Table 4.16). In the renewable energy generation subsector, 97.5% of evaluated assets are rated *red flag* or *high*, compared with 81.4% for oil and gas transmission and 69.4% for conventional generation.

Table 4.16: Percent of Energy Assets Exposed to Extreme Heat in South Asia

	Subsector	Red Flag	High	Medium	Low	None
Extreme heat	Conventional energy generation	10.4	60.4	28.9	0.3	0.0
	Hydropower generation	8.6	56.8	23.0	11.5	0.0
	Renewable energy generation	7.0	90.5	2.5	0.0	0.0
	Oil and gas transmission	36.1	45.4	18.6	0.0	0.0
	Electricity transmission	13.7	55.8	30.6	0.0	0.0

Source: ADB estimates.

Energy infrastructure in the region is projected to increase by an average of about 500 cooling degree days by 2040—a proxy for measuring potential increase in electricity demand—compared with the 1975–2005 baseline period, resulting in an increase in electricity usage and associated costs. At least 150 coal and oil refineries in the region are likely to experience significant reductions in water cycle efficiency due to the projected large increase in cooling degree days.

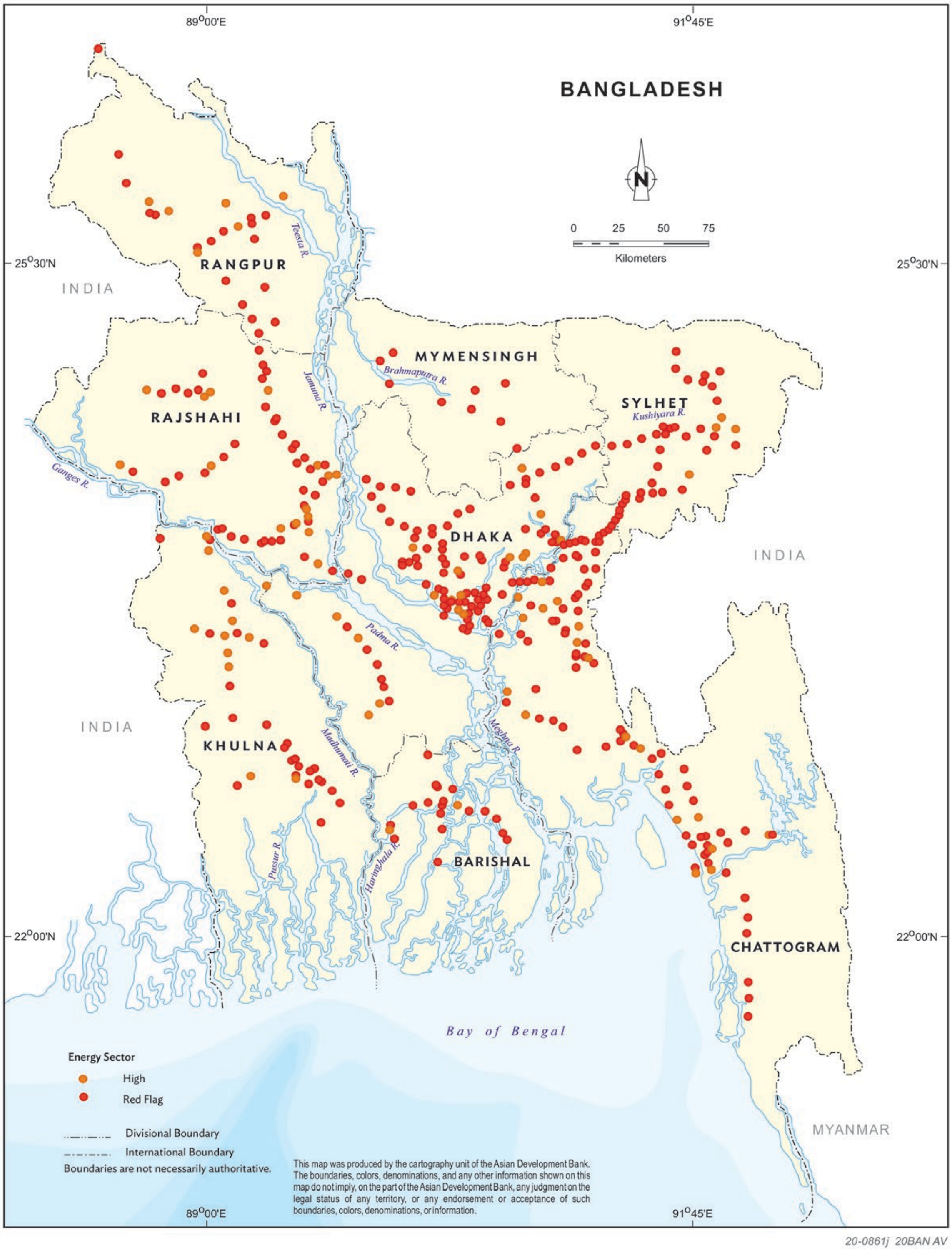
Although energy systems are generally designed to consider some climate hazards in their operations and planning, emerging climate conditions may place additional stress on existing systems and further increase the potential for disruption. For instance, rising temperatures can lead to surges in energy demand, higher electrical energy losses, and line sag that can add to the risk of fire ignition. In addition, water stress is likely to reduce hydropower production in South Asia.

In addition to extreme heat, 36.6% of the evaluated assets in the energy sector are rated *high* and *red flag* for flood hazards. In Bangladesh, 14.4% and 56.4% of the 1,101 energy assets analyzed are rated *red flag* or *high* for extreme heat, respectively (Map 4.9), and more than half of the electricity transmission lines are exposed to some degree of riverine flooding.

Inland fossil fuel production facilities tend to be prone to inland flooding, while distribution and transmission networks are exposed to nearly all climate hazards, increasing the likelihood of disruptions of services, which depend on the continued operability of each node in the energy supply chain.

The assessment shows that Bangladesh, India, and Sri Lanka are also exposed to sea level rise (8.9% of evaluated assets) and cyclones (with 65.6% of evaluated assets). It is important to reiterate that coastal flooding in areas more than 5 km inland from the coast is not included in this study. Finally, earthquakes are also a significant hazard in the region, especially in Nepal where about 40% of the evaluated transport assets are rated *red flag* or *high*. The exposure of Nepal's airports to earthquakes is discussed in Box 4.6.

Map 4.9: Energy Assets Rated *Red Flag* or *High* for Extreme Heat in Bangladesh



Source: ADB estimates.

Box 4.6: Exposure of Nepal's Airports to Earthquakes

Airports are critical to economic development and rural–urban connectivity in Nepal, where mountainous terrain can isolate communities. Airports provide vital connectivity to the outside world, underpin the key economic sector of tourism, and enable the flow of humanitarian aid during and after disasters. Of the 78 airports evaluated in Nepal—most located in the western and central parts of the country—23 are rated *red flag* or *high* and are susceptible to shaking that would damage most poorly built buildings, according to the Modified Mercalli Intensity Scale (MMI). Since 1923, western Nepal has been hit by two earthquakes with a magnitude of 6.0 or greater in 1966 and 1980. Airports in these regions, including those in Bajhang, Silgadhi, and Darchula districts, are exposed to seismic events. Damage to airports in this area can restrict access to rural western Nepal.

Kathmandu's main airport, Tribhuvan International Airport, is located in the east of the city. The 2015 earthquake had a shaking intensity of about 6.8 on the MMI scale, which can cause slight to moderate damage even to well-built buildings. The airport had to be closed due to damage to the runway. Such closures can prevent humanitarian aid from reaching affected areas after a disaster. In 1988 and 2015, six earthquakes with a magnitude greater than 6.0 and their aftershocks occurred in the central and eastern parts of Nepal. The airport of Nepal's second largest city, Biratnagar, as well as the nearby airport in Rajbiraj, were exposed to quakes with a magnitude of more than 7.0 on the MMI scale. Given the proximity to Kathmandu and growing tourism, damage to airports in this region will have an impact on the broader economy of the region.

Nepal has made significant progress in disaster risk management following the 2015 earthquake, which exposed Nepal's vulnerability and highlighted the need to improve resilience. In 2017, the Disaster Risk Reduction and Management Act was passed, establishing the National Disaster Risk Reduction and Management Authority and proposing a multitiered institutional structure for disaster risk reduction and management at the national, provincial, district, and local levels. In 2017, the National Disaster Risk Reduction Policy and Strategic Action Plan 2017–2030 was finalized. The plan identifies strategies and priorities, including the need for interagency coordination for multi-hazard risk assessment, and promotes public and private investment in resilience building.

Sources: Authors.

4.5 Southeast Asia

The analysis for Southeast Asia covers a total of 6,268 assets, of which 2,137 are in the energy sector and 4,131 in the transport sector. Indonesia and Myanmar dominate the analysis with a combined 5,347 assets. A multi-hazard analysis reveals that Southeast Asian countries have one of the highest levels of exposure to multiple hazards in the region—95.8% of the assets analyzed are exposed to more than three hazards, while 38.8% are exposed to 5 or more hazards (Table 4.1).

Flooding is a significant risk in the subregion, with 57.3% of assets in the transport sector and 37.0% of assets in the energy sector rated *red flag* (Table 4.17). Within the transport sector, roadway bridges are highly exposed, with 60.5% of evaluated assets rated *red flag* and another 8.8% rated *high*. Air transport is also highly exposed, with 52.1% of assets included in the study rated *red flag* or *high* (Table 4.18).

Table 4.17: Percent of Assets Exposed to Sources of Hazards in Southeast Asia

Sector	Red Flag	High	Medium	Low	None
	Extreme heat				
Energy	26.5	43.5	29.4	0.5	0.0
Transport	8.5	40.5	50.7	0.3	0.0
Total	**14.6**	**41.5**	**43.5**	**0.4**	**0.0**
	Water stress				
Energy	0.2	6.4	21.0	58.9	0.0
Transport	0.1	2.0	5.9	52.5	0.0
Total	**0.1**	**3.5**	**11.0**	**54.7**	**0.0**
	Floods				
Energy	37.0	7.9	1.5	53.6	0.0
Transport	57.3	9.0	0.8	33.0	0.0
Total	**50.4**	**8.6**	**1.0**	**40.0**	**0.0**
	Sea level rise				
Energy	2.3	0	5.3	8.5	83.9
Transport	5.8	0.1	8.9	3.4	81.8
Total	**4.6**	**0.1**	**7.7**	**5.2**	**82.5**
	Cyclones				
Energy	4.9	3.4	3.6	31.4	56.8
Transport	2.7	0.4	1.0	60.7	35.2
Total	**3.5**	**1.4**	**1.9**	**50.7**	**42.6**
	Earthquakes				
Energy	4.3	9.6	47.3	28.8	10.0
Transport	2.4	9.1	61.2	25.3	1.9
Total	**3.1**	**9.3**	**56.5**	**26.5**	**4.6**

Note: Percentages may not total 100% because of rounding.
Source: ADB estimates.

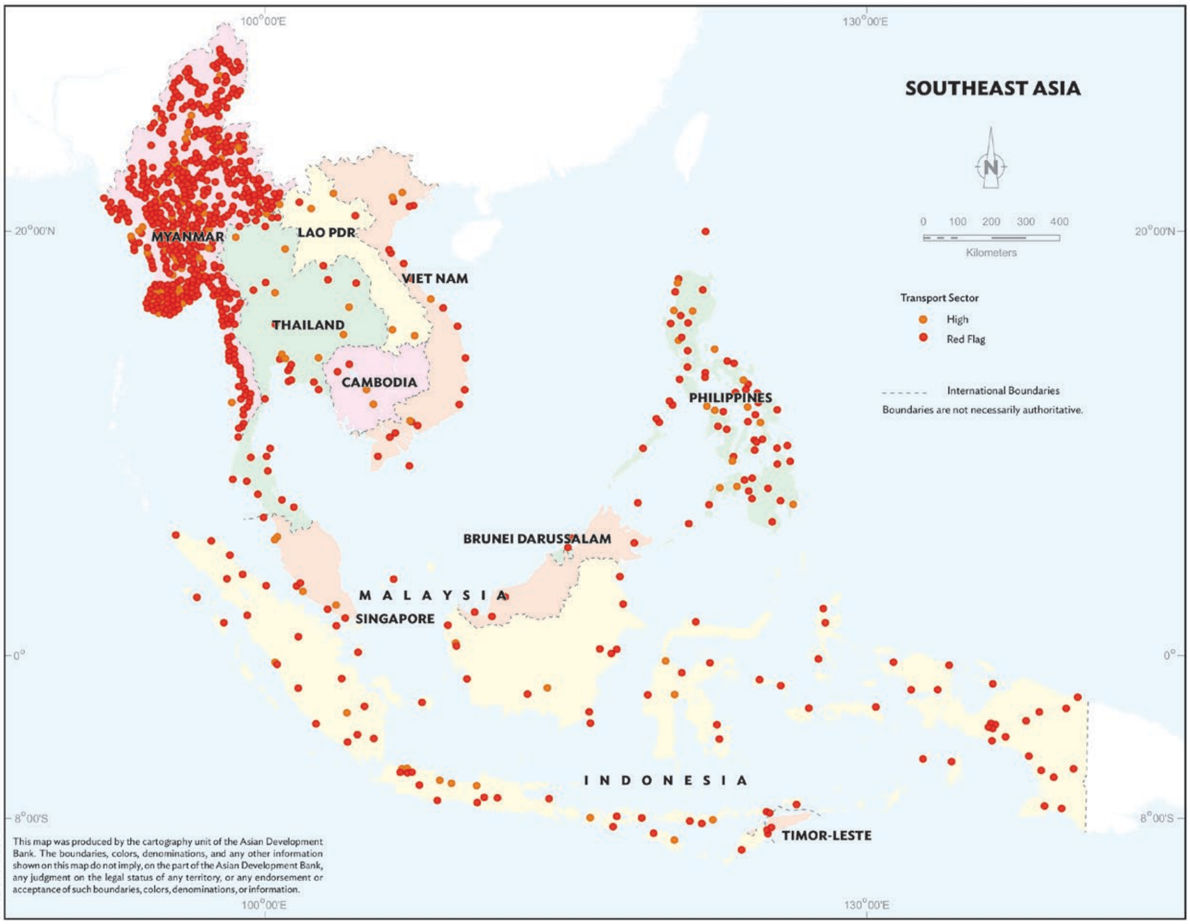
Table 4.18: Percent of Transport Assets Exposed to Floods in Southeast Asia

	Subsector	Red Flag	High	Medium	Low	None
Floods	Air transport	41.0	11.1	0.9	46.9	0.0
	Multimodal logistics	36.9	6.1	1.0	56.1	0.0
	Roadway bridges	60.5	8.8	0.7	29.9	0.0

Source: ADB estimates.

Map 4.10 shows that transport assets throughout the region are exposed to flooding. In Myanmar, 68.9% of the 3,513 transport assets analyzed are rated *red flag* or *high* for floods. Within the transport sector, approximately 60% of the analyzed assets in roadway bridges and multimodal logistics are rated *red flag*, while 41% in air transport are rated *red flag* (Table 4.19).

Map 4.10: Transport Assets Rated *Red Flag* or *High* for Floods in Southeast Asia



Lao PDR= Lao People's Democratic Republic.
Source: ADB estimates.

Table 4.19: Percent of Transport Assets Exposed to Floods in Myanmar

	Subsector	Red Flag	High	Medium	Low	None
Floods	Air transport	41.0	8.2	1.6	49.2	0.0
	Multimodal logistics	60.0	0.0	0.0	40.0	0.0
	Roadway bridges	60.4	8.8	0.8	30.0	0.0

Note: This table is based on information available as of 31 January 2021.
Source: ADB estimates.

The subregion is also subject to significant exposure to extreme heat. Across the region, the relative increase in the frequency of hot days is highest in southern Indonesia, particularly in central and south Kalimantan. The area could experience a fourfold increase in the number of very hot days (i.e., those exceeding the historical 90th percentile), from 37 days per year in 1975–2005 to 150 days per year in 2040 under a high emissions scenario. This large increase in extreme heat and dry conditions could lengthen the fire season in Indonesia and put energy infrastructure at greater risk from wildfire impacts. A significant rise in the number of hot and dry days in central and south Kalimantan will likely threaten energy continuity and intensify human health impacts due to more frequent and prolonged fire-related smoke in the country's new capital in southeastern Kalimantan. On the island of Java, Indonesia, nearly half of the electrical substations evaluated are among the assets with the highest 5% of extreme heat exposure in the Asia and Pacific region. In the analysis, which includes 799 individual energy assets, about 90% are rated *red flag* or *high* risk (Table 4.20).

Table 4.20: Percent of Energy Assets Exposed to Extreme Heat in Indonesia

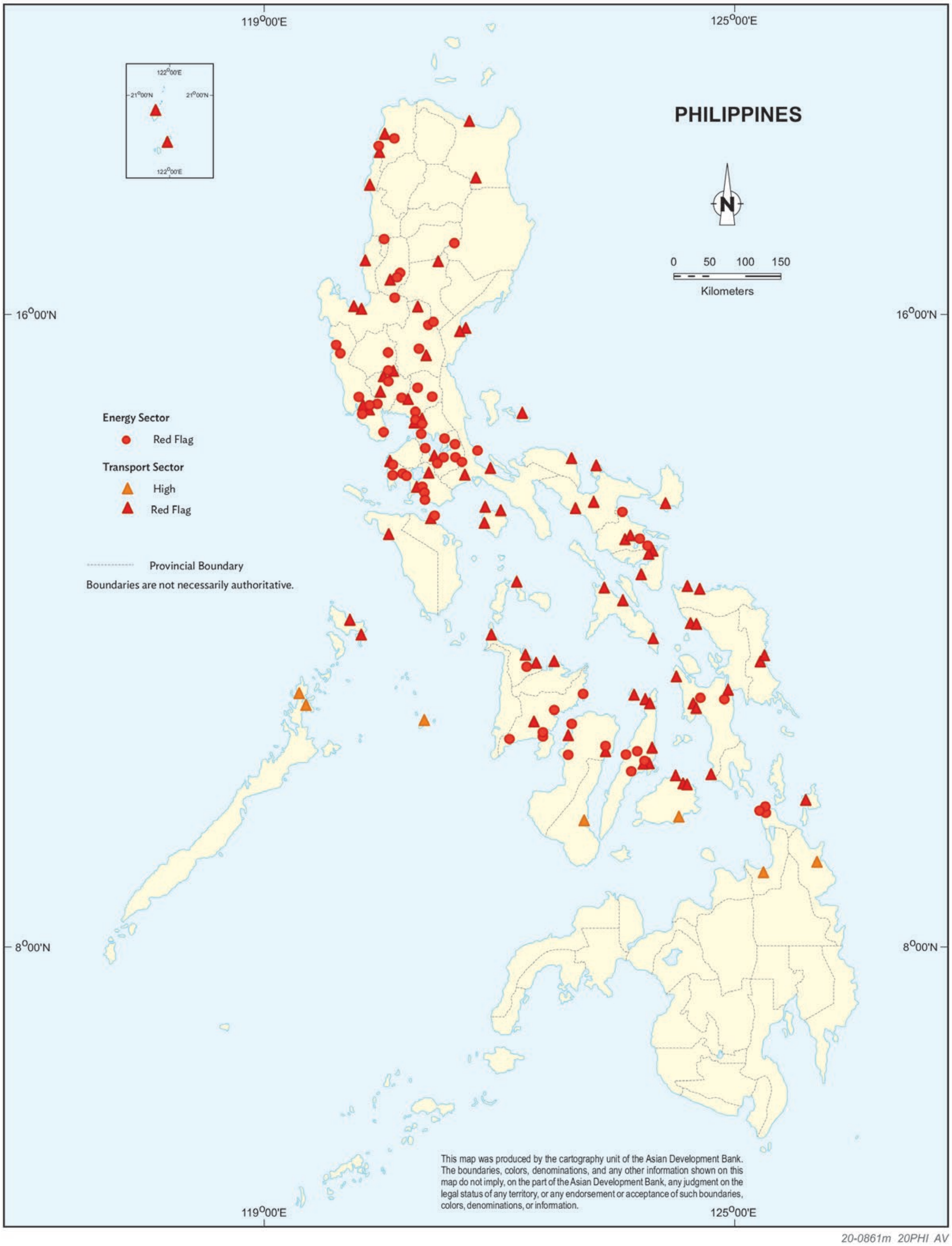
	Subsector	Red Flag	High	Medium	Low	None
Extreme heat	Conventional energy generation	34.8	59.8	3.3	2.2	0.0
	Hydropower generation	17.0	70.2	12.8	0.0	0.0
	Renewable energy generation	37.5	62.5	0.0	0.0	0.0
	Oil and gas transmission	48.9	41.1	8.9	1.1	0.0
	Electricity transmission	54.1	34.9	9.6	1.4	0.0

Source: ADB estimates.

Extreme heat also poses a significant hazard to the energy sector of the Philippines. More than 70 of the 103 energy assets evaluated, including a cluster of coal-fired power plants on the island of Luzon, are among the top 5% of assets most exposed to extreme heat in the entire Asia and Pacific region. In this analysis, 100% of the assets in the hydropower generation and renewable energy generation subsectors receive *red flag* or *high* extreme heat rating. In addition, 86% of the assets evaluated in the conventional energy generation and oil and gas transmission subsectors also receive a *red flag* or *high* rating for extreme heat risk.

The analysis further shows that the region is at significant risk from cyclones, with 57.4% of the analyzed assets exposed and 4.9% rated *red flag* or *high*. The exposure to cyclones is particularly high in the Philippines and Viet Nam, with more than 95% of the assets evaluated at risk. In the Philippines, of the 135 transport assets included in the analysis, 94 assets are rated *red flag* for cyclones, while another 7 assets are rated *high*. Similarly, 86 of the 103 energy assets included in this study are rated *red flag* for exposure to cyclones (Map 4.11). In Viet Nam, 55.6% of the multimodal logistics and 34.6% of the air transport infrastructure included in the study are rated *red flag* or *high* for cyclones (Table 4.21).

Map 4.11: Transport and Energy Assets in the Philippines Rated *Red Flag* or *High* for Cyclones



Source: ADB estimates.

Table 4.21: Percent Exposure to Cyclones of Energy Assets in the Philippines and Transport Assets in Viet Nam

	Subsector	Red Flag	High	Medium	Low	None
Cyclones	**Energy assets in the Philippines**					
	Conventional energy generation	82.8	0.0	3.4	6.9	6.9
	Hydropower generation	70.6	0.0	0.0	29.4	0.0
	Renewable energy generation	88.9	0.0	2.8	8.3	0.0
	Oil and gas transmission	85.7	0.0	4.8	4.8	4.8
	Transport assets in Viet Nam					
	Air transport	34.6	15.4	19.2	30.8	0.0
	Multimodal logistics	55.6	22.2	5.6	16.7	0.0

Source:ADB estimates.

Earthquakes also pose a significant risk in the subregion, with 95.4% of all assets analyzed at risk, 12.4% of which are rated *red flag* or *high*. The Philippines stands out, with 68% of evaluated energy assets and 57.8% of evaluated transport assets rated *red flag* or *high* to earthquakes, while 41.9% of evaluated roadway bridges in Indonesia are rated *red flag* (Table 4.22).

Table 4.22: Percent of Assets Exposed to Earthquakes in Indonesia

	Subsector	Red Flag	High	Medium	Low	None
Earthquakes	Air transport	17.1	16.5	43.5	20.0	2.9
	Multimodal logistics	9.4	15.6	50.0	20.3	4.7
	Roadway bridges	41.9	0.0	58.1	0.0	0.0
	Highway and street	0.0	10.0	70.0	20.0	0.0

Source: ADB estimates.

5

CONCLUSION AND WAY FORWARD

Key energy and transport assets in the Asia and Pacific region are exposed to varying degrees of climate and earthquake hazards. To ensure sustainable development of the region, the potential risks posed by these hazards must be identified, assessed, and addressed to the extent technically and economically feasible. This report aims to contribute to the understanding of the exposure of infrastructure in the region to climate change and earthquakes, and to raise awareness of the importance of incorporating resilience measures in infrastructure planning.

This report uses an innovative methodology to assess the exposure of more than 30,000 transport and energy infrastructure assets in the Asia and Pacific region to extreme heat, water stress, floods, extreme precipitation, sea level rise, cyclones, and earthquakes. The analysis shows that transport and energy assets in the region face significant threats from climate change and earthquakes. About 62% and 44% of transport assets included in the study are rated *red flag* or *high* (the two highest exposure categories in this report) for floods and extreme heat, respectively. Water stress accounts for the largest proportion of energy assets evaluated that are rated *red flag* or *high* (45.1%). A significant share of assets included in this analysis are exposed to earthquakes (72.4%), cyclones (22.4%), and sea level rise (8.3%). Furthermore, the analysis underscores the importance of taking a multi-hazard approach to building infrastructure resilience. Nearly 75% of all assets in this study are exposed to four or more hazards, while more than one in three are rated *red flag* or *high* for two or more hazards. The proportion varies across regions and is particularly high in the Pacific (55.8%), South Asia (48.4%) and Southeast Asia (41.7%).

The exposure assessment presented in this report can only serve as a first step in understanding the risk. While this report cannot provide information on the specific level of risk, the results of this analysis can be used to identify assets in the energy and transport sectors that appear most likely vulnerable to these hazards. Further assessment of the assets' sensitivity to the hazards is needed to determine their vulnerability and potential adaptation measures. Therefore, appropriate additional information on asset vulnerability should complement the exposure assessment to guide the implementation of resilience-building efforts.

Based on this exposure assessment, three important steps can be taken to inform actions pertaining to building infrastructure resilience:

1. **First, adopt a multi-hazard approach to infrastructure resilience.** The findings of this report show that a large number of assets are exposed to climate-related hazards and earthquakes. In Papua New Guinea (PNG), for example, a large percentage of assets in the transport sector (479 assets were assessed) are rated *high* or *red flag* for exposure to multiple hazards:

95.2% extreme heat, 41.8% floods, 33.2% earthquakes, 4.6% water stress, and 1.9% sea level rise. A multi-hazard approach considers all hazards at a given location and the interrelationship among these hazards, including their potential simultaneous or cumulative occurrence and the implications to the infrastructure asset. Adopting a multi-hazard approach also exposes underlying vulnerabilities and allows them to be addressed holistically, while recognizing that an asset's vulnerability to one hazard may increase due to its exposure to another hazard. Given the scarcity of resources to develop policies and plans as well as physical infrastructure, the co-benefits of resilience measures should be added to the key decision-making criteria. At the policy and implementation levels, similar approaches are needed to strengthen infrastructure resilience regardless of the hazard. These include risk governance approaches such as risk assessment, use of standards, enforcement of regulations, improved preparedness planning, and multi-stakeholder partnerships and coordination—providing a stronger basis for managing multiple hazards together.

2. **Second, use a systems approach to understanding risk and building resilience.** Infrastructure plays a key role in advancing socioeconomic development in Asia and the Pacific. Access to reliable road networks, power supply systems, and port infrastructure is inarguably critical to inclusive economic development. However, infrastructures are interconnected to deliver goods and services. To ensure that goods and services are delivered in the face of increasing shocks and stresses, infrastructure resilience must be pursued at the system level. In this regard, it is necessary to understand climate and disaster risk at the system level and find solutions to strengthen the resilience of the wide range of sectors and stakeholders that are part of the system. This can be seen in the case of Fiji's maritime ports, which underpin key economic sectors such as tourism and trade. Because of their extremely low-lying location, portions of the ports evaluated in this analysis are already flooded during spring tides (ADB 2017d). A storm surge of 1 meter renders some parts of the port unusable, an event that is likely to recur regularly by mid-century. In addition to the exposure of the port infrastructure itself, the wider system must also be assessed, such as the access roads to the port, which are vital for moving people and goods to and from other parts of the islands. Because the islands are also low-lying and prone to coastal flooding, focusing on building resilience of the port alone would leave the entire system vulnerable. Building overall resilience would require an assessment of the interconnected aspects of transport systems and ensuring that measures increase the resilience of the entire system, not just individual assets. Therefore, solutions to strengthen infrastructure resilience should include measures that go beyond asset strengthening to include promoting demand-side management among infrastructure users, diversifying the supply chain, and decentralizing infrastructure systems.

3. **Third, guide the adoption of risk-informed sector development.** A good understanding of asset exposure helps make a case for integrating risk information in the formulation and updating of sector policies and plans to steer sector development toward resilience. Incorporating risk information at the wider sector level can provide the basis for individual projects to systematically consider climate and disaster risks at the identification, preparation, and appraisal stages and to introduce the necessary structural and nonstructural measures to build resilience. The National Development Agency (BAPPENAS) of Indonesia, for example, found in a study of climate change adaptation in the transport sector, that most transport institutions in Indonesia do not have planning documents, systematic schemes,

or special units for climate change adaptation. The lack of integration of hazard information into sectoral planning, despite the high exposure of Indonesian transport infrastructure to extreme heat and flooding (76.7% and 51.6% are rated *high* or *red flag*, respectively), results in mainly responding to damage, with no systematic plan to prevent them (Kusumaningrum 2016). Similarly, in Mongolia, despite the fundamental role of the transport sector in economic development, the significant exposure to flooding (79.5% of assets are rated *red flag* or *high*) is not reflected in the country's adaptation priorities. Mongolia's overarching development strategy, which also sets policy priorities for the Ministry of Road and Transport Development, does not address adaptation needs in the transport sector (Government of Mongolia 2016). As a result of inadequate inclusion of sector-specific vulnerabilities and resilience-building needs in sectoral planning, many governments only consider exposure to climate and earthquake hazards at the project level and do not focus on assessing the risks of these hazards to the sector as a whole to identify key investments in critical assets that would increase overall sector resilience. While it is important to adapt climate-relevant design measures, it is paramount to apply upstream risk mapping, strategic and spatial planning, and capacity development to identify broader risks and resilience priorities beyond the individual project to contribute to increased resilience of the entire system.

While more work is needed to embed these three steps into infrastructure maintenance and development, this report provides a starting point by assessing the exposure of existing energy and transport infrastructure to climate-related hazards and earthquakes. International lending institutions such as ADB play an important role in helping their member countries build the resilience of their key infrastructure assets. Ongoing collaboration between ADB and its developing members is essential to further deepen understanding of climate and earthquake risks and to help in assessing and adapting to these risks.

APPENDIX:
INFRASTRUCTURE DATA SOURCES

The following data sources were used for georeferencing infrastructure data in the Asia and Pacific region (all open access sources and/or with authors' permission to use):

Coal, Hydroelectric, Oil, Solar, and Gas Generation: Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute. 2018. Global Power Plant Database. Published on Resource Watch and Google Earth Engine. http://resourcewatch.org/; https://earthengine.google.com/ (accessed May 2019).

Reservoirs and Hydro: Lehner, B. et al. 2011. Global Reservoir and Dam Database, Version 1 **(GRanDv1):** Dams, Revision 01. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4N877QK (accessed June 2018).

Oil and Gas: The Harvard WorldMap Project. https://worldmap.harvard.edu/maps/6718 (accessed 2019).

Nuclear Power: Center for International Earth Science Information Network (CIESIN), Columbia University. 2015. Population Exposure Estimates in Proximity to Nuclear Power Plants, Locations. Palisades, NY: NASA SEDAC. https://doi.org/10.7927/H4WH2MXH (accessed May 2019).

Airports: Natural Earth Airports. https://www.naturalearthdata.com/downloads/10m-cultural-vectors/airports/ (accessed May 2019); WFP Global Airports. https://geonode.wfp.org/layers/geonode%3Awld_trs_airports_wfp (accessed May 2019).

Ports, Piers, and Terminals: WFP Global Ports (WFP SDI-T – Logistics Database) (accessed through Humanitarian Data Exchange in June 2019).

Desalination: OpenStreetMap (OSM).

Desalination: Google Maps. [Desalination] for country of interest. Retrieved May 2019.

Bridges: Manually geocoded through OpenStreetMap Overpass Query, whereas bridge location was identified through intersecting river shapefile (via River, Lake Centerlines. Natural Earth. https://www.naturalearthdata.com/downloads/110m-physical-vectors/110m-rivers-lake-centerlines/ (accessed May 2019 via World Roads. UCLA Institute for Digital Research and Education. https://apps.gis.ucla.edu/geodata/dataset/world_roads).

REFERENCES

Allen, M. R. and W. J. Ingram. 2002. Constraints on Future Changes in Climate and the Hydrologic Cycle. *Nature*. 419 (6903). pp. 224–232.

Asada, K. and G. Li. 2020. Asia at Risk of Losing Annual $8.5tn from Climate Change. *Nikkei Asia*. https://asia.nikkei.com/Spotlight/Datawatch/Asia-at-risk-of-losing-annual-8.5tn-from-climate-change.

Asian Development Bank (ADB). 2012. *Climate Risk and Adaptation in the Electric Power Sector*. Manila.

———. 2015. *Economic Analysis of Climate-Proofing Investment Projects*. Manila.

———. 2017a. *A Region at Risk – The Human Dimensions of Climate Change in Asia and the Pacific*. Manila.

———. 2017b. *Meeting Asia's Infrastructure Needs*. Manila.

———. 2017c. *Climate Risk Vulnerability Assessment. Mongolia – Regional Improvement of Border Services Project.* Manila.

———. 2017d. *Fiji: Ports Development Master Plan in Fiji.* Manila.

———. 2018. *Strategy 2030: Achieving a Prosperous, Inclusive, Resilient, and Sustainable Asia and the Pacific*. Manila.

———. 2021. ADB Statement on Afghanistan. News release. Manila.

Bamber, J. L. et al. 2019. Ice Sheet Contributions to Future Sea-Level Rise from Structured Expert Judgment. *Proceedings of the National Academy of Sciences*. 116 (23). pp. 11195–11200.

Bartos, M. et al. 2016. Impacts of Rising Air Temperatures on Electric Transmission Ampacity and Peak Electricity Load in the United States. *Environmental Research Letters*. 11 (11). p. 114008.

Canfei, H. and L. Yang. 2011. *Urban Development and Climate Change in PRC's Pearl River Delta*. Cambridge: Lincoln Institute of Land Policy.

Chaturvedi, R. K. et al. 2014. Glacial Mass Balance Changes in the Karakoram and Himalaya Based on CMIP5 Multi-model Climate Projections. *Climatic Change*. 123 (2). pp. 315–328.

China National Emergency Broadcasting. 2018. Typhoon Mangkhut Caused Direct Economic Loss of 4.249 Billion Yuan. http://www.cneb.gov.cn/2018/09/17/ARTI1537181884494900.shtml.

Chou, C., J. Y. Tu, and P. H. Tan. 2007. Asymmetry of Tropical Precipitation Change under Global Warming. *Geophysical Research Letters*. 34 (17). pp. 1–5.

Christensen, J. H. et al. 2013. Climate Phenomena and Their Relevance for Future Regional Climate Change. In *Climate Change 2013: The Physical Science Basis. Contribution of Working GroupI to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom (UK), and New York, NY: Cambridge University Press.

Collins, M. et al. 2013. Long-Term Climate Change: Projections, Commitments and Irreversibility. In Stocker, T. F. et al., eds. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY: Cambridge University Press.

Cradden, L. et al. 2010. Sensitivity of Thermal Power Generation to Climate Change. In *Future Climate and Renewable Energy: Impacts, Risks and Adaptation*. https://www.researchgate.net/publication/257868833_Sensitivity_of_thermal_power_generation_to_climate_change.

Dai, A. 2021. Hydroclimatic Trends during 1950–2018 over Global Land. *Climate Dynamics*. 56. pp. 4027–4049. https://doi.org/10.1007/s00382-021-05684-1.

Dasgupta, S. et al. 2009. The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. *Climatic Change*. 93 (3). pp. 379–388.

DeConto, R. M. and D. Pollard. 2016. Contribution of Antarctica to Past and Future Sea-Level Rise. *Nature*. 531. pp. 591–597.

Denham, D. and W. Smith. 1993. Earthquake Hazard Assessment in the Australian Southwest Pacific Region. A Review of the Status Quo. *Annals of Geophysics*. XXXVI (3–4). pp. 27–39.

Elsner, J. B., J. P. Kossin, and T. H. Jagger. 2008. The Increasing Intensity of the Strongest Tropical Cyclones. *Nature*. 455. pp. 92–95.

Emanuel, K. 2005. Increasing Destructiveness of Tropical Cyclones over the Past 30 Years. *Nature*. 436 (7051). pp. 686–688.

Food and Agriculture Organization (FAO). 2019. *Georgia at a Glance*. FAO: Tbilisi.

G20. 2018. G20 Principles for Quality Infrastructure Investment. https://www.mof.go.jp/english/international_policy/convention/g20/annex6_1.pdf.

Gao, Y., H. Wang, and D. Jiang. 2015. An Intercomparison of CMIP5 and CMIP3 Models for Interannual Variability of Summer Precipitation in Pan-Asian Monsoon Region. *International Journal of Climatology*. 35. pp. 3770–3780.

Gassert, F. et al. 2014. *Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators*. Washington, DC: World Resources Institute.

Government of Mongolia. 2016. *Sustainable Development Vision 2030*. Ulaanbaatar.

Hanson, S. et al. 2011. A Global Ranking of Port Cities with High Exposure to Climate Extremes. *Climatic Change*. 104 (1). pp. 89–111.

Held, I. M. and B. J. Soden. 2006. Robust Responses of the Hydrological Cycle to Global Warming. *Journal of Climate*. 19 (21). pp. 5686–5699.

Holland, G. and C. L. Bruyère. 2014. Recent Intense Hurricane Response to Global Climate Change. *Climate Dynamics*. 42. pp. 617–627.

Huang, Z., Y. Zong, and W. Zhang. 2004. Coastal Inundation Due to Sea Level Rise in the Pearl River Delta, PRC. *Natural Hazards*. 33 (2). pp. 247–264.

Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens. 2010. Climate Change Will Affect the Asian Water Towers. *Science*. 328 (5984). pp. 1382–1385.

International Hydropower Association (IHA). 2016. *2016 Hydropower Status Report*. London.

Intergovernmental Panel on Climate Change (IPCC). 2013. *Climate Change 2013: The Physical Science Basis*. Working Group I Contribution to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.

Kamiguchi, K. et al. 2006. Changes in Precipitation-Based Extremes Indices Due to Global Warming Projected by a Global 20-Km-Mesh Atmospheric Model. *SOLA*. 2. pp. 64–67.

Kazakhstan Electricity Grid Operating Company (KEGOC). 2019. *KEGOC Annual Report 2018*. Astana.

Kimmelman, M. 2017. Rising Waters Threaten PRC's Rising Cities. *New York Times.* 7 April.

Koirala, S. et al. 2014. Global Assessment of Agreement among Streamflow Projections Using CMIP5 Model Outputs. *Environmental Research Letters*. 9 (6). 064017.

Koks, E. E. et al. 2019. A Global Multi-Hazard Risk Analysis of Road and Railway Infrastructure Assets. *Nature Communications*. 10. 2677.

Kopp, R. E. et al. 2014. Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide-Gauge Sites. *Earth's Future*. 2 (8). pp. 383–406.

Kossin, J. P., K. A. Emanuel, and S. J. Camargo. 2016. Past and Projected Changes in Western North Pacific Tropical Cyclone Exposure. *Journal of Climate*. 29 (16). pp. 5725–5739.

Kossin, J. P., K. A. Emanuel, and G. A. Vecchi. 2014. The Poleward Migration of the Location of Tropical Cyclone Maximum Intensity. *Nature*. 509. pp. 349–352.

Kundzewicz, Z. W. et al. 2013. Flood Risk and Climate Change: Global and Regional Perspectives. *Hydrological Sciences Journal*. 59 (1). pp. 1–28.

Kusumaningrum, R. 2016. As Climate Change Threatens Transport, Indonesia Needs to Plan Ahead. Asian Cities Climate Change Resilience Network (ACCCRN) blog. https://news.trust.org/item/20160719150821-1tsrv.

Le, T. V. H. et al. 2007. The Combined Impact on the Flooding in Vietnam's Mekong River Delta of Local Man-Made Structures, Sea Level Rise, and Dams Upstream in the River Catchment. *Estuarine, Coastal, and Shelf Science*. 71 (1–2). pp. 110–116.

Lehmann, J., D. Coumou, and K. Frieler. 2015. Increased Record-Breaking Precipitation Events under Global Warming. *Climatic Change*. 132. pp. 501–515.

Luck, M., M. Landis, and F. Gassert. 2015. *Aqueduct Water Stress Projections: Decadal Projections of Water Supply and Demand Using CMIP5 GCMs*. Washington, DC: World Resources Institute.

Lutz, A. F. et al. 2014. Consistent Increase in High Asia's Runoff Due to Increasing Glacier Melt and Precipitation. *Nature Climate Change*. 4 (7). pp. 587–592.

Mach, K. J., S. Planton, and C. von Stechow, eds. 2014. Annex II: Glossary. In Pachauri, R. K. and L. A. Meyer, eds. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC. pp. 117–130.

Maurer, J. M. et al. 2019. Acceleration of Ice Loss Across the Himalayas over the Past 40 Years. *Science Advances*. 5 (6). eaav7266.

McKinsey Global Institute. 2020. Climate Risk and Response: Physical Hazards and Socioeconomic Impacts. https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-risk-and-response-physical-hazards-and-socioeconomic-impacts.

Mcleod, E. et al. 2010. Sea-Level Rise Vulnerability in the Countries of the Coral Triangle. *Sustainability Science*. 5 (2). pp. 207–222.

McSweeney, C. F., R. G. Jones, R. W. Lee, and D. P. Rowell. 2015. Selecting CMIP5 GCMs for Downscaling over Multiple Regions. *Climate Dynamics.* 44. pp. 3237–3260.

Mei, W. and S. P. Xie. 2016. Intensification of Landfalling Typhoons over the Northwest Pacific Since the Late 1970s. *Nature Geoscience.* 9 (10). pp. 753–757.

Mendelsohn, R. et al. 2012. The Impact of Climate Change on Global Tropical Cyclone Damage. *Nature Climate Change*. 2 (3). pp. 205–209.

Menon, A. et al. 2013. Consistent Increase in Indian Monsoon Rainfall and Its Variability across CMIP-5 Models. *Earth System Dynamics*. 4 (2). pp. 287–300.

Milly, P. C. D. et al. 2002. Increasing Risk of Great Floods in a Changing Climate. *Nature*. 415 (6871). pp. 514–517.

Mimura, N. et al. 2011. Damage from the Great East Japan Earthquake and Tsunami–A Quick Report. *Mitigation and Adaptation Strategies for Global Change.* 16. pp. 803–818. https://doi.org/10.1007/s11027-011-9297-7.

National Aeronautics and Space Administration (NASA). 2013. *NASA Shuttle Radar Topography Mission Global 1 Arc Second* [Data set]. NASA EOSDIS Land Processes DAAC. https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL1.003 (accessed 10 October 2019).

Pall, P., M. R. Allen, and D. A. Stone. 2007. Testing the Clausius–Clapeyron Constraint on Changes in Extreme Precipitation under CO2 Warming. *Climate Dynamics*. 28 (4). pp. 351–363.

Pritchard, H. D. 2017. Asia's Glaciers Are a Regionally Important Buffer against Drought. *Nature*. 545 (7653). pp. 169–174.

Rajeevan, M., J. Bhate, and A. K. Jaswal. 2008. Analysis of Variability and Trends of Extreme Rainfall Events over India Using 104 Years of Gridded Daily Rainfall Data. *Geophysical Research Letters*. 35 (18). L18707.

Riahi, K. et al. 2011. RCP 8.5 – A Scenario of Comparatively High Greenhouse Gas Emissions. *Climatic Change*. 109 (1). pp. 33–57.

Rodell, M., I. Velicogna, and J. S. Famiglietti. 2009. Satellite-Based Estimates of Groundwater Depletion in India. *Nature.* 460. pp. 999–1002.

Rodell, M. et al. 2018. Emerging Trends in Global Freshwater Availability. *Nature*. 557 (7707). p. 651.

Sen Roy, S. 2009. A Spatial Analysis of Extreme Hourly Precipitation Patterns in India. *International Journal of Climatology*. 29 (3). pp. 345–355.

Shahgedanova, M., G. Nosenko, S. Kutuzov, O. Rototaeva, and T. Khromova. 2014. Deglaciation of the Caucasus Mountains, Russia/Georgia, in the 21st Century Observed with ASTER Satellite Imagery and Aerial Photography. *The Cryosphere*. 8 (6). pp. 2367–2379.

Sherwood, S. C. and M. Huber. 2010. An Adaptability Limit to Climate Change Due to Heat Stress. *Proceedings of the National Academy of Sciences*. 107 (21). pp. 9552–9555.

Shrestha, A. et al. 2015. *The Himalayan Climate and Water Atlas: Impact of Climate Change on Water Resources in Five of Asia's Major River Basins*. Kathmandu, Nepal: International Centre for Integrated Mountain Development.

Sillmann, J. et al. 2013. Climate Extremes Indices in the CMIP5 Multi-model Ensemble. Part 2: Future projections. *Journal of Geophysical Research*. 188 (6). pp. 2473–2493.

Sperber, K. R., H. Annamalai, I-S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou. 2013. The Asian Summer Monsoon: An Intercomparison of CMIP5 vs. CMIP3 Simulations of the Late 20th Century. *Climate Dynamics.* 41. pp. 2711–2744.

Stoler, J. et al. 2021. Connecting the Dots between Climate Change, Household Water Insecurity, and Migration. Current Opinion in Environmental Sustainability. 51. pp. 36–41.

Tollefson, J. 2016. Antarctic Model Raises Prospect of Unstoppable Ice Collapse. *Nature News*. 531 (7596). p. 562.

Underwood, B. S., Z. Guido, P. Gudipudi, and Y. Feinberg. 2017. Increased Costs to US Pavement Infrastructure from Future Temperature Rise*. Nature Climate Change*. 7 (10). pp. 704–707.

United Nations Development Programme (UNDP). 2018. National Adaptation Plans in Focus: Lessons from the Republic of Kazakhstan. National Adaptation Plan Global Support Programme. NAP-GSP.

Unurzul, M. 2018. Train with 328 Passengers on Board Crashed in Dornogobi Aimag. *Montsame*. 13 August 2018. https://www.montsame.mn/en/read/136324.

Wang, X. and P. L. F. Liu. 2006. An Analysis of 2004 Sumatra Earthquake Fault Plane Mechanisms and Indian Ocean Tsunami. *Journal of Hydraulic Research*. 44 (2). pp. 147–154.

Wester, P. et al. 2018. *The Hindu Kush Himalaya Assessment*. Berlin: Springer.

Westra, S. et al. 2014. Future Changes to the Intensity and Frequency of Short-Duration Extreme Rainfall. *Review of Geophysics*. 52 (3). pp. 522–555.

Xia, J. et al. 2015. Projection of the Zhujiang (Pearl) River Delta's Potential Submerged Area Due to Sea Level Rise During the 21st Century Based on CMIP5 Simulations. *Acta Oceanologica Sinica*. 34 (9). pp. 78–84.

Climate Change and Earthquake Exposure in Asia and the Pacific

Assessment of Energy and Transport Infrastructure

This study analyzes the exposure of energy and transport assets in Asia and the Pacific to climate change and earthquake hazards. It identifies significant risks across the region by geolocating 30,000 transport and energy assets and evaluating their exposure to sea level rise and coastal floods, extreme heat, water stress, inland floods, and extreme precipitation. It shows that three quarters of assets examined are at significant risk from climate change and earthquakes and highlights how holistic, multi-hazard assessment can help strengthen the resilience of the region's crucial infrastructure. Multi-hazard assessment and an understanding of the potential impacts of these hazards need to be systematically integrated into the planning, design, and financing of infrastructure upgrades and maintenance.

About the Asian Development Bank

ADB is committed to achieving a prosperous, inclusive, resilient, and sustainable Asia and the Pacific, while sustaining its efforts to eradicate extreme poverty. Established in 1966, it is owned by 68 members —49 from the region. Its main instruments for helping its developing member countries are policy dialogue, loans, equity investments, guarantees, grants, and technical assistance.

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