Global transportation infrastructure exposure to the change of precipitation in a warmer world

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Abstract

Transportation infrastructures are generally designed to have multi-decadal service lives. The design of transport infrastructure, however, is largely based on historical conditions. Yet in the face of global warming, climatic variables are likely going to have more intense and frequent extreme events, and this would put infrastructures at severe risk. In this study, we undertake a comprehensive analysis of the exposure of transportation infrastructure assets to changes in precipitation return periods globally. Under RCP8.5, 44.45%/58.64% (1.5°C/2.0°C) of the transportation assets will experience a reduction in the return period ratio of more than 25%. Eastern North America, Northern Western Europe, Central Europe and East Asia experience the highest absolute exposure to changes in precipitation return periods, mainly attributed to their dense transportation networks. We recommend considering future climate change effect during transportation infrastructure design process by introducing a design amplification factor, which is a more robust variable compared to return period change ratio.

Introduction

Reliable transport infrastructure is the backbone of international trade and well-functioning economies¹. Yet, the reliability of transport infrastructure is regularly under threat due to natural hazards. Globally, the multi-hazard risk due to direct damage to road and railway assets is estimated to range between 3.1 to 22 billion US dollars². At the same time, local examples of damaged and destroyed infrastructure assets are numerous. In March 2020, for instance, heavy precipitation caused the destruction of an important bridge that connects Tanzania with Rwanda, causing disruptions in cross-border trade³. In October 2020, approximately 280 roads were destroyed as a result of tropical storms Eta and Zeta in Jamaica⁴, while several roads were destroyed in France and Italy due to extratropical storm Alex, causing flash floods and rainfall-induced landslides⁵. In July 2021, heavy rainfall caused the destruction of multiple railway segments, roads and bridges in The Netherlands, Belgium and Germany⁶. Similar in Zhengzhou city, which is the key transport hub in China and is one of the five major consolidation centers for China-Europe trains, was inundated by torrential downpours in July 2021, causing the cancellation of thousands of train trips⁷.

As a result of an increasing global mean temperature rise, it is expected that climate extremes may both increase in intensity and frequency towards the future^{8–10}. For example, rainfall reached 201.9 mm in one hour in Zhengzhou City on July 20, breaking the extreme hourly rainfall on mainland China¹¹. This increased pressure on transport infrastructure may cause further deterioration of infrastructure assets and increased maintenance and replacement costs¹. As such, building and maintaining resilient, sustainable and reliable infrastructure is one of the key targets of Sustainable Development Goal 9 (SDG9). To achieve this goal, low- and middle-income countries have to spend between 0.5 percent and 3.3 percent of their GDP annually (US\$157 billion to 1 trillion) in new transport infrastructure by 2030 – plus an additional 1 percent to 2 percent of GDP to maintain their network – depending on their ambition and their efficiency in service delivery¹².

To successfully achieve SDG9, through building climate resilient and sustainable infrastructure, one first need to better understand the impacts of climate extremes on infrastructure assets. While much work has been done on understanding the direct economic damage on infrastructure assets^{2,13}, and some work on the indirect

economic losses through network disruptions^{14,15}, little work has been done on understanding how design standards should change towards the future to mitigate the impacts of climate extremes on these infrastructure assets. As such, this study aims to better understand how the probability of extreme precipitation events may change towards the future, and where, and by how much, design standards should change to achieve and maintain reliable and well-functioning infrastructure.

Here, we analyze the future changes in transportation exposure (roads, and railways) to precipitation around the world at 1.5 and 2°C warmer worlds, by employing multi-model projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5). To do so, we first estimated precipitation return period shifts under different global circulation models (GCMs) and then investigate how this change influences transportation exposure by incorporating the design standards of infrastructure drainage system. We show that roughly 93% of the global land mass is projected to have a decrease in return period (increased frequency). Greenland, Northeastern North-America, Northern South-America, Central Africa, Central Siberian plateau, Central India, Southwest and Northeast China, and Southeast Asia, are regions experience some of the most pronounced precipitation return period changes. Nearly 97% of global transportation assets will face a shorter precipitation return periods under Representative Concentration Pathway 4.5 (RCP4.5) scenario, among them, 36.37%/53.81% (1.5°C/2.0°C) of assets will experience a shorten return period exceeding 25% (e.g. what used to be 1-in-10-yr event for the period 1971-2000 is less than 1-in-7.5-yr in the corresponding simulation). The United States, China, and Russia experience the largest absolute exposure given the large quantity of transportation assets, while Small Island Developing Countries are more sensitive to climate change in terms of relative exposure. Canada, Finland, Norway, South Korea, Kazakhstan and Japan rank highest in both absolute and relative exposure, reflecting the dual risk of assets concentration and climate change.

Our study reveals the magnitude of the threat to transportation infrastructures from climate change at the global scale. The results demonstrate that realizing the 1.5°C low warming target would robustly reduce the transportation exposures to precipitation extremes, compared to a warming of 2°C. The avoided impacts are more remarkable for Northern South-America, Central Africa, Central India, Southwest China, and Southeast Asia. Detailed regional differenced amplification factors are suggested to the designed precipitation for transportation drainage system to cope with a changing climate.

Results

2.1. Change in precipitation return period

Figure 1 shows the global spatial distribution of how the probability of a 1-in-10-year precipitation event (an event that has an average of 10% chance of occurring every year) in the baseline situation (1971-2000) changes at 1.5°C and 2°C degrees of global warming under RCP4.5 and RCP8.5 scenarios. Roughly 93% of the global land mass experiences a decreasing return period (increased frequency) as a result of global warming. An increasing return period is primarily observed in Northern Africa, South west of South America, and Saudi Arabia. Under RCP4.5 scenario, ~72.2% (1.5°C) and 81.8% (2°C) of the world is projected to have a decrease in return periods of up to 25% (i.e. what used to be 1-in-10-yr event for the period 1971-2000 is less than 1-in-7.5-yr in the corresponding simulation). Under RCP 8.5 scenario, the numbers increase to 70.4% and 83.4%, for respectively 1.5°C and 2°C. Greenland, Northeastern North-America, Northern South-America, Central Africa,

Central Siberian plateau, Central India, Southwest and Northeast China, and Southeast Asia, are regions most sensitive to global warming and will face the most significantly shortened return period of precipitation when the global mean temperature increase rises from 1.5°C to 2.0°C.

2.2. Exposure Analysis

Infrastructures are most often designed to be able to resist a certain return period rainfall event. When the probability of the rainfall event exceeds this design threshold, damage is expected to occur. In other words, the infrastructure drainage system is expected to protect the infrastructure against rainfall events with return periods smaller than the design return period. Under global warming scenarios, the designed return period based on the historical precipitation record may become shorter, putting infrastructures at greater risk. For instance, an infrastructure was initially designed for 10-year rainfall event, in the future it may become 5-year rainfall event based on historical probability distribution function (PDF), making the infrastructure less reliable as one might anticipate. In this study, we investigate the change of infrastructure design return period under different warming scenarios. Different design standards (i.e., design return periods) of drainage system are assigned for countries with different income groups as well for different assets (See Method and Table S1). Figure 2 shows the percentage distribution of transportation infrastructure assets facing a change in design return period. The design return period of nearly 97% of global transportation assets will become shorter (between 0% and 50%) relative to the historical period 1971–2000, with an average decrease of 23.8%/28.35% (1.5°C/2.0°C, mean of RCP4.5 and RCP8.5) and a standard deviation of 13.7%/14.75% (1.5°C/2.0°C, mean of RCP4.5 and RCP8.5). The percentage distribution under 2.0°C warming shifts to the left compared to that of 1.5°C warming situation, especially the 0-25% interval moves significantly towards the 25%-50% interval, and the proportion above 50% change is increasing as well. Under RCP4.5 scenario, 36.37%/53.81% (1.5°C/2.0°C) of assets will face a shorten return period exceeding 25%. While under RCP8.5 scenario, the two proportions are, respectively, 44.45% and 58.64% (1.5°C/2.0°C).

The exposure of infrastructure assets to changes in precipitation is affected by two factors: the spatial distribution of assets and the change in the design return period at a given location. Figure 3 shows the spatial distribution of absolute exposure of global transportation infrastructure, which is expressed by the sum of all road and railway assets facing a more than 25% decrease in precipitation design return period within a grid of 25x25km (See Method). The individual exposures for each road and railway asset categories can be found in Supplementary Figure 1. The distributions of absolute exposure are similar under RCP4.5 scenario and RCP8.5 scenario. Under RCP4.5 scenario, 8.4 million km (1.5°C) and 11.4 million km (2.0°C) of global road and railway assets will be exposed to more frequent extreme precipitation (i.e., a reduction ratio in the design return period of more than 25%), representing 39% and 53% of the global land transport infrastructure. Among these assets, ~24% of the exposed transportation assets are secondary roads, followed by primary roads and railways, both account for ~16%. Under RCP8.5 scenario, the exposed transportation assets increase to 9.8 million km (1.5°C) and 12.6 million km (2.0°C), accounting for 45% (1.5°C) and 59% (2.0°C) of global transportation assets. Regions that experience high absolute exposure are profoundly in Eastern North America, Northern Western Europe, Central Europe and East Asia, mainly attributed to their dense transportation networks.

Figure 4 shows the relative global transport infrastructure exposure exceeding a 25% reduction in precipitation design return periods. Under RCP4.5 scenario, the grids with an exposure ratio larger than 80% (see Methods)

account for ~25.9% (1.5°C) and ~39.9% (2.0°C) of the total exposed grids. We find that risk in relative exposure varies widely across the world. Under RCP8.5 scenario, the percentage of grids with an exposure ratio larger than 80%, increases to ~30.4% (1.5°C) and ~46.6% (2.0°C). These highly exposed areas are concentrated in the Eastern and Western United States, Southeastern South-America, Central and Northern Europe, Southwestern China, and Southeast Asia. The highly exposed regions expand to Central Africa, Central India and Southeastern Australia. Interestingly, we find some countries that experience a low absolute exposure, but a high relative exposure. As for example, ~61% of grids in Myanmar (total transportation assets of 54,090 km) will face an exposed ratio over 80% under 2.0°C under RCP8.5 scenario, making a large proportion of transportation infrastructure in Myanmar highly vulnerable to rising temperatures.

Due to the high uncertainty in climate models, we present the multi-model median results and the part with high agreement (defined as more than ~66% climate models supporting the change of exceeding 25% shorten in precipitation return periods^{16,17}). Figure 5 shows the absolute and relative exposure of the four World Bank income groups¹⁸. Between 1.5°C to 2.0°C, the exposure of the four income groups increases by 1.2-2.7 times. High income countries and upper middle income countries experiences the largest increases in absolute exposure, which is expected as they have dense transport infrastructure and higher design standards of their assets. According to the shape of the PDF of the return period T, a small change in precipitation can lead to a large change in design return period for high design standards. Under RCP8.5, with a 2°C warming scenario, high income countries may experience an absolute exposure of approximately 7.1 million km, which is around 73% of all infrastructure assets in these countries. The upper middle income countries come second, with approximately 4.8 million km of asset length. At the global perspective, considerably less exposure is found in lower middle and low middle income countries due to the significantly lower amount of infrastructure assets. However, the differences appear to be smaller in relative exposure compared, with 22% in relative exposure for low and low middle income countries while 58% and 73% in upper middle income and high income countries respectively. The smaller relative exposure changes in low and lower middle income countries are due to the lower design standards. The assets in these countries were already severely exposed to precipitation events with low return periods. As such, they are relatively less affected by the estimated changes in this study. Of course, this does not mean their transportation assets are less threatened by global warming, on contrary, they are affected by all rainfall events in excess of their design return period. Compared to high return periods, lower return periods require larger change in precipitation to realize the same proportion change in return period. When we increase the design standards (Table S1), the relative exposure increases to 39.3% for low and low middle income countries.

Figure 6 shows the top-30 countries with the highest absolute and relative exposure under RCP4.5 scenario and RCP8.5 scenario. The most exposed countries can be found in Asia, Europe and America. The United States (US) ranks first in absolute exposure due to its high density of transport infrastructure assets and decreasing precipitation return periods, especially along the East and West coast. Under RCP4.5 scenario, the amount of US exposed assets will reach 1.82 (1.5°C) and 2.36 (2.0°C) million km (with a high agreement of 0.77 (1.5°C)/1.48 (2.0°C) million km), which accounts for 57% (1.5°C) and 74% (2.0°C) of its total assets (with a high agreement of 24% (1.5°C) /46% (2.0°C)). China with 1.28 (1.5°C) and 1.75 (2.0°C) million km of exposed roads, ranks second at absolute exposure (with a high agreement of 0.68 (1.5°C)/1.22 (2.0°C) million km), which accounts for 50% (1.5°C) and 68% (2.0°C) of its assets (with a high agreement of 26% (1.5°C)/47% (2.0°C)). A total of

fourteen European countries can be found in the top-30, with Russia in third place globally due to its large number of assets, followed by France and Germany. Russia's exposed assets volume will reach 0.88 (1.5°C) and 1.18 million km (2.0°C) (with a higher agreement of 0.51/0.85 million km), which accounts for 52% (1.5°C) and 70% (2.0°C) of its assets (with a higher agreement of 30% (1.5°C)/50% (2.0°C)). There are nine Asian countries in the top30, including China, Japan and India, etc. A rise of 1.5°C to 2°C has the greatest impact on Romania, Japan and Brazil, resulting in a 253%, 108% and 101% increase in absolute exposure.

Small countries are more sensitive to climate change in relative exposure. Under RCP4.5 scenario, eight countries with a total asset length of less than 5000km, show a high ratio of exposure and high consistency (up to 100%) on all climate models, such as some of the French Overseas Territories (e.g. Guiana, Mayotte). A total of thirteen European countries made the list, with Latvia showing the highest relative exposure, ranking third globally, up to 92.2% (1.5°C) and 94.5% (2.0°C) (with a higher agreement of 76% (1.5°C) and 88% (2.0°C)). Four Asian countries —South Korea, Kazakhstan, Japan and Qatar—made the list. Canada, Finland, Norway, South Korea, Kazakhstan and Japan are both on the absolute and relative exposure lists, reflecting the dual risk of assets concentration and climate change.

The thirty countries that experience the highest absolute exposure for RCP8.5 and RCP 4.5 are very similar, with 29 countries overlapping. Under RCP8.5 scenario, the exposed assets of these 29 countries increase by 0.034 million km on average for both 1.5°C and 2°C (with a higher agreement of 0.017 (1.5°C) and 0.025 (2°C) million km). We find twelve countries exhibit high risk in both absolute and relative exposure, including the United States, Canada, Great Britain, Germany, Finland, and Thailand.

2.3. Design amplification factor

Most of transportation infrastructures are designed and built based on the assumption that precipitation will resemble historical patterns¹⁹. As shown in our study, change of precipitation in a warmer world would make infrastructures assets in most regions of the world more exposed than it used to be, resulting in a potential decrease in network resilience and reliability due to increased probabilities of network disruptions through damaged assets. We therefore recommend using a design amplification factor for upgrading existing infrastructures or designing new infrastructures to make them maintain the same level of acceptable risk under future warming scenarios. Figure 7 shows the spatial distribution of the amplification factor (see Methods) to current design standards, which represents the ratio of the future precipitation intensity corresponding to the design return period of various transportation assets to the precipitation intensity in the baseline period. For example, the design amplification factor is 1.5 if the precipitation intensity of the same design return period is 20mm and 30 mm for current state and future scenario, respectively. We find that the design amplification factor is mainly distributed between 1 and 1.2 around the world. Under RCP4.5, 86.0% (1.5°C) and 82.5% (2.0°C) of the global mass has an amplification factor of 1-1.2; 1.2% (1.5°C) to 4.8% (2.0°C) of the global mass has an amplification factor larger than 1.2, which is mainly concentrated in Tibet, Central India and the Andes (South America). Under RCP8.5, 84.6% (1.5°C) and 76.9% (2.0°C) of the global land mass has an amplification factor of 1-1.2; 2.0% (1.5°C) and 9.2% (2.0°C) of the global land mass has an amplification factor of over 1.2, mainly occurs in India, Southwest China and Indo-China Peninsula, East Africa, Andes of South America and north of 50°N.

We also found that areas with a high amplification factor do not coincide completely with areas with a high degree of return periods shortening (Section 2.1). This again implies that a small increase of precipitation may not make a large difference in an area where design standards for infrastructure are high, and where we observe a large change in design return periods. We also perform a sensitivity analysis to assess the change of design amplification factor while considering uncertainties in design standards (see Methods). With higher design standards assumption, under RCP4.5, 84.5%/ 82.4% (1.5°C/2.0°C) of the global mass has an amplification factor between 1 and 1.2; 1.1% /3.9% (1.5°C/2.0°C) of the world land area has an amplification factor larger than 1.2. This indicates that the dynamic amplification factor is more robust in guiding engineering design compared to return period change ratio. Considering the uncertainty in the tail of the PDFs of return period, using an amplification factor to current design precipitation intensity would be more feasible and easier.

The design amplification factor achieves a reasonably estimates for the future. Figure 7 shows that a design amplification factor of 1.2, although approximate, works sufficient for most regions of the world for a quick calculation in the design process (86.0%/76.9(1.5°C/2.0°C, RCP8.5). We should encourage and accept infrastructure managers or engineers to consider future climate extremes in the design process. By considering a design amplification factor, the transportation assets are expected to maintain the same risk level in the future as they were designed for. Climate researchers, construction designers, and stakeholders should work together to make infrastructures reliable in a warming world.

Discussion And Conclusion

In this study, we have analyzed the exposure of global transportation assets to changes in precipitation design return periods under different future warming scenarios. The change of extreme precipitation return period challenges the adaptability of design return periods of infrastructure drainage facilities.

Our results show that about 97% of global transportation assets will be exposed to precipitation with higher frequency return periods, with increased frequencies between 0 and 50% for both RCP4.5 and RCP8.5 scenarios. Under RCP4.5 scenario, a total of 8.4 million km (1.5°C) and 11.4 million km (2.0°C) of global transportation assets will be exposed to more frequent (frequency change larger than 25%) extreme precipitation. In relative terms, 25.9% (1.5°C) and 39.9% (2.0°C) of grids' relative exposure ratio is over 80%. Under RCP8.5, exposure reaches up to 9.8 million km (1.5°C) and 12.6 million km (2.0°C), with the proportion of highly exposed grids proportion increasing to 30.4% (1.5°C) and 46.6% (2.0°C), compared to RCP4.5. Regions that experience the highest absolute exposure regions are distributed among Eastern North America, Northern Western Europe, Central Europe and East Asia. This can primarily be explained by their high density of transportation infrastructure (Meijer et al., 2018). Among these regions, the US experiences the largest exposure due to its high asset distribution overlapping with areas with shortened return periods (on both the East and West coast).

A design amplification factor applied to design precipitation intensity determined by historical stationary records provides a practical and useful tool for approximating climate change effect. A change of 1.2 obtains a good approximation of the climate change effect for most regions of the world, which provides a practical and useful tool in design over a future planning horizon. In particular, India, Southwest China and the Indo-China Peninsula, East Africa and the Andes in South America experience higher amplification factors. The amplification factor is less sensitive to uncertainties in design return periods compared to the variations in

precipitation design return period, i.e., the value of amplification factor maintains 1-1.2 for most regions of the world regardless the change of design standards. The results of this study also highlight that low income countries are more susceptible to damage (due to lower design standards), but in general they face a relative smaller absolute change in return periods.

While this study did not assess the feasibility of adaptation measures to reduce the impacts, several measures are possible to reduce the damage to roads and railways, of which updating drainage systems is the most prominent one. Updating or implementing a road or railway drainage system, however, will substantially increase the cost of required infrastructure for a specific location. According to a case study of a 1.7 km² street in China, it is estimated that about 0.7 million USD was need to improve its drainage capacity from 1-in-2-year to 1-in-5-year²⁰. To assess whether it is cost-effectivity to implement, a cost-benefit analysis is required. However, it should be emphasized that benefits will be much larger if we consider not only the direct damages, but also the indirect loss caused by transportation disruption.

To conclude, our results help to identify highest risk assets and facilitate decision making about which and where assets to prioritize upgrading drainage system, based on the potential increase in future exposure. We emphasize that uncertainties are a key element in designing resilient infrastructure in a future climate. In particular in the case of infrastructure, which generally has a long lifespan, it is essential to incorporate potential future changes in exposure to keep infrastructures reliable over multi-decadal service lives with growing climatic uncertainty.

Methods

Future extreme precipitation changes are assessed through two aspects: frequency and intensity. To quantify the transportation assets exposed to extreme precipitation, we use return periods to describe the change between the 1.5°C and 2.0°C warming and the baseline period (1971-2000). A return period indicates the recurrence interval, which is an average time period between two events to occur. For example, the return period of precipitation of 10 years means its probability of occurring being 1/10, or 10% in any one year. To determine the precipitation intensity of different return periods, we fit a distribution function of the annual maximum daily precipitation (RX1D) for the baseline and future time periods^{21,22}. RX1D is defined as the annual maxima of daily precipitation amount per year. We fit the RX1D-return period distribution for both historical condition and future warming scenarios. Using these distributions, we estimate the precipitation intensity corresponding to the return period of contemporary asset drainage design into the future distribution function to calculate the return period under the same precipitation intensity. Based on this, we develop an exposure analysis to calculate the amount of assets facing significant return period changes. To describe how precipitation intensity under the contemporary design return period would change in the future, we introduce a design amplification factor to express the ratio of precipitation intensity in the return period of contemporary design to that in the same return period in the future. Figure S1 gives the methodology.

Base design return period for different infrastructure

Considering that countries with different development levels have different design drainage capabilities of transport infrastructures, we divide the countries into four categories — High income, Upper middle income, Lower middle income and Low income—based on the four levels of development standards of World Bank (<https://datahelpdesk.worldbank.org/knowledgebase/articles/906519>). According to Kuznet's theory²³ and the studies of Koks et al.², low income countries usually can't invest much in infrastructure construction, nor guarantee the expenditure on disaster recovery capacity; Lower middle income countries can invest relatively more in infrastructure construction but also can't invest much on disaster recovery capacity; Upper middle income and high income can invest much in both infrastructure construction and disaster recovery capacity, with higher investment in high income countries. Accordingly, we assign different design return periods of drainage system for countries with different income groups (See Table S1).

While there are differences between countries with regards to design standards, the same can be said about different assets: different infrastructure types have different design drainage capabilities. In this study, we have divided the assets into three types: (1) Railway; (2) Motorway/Trunk/Primary/Secondary; and (3) Tertiary. Railways tend to be the most strictly designed infrastructure, followed by Motorway/Trunk/Primary/Secondary, which are usually built using similar engineering design standards²⁴⁻²⁸. The third type, tertiary roads, tends to have uneven quality and may not have professional drainage^{29,30}. The assumptions of design return periods of drainage system of different types of transportation infrastructure are provided in Table S1. We assumed two different design return periods levels: a higher design return periods and the lower return periods.

Fitting function for calculating precipitation under different return periods

To obtain the daily precipitation of each grid in different return periods, the generalized extreme value distribution (GEV) is used. The GEV distribution is parameterized with three parameters including location (μ ; describing the center of distribution), scale (σ ; describing the deviation around the mean) and shape (ξ ; describing the tail behavior of the distribution) of the distribution³¹. We can fit a sample of extremes to the GEV distribution to obtain the parameters that best explains the probability distribution of the extremes. In this study, the GEV parameters were estimated by fitting annual maximum daily precipitation series for each grid, and the GEV parameters were spatially smoothed by averaging the 8 adjacent grids around it. Kolmogorov-Smirnov (KS) test was used to test the fitting degree of the GEV distribution at the significance level of 5%³². L-Moments method was used to estimate GEV distribution parameters (based on the python package "lmoments3", <https://github.com/OpenHydrology/lmoments3>). The data of 30 years was used for both contemporary and future, and the 30 years data was taken from 15 years before and after the warming arrival

year. Spatial smoothing is used to deal with the noise in the models of extreme precipitation variability from the sample, and similar approaches can be found in references ^{21,33}.

Estimation of exposure

We calculated the exposure of the assets at a grid scale. Absolute exposure (AE) describes the total amount of assets exposed to "more frequent extreme precipitation" within a grid, expressed as an 25% decrease in the design return period in the future. Relative exposure (RE) expresses the proportion of assets exposed to a "significant frequency change" within a grid, 25% decrease in the design return period in the future. AE and RE can be adapted as eq. 1 and eq. 2:

$$AE_g = \sum_i^n EL_{i,g} \quad (1)$$

$$RE_g = \frac{1}{TL_g} \times \sum_i^n EL_{i,g} \quad (2)$$

where AE_g is the absolute exposure of grid g ; RE_g is the relative exposure of grid g ; i is the type of asset, with a total of n types; EL_g is the length of the assets exposed to a "significant frequency change" within the grid g ; TL_g is the total length of the assets within the grid g .

Estimation of amplification factor

We used the amplification factor to describe the ratio of future extreme precipitation to contemporary extreme precipitation, as expressed by eq.3:

$$AMF_g = \frac{1}{n} \times \sum_i^n \frac{Rx1d_{f,g}}{Rx1d_{p,g}} \quad (3)$$

where AMF_g is the amplification factor of the grid g ; i is the type of asset, with a total of n types; $Rx1d_{f,g}$ is the future annual maximum daily precipitation in grid g ; $Rx1d_{p,g}$ is the contemporary annual maximum daily precipitation in grid g .

Data

Climate data

Downscaling data from NASA were used in this study, which is based on the 21 models of CMIP5. The BCSD (Bias Correction and Spatial Disaggregation) methods were used to improve the resolution to ~25km. More information is available on <https://nex.nasa.gov/nex/projects/1356/>. Compared with the coarse resolution of CMIP5, NEX-GDDP data shows stronger ability to simulate extreme precipitation.

The timings arriving 1.5°C and 2.0°C warmer world were defined as the year in which the global average temperature first rise to the corresponding temperature compared to the period of the Industrial Revolution (1861-1890). Following this definition, we calculated the year of arrival for each model using CMIP5 mean temperature data. The models we used and the temperature arrival years are provided in Table S2.

We use the multi-model median projected changes to express the spatial distribution, which is a relatively robust way to prevent the overall results from being affected by one model estimation being too high or too low, and make sure that at least half of the models support changes in the same notation.

Infrastructure data

Roads and railways were chosen for our study as the main land transport infrastructure. We extracted these data as of March 2020 from OpenStreetMap (OSM). OSM is a large and open global infrastructure database that is now at a high level of completion, which has been widely used in various research^{2,34,35}. Based on OSM's classification of roads, we chose the most important five categories of roads, i.e. motorway, trunk, primary, secondary and tertiary, which is principal connectors of the cities, towns and villages. Other roads, such as footway, were not considered as it is often uncertain whether drainage design has been considered when they were built. Table S3 gives the description and length of different categories of transportation assets and their spatial distribution is given in Fig.S2.

References

1. Hallegatte, S., Rentschler, J. & Rozenberg, J. *LIFELINES: The resilient infrastructure opportunity*. (World Bank Publications, 2019).
2. Koks, E. E. *et al.* A global multi-hazard risk analysis of road and railway infrastructure assets. *Nature communications* **10**, 1–11 (2019).

3. The New Times. *Relief as traffic resumes on Tanzania highway*, <<https://www.newtimes.co.rw/news/relief-traffic-resumes-tanzania-highway>> (2020).
4. FloodList. *Jamaica – Over 280 Roads Damaged by Floods From Tropical Storms Eta and Zeta*, <<https://floodlist.com/america/jamaica-flood-damage-eta-zeta-november-2020>> (2020).
5. BBC News. *Storm Alex: Buildings, roads and bridges destroyed in southern France*, <<https://www.bbc.com/news/av/world-europe-54404754>> (2020).
6. The Guardian. *Flash floods cause havoc across Europe – in pictures*, <<https://www.theguardian.com/environment/gallery/2021/jul/15/flash-floods-cause-havoc-across-europe-in-pictures>> (2021).
7. Global Times. *Eurasian train resumes as flood recedes in Zhengzhou*, <<https://www.globaltimes.cn/page/202107/1229670.shtml>> (2021).
8. Seneviratne S.I. *et al.* Weather and Climate Extreme Events in a Changing Climate. (2021).
9. Easterling, D. R. *et al.* Climate extremes: observations, modeling, and impacts. *science* **289**, 2068-2074 (2000).
10. Fischer, E. M., Beyerle, U. & Knutti, R. Robust spatially aggregated projections of climate extremes. *Nature Climate Change* **3**, 1033–1038 (2013).
11. CCTV news. *24 hours 622.7mm! Record rainfall has broken in Zhengzhou, Henan Province*, <https://web.archive.org/web/20210721125656/https://www.thepaper.cn/newsDetail_forward_13673710> (2021).
12. Rozenberg, J. & Fay, M. *Beyond the gap: How countries can afford the infrastructure they need while protecting the planet*. (World Bank Publications, 2019).
13. Van Ginkel, K. C., Dottori, F., Alfieri, L., Feyen, L. & Koks, E. E. Flood risk assessment of the European road network. *Natural Hazards and Earth System Sciences* **21**, 1011–1027 (2021).
14. Colon, C., Brännström, Å., Rovenskaya, E. & Dieckmann, U. Fragmentation of production amplifies systemic risks from extreme events in supply-chain networks. *Plos one* **15**, e0244196 (2020).
15. Colon, C., Hallegatte, S. & Rozenberg, J. Criticality analysis of a country's transport network via an agent-based supply chain model. *Nature Sustainability* **4**, 209–215 (2021).
16. Power, S. B., Delage, F., Colman, R. & Moise, A. Consensus on twenty-first-century rainfall projections in climate models more widespread than previously thought. *Journal of Climate* **25**, 3792–3809 (2012).
17. Solomon, S. *et al.* Climate change 2007: The physical science basis. *Intergovernmental Panel on Climate Change (IPCC)*, Cambridge University Press, Cambridge (2007).
18. World Bank. *New World Bank country classifications by income level: 2020-2021*, <<https://blogs.worldbank.org/opendata/new-world-bank-country-classifications-income-level-2020-2021>> (2020).
19. Almansour, H., Cusson, D. & Lounis, Z. Climate resilient bridges-state of practice. in *10th International Conference on Short and Medium Span Bridges*.
20. Yang, Y., Li, M., Xiong, M. & Cao, J. Return period for urban rainwater drainage networks based on the lowest total social investment method: a case study in Tianjin, China. *Polish Journal of Environmental Studies* **28** (2019).

21. Zhang, W., Zhou, T., Zou, L., Zhang, L. & Chen, X. Reduced exposure to extreme precipitation from 0.5°C less warming in global land monsoon regions. *Nature Communications* **9**, 1–8 (2018).
22. Hirabayashi, Y. *et al.* Global flood risk under climate change. *Nature climate change* **3**, 816–821 (2013).
23. Stern, D. I. The rise and fall of the environmental Kuznets curve. *World development* **32**, 1419–1439 (2004).
24. GYMREIG, Y. S. & IRELAND, N. Introduction to the Design Manual for Roads and Bridges. (1997).
25. Spink, T., Duncan, I., Lawrance, A. & Todd, A. Transport infrastructure drainage: condition appraisal and remedial treatment. *CIRIA, London* (2014).
26. Sañudo, R., Miranda, M., García, C. & García-Sánchez, D. Drainage in railways. *Construction and Building materials* **210**, 391–412 (2019).
27. Fei Yueying & Yang, Y. Study on the determination of rainfall return period of railway subgrade drainage facilities. *Subgrade Engineering* **3**, 100–101 (2009).
28. Han Liu & Weiping, T. Investigation on design of rainfall reappearing period in highway drainage facilities. *Technology of Highway and Transport*, 22–24 (2009).
29. JICA. Preparatory Survey for Road Network Development Project in Conflict-Affected Areas in Mindanao. (Republic of the Philippines Department of Public Works and Highways, 2018).
30. White, S. J. Maintenance and Control of Erosion and Sediment Along Secondary Roads and Tertiary Trails. (Construction Engineering Research Lab (Army) Champaign IL, 1997).
31. Hosking, J. R. M., Wallis, J. R. & Wood, E. F. Estimation of the generalized extreme-value distribution by the method of probability-weighted moments. *Technometrics* **27**, 251–261 (1985).
32. Massey Jr, F. J. The Kolmogorov-Smirnov test for goodness of fit. *Journal of the American statistical Association* **46**, 68–78 (1951).
33. Kharin, V. V. & Zwiers, F. W. Estimating extremes in transient climate change simulations. *Journal of Climate* **18**, 1156–1173 (2005).
34. Meijer, J. R., Huijbregts, M. A., Schotten, K. C. & Schipper, A. M. Global patterns of current and future road infrastructure. *Environmental Research Letters* **13**, 064006 (2018).
35. Barrington-Leigh, C. & Millard-Ball, A. The world's user-generated road map is more than 80% complete. *PloS one* **12**, e0180698 (2017).

Figures

Figure 1

Multi-model median return period for precipitation in future for the 1-in-10-year precipitation based 1971-2000.
a) 1.5 °C warming under RCP4.5 scenario b) 2 °C warming under RCP4.5 scenario c) 1.5 °C warming under RCP8.5 scenario d) 2 °C warming under RCP8.5 scenario.

Figure 2

Percentage of transportation assets facing a change of return periods. (black line: no change; orange color: 25% decrease; red color: 50% decrease)

Figure 3

Absolute global transport infrastructure exposure exceeding 25% shorten in precipitation design return periods.
a) 1.5 °C warming under RCP4.5 scenario b) 2 °C warming under RCP4.5 scenario c) 1.5 °C warming under RCP8.5 scenario d) 2 °C warming under RCP8.5 scenario.

Figure 4

Relative global transport infrastructure exposure exceeding 25% shorten in precipitation design return periods change. a) 1.5 °C warming under RCP4.5 scenario b) 2 °C warming under RCP4.5 scenario c) 1.5 °C warming under RCP8.5 scenario d) 2 °C warming under RCP8.5 scenario

Figure 5

Exposure exceeding 25% shorten in precipitation design return periods for four income group a) Absolute exposure under RCP4.5 scenario b) Absolute exposure under RCP8.5 scenario c) Relative exposure under RCP4.5 scenario d) Relative exposure under RCP8.5 scenario. (sky color represents multi-model median results, deep color represents the part of 2/3 models agree)

Figure 6

Ranking of countries exposure exceeding 25% change in the precipitation design return periods a) Ranking of countries in absolute exposure under RCP4.5 scenario b) Ranking of countries in absolute exposure under RCP8.5 scenario c) Ranking of countries in relative exposure under RCP4.5 scenario d) Ranking of countries in relative exposure under RCP8.5 scenario

(sky color represents multi-model median results, deep color represents the part of 2/3 models agree)

Figure 7

Amplification factor to current design standards. a) 1.5 °C warming under RCP4.5 scenario b) 2 °C warming under RCP4.5 scenario c) 1.5 °C warming under RCP8.5 scenario d) 2 °C warming under RCP8.5 scenario

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