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Changes in the exposure of California's levee-protected critical infrastructure to flooding hazard in a warming climate

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Abstract

Levee systems are an important part of California's water infrastructure, engineered to provide resilience against flooding and reduce flood losses. The growth in California is partly associated with costly infrastructure developments that led to population expansion in the levee protected areas. Therefore, potential changes in the flood hazard could have significant socioeconomic consequences over levee protected areas, especially in the face of a changing climate. In this study, we examine the possible impacts of a warming climate on flood hazard over levee protected land in California. We use gridded maximum daily runoff from global circulation models (GCMs) that represent a wide range of variability among the climate projections, and are recommended by the California's Fourth Climate Change Assessment Report, to investigate possible climate-induced changes. We also quantify the exposure of several critical infrastructure protected by the levee systems (e.g. roads, electric power transmission lines, natural gas pipelines, petroleum pipelines, and railroads) to flooding. Our results provide a detailed picture of change in flood risk for different levees and the potential societal consequences (e.g. exposure of people and critical infrastructure). Levee systems in the northern part of the Central Valley and coastal counties of Southern California are likely to observe the highest increase in flood hazard relative to the past. The most evident change is projected for the northern region of the Central Valley, including Butte, Glenn, Yuba, Sutter, Sacramento, and San Joaquin counties. In the leveed regions of these counties, based on the model simulations of the future, the historical 100-year runoff can potentially increase up to threefold under RCP8.5. We argue that levee operation and maintenance along with emergency preparation plans should take into account the changes in frequencies and intensities of flood hazard in a changing climate to ensure safety of levee systems and their protected infrastructure.

1. Introduction

Levees are crucial water infrastructure systems that are engineered to provide resilience against flooding events. These man-made structures are among the critical water infrastructure systems to protect adjacent drylands and floodplains from flooding and associated damages (ASCE 2009, Barbetta *et al* 2017, Peyras *et al* 2017). Building levee systems provides a sense of security against flooding events in the levee protected regions (Di Baldassarre *et al* 2015), which along with the advantages of living in close proximity to water attract population growth within

leveed protected regions (Di Baldassarre *et al* 2013, 2018, Collenteur *et al* 2015, Barendrecht *et al* 2017, Hutton *et al* 2018). The integrity of levee systems in California, the nation's most populous state and largest agricultural producer with more than 15 000 km of levees (USACE 2018), is an important concern requiring urgent attention. (Burton and Cutter 2008) indicated that around 1.3 million people, mostly low-income and elderly, are at risk of possible levee failure in the Sacramento, San Joaquin, and Yolo counties. Recently, during a flood event generated by a series of extreme precipitation events, a levee break near Manteca,

California resulted in the evacuation of 500 residents (Vahedifard *et al* 2017).

A majority of levees in the United States and in particular in California are earthen systems that were built in the previous century based on the stationary assumption with data records of the time (Remo *et al* 2009, Dierauer *et al* 2012, Salas and Obeysekera 2014, Vahedifard *et al* 2015, 2016, ASCE 2017). The stationary assumption indicates that the distribution of past observed events is representative of possible future conditions (Sadegh *et al* 2015, 2019). However, numerous studies in recent years contradicted with the stationary assumption and showed that changes in climate are anticipated to alter the characteristics of flooding events (e.g. Barnett *et al* 2005, Kundzewicz *et al* 2014, Mallakpour and Villarini 2015, Asarian and Walker 2016, Asadieh and Krakauer 2017, Ehsani *et al* 2017, Najibi *et al* 2017). For instance, (Das *et al* 2013) projected about 30%–100% increase in the magnitude of annual maximum streamflow over California. Also, (Mallakpour *et al* 2018) showed that while the annual average daily discharge is projected to remain unchanged over California, the magnitude of the annual maximum daily discharge is projected to increase significantly by the end of this century. For coastal southern California, (Feng *et al* 2019) projected that 100-year flood magnitude could increase up to 185% due to global warming.

Literature shows that part of the observed increase in flood damage over the United States can be attributed to the growth in human activities over flood-prone regions (e.g. Pielke and Downton 2000, Gall *et al* 2011, Peterson *et al* 2013). (Heine and Pinter 2012) conceptually and empirically showed the effect of constructing levees on discharge and adjacent floodplain. They indicated that building levees can decrease the area of land that can store flood water, and can result in a higher flood risk upstream of levee infrastructure. Changes in climate can also result in possible changes in intensity and frequency of flood events that will in turn impact the flooding risk (Moftakhari *et al* 2017, Sadegh *et al* 2018). Possible increase in the flood hazard could cause large socioeconomic consequences over the leveed region. (Florsheim and Dettinger 2007) investigated levee breaks in California from 1852–2006 and reported that ‘*the long-term climate and flood variability govern levee breaks.*’ (Florsheim and Dettinger 2015) indicated that 81% of levee failure in the Central Valley of California since 1951 happened due to wintertime flooding generated by warm and wet storms transported by atmospheric rivers (AR) during the winter season. Also, (Deverel *et al* 2016) identified the impacts of climate change on flooding as one of the challenges that threaten the integrity of levee systems across California in the future.

This paper seeks to address the possible changes in the direction of flood hazard over the leveed area of California and quantify the change in the exposure

of critical infrastructure (e.g. roads, electric power transmission lines, natural gas pipelines, petroleum pipelines, and railroads) to flood hazard. The overarching goal of this study is to define the vulnerability of leveed systems across California to possible changes in the future flood hazard. We use four global circulation models (GCMs) from the Fifth Coupled Model Intercomparison Project (CMIP5) to investigate the possible relative changes in the future flood hazard. These four models best represent historical observations in California among the 32 GCMs investigated by the 4th California Climate Assessment workforce, and are deliberately selected to portray a wide range of variability among climate projections. The false sense of security against flooding events motivated humans to boost development across the leveed areas, a notion known as levee effect (Hutton *et al* 2018); which in turn increases vulnerability of human settlements to flooding hazards, especially in a changing climate (Ludy and Kondolf 2012). Therefore, potential changes in flood hazard could leave very large economic and social repercussions over the leveed area (e.g. fatalities, agricultural losses, property losses). The insights gained from this study will help water manager and risk management community to get a crucial understanding of the potential threats of future flood hazard in the California levee protected regions. Findings of this study will inform necessary mitigation actions in a timely manner to adapt levee and critical infrastructure systems to the possible changes in the future. To our knowledge, this is the first study that identifies possible future changes in the flood hazard in a changing climate and its consequences on the levee protected regions of California. A comprehensive flood risk assessment in leveed areas is a function of three components, hazard (likelihood of the flood event), exposure (assets and population exposed to the flood events), and vulnerability (capacity of a system to damp the impact of a flood event; e.g. Collenteur *et al* 2015, USACE 2018). Here, we only focus on the direction of flood hazard changes and critical infrastructure exposure to these changes.

2. Data and method

This study focuses on the levee protected areas of California based on the National Levee Database (NLD) maintained by the U.S. Army Corps of Engineers (USACE) (NLD 2018). There are 3242 levee systems in California with an average age of 57 years. In this state, 82% of counties (48 counties) have at least a levee system with a 1 km length. For California, levee systems play an important role by protecting over 6 million people, and an estimate of \$8 billion in the property (NLD 2018). All information related to the location of levee systems and their protected area were obtained from the NLD dataset (figure S1(stacks.iop.org/ERL/15/064032/mmedia)).

We used simulated daily gridded total runoff (mm/day) to assess the impacts of climate change on flood hazards over the leveed area. This dataset has a horizontal grid resolution of 0.0625° (approximately 6 km) for the period of 1950–2099. Flooding in the levee protected regions can occur due to levee overtopping and breaching, prolonged extreme precipitation events over the levee protected area, and water going around the floodwalls (USACE 2018). Total runoff is a proper hydrological variable to represent the changes in flood hazard over levee protected areas, as it incorporates all of the aforementioned flood conditions.

The gridded total runoff was developed at the Scripps Institution of Oceanography, University of California, San Diego, and was obtained from the web-based climate adaptation planning tool (Cal-Adapt 2019). They used the high-resolution Localized Constructed Analogs (LOCA) downscaled and bias-corrected minimum and maximum temperature, and precipitation to force the Variable Infiltration Capacity (VIC; Lohmann *et al* 1996, 1998) hydrological model to calculate different hydroclimate variables such as the total runoff (details are described in Pierce *et al* 2016, 2018). The VIC model parameters were calculated based on the University of Colorado hydrological dataset for California (Livneh *et al* 2013). Researchers use downscaling techniques to refine the coarse spatial resolution in the GCMs for climate change impacts assessment studies (Mehrotra and Sharma 2015). The LOCA method has been adopted by the 4th California Climate Assessment workforce as the downscaling technique. The LOCA method computes the downscaled minimum and maximum temperature, and precipitation using a multiscale spatial matching framework in order to pick the suitable analog days from the historical observations for each grid. (Pierce *et al* 2014) indicated that the LOCA method is a framework that can preserve regional patterns in temperature and precipitation. Climate model simulations are subject to biases and uncertainties, hence bias correction methods are often used to improve the LOCA forcing.

The gridded total runoff dataset used in this study is based on four GCMs, namely HadGEM2-ES (Jones *et al* 2011), CNRM-CM5 (Voldoire *et al* 2013), CanESM2 (Chylek *et al* 2011) and MIROC5 (Watanabe *et al* 2010) from the CMIP5 that represent warm/dry, cool/wet, average and complement climate conditions across California for two representative concentration pathways (RCPs): RCP4.5 (relatively moderate scenario) and RCP8.5 (business as usual scenario; (Climate Change Technical Advisory Group (CCTAG, 2018)). As described by (Pierce *et al* 2016) these four GCMs were selected from the 32 different CMIP5 models for climate change impacts assessment studies in California. We chose these four models recommended by

the Climate Action Research Working Group of the 4th California's Climate Change Assessment, because the future climate related policies in California will be devised based on the outputs of these models (California Department of Water Resources (CDWR, 2015)). Our selected models represent a wide range of variability between climate projections. We emphasize that climate models display a range of variation that can influence the estimation of flood hazard (Giuntoli *et al* 2015, Mehrotra and Sharma 2016). However, they are useful means that can inform possible changes in flood hazard under the projected climate change scenarios.

To assess the extent of critical infrastructure located in the leveed area, we used several publicly available datasets (all updated in 2018):

- (a) The distribution of natural gas pipelines, and petroleum pipelines were obtained from the U.S. Energy Information Administration (EIA 2018).
- (b) The distribution of electric power transmission, including lines that convey high voltages varying from 69 kV up to 765 kV, and railroads were obtained from the Homeland Infrastructure Foundation-Level Data (HIFLD 2018).
- (c) Information related to the roads was acquired from the Topologically Integrated Geographic Encoding and Referencing (TIGER) product developed by the United States Census Bureau (TIGER 2018).

These are among the critical infrastructure important for the economic and social growth in the region, and are spatially distributed inside the leveed protected regions. Initially, we calculated the length of roads, electric power transmission conductors, natural gas pipelines, petroleum pipelines, and railroads that are protected by levee systems. We assumed that a possible change in the flood hazard of a levee system would equally impact the exposure of all the infrastructure within that system. The exposure of an individual infrastructure depends on factors such as distance to water bodies, size of the watershed, land use and land cover, topography and their position relative to the ground level. As indicated by (Moftakhari and Aghakouchak 2019), a comprehensive assessment of risk associated with the change in hazards should consider these factors as well.

We used the Generalized Extreme Value (GEV) distribution to estimate the flood frequency distribution for each of the levee systems. We first utilize the annual block maximum sampling technique to extract the maximum daily runoff for each year and for each of the four climate models and two scenarios. Then, we fit the GEV distribution to estimate the flood frequency distribution for each pixel using extReme 2.0 package in R (Gilleland and Katz 2016).

The cumulative distribution function of the GEV distribution can be written as (Coles 2001, Cheng *et al* 2014):

$$F(x; \mu, \sigma, \xi) = \exp \left\{ - \left[1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right]^{-1/\xi} \right\} \quad (1)$$

where μ is the location parameter, σ is the scale parameter and ξ is the shape parameter. To estimate these parameters, we used the maximum likelihood method (Coles 2001; Rahnamay Naeini *et al* 2018). This statistical model has been used in many hydrological studies to characterize the behavior of extreme events (Katz *et al* 2002, Aghakouchak 2013, Cheng *et al* 2014). The GEV distribution adequately represents the tail properties of peak runoff distribution according to the bootstrap p-values of the goodness-of-fit tests (the Kolmogorov–Smirnov, Anderson–Darling, and Cramer–von Mises tests (figure S2–S4)), that are larger than 5% in all the cases. Using the extreme value theory, we then computed the percent change between the magnitudes of a 100-year runoff in the future (2020–2099) relative to the historical (1950–2005) period as an indicator of change in the flood hazard for each pixel and for each climate model and scenario using normalized percent change:

$$\frac{\text{Future} - \text{Historical}}{\text{Historical}} \times 100 \quad (2)$$

Then, we spatially averaged the percent change in the magnitude of the 100-year runoff over each levee protected area to compute the change in the flood hazard for each levee system. In this study, we used the 100-year runoff concept since the majority of levee systems in California have been designed to withstand at least a peak flow with a 1% annual chance of occurrence (i.e. 100-year flood; Burton and Cutter 2008, Ludy and Kondolf 2012). Moreover, the 100-year flood was selected as the minimum flood protection level by the US National Flood Insurance Program (NFIP) and Federal Emergency Management Agency (FEMA). Based on FEMA guideline a levee system can be accredited (i.e. certified to provide protection against a base flood) that protect floodplain from 100-year event.

3. Results and discussion

We first quantify the length of roads, electric power transmission conductors, natural gas pipelines, petroleum pipelines, and railroads that are protected by each of the Californian levee systems using the NLD and critical infrastructure datasets (figure 1; Table S1 summarizes the results). Figure 1(A) shows the length of paved roads protected by each of the levee systems across California. This figure reveals that the highest length of roads is protected by the ‘Santa Ana River 1’ levee system (~2890 km) in Southern California followed by ‘MA-09 of City of Sacramento’

(~2650 km) and ‘Sacramento River West Bank’ levee systems (~1500 km) in California’s Central Valley. Figure 1(B) presents the length of electric power transmission conductors inside leveed regions, where ‘MA-09 of City of Sacramento’ and ‘Santa Ana River 1’ levee systems protect the highest length of electrical conductors (~404 km and ~360 Km, respectively).

Figure 1(C) depicts the length of natural gas pipelines located within the service area of each levee system across California, where the ‘Sacramento River West Bank’ levee system has the highest length of pipelines (~183 km). For Southern California, exposure of gas pipelines is relatively higher for the levee systems that are closer to the coast. In this region, the highest length of natural gas pipelines is located inside the ‘Santa Ana River 1’ levee system (~54 km) in Orange County. For Los Angeles County, the ‘Los Angeles River/Compton Creek 2’ levee system has the highest length of natural gas pipelines (~40 km). Figure 1(D) shows the length of petroleum pipelines inside the levee systems in California, where the ‘San Joaquin County Levee 96’ (~165 km) in the Central Valley protects the highest length of petroleum pipelines. Figure 1(E) displays the length of railroads surrounded by each levee system. Here, the ‘MA-09 of City of Sacramento’ levee system, followed by ‘Santa Ana River 1’, has the highest length of railway tracks (~90 km and ~50 km, respectively). In general, levee systems located over the northern part of the Central Valley and coastal counties of Southern California (Los Angeles and Orange Counties) contain the highest length of critical infrastructure systems.

After computing the length of critical infrastructure within the service area of the levee systems across California, it is vital to investigate how the flood hazard would possibly change for them in a changing climate. Figure 2 show the percent change in the magnitude of a 100-year runoff in the future relative to the baseline period as a proxy to examine the direction of changes in the flood hazard under RCP 4.5. The spatially distributed results show that there is a significant number of levee systems that exhibit increase in the magnitude of 100-year runoff in the projection period relative to the historical period. The CanESM2 model, which is projected to be associated with an average climate condition for the state of California in the future, shows that other than levee systems located in the southern part of the Central Valley with up to 68% projected decrease in the flood hazard, all the levee systems will likely experience a higher flood hazard up to a threefold increase by the end of this century (figure 2(A)). Under the CanESM2 projections, about 30% of the levee systems across California show a decrease in their flood hazard in the future. The CNRM-CM5 model, which represents a cool and wet condition across California in the future, shows the highest increase in the magnitude of 100-year runoff relative to the other three models (figure 2(B)). Under this model, about 93% of the levee systems display

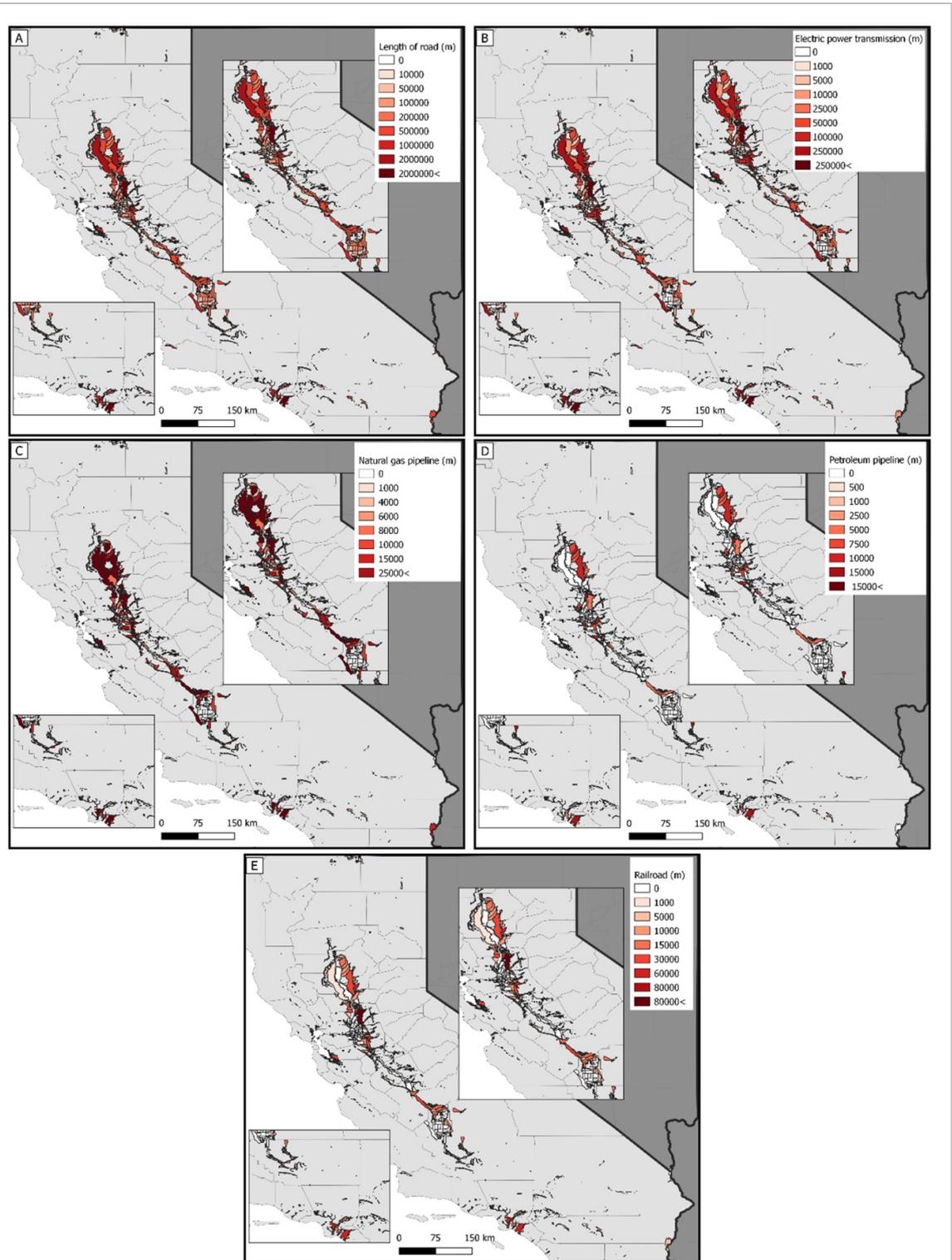


Figure 1. The length of (A) roads, (B) electric power transmission lines, (C) natural gas pipelines, (D) petroleum pipelines, and (E) railroads that are protected by the levee systems over California. Polygons show the levee protected regions in California. Inset maps in each panel show the map of levee systems of California's central valley (right inset map) and levees over Southern California (left inset map). Darker red color shows a higher length of the infrastructure is protected by a levee system.

increase in the flood hazard (up to five times more likely) in the future. Figure 2(C) shows the result for HadGEM2-ES, a model that represents a warmer and dryer future across California, where about 26% of the levee systems display up to 65% decrease in the magnitude of 100-year runoff in the future. However, even with this model, a substantial number of levee

systems (about 74%) are projected to have at least a slight increase in the magnitude of 100-year runoff. Results for projected change in the magnitude of 100-year runoff for MIROC5 model (representing a complement climate condition) reveal that the levee systems in northern and central parts of the Central Valley show an increase up to twofold in flood hazard

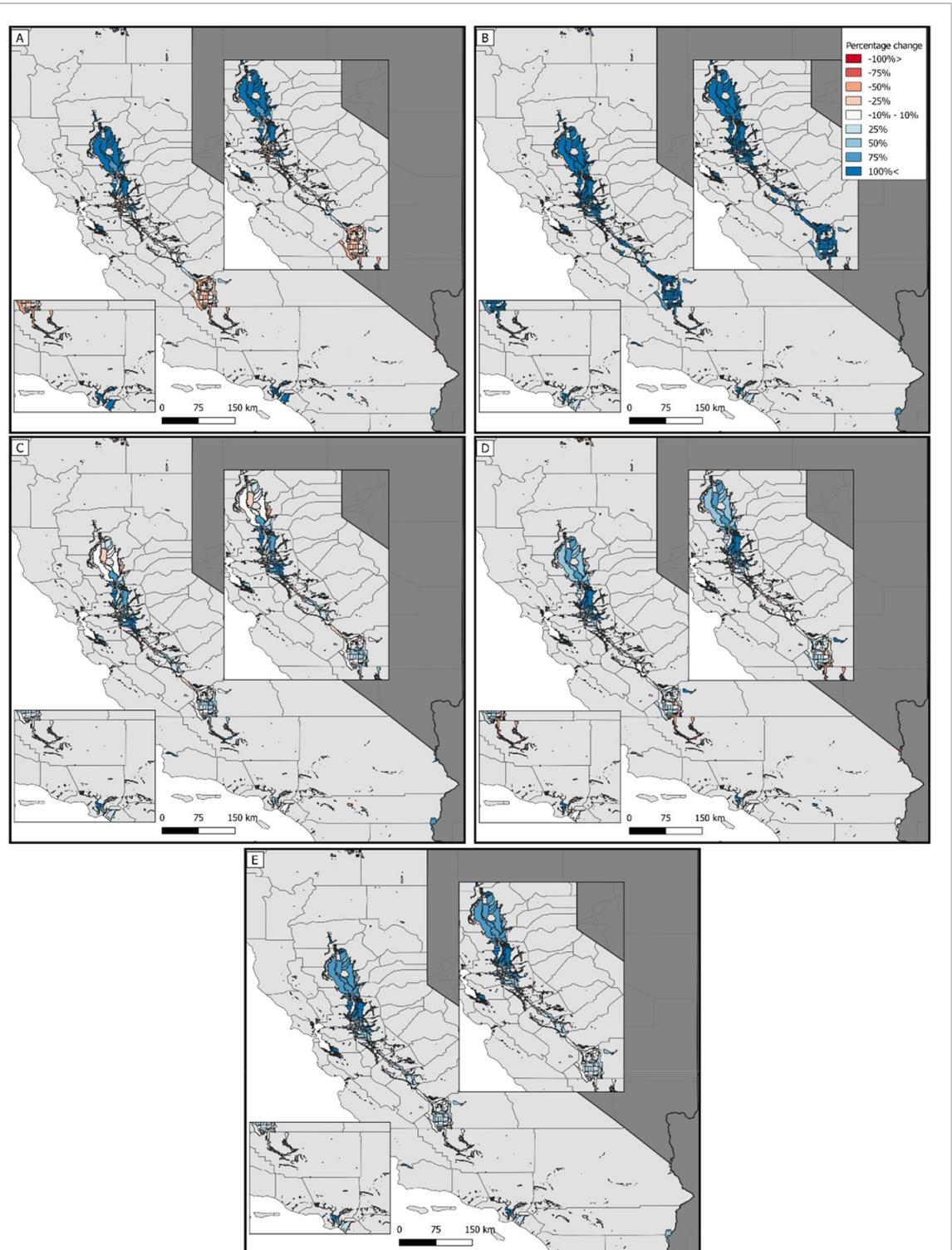
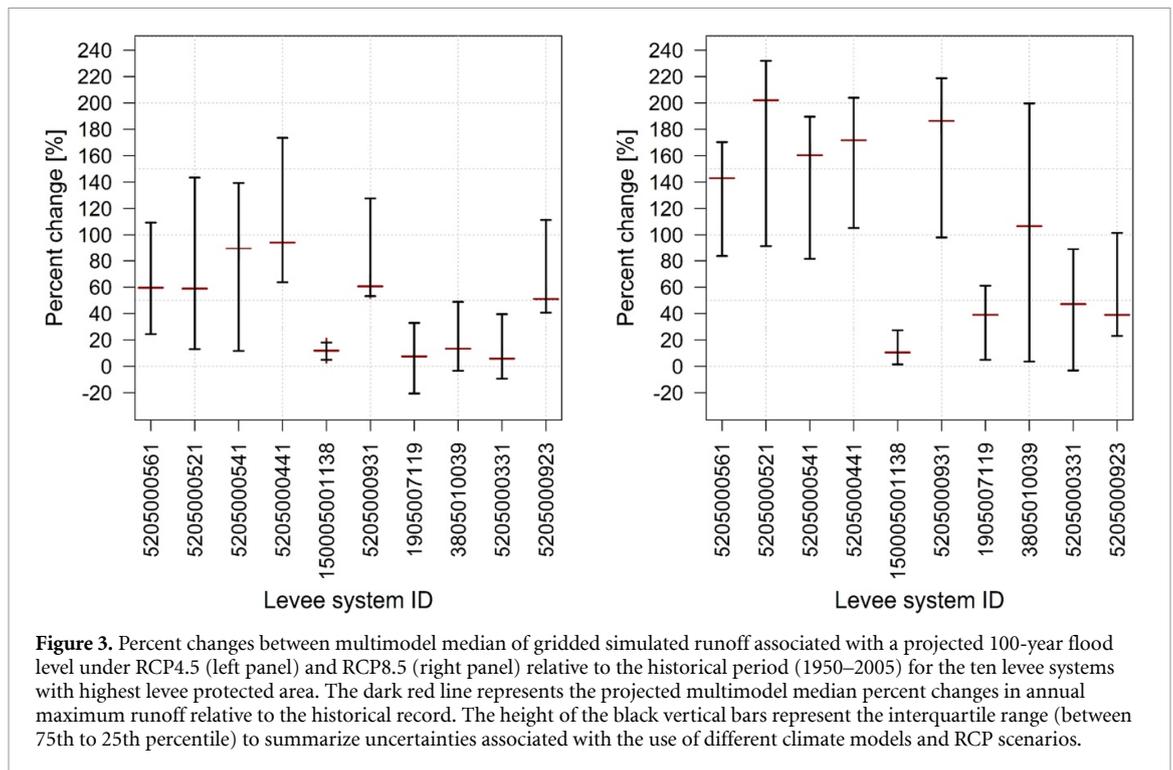


Figure 2. Percent changes in the spatial averaged magnitude of 100-year runoff in the projected period (2020–2099) relative to the baseline period (1950–2005) for (A) CanESM2, (B) CNRM-CM5, (C) HadGEM2-ES, (D) MIROC5, and (E) ensemble median of climate models under RCP4.5 scenario over the leveed region of California. Polygons show the levee protected regions in California. The color bar displays the percentage change [%] in the magnitude of 100-year runoff where the blue (red) color shows levee systems that magnitude of the 100-year runoff expected to increase (decrease) under a warming climate in the future. Inset maps in each panel show map of levee systems of California's central valley (right inset map) and levees over Southern California (left inset map).

in the future, while southern regions show a decreasing pattern up to 70% in the magnitude of the 100-year runoff (figure 2(D)). Under the MIROC5 model, about 65% of the levee systems show increase in the flood hazard in the future. Figure 2(E) summarizes

the projected change in the flood hazard in the leveed areas of California based on the ensemble median of the four climate models in this study. The results depict that the direction of change in the frequency of high runoff events is likely toward increasing pattern



(up to twofold) across the leveed area of California, with about 86% of levee systems showing at least a slight increase in the magnitude of 100-year runoff. Expectedly, the increasing pattern is more marked under the RCP8.5 (figure S5 and table S1) for all models and the multimodel median.

The most evident change occurs in the northern region of the Central Valley, including Butte, Glenn, Yuba, Sutter, Sacramento, and San Joaquin counties. These counties may experience up to a threefold increase in the flood hazard relative to the historical period, on average, based on RCP 4.5. In general, annual precipitation in northern California is higher than southern California (Jones 2000, Swain *et al* 2018). The projected increase in the runoff can be attributed to earlier snowmelt, intensification of precipitation events, and more precipitation falling as rain rather than snow (e.g. Dettinger and Cayan 1995, Stewart *et al* 2005, Das *et al* 2011, Ragno *et al* 2018). This becomes even more important given majority of levee breaks across California historically happened in the November to June period, emphasizing the important role of winter storms (Florsheim and Dettinger 2007, 2015). For instance, (Florsheim and Dettinger 2015) identified wintertime AR precipitation events as the main cause for levee failures in California's Central Valley. (Espinoza *et al* 2018) and (Jeon *et al* 2015) projected that AR events would bring more frequent and severe precipitation events to California in a warming climate. The projected increases in AR events might lead to an increase in the severity of flood hazard that can affect the leveed regions.

To explore the uncertainty related to the estimate of the flood hazard with GCMs, we examine the percent changes between multimodel median of annual maximum runoff associated with the projected 100-year runoff level under RCP4.5 (figure 3) and RCP8.5 (figure S6) relative to the baseline period for ten levee systems with the highest service lands. Red lines, in figure 3, signify the most likely change in the flood hazard and interquartile range show variability between different climate models used in this study. This figure implies that while uncertainty from different sources including the climate models and scenarios are present, there is an agreement between climate models that flood hazard over these ten levee systems is likely to increase in the future. For these ten levee systems, the multimodel median of flood hazard project, on average, about 45% (110%) increase in the flood hazard in the future under RCP 4.5 (8.5). Therefore, there is a greater chance that the flood hazard for these ten leveed regions to increase under the high greenhouse gas concentration levels (RCP 8.5). We acknowledge the uncertainties associated with runoff projections that cascade from the GCM forcing into the VIC model simulations, which are in turn compounded by the VIC model structural and parameter uncertainties. Moreover, flood frequency analysis (through choice of distribution and its parameters) also introduces a level of uncertainty to the analysis. However, GCM projections are the state-of-the-art method for projection of future hazards, and are proven valuable for devising adaptation strategies (e.g. van Vliet *et al* 2016). For a detailed discussion of the uncertainty sources in flood frequency

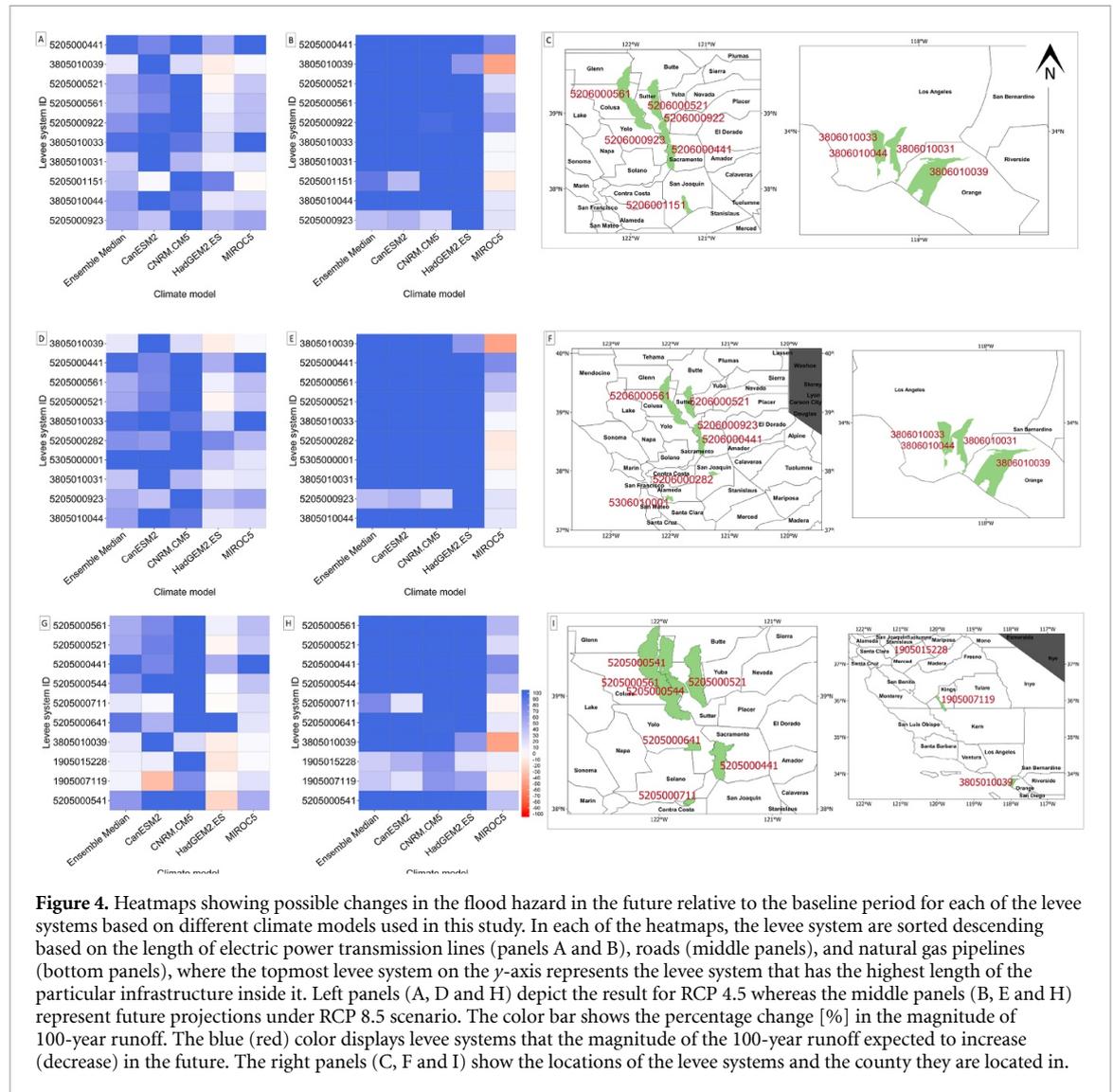


Figure 4. Heatmaps showing possible changes in the flood hazard in the future relative to the baseline period for each of the levee systems based on different climate models used in this study. In each of the heatmaps, the levee system are sorted descending based on the length of electric power transmission lines (panels A and B), roads (middle panels), and natural gas pipelines (bottom panels), where the topmost levee system on the y-axis represents the levee system that has the highest length of the particular infrastructure inside it. Left panels (A, D and H) depict the result for RCP 4.5 whereas the middle panels (B, E and H) represent future projections under RCP 8.5 scenario. The color bar shows the percentage change [%] in the magnitude of 100-year runoff. The blue (red) color displays levee systems that the magnitude of the 100-year runoff expected to increase (decrease) in the future. The right panels (C, F and I) show the locations of the levee systems and the county they are located in.

analysis using GCM projections, refer to (Mallakpour et al 2019).

Next, we provide a detailed analysis of the levee systems that are more susceptible to exposure of critical infrastructure to the projected changes in the flood hazards in the future (figure 4 and table S1). For the sake of brevity, we only present results for the ten levee systems that encompass the highest length of electric power transmission (figure 4 top panels), roads (figure 4 middle panels), and natural gas pipelines (figure 4 bottom panels). Right panels in figure 4 show the location and county of these leveed protected regions. Table S1 in the supplementary material enlists the flood hazard susceptibility results for all of the levee systems and for all of the critical infrastructure systems of this study. In figure 4, each cell represents percentage change in the magnitude of the 100-year runoff as a proxy to evaluate future changes in the flood hazard in the service area of each levee system based on the aforementioned four models and their ensemble median. Here, the multimodel median values summarize the possible

values of the magnitude and direction of changes in the flood hazard in the future. In addition, the magnitude and direction of flood hazard level for the four models represent the possible range of uncertainties associated with the use of different GCMs. Figure 4 shows that from the ten studied levee systems, at least two show more than 80% increase in the ensemble median of the flood hazard under RCP 4.8. These numbers increase significantly under RCP 8.5. Under the RCP 8.5 scenario, as expected, increases in the flood hazard are more marked and larger on average.

The information provided here can be used by water managers to prioritize resources allocated for rebuilding and maintaining the levee systems based on possible changes in the flood hazard and exposure of the critical infrastructure to the projected change in flood hazard in a warming climate. For example, the highest length of roads is located within ‘Santa Ana River 1’ (ID = 3805 010 039) that shows a relatively small increase in the flood hazard. However, the second ranked levee system with the highest length of roads is ‘MA 09—City of Sacramento’

(ID = 5205 000 441), which is relatively more susceptible to change in the flood hazard. Based on these results, water managers can invest on emergency preparation plans to increase resiliency and improve response effectiveness that can lead to a reduction in potential loss of life and property during a possible levee incident (Ludy and Kondolf 2012).

4. Conclusions

We investigate the possible impacts of a changing climate on flood hazard across levee protected lands in California based on the US Army Corps of Engineers levee portfolio. We use gridded maximum daily runoff from four GCMs that are recommended by the California's Fourth Climate Change Assessment under RCP4.5 and RCP8.5 scenarios. We also quantify the possible changes in the exposure of critical infrastructures (e.g. roads, electric power transmission lines, natural gas pipelines, petroleum pipelines, and railroads) to flood hazard. Thereby, we identify levee systems that are susceptible to projected changes in the flood hazard. We calculate the length of each of the critical infrastructure protected by the levees across California. While projections in the flood hazard change varies across climate models, and is subject to uncertainty, their estimates predominantly point to a higher flood hazard in the leveed regions of California. In general, changes in the flood hazard under the RCP 8.5 pathway are more pronounced, indicating that under a high emission scenario (business as usual), we will likely encounter higher high runoffs with magnitudes of up to threefold larger.

Our results demonstrate that levee systems in the northern part of the Central Valley and coastal counties of Southern California, which are the most populous areas of the state, experience the highest likelihood of changes in the flood hazard. Consequently, the infrastructure protected by these levee systems are expected to observe substantially higher rates of exposure to flooding in the future. These possible changes in the flood hazard are neither considered in the current levee assessments nor in the future water resource planning and management for the levee operation and maintenance. Climate change is expected to accelerate the global hydrological cycle, and increase the number of extremely dry and wet years across California (Swain *et al* 2018). (Ragno *et al* 2018) showed that intensity, duration, and frequency of future extreme precipitation events are likely to increase in California; hence, the enhanced risk associated with flooding over the leveed regions cannot be neglected. Moreover, the leveed areas can experience additional loss of lives, since during a flood event, the power outage and roadblock can delay emergency response. Our study provides a deeper understanding of the expected changes in the hazard

levels of the critical infrastructure in the future relative to the past. In more detail, we identify particular levee systems that are more susceptible to exposure of critical infrastructure to the projected changes in the flood hazards.

Note that the results of this study do not indicate that levee systems, or the critical infrastructure within their service area, are in any immediate danger of failure. Here, in face of the modeling uncertainties, we focus on the likely change in the direction of flood hazard and critical infrastructure exposure to these possible changes in the future. Climate is changing and calling into question the infrastructure systems' ability to cope with hazards. Using general circulation models (GCMs) to investigate possible changes in the flood hazard under the projected climate change scenarios is known as the top-down approach or predict-then-act method (e.g. Schlef *et al* 2018, Taner *et al* 2019). GCMs can be used to investigate possible changes in the hydrological cycle under the projected climate change scenarios. There is a need for further investigations to integrate the outcome of our study into a decision making framework. To amend and augment the GCM projections, a bottom-up approach is also needed to link the possible changes in a natural hazard to the local and regional policies (Whateley *et al* 2016, Spence and Brown 2018, Ray *et al* 2019). The importance of incorporating climate change impacts on infrastructure has been acknowledged by the California State Legislature as an emerging problem through Assembly Bill No. 2800 (AB-2800 2016). The goal of California's AB-2800 is to achieve a set of climate adaptive strategies and guidelines to ensure serviceability, safety, and durability of California's infrastructure systems in the future. The insight gained from assessing potential changes in the flood hazard under a warming climate in levee protected areas is one of the means by which water managers and decision-makers can devise possible climate adaptive strategies to ensure safety and functionality of levees and levee protected infrastructure. We argue that the future developments in the leveed regions need to consider the possible changes in the flood hazard in a changing climate. To ensure the adaptation and mitigation strategies are able to reduce flood impacts in the leveed area, we need to include hydrological risks into guidelines and actions that address water challenges. These strategies, if informed by climate change analyses, can lead to increased public safety and security of infrastructure systems protected by the levees.

We should emphasize that there is no single solution for resolving flooding threats to different levee systems; each system is unique and must be evaluated on its own. In this study, we did not perform any physical failure analysis of levees and critical infrastructure or flood mapping. However, the leveed regions that we find as more vulnerable, can

be prioritized to perform regional mechanistic modeling. Physical mechanistic modeling frameworks are typically used in structural and geotechnical engineering. Integrating forcing from the hydrological analysis, we can investigate the performance of levee systems in the future. For such a study, we need to have a runoff dataset with a higher temporal and spatial resolution that takes into account the changes in both the climate and the land use and land cover of the levee protected regions. Therefore, we also need to invest in developing the local and global hydraulic models (Wing et al 2019, Johnson et al 2020) with forcing from the GCMs to get a higher temporal and spatial resolution runoff datasets.

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Data availability

The data that support the findings of this study are openly available from:

The U.S. Army Corps of Engineers levee dataset (<https://levees.sec.usace.army.mil/#/>), Cal-Adapt (<https://cal-adapt.org>), the U.S. Energy Information Administration (www.eia.gov/maps/layer_info_m.php), the Homeland Infrastructure Foundation-Level Data (<https://hifld-geoplatform.opendata.arcgis.com>), and the U.S. Census Bureau (www.census.gov/geographies/mapping-files/time-series/geo/tiger-geodatabase-file.html).

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