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Flood exposure of critical infrastructures in the United States

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ABSTRACT

This study provides a nationwide spatial assessment of flood exposure of critical infrastructures (CI) in the United States. By combining the FEMA flood maps and the USGS National Structure Database, the exposure of CI facilities to 100-year-flood was estimated for the country and states. Spatial analyses and statistical tests were conducted to analyze variations of flood exposure of the CIs in different states, counties, sectors and categories. At the national level, the ratios of CI flood exposure ranges from 2.7% to 27.1% in different sectors. The spatial analyses indicate that the southern states near the Gulf Coast (particularly Louisiana and Florida) have a high exposure ratio in most of the CI sectors. Hot spot analysis was applied to detected local clusters of high flood exposure, where actions of flood risk reduction should be potentially prioritized. By comparing the flood exposure of the CI facilities with the general urban exposure (i.e. baseline exposure), states and CI sectors where the flood exposure is deviated from the expected value are identified. This study reveals the general trend of CI flood exposure in the U.S. and identified outliers deviated from the trend. The underlying factors behind these deviations are discussed. Overall, this study provides valuable information for U.S. policy-makers at different levels to better evaluate and mitigate potential flood risk from these 'lifeline' systems.

1. Introduction

Critical infrastructures (CI) are viewed as 'lifeline systems' and the foundation of the economic prosperity, social welfare, sustainability, and security of a country. In the United States, early attention was mainly paid to CI protection under threats of military attack, energy crisis and terrorist attacks [1,2]; Fekete et al., 2017). Recently, natural disasters are increasingly viewed as a major threat to the country due to the serious damages and losses of lives and economy in the recent disaster events. Accordingly, attention of policy-makers and scientists has been paid to the risk, vulnerability and resilience of CIs in natural disasters [3]. Natural disasters can physically damage CI facilities, affect utilities provided by CIs, and cause domino effects to other systems beyond the direct impact to CIs [4]. The importance and vulnerability of CIs in natural disaster has been demonstrated in recent disaster events. For instance, Hurricane Sandy in 2012 caused power outages to over 8 million customers for days or even weeks, which disrupted wireless and internet services in a large area [5,6]. The failures of these systems not only shifted people's lives and activities to a 'standstill' status, but also caused cascading failures to other dependent CIs and social systems [7,8]. Other than impacts to individuals' daily activities, failures of the CIs (particularly the energy, transportation, emergency response and medical sectors) may hamper disaster response [9,10] and delay post-disaster recovery [11]. Given the importance of CIs in natural disasters, disaster risk of CIs is often included as an indicator in the assessments of social vulnerability [12,13] and resilience [14,15]. For emergency response agencies, policy makers and individuals, understanding the disaster risk of CI is of vital importance for reducing vulnerability and enhancing resilience of human communities.

Despite the various types of disasters threatening CIs, this study specifically focuses on flooding, which is the most common and costliest natural disaster in the United States [16,17]. Also, recognizing the confusion of terminology in the broad field of hazard, risk, and vulnerability, we adopt the IPCC's framework to define the concepts used in this study: Flood risk (R) is a function of three determinants, including flood hazard (H), exposure (E) and vulnerability (V) [18]. In this framework, flood hazard refers to the locality, probability, frequency and seasonality of flooding events. Exposure is the presence of human-beings and their livelihood, assets, infrastructures and resources in places where flood hazard could occur. Vulnerability is the propensity of exposed human elements to suffer adverse effects caused by hazard events. Extending from the IPCC's definition, the flood risk of CI (R_{CI}) can be defined as a function of flood hazard (H), exposure of CI to flood hazard (E_{CI}), and vulnerability of CI (V_{CI}). E_{CI} specifically refers to the presence of CI elements in places where flood hazards may occur. V_{CI} is the propensity of the exposed CI elements to be adversely impacted by flood hazards. From a management point of view, R_{CI} can be reduced by reducing either E_{CI} or V_{CI}. For instance, E_{CI} can be reduced

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by planning or constructing CIs in areas with a low probability of flood hazard. Approaches to reduce V_{CI} include but are not limited to increasing physical strength, elevating structures or preparing backup power for CI facilities.

Flood exposure of CI is dependent on decision-makers and planners' localization choices of the CI construction. In the U.S., policies and regulations have been issued by federal agencies to reduce exposure of private and public structures to flood hazard. In 1968, the National Flood Insurance Program (NFIP) was created by the U.S. Congress for property owners to protect themselves financially from flood events. The NFIP requires all participating communities to comply to certain construction standards for new dwellings and structures built in flood zones to be qualified for flood insurance and federal assistance for disaster relief [19]. The Federal Emergency Management Agency (FEMA) has also provided guidelines of flood risk management to encourage facility owners, planners, and designers to avoid flood hazard areas for building critical facilities to minimize the life-safety risk to the general public [20]. Recently, FEMA further recognized the importance of certain critical facilities to general public in flooding events and raised the level of flood to be regulated from the 100-year-flood to 500-year-flood [21]. This ‘higher standard’ guide specifically highlights a number of critical facilities that should be primarily addressed, including schools, health facilities, power generation center, fire stations, police stations and emergency operation centers. Despite the general guidelines issued at the federal level, various standards, policies and actions for CI flood management have been implemented by local authorities and stakeholders, which potentially lead to spatial variation of CI flood exposure.

Currently, considerable work has been done in assessing the exposure of general population and economies to flood hazards [22–27]. However, assessments of flood exposure of CIs are relatively rare and focused on specific cities and regions [28–30]. In spite of the increasing attention from both the academia and government agencies, quantitative assessments of CI flood exposure are still lacking in the U.S. To fill this void, this study presents a nationwide assessment of flood exposure of major CIs in the 50 United States and Washington, D.C. By intersecting the spatial locations of CI facilities and flood hazard maps, numbers and ratios of CI facilities exposed to flood hazard are estimated for the country, states, counties, CI sectors and facility categories. The flood exposure of the CIs is compared with the flood exposure of the overall urban flood exposure (baseline exposure). This study aims to report the general trend of CI flood exposure in the U.S. and reveal areas and sectors where the CI exposure is deviated from general trend. The results provide insights to underlying factors that may cause the variations and identify areas where efforts of flood risk reduction should be prioritized.

2. Data

2.1. Flood map

In this study, the locality of flood hazards is represented by flood zones in the FEMA flood maps. The digital version of FEMA flood maps is stored in the ESRI shapefile format, which are freely accessible from FEMA Flood Map Service Center (https://msc.fema.gov/portal). The flood maps were created in the following steps (1) estimating design flow (e.g., 100/50-year return period flow): using a hydro-logic model and precipitation input; (2) estimating water surface elevation using a hydraulic model and design flow estimated in Step 1; and (3) contracting digital elevation model with the estimated water sur-face to identify inundated areas as flood zones [31]. In addition to the FEMA flood maps, other flood zone delineations created using other methods are available (e.g. Ref. [32]. In this study, the FEMA flood maps are adopted due to its high spatial resolution, systematical quality control, and often being used as in policy and planning documents in the U.S. Other flood maps could can be potentially applied to validate analysis results derived in this study. The flood maps define three general categories of zones according to the annual chance of flood inundation. First, high flood risk zones are defined as areas that have equal to or more than 1% chance of being inundated by flood in any given year [33]. The 1-percent-annual-chance flood is also known as base flood or 100-year flood, which include both riverine flood and coastal flood due to high tide or storm surge. In NFIP, the 100-year-flood zones is defined as Special Flood Hazard Area (SFHA) in which floodplain management regulations are enforced and purchase of flood insurance is mandatory [19]. Second, moderate–low flood risk zones are defined as areas that have less than 1% annual flood chance. Third, undetermined flood zones are areas where flood chance is possible but undetermined. In this study, the locality of flood hazards was represented by the 100-year-flood zones, which was denoted as flood zones for simplicity in the remainder of this article. We acknowledge that recent guidelines of FEMA recommend to raise the level of flood hazard from 100-year-flood to 500-year-flood in flood risk management for CIs [21]. However, due to the incomplete delineation of 500-year-flood zone in the current flood maps and fragmented regulations and guidelines about the implementation of this higher standard, we still use 100-year-flood as the threshold to define flood hazard in this study. The undetermined flood zones were excluded from the analyses due to the undetermined flood risk in such zones.

The flood maps used in this study (acquired in September 2017) covers 57.3% of the territory of the 50 United States and Washington, D.C. In general, areas with a moderate population density are covered by flood maps. The void areas of flood map are mostly in the middle and northwest mountainous areas where the population density is very low. According to the assessment by Qiang et al. [25]; until 2017 the FEMA flood maps have covered above 90% urban area and population in the U.S. Additionally, the FEMA flood maps cover 83.5% of the CI facilities of the dataset used in this study. Therefore, the analyses conducted using the flood maps can generally reflect the trends at the national scale.

2.2. Critical infrastructure

The locations of CI were obtained from the National Structures Dataset (NSD) of U.S. Geological Survey (acquired from https://www.gov///b240e4b058caae3f8e1b), which include 16 general sectors of CI. The footprints (point locations) and attribute information (e.g. name, address, type, and sector) of the CI facilities are stored in a ESRI Geodatabase. In the database, six CI sectors do not have complete data for all states. For the consistency of analysis, only the sectors that have complete data in all the states are selected for analysis, leading 10 qualified sectors including Education (Edu), Emergency Response and Law Enforcement (ER&LE), Energy, Health and Medical (H&M), Industry, Information and Communication (I&C), Mail and Shipping (M&S), Public Attraction and Landmark (PA&L), Water Supply and Treatment (Water), and Transportation (Trans) facilities. Next, the dataset was cleaned by removing duplicate structures that have identical names and addresses. In the Trans sector, water-dependent structures such as bridges and water transportation facilities (e.g. harbor, port, wharf, and boat ramps) are excluded in the analyses as these structures are typically located near or in water bodies, which are usually in flood zones. Note that the data in the NSD only represent a sample of CI facilities in the country. The composition of facility types may not reflect the actual composition of the CI facilities in different sectors. As shown in Fig. 1, some sectors in the NSD are highly screwed to certain types of structures. For instance, the M&S sector only includes post offices. Therefore, the analyses and discussion are limited to the structures included in this database.

2.3. Land cover data

Land cover data is used to calculate the exposure of developed land

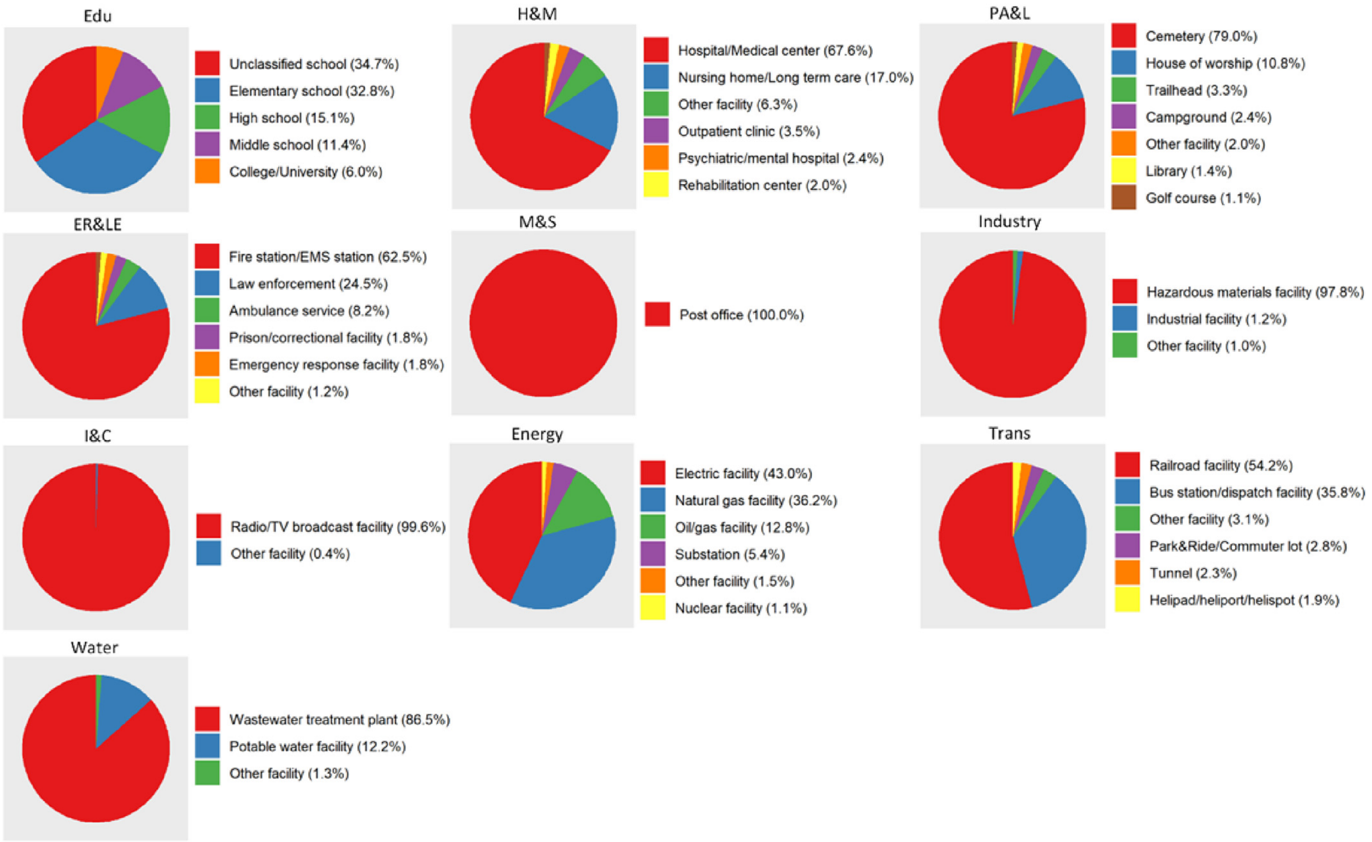

Fig. 1. Compositions of structure types in different CI sectors.

to 100-year-flood, which is considered as the baseline flood exposure. The developed areas of the Contiguous U. S. and Alaska were acquired from the 2011 land cover data from the National Land Cover Database (https://www.mrlc.gov) at a 30-m resolution. The developed areas of the State of Hawaii were acquired from NOAA C-CAP database (https://coast.noaa.gov/digitalcoast/tools/lca), which were collected between 2010 and 2011 at a 2.4-m resolution. Both the NLCD and C-CAP are based the Anderson Land Cover Classification System [34]. Pixels classified as developed land at the first level of the Anderson classification are considered as developed area. As only one of the fifty-one states and DC is estimated at different spatial resolution, we think the effect of the resolution inconsistency on the analysis results is minimal. All other types of land excluding open waters and restricted land (e.g. military sites, wildlife refuge and management area, federal land, and national parks) are used as the denominator to calculate the ratio of developed land in flood zone, which is referred to as the baseline exposure ratio in this article.

3. Analysis

Three quantitative analyses are conducted to assess the flood exposure of the CIs:

First, flood exposure of the CI facilities is calculated by overlaying the footprints of the CI facilities with the FEMA flood maps in a geographic information system (GIS). Fig. 2 illustrates an example of the overlay between CI facilities and flood zones in the city of Houston, Texas. Using spatial join, a binary attribute (true/false) is appended to each facility encoding whether the footprint of the facility is located in 100-year-flood zone. The numbers and ratios of the CI facilities in flood zones are calculated in the national and state boundaries. The national-level estimation reports the overall exposure of the CI facilities to 100-year-flood in the country. The state- and county-level estimations reflect the spatial variations of flood exposure of the CIs.

Second, Getis-Ord Gi* statistic [35] was applied to detect local clusters of counties with low and high ratios of CI flood exposure. Getis-Ord Gi* statistic (also known as hot spot analysis) is a geostatistic method for calculating local spatial autocorrelation. Getis-Ord Gi* statistic can distinguish areas with a positive spatial autocorrelation (i.e. similar values are located near each other) from the complete spatial randomness (i.e. values are randomly distributed across space). Getis-Ord Gi* can eliminate the "salt-and-pepper" effect in the original exposure maps and detect clusters of counties with high and low CI flood exposure. Clusters of counties with a high CI exposure ratio were detected as "hot spot", where counties with a high exposure ratio are surrounded by counties with a high exposure ratio. Conversely, clusters with low exposure ratios are denoted as "cold spot". Each detected clusters is associated a *p* value, which indicates the deviation of the spatial pattern from a purely random process. A lower *p* value implies a higher confidence or probability that the cluster is not a coincidence in a random process. The spatial weight matrix is based on queen contiguity, namely, counties that share a common boundary or vertex are defined as neighbors. Due to the isolation of counties with CI facilities and flood maps, Hawaii and Alaska are not included in the Getis-Ord Gi* analysis.

Third, the ratio of the infrastructure flood exposure is compared with the baseline ratio of flood exposure to evaluate the implementation of flood risk management in different CI sectors and states. The baseline flood exposure is defined as the ratio of developed area in flood zone to all developed area. As the CI is part of the general urban development, the ratio of CI in flood zones (P_{CI}) is expected to be equal to the ratio of developed land in flood zone (P_{D}). A negative difference of the two ratios (i.e. $P_{\mathrm{CI}} < P_{\mathrm{D}}$) indicates that the regulations for CI flood risk control are more restrictive than the regulations for the general urban development. A positive difference (i.e. $P_{\mathrm{CI}} > P_{\mathrm{D}}$) may indicate the opposite situation: the regulations for the CI are less restrictive than those for urban development. In some CI sectors, the positive difference

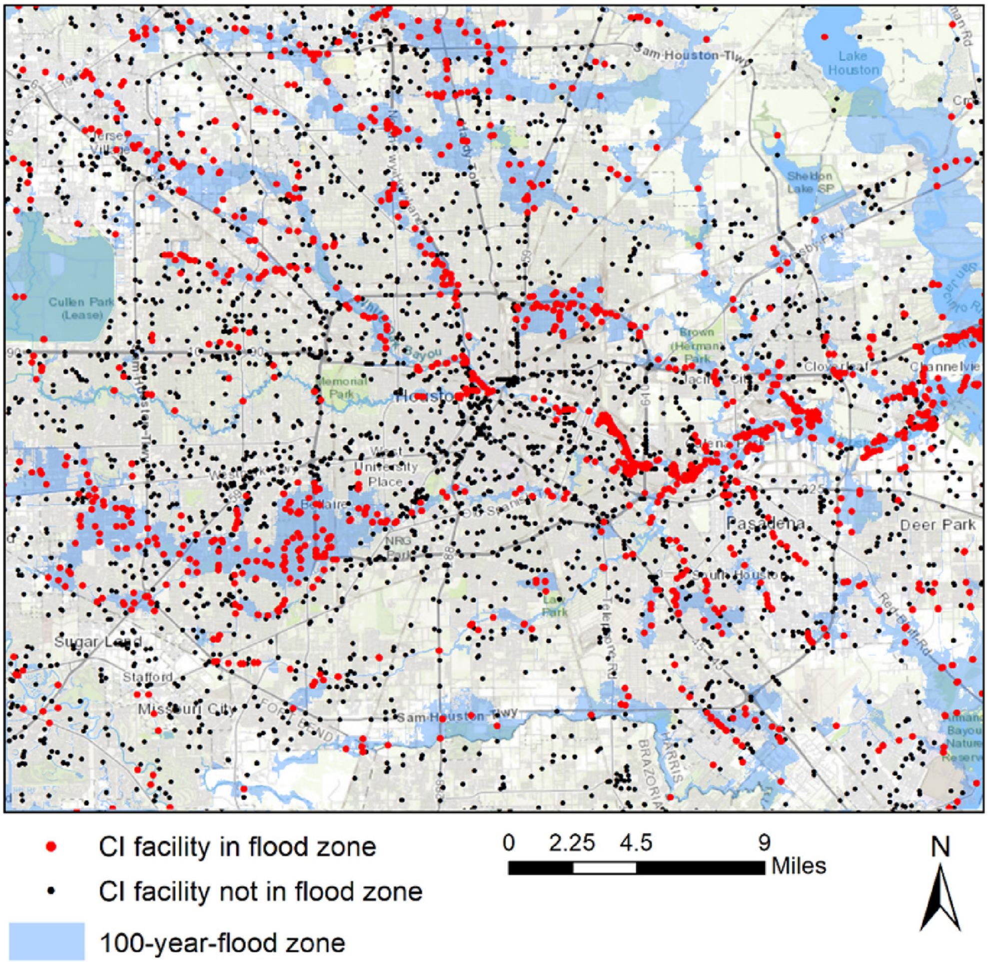

Fig. 2. Overlaying footprints of CI facilities with flood map in the city of Houston.

can also be a result of high dependence of the CI facilities to certain utilities in flood zones (e.g. water resource or transportation). Comparison are conducted in the entire country, the states, and different CI sectors. The statistical test of proportions is used to test the null hypothesis (i.e. $P_{\mathrm{CI}} = P_{\mathrm{D}}$). The z-score of the test of proportions is calculated as:

$$z = \frac{P_{CI} - P_D}{\sqrt{\frac{P_{CI}(1 - P_D)}{n}}} \tag{1}$$

where n is the number of CI facilities [36].

4. Results

At the national level, the ratios of flood exposure of the CI are illustrated in Fig. 3 in an ascending order, which shows strong variation in different CI sectors. In the lower end, only 2.7% of Edu and H&M facilities are located in flood zones compared to 17.9% of Trans and 27.1% of Water facilities in the higher end. In the same CI sector, the ratios of flood exposure also vary among specific structure types (Fig. 4). For instance, in the Energy sector, substations have a much lower exposure ratio than other types of structures in this sector. In the Trans sector, railroad facilities have higher exposure ratios than other transportation facilities (e.g. bus station/dispatch facilities, helipad/heliport/helispot, Park&Ride and commuter lots). The numbers of structures in each category is shown in Table 1.

The spatial analyses show that the exposure ratios of the CI vary from state to state (Fig. 5). In general, the southern states near the Gulf Coast (especially Louisiana and Florida) have a higher exposure ratio in most of the CI sectors. As shown in the county level analyses (e.g. Fig. 6), a large proportion of facilities in this region are located in the low-lying coastal areas that are prone to both coastal and riverine flooding. The Getis-Ord Gi* analysis highlights local clusters of counties with high and low exposure ratios at different levels of statistical significance. A low p value indicates a high statistical significance of the detected cluster.

Local hot spots of many CI facilities can be found in coastal Louisiana and southern Florida (e.g. Fig. 7 and the supplementary material). The inland states have relatively low flood exposure, except a few outliers. As an example, West Virginia, an inland state along Appalachian Mountains, has a high exposure ratio in the sectors of ER&LE, M&S, and Water. Most of these facilities are located in riverine floodplains. The Getis-Ord Gi* analysis can effectively eliminate the 'salt-and-pepper' effect in the original exposure maps and pinpoint areas where the CI exposure ratio is significantly higher or lower. The hot spots identify areas where the CIs are potentially more susceptible for flood hazards. Further investigations are needed to reveal the underlying factors of 'unexpected' flood exposure.

The exposure ratios of the CI facilities are significantly ($p < 0.01$) correlated to the exposure ratios of the general developed land in the states. Difference between the two ratios would indicate a deviation of the CI flood exposure from the urban flood exposure (baseline). To detect the deviations, the statistical test of proportion was applied to compare the ratio of CI facilities in flood zone (P_{CI}) and the baseline ratio of flood exposure (P_{B}, the ratio of developed land in flood zone). At the national level, the null hypothesis (i.e. $P_{\mathrm{CI}} = P_{\mathrm{B}}$) is rejected for all the CI sectors at a significance level of $p < 0.001$, meaning that the

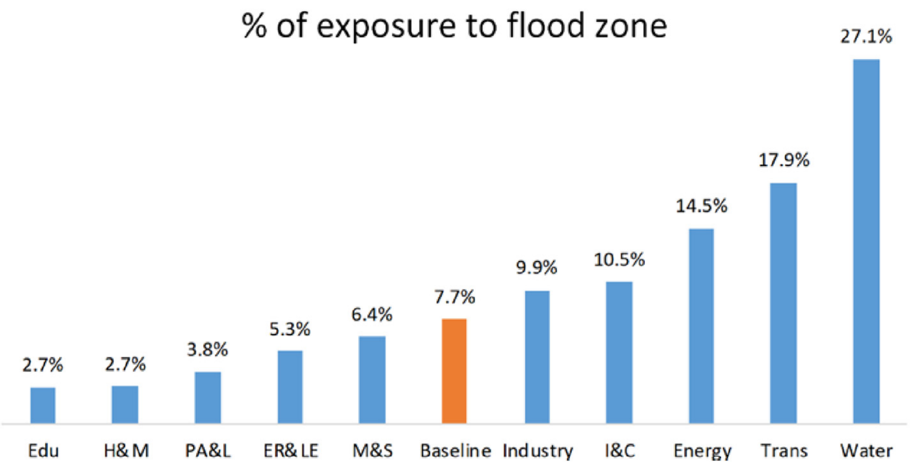

Fig. 3. The ratios of structures located in flood zones in the United States.

exposure ratios of the CIs are deviated from the baseline exposure. The Edu, H&M, Landmark, ER&LE, and M&S sectors have a lower ratio of flood exposure than the baseline ratio (Fig. 3). This result potentially implies that more restrictive regulations are enforced to avoid building these facilities in flood zones. The other five sectors (including Industry, I&C, Energy, Trans, and Water) have a higher ratio of exposure than the baseline ratio, meaning that facilities in these sectors are more likely to be located in flood zones than general urban areas.

Various deviations from the baselines can be found at the state level. Table 2 lists the numbers of states where the exposure ratios of the CIs are significantly higher and lower than the baseline ratios in states. For instance, although the exposure ratio of ER&LE (5.3%) is lower than the baseline in the national aggregation, there are 10 states (20% of all states) where the exposure ratio of ER&LE is higher than the state baseline. The choropleth maps in Fig. 8 illustrate the states where the CI exposure ratios are deviated from the state baselines. For instance, in the Edu sector, most states have a lower-than-baseline exposure ratio except New Mexico, Wyoming, West Virginia, and Hawaii where the exposure ratios of Edu facilities are not significantly different from their state baselines. Moreover, the exposure ratios of PA&LB in Texas, Washington, and Maryland are significantly lower than the state baselines, despite that the exposure ratios of most other states and the entire country are lower than the corresponding baselines. These outlier states contradict the national trend are particularly worthnoting. Further studies are needed to discover the underlying factors of the outliers.

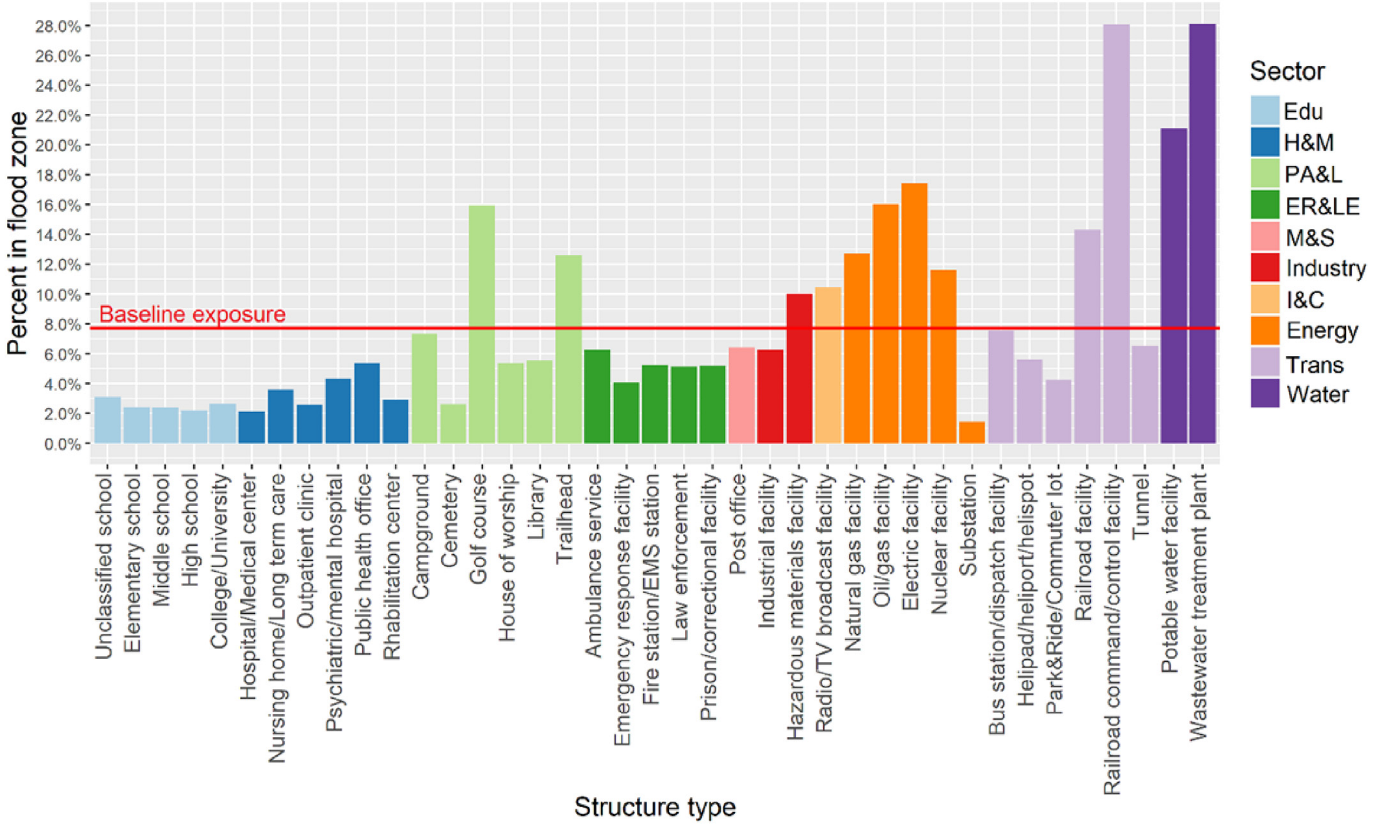

Fig. 4. Percentages of specific structure types in flood zones.

Table 1
List of structures in different sectors analyzed in this study.

CI Sector	Abbreviation	Total number	Number in flood zone	% of structures in flood zone
Education	Edu	120501	3194	2.7%
Health and Medical	H&M	8745	236	2.7%
Public Attractions and Landmark Structures	PA&L	146136	5551	3.8%
Emergency Response and Law Enforcement	ER&LE	68701	3656	5.3%
Mail and Shipping	M&S	24375	1569	6.4%
Industry	Industry	26102	2588	9.9%
Information and Communicaion	I&C	13366	1402	10.5%
Energy	Energy	6341	919	14.5%
Transportaion Facilities	Trans	6830	1824	17.9%
Water Supply and Treatment	Water	16199	4390	27.1%
Baseline exposure	**Baseline**			**7.7%**

5. Discussion

Due to the significance of CIs to the national well-being and security, reducing the risk of natural hazards to CIs has been mentioned in various policy and planning documents in the U.S. (the [37,38]. After Hurricane Katrina, FEMA has issued a series of practical guidelines for reducing flood risk of CIs [20,21]. These guidelines specifically suggest that avoidance of flood zone is the most effective way to minimize the risk to the occupants and general public who rely on CIs. When avoidance is not practical, other mitigation measures, such as elevated foundation, building anchoring, flood-resistant design, and purchase of flood insurance, are suggested for the exposed facilities. Despite the general and minimum guidelines suggested by FEMA, the specific measures of flood risk management are implemented by various levels of governments and stakeholders (2018b), leading to various regulations, building codes and standards issued and enforced at different places. For instance, in the New Jersey Department of Environment Protection and Department of Community Affairs have statutory authorities for floodplain management in the State of New Jersey [39]. The Floodplain Management and Hazard Mitigation Department in Jefferson Parish, Louisiana, provide guidance and assistance for floodplain management at a county level. So far, there is no nationwide legislations or standards that regulate CI development in floodplains. In practice, local governments and communities can go beyond the FEMA guidelines and impose additional building code and flood-zoning regulations [40,53]). The spatial variations of CI flood exposure revealed in this study potentially imply different flood management strategies applied in different areas and sectors, which is dependent on decision-makers' awareness of and responsiveness to flood hazard, operational conditions of the CI facilities, and the local socio-environment conditions.

At the national scale, different flood exposure among the CI sectors reflects different flood risk management being applied in these sectors. The exposure ratios of the Edu, H&M, PA&L, ER&LE and M&S facilities are significantly lower than the national baseline, potentially indicating more restrictive regulations or/and higher standards of flood risk

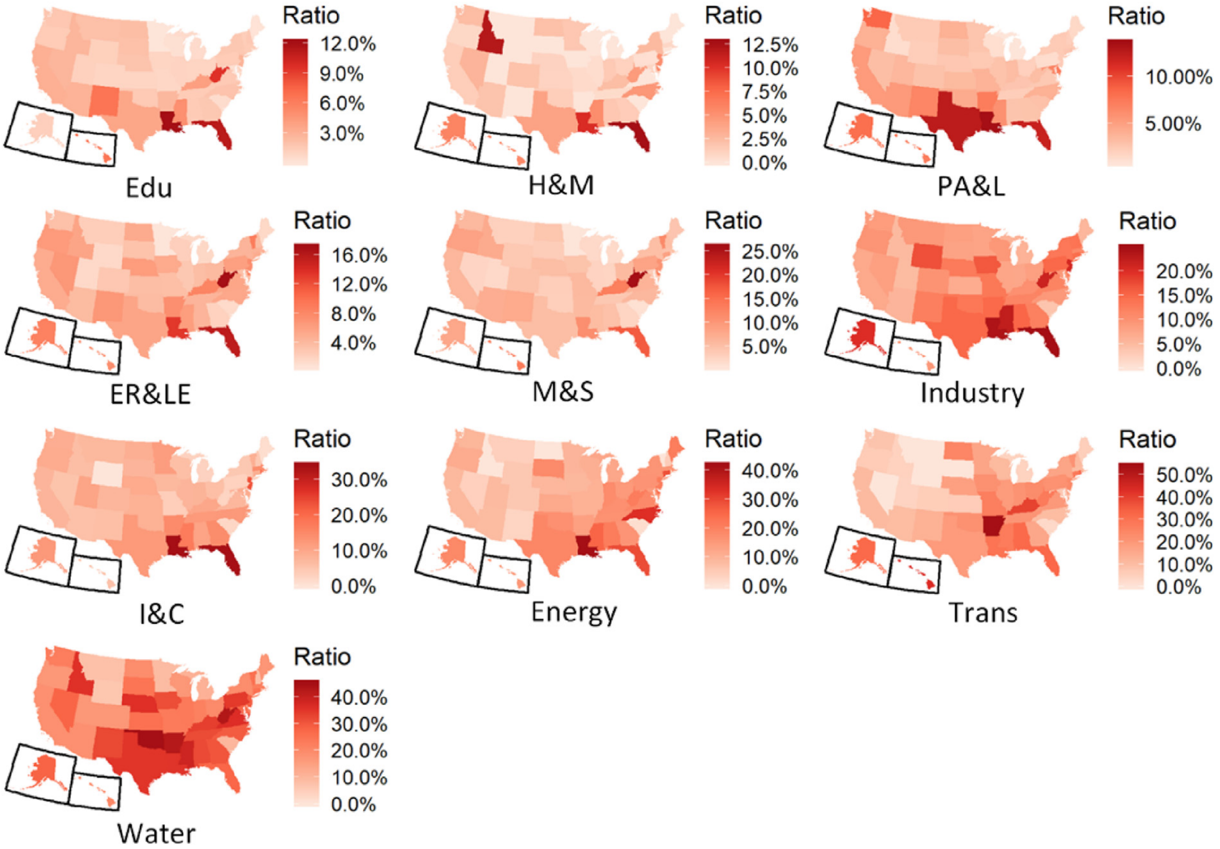

Fig. 5. Ratio of infrastructures in flood zone per state.

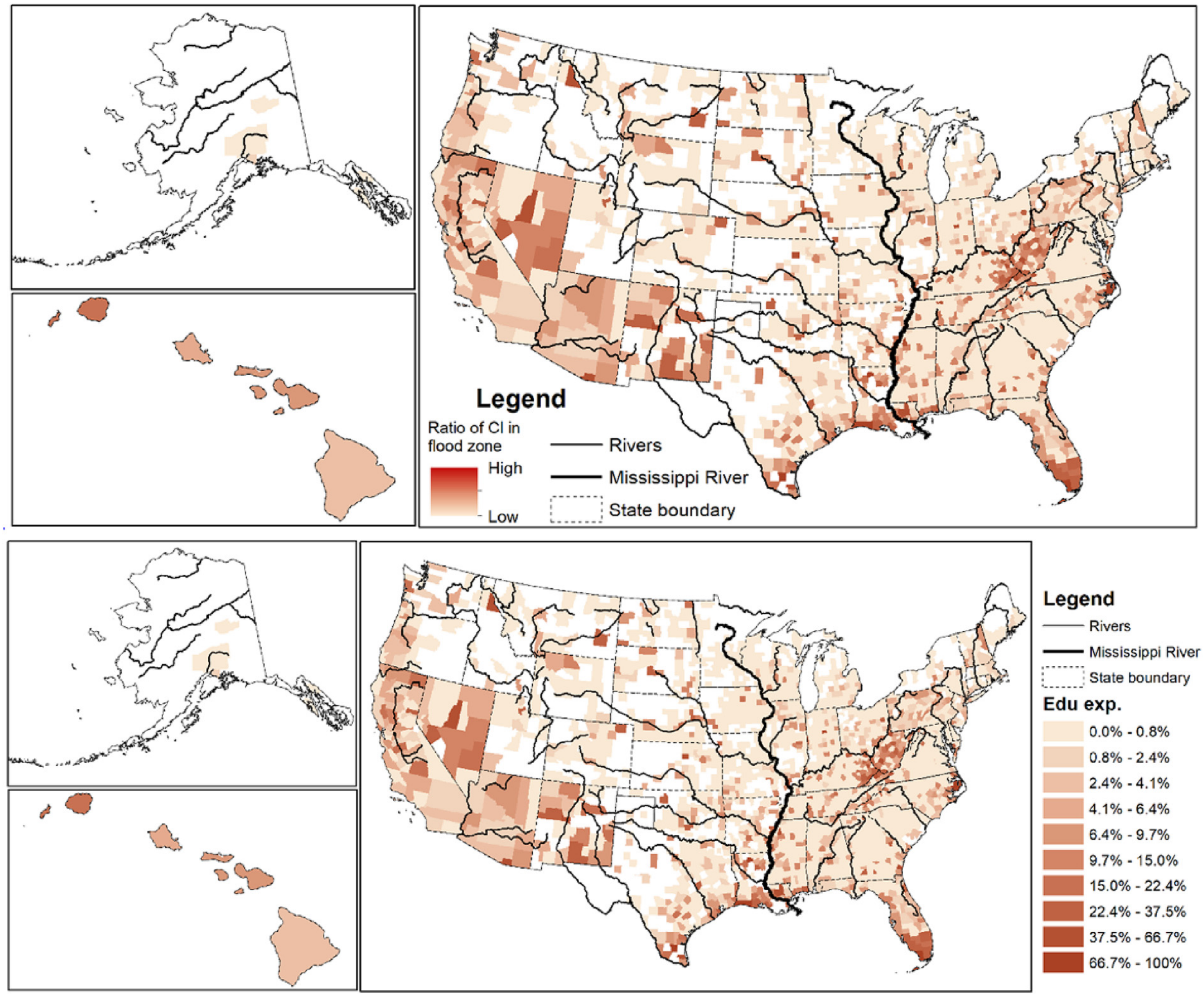

Fig. 6. Exposure ratios of education facilities in counties. Blank areas are counties with no flood maps or facilities. County-level maps of other facilities can be found in the supplementary material (Appendix A).

control being enforced in these CI sectors at the national level. The spatial analyses identified states that are deviated from the national trend. As illustrated in Fig. 8, the exposure ratios of Edu facilities (i.e. schools) in West Virginia, Wyoming, New Mexico and Hawaii are not significantly lower than the baseline ratios, which may imply two possible scenarios: 1) schools are not prioritized in flood risk management in these states, or 2) flood management in these states focus on other measures (e.g. elevating buildings, anchoring foundations and making evacuation plans). Given the vulnerability of children to natural disasters [41–43] and high children fatalities in flooding events [44,45], more attention should be paid to reduce the flood risk of schools in these states. Moreover, Fig. 8 identifies that West Virginia is the only state where the ER&LE facilities (mainly fire stations, EMS stations, police stations and ambulance services) has a higher-than-baseline exposure. These facilities plays an important role in disaster response and are also emphasized in FEMA guidelines for higher standards in flood risk management [21]. The underlying factors of this outlier deserve further investigation.

Despite the policy levers issued by the governments, several CI sectors still have a higher-than-baseline exposure at the national level. An alarming finding is that the Industry structures (mostly hazardous materials facilities) have an exposure ratio higher than the baseline ratio at the national level (Fig. 4). This finding contradicts with the guidelines of Environmental Protection Agency and FEMA's which enforce stricter construction requirements for hazardous materials facilities [46,47]. Flooding events may cause spills or leaks of hazardous materials from the storage facilities. According to a report by Frank and Lise [48]; more than 100 toxic releases occurred in the Houston area after the landfall of Hurricane Sandy, which may cause long-term impacts to public health and the environment in the surrounding region. Also, vigilance should be paid to the high exposure of the Energy sector, especially the nuclear facilities, oil/gas facilities, electric facilities (except substations) which have a higher-than-baseline exposure (shown in Fig. 4). As the utility provider of other CIs, the Energy facilities are important components in interdependent CI systems. As evidenced in recent flooding disasters such as Hurricane Harvey and Sandy, electric blackouts combined with the cascading effects to other CIs (such as information and communication, water treatment and transportation) may cause significant socio-economic impacts [5,49]. Additionally, the 2011 Fukushima–Daishi nuclear disaster has aroused extensive discussions on the security of nuclear facilities in extreme events and global policy changes about nuclear development [50]. The high flood exposure of nuclear facilities could be a potential threat to the national security, especially in the changing climate.

This study integrated multiple public databases to evaluate the CI flood exposure at the national, state and county scales. The analyses results provide important information for guiding further studies about the underlying factors that caused the spatial heterogeneity. The identified outliers and ‘hot spots’ pinpoint places where risk reduction efforts could be prioritized. Additionally, the analysis methods can be applied for continuous monitoring of CI flood exposure over time to evaluate the effectiveness of specific risk reduction strategies at

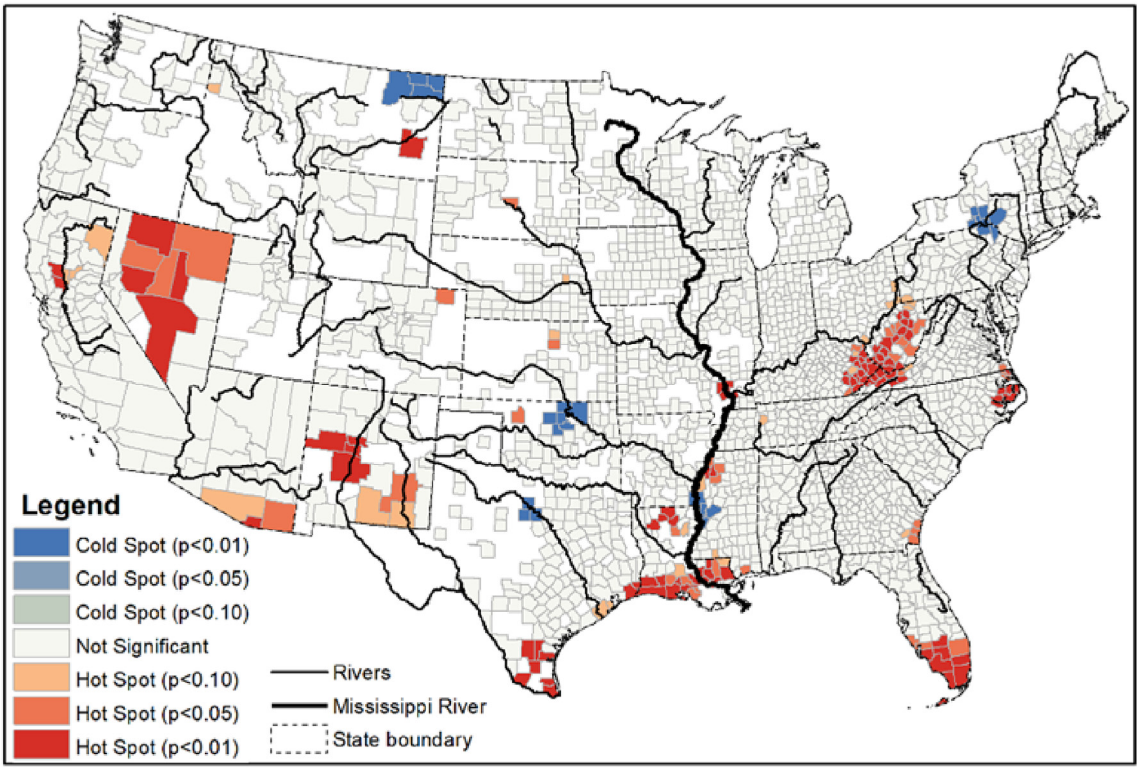

Fig. 7. Hot spot analysis of flood exposure ratios of education facilities in counties. Blank areas are counties with no flood maps or facilities. Results of hot spot analyses of other facilities can be found in the supplementary material (Appendix A).

Table 2
Number and ratio of states where the CI exposure ratio is significantly different from the baseline exposure ratio.

Structure type	Number and ratio of state significantly different from the baseline exposure		
	Low ($p < 0.05$)	Not significant	High ($p < 0.05$)
Edu	47 (92%)	4 (8%)	0 (0%)
H&M	29 (57%)	22 (43%)	0 (0%)
PA&L	40 (78%)	8 (16%)	3 (6%)
ER&LE	30 (59%)	20 (39%)	1 (2%)
M&S	17 (33%)	29 (57%)	5 (10%)
Industry	1 (2%)	22 (43%)	28 (55%)
I&C	3 (6%)	34 (67%)	14 (27%)
Energy	2 (4%)	23 (45%)	26 (51%)
Trans	0 (0%)	22 (43%)	29 (57%)
Water	0 (0%)	7 (14%)	44 (86%)

different spatial scales. Not only for the U.S., these methods are applicable to other countries with substitutions of the datasets. For instance, land cover data are publicly available in many other countries or can be classified from remotely sensed imageries. Global flood models (e.g. Ref. [51] are available to substitute the FEMA flood maps. CI footprints can be acquired from relevant data inventories in different countries or online map services such as Google Maps® or OpenStreetMaps.

Some limitations of the datasets and applied methods need to be considered when interpreting the results. First, the NSD only represents an incomplete sample of CI facilities. Some important components of the CIs are not included in the dataset. The simplified footprints (i.e. points) may also introduce uncertainty in the analysis. A more accurate assessment of CI flood risk relies on complete databases of the entire CI systems, including accurate footprint boundaries and the networks connecting the facilities and population. In future studies, integrated and network-based models need to be developed to evaluate the interdependency among different CIs in potential flood risk (e.g. Refs. [29,52]. Second, additional data and investigations are needed to understand the underlying factors that influence the CI flood exposure. Other than the policy levers discussed above, the risk reduction strategies applied in different places and CI facilities need to be analyzed to explain the spatial variations and clusters. The actual flood risk is dependent on the combined effects of both exposure and vulnerability. Additional data of the physical properties of CI facilities (e.g. aging, deterioration condition, design limit, and building structure) are needed to assess the CI vulnerability. Moreover, empirical observations of actual damages in flooding events can help to validate the analysis results and quantify other factors that influence CI flood risk. Third, the Modifiable Areal Unit Problem (MAUP) should be considered when interpreting the results of the spatial analyses. This study found different ratios and spatial patterns at the national, state and county scales. Further analyses are needed to understand the influencing factors at different spatial scales to guide decision- and policy-making at the appropriate scales. Finally, the baseline exposure (i.e. urban exposure) may not be applicable for all the CI facilities. Some CI facilities with inherent reliance on water resources (e.g. water and transportation facilities) have higher flood exposure. In future studies, the actual effect of flooding for specific types of CI facilities should be quantified to assess the overall flood risk in different places with different CI facilities exposed to flood hazards.

6. Conclusion

This study introduces the first nationwide spatial assessment of flood exposure of critical infrastructures (CIs) in the United States. Spatial analysis and statistical methods were applied to reveal the variations of flood exposure at the national, state and county scales. The analyses provide baseline information on the exposure of different CI facilities to 100-year-flood and the spatial pattern of the exposure. The analysis results show strong variations of flood exposure of CI facilities

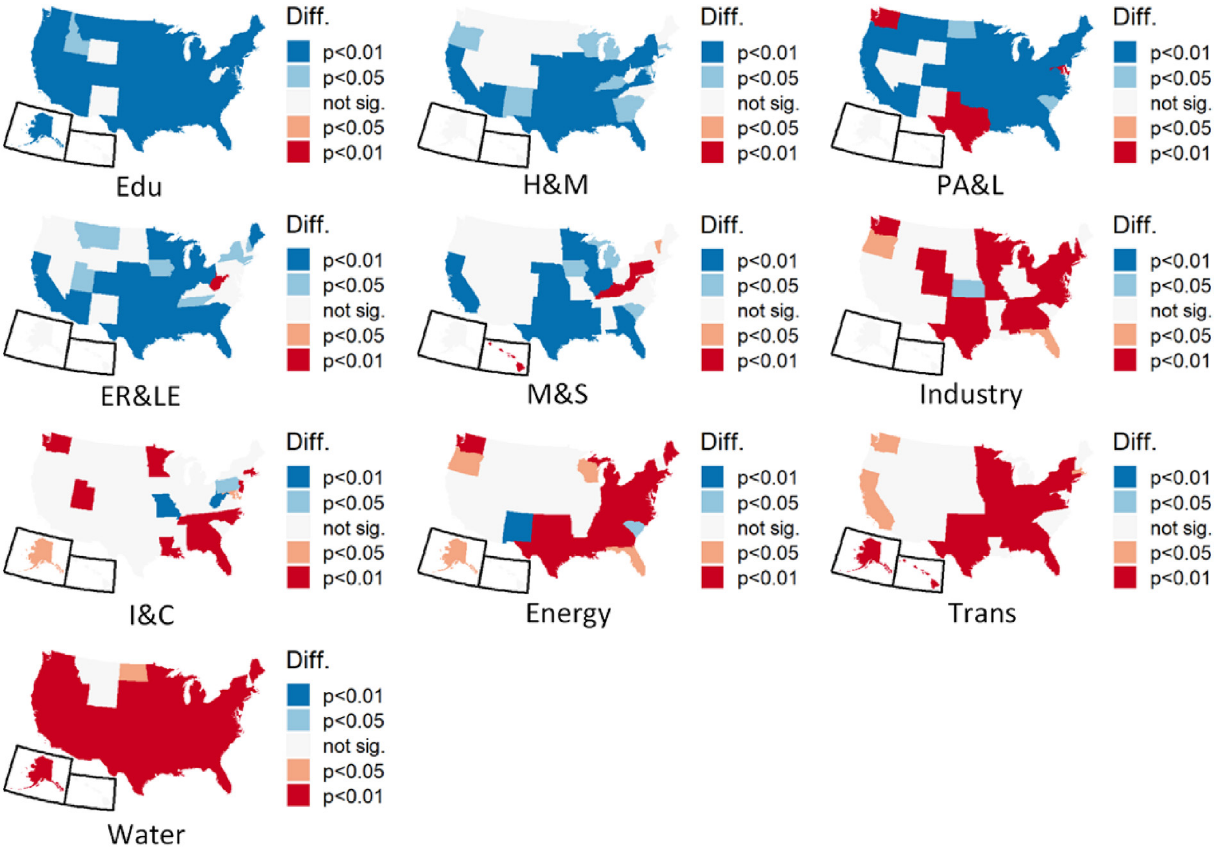

Fig. 8. Difference between CI exposure ratios and the baseline ratios. Blue indicates the CI exposure ratio is lower than the baseline ratio (i.e. $P_{CI} < P_B$) and red means the opposite (i.e. $P_{CI} > P_B$). The color intensity represents significance levels of the difference (i.e. p-value). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

in different states and sectors. The ratio of exposure to 100-year-flood ranges from 2.7% to 27.1% in different CI sectors at the national level. The state-level results indicate that the southern states near the Gulf Coast (particularly Louisiana and Florida) generally have a high exposure ratio in most of the CI sectors. This generally confirms the historical financial losses reported by FEMA according to claims and payments of the national flood insurance program (Figs. 21–23 in the supplementary material). The difference between the CI flood exposure and general urban exposure (i.e. baseline exposure) was compared. The comparison results indicate that facilities in the sectors of education, health and medical, public attraction and landmarks, emergency response and law enforcement, and mail and shipping have a lower flood exposure than the overall urban flood exposure. In contrast, the flood exposure of the other sectors (i.e. industry, information and communication, energy, transportation, and water) are higher than the baseline. The high exposure ratios of the energy and industry facilities are particularly noticeable. Given the importance and sensitivity of the facilities (especially energy and industry facilities) in natural disasters, further efforts should be made to evaluate and reduce the flood risk of these facilities.

Due to the lack of centralized standards and regulations, various forms of policies and strategies for CI flood management are implemented by local governments and stakeholders. The introduced methods provide valuable insight to the various policies and strategies of flood management implemented in different places and CI sectors. In addition to the government issued guidelines and regulations, the variations are also related to the diverse socio-economic and environmental conditions as well as the inherent properties of the CI facilities. Additional data and investigations are needed to better understand these relationships and assess the overall flood risk of the CIs. For scientific research, the spatial patterns of CI flood exposure presented in this study provide guidance for further studies about the underlying factors that caused the spatial heterogeneity. The results of spatial analysis can be easily overlaid with other spatial variables to test the hypothesized relationships. Moreover, the multi-scale spatial assessments provide support for decision- and policy-makers at different levels to prepare, adapt and respond to flood impact to these 'lifeline' systems. The outliers and 'hot spots' detected in this study pinpoint places and CI sectors where actions of flood risk reduction should be prioritized.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101240.

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