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American archives and climate change: Risks and adaptation

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ABSTRACT

Climate change directly affects the future security of cultural resources. Cultural heritage and in particular, archives, are increasingly at risk of degradation due to climate change threats and triggers. This study evaluated present and future consequences of water-related climate change impacts using a mapping methodology to assess exposure of American archives to incompatible weather extremes. Susceptibility to climate change threats like sea level rise, storm surge, surface water flooding, and humidity, all influenced by a combination of temperature rise and increased precipitation, at a worst-case scenario were assessed for 1232 archival repositories. Results indicate that approximately 98.8% of archives are likely to be affected by at least one climate risk factor, though on average, most archives are at low risk of exposure (90%) when risk factors are combined. Future storm surge plus sea level rise was likely to impact 17.7% of archival repositories with 22.1% affected by only storm surge and 4.3% affected by only sea level rise (1.8-m scenario). Fewer archives were likely to be susceptible to surface water flooding (2.4%). More than 90% of archives were estimated to have a temperature change greater than ±1 °C, with 7.5% of sites likely to change by ±10 °C, and 69.5% of archives were likely to receive at least 152 mm more rainfall by 2100 over current annual averages. In terms of sustainability, developing appropriate socio-economic planning schemes that integrate cumulative exposure of archives to future climate patterns is critically important for safeguarding society and its heritage. The outcomes from the risk assessment in this study aid in the decision-making process by promoting strategic adaptation protocols and providing administrators a way to prioritize archival management goals based on the expected severity of future climate change impacts.

1. Introduction

Climate change is increasingly recognized as a threat to cultural heritage (Rockman et al., 2016; Fatorić and Seekamp, 2017a). Cultural heritage includes both tangible forms such as paintings, buildings, monuments, and other material objects, and intangible forms, such as folklore, customs, and traditional knowledge. The well-accepted water-related climate change threats and climate-triggered phenomena that can impact cultural heritage resources include: sea level rise (Taboroff, 2000; Adger et al., 2013; Marzeion and Levermann, 2014; Anderson et al., 2017); storm surge (Gontz et al., 2011; Balica et al., 2012; Daire et al., 2012; Lickley et al., 2014); surface flooding (Dupont and Van Eetvelde, 2013; Wang, 2015; Vojinovic et al., 2016); precipitation (Haugen and Mattsson, 2011; Wang, 2015); temperature change (Hong et al., 2012; Huijbregts et al., 2012; Leissner et al., 2015); and humidity (Bernikola, et al., 2008; Bratasz et al., 2012; Lankester and Brimblecombe, 2012; Morawitz et al., 2013; Tornari et al., 2013; Camuffo et al., 2014;

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Bertolin et al., 2015; Tornari et al., 2015).

Much of the recent work on assessing climate risks to cultural heritage has largely focused on immovable heritage such as archaeological sites (Anderson et al. 2017; Constantinidis, 2009; Reeder-Myers, 2015), cultural landscapes (Dupont and Van Eetvelde, 2013), buildings (Grossi et al., 2007; Bonazza et al., 2009a; Bonazza et al., 2009b; Haugen and Mattsson, 2011; Wu, et al., 2014; Wang, 2015), and UNESCO World Heritage sites (Smith et al., 2011; Viles and Cutler, 2012; Marzeion and Levermann, 2014; Margottini, 2015; Howard et al., 2016; Vojinovic et al., 2016). This body of literature has often focused on risks around coastal or riverine communities given the long history of human settlement in these environments (Reeder-Myers, 2015). A recent systematic literature review examined the integration of climate change and cultural heritage scholarship, which began about 14 years ago (Fatorić and Seekamp, 2017a). According to Fatorić and Seekamp (2017a), research to date focused primarily on European areas, was highly interdisciplinary, and reflected a large range of quantitative and qualitative research methods. Little of the existing work "explore[s] or acknowledge[s] the barriers, limits, and constraints to adaptation or preservation," and significant gaps remain on the topic of adaptation planning across cultural heritage professions (Fatorić and Seekamp, 2017b).

Perhaps because they largely preserve movable cultural heritage (e.g., paintings, museum objects, furniture, documents), archives[1] have received less attention in the climate risk literature. Archives preserve historical records in multiple formats that are critical for legal matters, administrative accountability, and documentary cultural heritage (SAA, 2017). When these records and documents are lost following extreme weather events, for example, their absence severely handicaps socio-cultural and economic reconstruction efforts (Gordon-Clark, 2012).

To date, climate change risk studies of movable cultural heritage have emphasized the effects of relative humidity on the condition of objects, and other factors that lead to gradual degradation, using simulation and sampling methodologies (Bernikola et al., 2008; Bratasz et al., 2012; Hong et al., 2012; Huijbregts et al., 2012; Morawitz et al., 2013; Tornari et al., 2013; Camuffo et al., 2014; Bertolin et al., 2015; Leissner et al., 2015; Tornari et al., 2015). This focus is perhaps warranted as many archives dedicate a large number of resources to maintaining indoor environmental conditions (EPA OAR/CPPD, 2016), and these costs are expected to increase in many geographies under climate change (Energy Saver, 2011; Murphy, 2012; Zhang et al., 2013).

To support disaster preparedness, professional archival communities have published recommendations (NEDCC, 2012) and technical reports (SAA, 2016a), but these documents largely ignore spatial variation (i.e. detailed mapping), in the likelihood and potential magnitude of extreme weather events under present or projected future conditions. This is despite a well-developed scientific understanding of the spatial variation in climate risks, anticipated future change, and actual recent archival collection losses associated with extreme weather events (Pielke et al., 2002; UCAR, 2016). This lack of understanding hampers climate adaptation efforts (Fatorić and Seekamp, 2017b), disaster preparedness, and ultimately places some archival resources at undue risk due to a lack of awareness and understanding. This is exemplified by one anecdote from a New York City, U.S. archive manager who had prepared for and escaped Hurricane Irene in 2011 without losing any collections, only to lose everything on the lower two floors of his facility (except for those collections housed on the highest shelves) to the 14-foot[2] storm surge associated with Hurricane Sandy in 2012. The manager stated that losses were the result of "not so much a failure of preparation as it was a failure of imagination" (Miller, 2016). In this case, a lack of awareness that a storm surge of this magnitude was possible cost this archive a significant portion of their collection. The few existing studies (Gordon-Clark and Shurville, 2010; Gordon-Clark, 2012; Tansey, 2015) that acknowledge the variability of climate risk to archives offer qualitative regional summaries of generally well-accepted climate effects that may fall short of raising awareness and supporting management decision-making at the level of individual archives.

The current project assessed the spatial variability of climate risks to movable cultural heritage housed in U.S. archives using the latest climate change data and methods. This study used a risk assessment framework, which has provided a sound basis for climate adaptation planning in other fields (Gornitz et al. 1994; Füssel and Klein, 2006; Rao et al. 2008; Pramanik et al. 2016; Ecksteim et al. 2017). Our study objectives were to: (1) map U.S. archive locations from available data, (2) intersect archive locations with the best available climate change data representing the potential exposure of archives to incompatible extreme (or routine future) weather, and (3) develop a combined qualitative metric of climate risk exposure to support adaptation planning.

2. Material and methods

Publicly available datasets were used to map archive locations and explored potential repository exposure to water-related impacts and climate triggers. Data representing five aspects of threats to archives were examined: sea level rise, storm surge, 500-year floodplains, and projected future temperature and precipitation change as both a direct threat (e.g. to operating costs) and a trigger of potential threats such as wildfires, landslides, and others. Our conceptual framework (Fig. 1) incorporates variables most likely to cause infrastructure damage and increase archive facility operating costs.

The inconsistent use of risk and hazard terminology such as 'threat', 'exposure', and 'vulnerability' warrants clarification. This study uses Knight's (1921) ideology suggesting risk as a quantifiable uncertainty with a higher probability of occurrence than that of a threat, which is less likely to occur, but can have substantial shortcomings. Exposure refers to a change in conditions that may be

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[1] Using the Society of American Archivists' (SAA) (2017) definition, this study defines an archival repository as "any type of organization that holds documents, including business, institutional, and government archives, manuscript collections, libraries, museums, and historical societies, and in any form, including manuscripts, photographs, moving image and sound materials, and their electronic equivalents." Although archives are often located within historical buildings (immovable heritage), archives can and often are physically alienated from the historical buildings of their original creation and/or initial storage.

[2] Quoting Miller 2016, not official National Hurricane Center reports of the event.

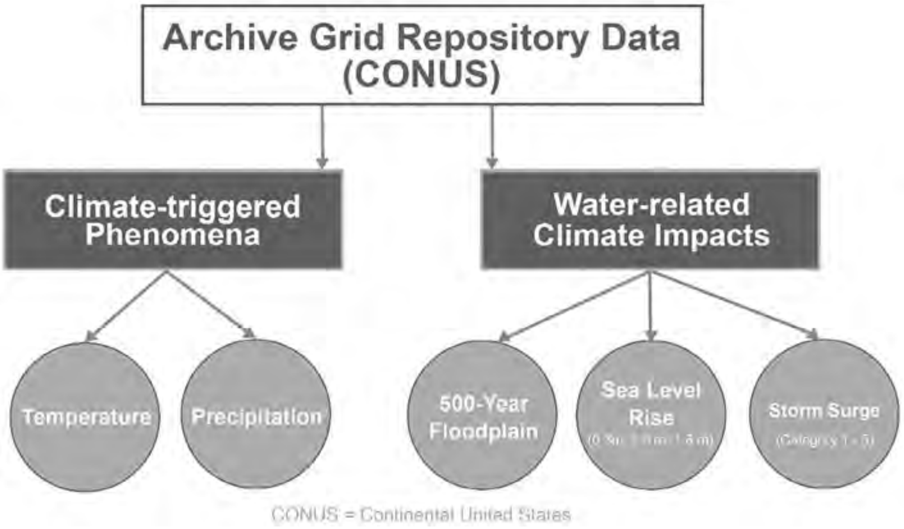

Fig. 1. Conceptual framework for risk assessment of archival repositories.

detrimental to an entity. The concentration and time frame of exposure help to characterize its significance in conjunction with observational data (iThe and R.A.N.D., 1997; Lee and Pickard, 2013). In relation to archives, resilience is the ability to absorb change in conditions without an undesirable result (Tansey, 2015). For instance, archives can promote resilience by adjusting disaster response plans to better account for the risks posed by changing environmental conditions. Vulnerability is a function of exposure, sensitivity, and adaptive capacity and can be expressed in terms of an expected magnitude of change across a given time-period (IPCC, 2001; Fisher and Cook, 2013). Evaluating climate change data alongside risk and hazard management, this study primarily focuses on archive exposure to climatic conditions to understand the severity and frequency of potential degradation to archives as well as the urgency of adapting risk management protocols at specific archival repositories.

2.1. *Data preparation and tools*

All archive and climate exposure spatial datasets were spatially subsetted to the contiguous U.S. and reprojected into the USA Contiguous Albers Equal Area (EPSG: 102003) projection prior to any overlay or spatial analysis. Data preparation and analyses were performed in ArcGIS 10.3.1 (ESRI, 2017) for all climate exposure datasets with the exception of those representing potential future temperature and precipitation. Future temperature and precipitation analyses were performed in R-statistical 3.2.4 (R Core Team, 2016), using the raster library version 2.5-8 (Hijmans, 2016) and rgdal 1.2-5 (Bivand et al., 2016). This study evaluated potential risk exposure of particular archives and did not evaluate current disaster management plans established for any specific archive.

2.2. *Mapping archive locations*

This study considered 1232 archival repositories from 48 states across the continental United States (Fig. 2). Other archive locations within the United States were not considered due to the unavailability of future climate exposure datasets in states like Alaska and Hawaii. The geographic coordinate locations of the archives were derived by geocoding in ArcGIS Online postal addresses from ArchiveGrid, a union catalog operated by the Online Computer Library Center (OCLC). Aware of potential inaccuracies of archive locations and consequences of errors of omission that were greater than errors of commission, this study verified archival repository locations through manual inspection within a 1000-m buffer of floodplains and sea level rise data. Manual inspection compared the geocoded locations of archives to other web and base map information about archives.

The repositories represented in the OCLC ArchiveGrid dataset are primarily archives at college and university libraries, state governments, and major museums. The dataset underrepresents small historical societies, corporate archives, and other institutions, a limitation that is further discussed in Section 2.9. The archives represented in this dataset primarily preserve documentary materials (records, photographs, films, manuscripts, etc), although many archives, especially those in museums, are located within institutions that have a broad curatorial mission which can include collection of museum and object artifacts.

Fig. 2. Study area of 1232 archive locations in the contiguous United States.

2.3. 500-year floodplains

To capture the effects of inland surface flooding, an updated 100-year and 500-year floodplain dataset from the Federal Emergency Management Agency was used (FEMA, 2017). FEMA developed flood zones according to level of risk based on annual peak streamflow values obtained from a nationwide network of streamgages (Holmes, 2016). The FEMA floodplain identification exercise identifies portions of the landscape that correspond to a probability of flooding as 1 in 100-years and 1 in 500-years (FEMA, 2003). In reality, flooding events may occur more frequently than anticipated (Burby, 2001; James, 2004). This means that multiple 500-year flood events can occur within a short period of time, although there is a relatively low probability of this as calculated by FEMA floodplain analyses (e.g., from 2004 to 2006, the Delaware River in Pennsylvania and New Jersey experienced three major flood events that caused significant property damage) (Schopp and Firda, 2008; Highfield et al., 2013; Brown, 2016).

2.4. Sea level rise

The National Oceanic and Atmospheric Association (NOAA), Office for Coastal Management has developed regional sea level rise scenarios to help coastal communities prepare and plan for inundation risk to local infrastructure (NOAA, 2012, 2017c). The NOAA dataset was produced using a "bathtub" approach with two primary inputs – mean higher high water (MHHW) and local-scale digital elevation data (DEMs) derived from LIDAR (NOAA, 2017a). To identify areas at risk of inundation, water levels were elevated above MHHW, and elevation was subtracted away from the new water level. A final step eliminated areas of potential inundation that were not hydrologically connected to open ocean water (Marcy et al., 2011; Simonovic, 2012; Batten et al., 2015). An important benefit of using NOAA's sea level rise data is that NOAA also produced quantifications of uncertainty associated with inaccuracies in both the LIDAR-derived elevation and MHHW (see the following for further discussion of data methods and confidence: Marcy et al., 2011; NOAA, 2017b).

Sea level rise scenarios were created for the contiguous U.S. at 0.3-m, 0.9-m, and 1.8-m intervals. These three scenarios span the entire range of global mean sea level rise by year 2100, projected by the IPCC fifth assessment report. In a final step, all risk layers associated with inundation from sea level rise were spatially resampled to 30-meter resolution using a bilinear resampling technique. Spatial resampling was required in order to combine sea level rise and storm surge inundation scenarios that were natively in different spatial resolutions (Table 1).

Table 1
Infrastructure and environmental exposure data by variable, data source, date, and native spatial resolution.

Variables	Data Source	Date of Access	Spatial Resolution
Archive repository locations	OCLC	2016	N/A*
Sea level rise	NOAA	2017c	$\sim 10.0\,\mathrm{m}^2$
Storm surge	NOAA & NWS (Arthur Taylor)	2015	$0.1–30.0\,\mathrm{m}^2$
500-year floodplain	FEMA	2017	N/A*
Present/Future Temperature (°C)	Fick & Hijmans	2017	30-arc seconds
Present/Future Precipitation (mm)	Fick & Hijmans	2017	30-arc seconds

* Spatial resolution is unavailable for vector data.

2.5. Storm surge

The National Weather Service (NWS) uses the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model to simulate potential storm surge inundation along the eastern and southern coasts of the United States from Texas to Maine. Inputs to the model include storm intensity, forward speed, radius size of maximum winds, angular positioning towards coastline, central pressure, and the elevation, configuration, and composition of the coastline in addition to the characteristics of past hurricanes (Jelesnianski et al., 1992; Houston et al., 1999; NHC, 2017). Numerous simulation runs of SLOSH were composited to generate a maximum area and depth of inundation for each of five storm categories in each of 27 simulation model basins (Sanderson et al., 1995; Glahn et al., 2009; Zachry et al., 2015). The Saffir-Simpson Hurricane Wind Scale was used to differentiate storm surge categories, ranging from a category 1 storm (wind speeds of 119–153 km/h) to category 5 storm (wind speeds of 252 km/h or higher) (Dolan and Davis, 1992; Irish et al., 2008). The accuracy of SLOSH models have been found to be within ±20% of true storm surge height predicted for a future hurricane event (Jarvinen and Lawrence, 1985; Jelesnianski et al., 1992). The intent of NWS storm surge modeling is to generate conservative estimates of risk of inundation from storm surge. At the time of writing, storm surge data was not available for the west coast of the U.S. nor for states north of North Carolina for category 5 storms. No hurricane stronger than a category 3 has made landfall in the northeastern part of the U.S. since 1900 (Vallee, 2000; Boose et al., 2001).

2.6. Sea level rise plus storm surge

Climate change effects are often cumulative in their impact and interact with other complex environmental and social phenomena in ways that are difficult to anticipate and/or represent quantitatively in simulation and forecasting models (Halfon, 2012; Chazdon, 2014; Little et al., 2015). An exception to this is sea level rise and coastal storm surge whose effects are expected to be additive in a way that can be reasonably represented in models for coastal areas (Maloney and Preston, 2014). Recent studies have begun to integrate the long-term effects of rising sea levels with the short-term impacts of storm surge to evaluate potential risk of inundation and resource degradation (Shepard et al., 2012; Bilskie et al., 2014; Maloney and Preston, 2014; Neumann et al., 2015). Following the methods of Maloney and Preston (2014), this study combined our most severe sea level rise scenario (1.8-m) with storm surge inundation as another way to assess worst-case scenarios of flooding potential for coastal archives. Sea level rise and storm surge heights were added together and subtracted from DEM elevations to obtain an inundation depth prediction for each cell. Inundation values were allowed to "flow" into neighboring cells of lower elevations, and inundated areas that were hydrologically unconnected to the open ocean were removed (NOAA, 2017a). These methods were applied in five inundation scenarios corresponding to category 1 through 5 storm surge plus 1.8-m sea level rise.

2.7. Temperature and precipitation change

Current and potential future temperature and precipitation data were acquired from the WorldClim database, version 1.4 (http://worldclim.org/; Hijmans et al., 2005), with a spatial resolution of 30-arc seconds to represent spatial variability in these climate-triggered phenomena. The present day baseline climate data that was subtracted from projected future scenarios described monthly average minimum, maximum, and mean temperatures for the time-period 1960–1990.

The range of likely future climate conditions were represented by 16 global circulation models (GCMs) published in the IPCC fifth assessment report (IPCC, 2013), all of which were averaged for the purposes of the present study. The study also considered two RCPs (4.5 and 8.5), and two future 30-year climate time-periods (2041–2060 and 2061–2080). For the purposes of the cumulative risk assessment ranking, the present study considered only the later time period and more severe RCP scenario. The authors note that recent global carbon emissions have largely tracked the high carbon concentration (RCP 8.5) scenario (Moss et al., 2010). To account for the potential that rising winter temperatures and reduced winter heating costs could offset increased summer temperatures and cooling costs, temperature change was calculated as mean maximum summer (June, July, August) temperature change (future minus present) minus mean minimum winter (December, January, February) temperature change. Precipitation change was reported as change (future minus present) in annual average maximum precipitation. Three GCMs (MIROC-ESM, CESM1-CAM5-1-FV2, and GFDL-ESM2G), that are included in the WorldClim database were not considered because they were not available at the study spatial resolution for each study time-period.

2.8. Future climate risk exposure ranking

A simplified cumulative risk assessment metric was developed to provide archivists (and others) with an accessible overview of risk potential from the anticipated effects of climate change. The ranking system used four environmental factors (sea level rise plus storm surge, 500-year floodplain, temperature change, and precipitation change) to calculate cumulative risk. A weighted storm surge (WSS) value was required in order to combine risk from multiple storm surge (SS) inundation scenarios. The WSS incorporated average SS inundation depths per SS category and accounted for the probability of occurrence for each category storm surge (i.e. category 1 storms are more common than category 5 storms), with a simple multiplier that increased from 0.2 for a category 5 storm to 1.0 for a category 1 storm:

$$WSS = (Cat.\ 1\,SS{*}1.0) + (Cat.\ 2\,SS{*}0.8) + (Cat.\ 3\,SS{*}0.6) + (Cat.\ 4\,SS{*}0.4) + (Cat.\ 5\,SS{*}0.2)$$

where *WSS* is the weighted storm surge value (m) and *Cat. 1–5 SS* is category 1 through category 5 storm surge (m). A WSS value was measured for each archive and applied to a final inundation value (FIV). To calculate FIV, the WSS value was added to future SLR inundation (1.8-m scenario), and each SLR plus WSS inundation value was organized into three risk levels: low, moderate, and high. Archives designated as low risk were given an initial value of 2 when future SLR plus WSS inundation was estimated within 0.03 and 3.04 m; archives at moderate risk received a value of 4 for sites likely to be exposed to 3.05–6.12 m of inundation; archives at high risk were given a value of 6 where estimated inundation for SLR plus SS was 6.13–9.45 m. In addition to inundation depths, not all future SLR scenarios had equal SLR inundation confidence as estimated by the data producers. To account for this, a confidence weighted ranking

(CWR) was created as a weighted variable that incorporated SLR scenario confidence values, where a high confidence ($\geq 80\%$) SLR measure had a stronger influence on FIV compared to a low confidence ($\leq 20\%$) or no SLR impact. A high confidence SLR measure received a value of 2, a low confidence SLR measure received a value of 1, and no SLR impact was given a value of 0. To clarify the process of calculating the FIV, the following is a hypothetical example:

$$\text{Given:WSS} + \text{SLR at } 1.8\,\text{m} = 9.05\,\text{m with a high confidence SLR measure}$$

$$\text{WSS} + \text{SLR at } 1.8\,\text{m} = 9.05\,\text{m} \rightarrow \text{High risk} = 6$$

$$\text{CWR} = \text{High confidence SLR measure} = 2$$

$$\text{FIV} = (\text{WSS} + \text{SLR at } 1.8\,\text{m}) + \text{CWR}$$

$$\text{FIV} = 6 + 2 = 8$$

where *FIV* is the final inundation value (unitless; values range from 0 to 8); *WSS* is the weighted storm surge value (m); *SLR* is sea level rise (m) using a 1.8-m scenario; *CWR* is the confidence weighted ranking value (unitless).

To determine cumulative risk exposure for each archive, sites within a 500-year floodplain were given a presence (2) and an absence (0) value – lower value ranges (i.e., 0–2) were devised to separate more easily anticipated risks from those less predictable. Temperature change and annual precipitation held less existential risk on archival repository degradation than surface flooding in general, and thus, each variable consisted of a lower value range of 0 to 1.5. A temperature change threshold of 1 °C and an annual maximum precipitation threshold of 152 mm were used to categorize archives into different levels of risk for each respective variable. The following equation was used to combine the four environmental risk factors:

$$CQM = FIV + FP + T + P$$

where *CQM* is the combined qualitative metric (unitless); *FIV* is the final inundation value (unitless) that accounts for storm surge plus sea level rise; *FP* is the 500-yr floodplain value (unitless); *T* is the temperature change value (unitless); *P* is the precipitation value (unitless). In the weighting system, FIV contributed most to the CQM due to the amount of risk associated with sea level rise and storm surge (values ranged from 0 to 8).

A final risk assessment classification (CQM), ranging from extremely high (CQM values 8.5–10.0) to low risk (i.e., 1.0–2.0), was devised. In an effort to be sensitive to the institutions included in this study, archival repository names were not presented in study results in favor of reporting regional and national summaries. Tables with final rankings and the datasets used to create them can be accessed from ScholarSphere (The Pennsylvania State University's institutional repository: https://scholarsphere.psu.edu/), or upon request to the authors.

2.9. Data and model limitations

The archive locations dataset (from OCLC's ArchiveGrid) represents the largest aggregation of American archival repositories known to the authors at the time of publication. The dataset has drawn from online catalog records and inventories that archives have made available for inclusion by OCLC, but the dataset is limited in significant ways. First, smaller archives such as historical societies and religious archives are underrepresented. Smaller archives are often open to the public, but do not have the technological resources to put their collection information online and are thus absent from the ArchiveGrid dataset. This means that the number of locations in this study is almost certainly much lower than the actual number of repositories in existence[3]. Second, the archive location information in ArchiveGrid is often an official address that may not accurately represent the actual physical location of archival collections. For example, the address provided may be the location where researchers go to use materials in a reading room, but the collections themselves may be housed at offsite storage facilities and then retrieved for use in the reading room. Finally, the dataset does not provide any detail about the storage facilities of collections. The location of collections inside a building can involve different risk factors; collections are often housed in underground basements or on top floors, and in both cases, may be exposed to flooding from increased precipitation.

An important limitation of this study was a lack of storm surge data for western (i.e. Pacific) coastal locations. The combined sea level rise and storm surge risk factor identified the most archival facilities as being at risk along the eastern seaboard and this risk factor was unfortunately missing for a substantial portion of our study area. Coastal archival facilities on the western seaboard could repeat our analysis when storm surge data become available, and/or consider the risks associated with being near the coast in lower elevation areas.

Interactions between the uncertainties and imprecisions in our data and models may have resulted in false positive (i.e., type I error) or false negative (i.e., type II error) results. The implications of false positive results could lead archivists to believe that their facilities and resources are more at risk to the effects of climate change than they actually are. Resources that these managers invest in moving a collection for example, or infrastructural changes could be seen as wasteful, or alternatively as increasing the overall resilience of the nation's archive facilities to natural disaster. The implications of false negative results are potentially more severe in that archivists may see their repository and collections as being secure, when in fact they are at risk of exposure to climate changes and climate-triggered phenomena with potentially negative consequences. With the potential for false negative results in mind, this study encourages archivists to be skeptical of negative results and to also consider the results for their neighbors and even for their region.

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[3] American archivists, Ben Goldman and Eira Tansey, are currently conducting a Society of American Archivists-funded project to establish the first comprehensive data set of all known US archival repositories.

3. Theory

The present study leans heavily on the data and principles of climate and geographic information science that prompt users to map discrete objects of interest and intersect those locations with numerous spatially explicit models of environmental risk factors, including future climate and extreme weather scenarios. Implicit in this methodological approach is an understanding that the simplifications of both the earth's three-dimensional surface and environmental factors that cascade across that surface are of a quality sufficient to identify local-scale risk factors that can and should inform infrastructure and cultural resource management planning decision-making. Critics of this approach point out substantial uncertainties in even our best contemporary environmental risk data (NOAA, 2010; Marcy et al., 2011), especially at the local level, while others point out issues of additive errors when combining multiple model outputs as was done in this study (NOAA, 2016). Finally, along with others, this study notes that empirical observations of the impact of some recent events do match well the projections of environmental risk models (see Evans, 2017 for a case where actual severity was worse than projected by models). Despite these shortcomings, studies like the present one can serve an important role of raising awareness of changing climate risks, stimulating conversations within professional communities of practice and supporting adaptation planning.

4. Results

The climate risk assessment indicated that future storm surge and sea level rise will increase the risk of American archives to flood hazards considerably by increasing the areas exposed to the highest flood risk. Overall, 2.4% of archival repositories were located within a 500-year floodplain (see Table 2 and Fig. 3a). Approximately 17.7% of archival repositories were susceptible to future storm

Table 2

Number of archive repositories affected by present and future water-related climate change and climate-triggered risks – 500-year floodplain, sea level rise, storm surge, temperature change, and annual precipitation.

Sea Level Rise	
Inundation Scenario (m)	*Number of Sites*
0.3	2
0.9	3
1.8	18
Storm Surge	
Category	*Number of Sites*
1	20
2	38
3	55
4	84
5	26*
500-Year Floodplain	
Classification	*Number of Sites*
In a Floodplain	30
Not in a Floodplain	1202
Temperature Change	
Variable Range (°C)	*Number of Sites*
(−15.60)–(−10.00)	39
(−9.99)–(−5.00)	120
(−4.99)–(−1.00)	288
(−0.99)–0.00	20
0.01–0.99	68
1.00–4.99	336
5.00–9.99	308
10.00–15.60	53
Annual Maximum Precipitation	
Variable Range (mm)	*Number of Sites*
0.0–152.0	376
152.1–202.0	459
202.1–253.0	304
253.1–358.0	93

* Category 5 Storm Surge estimations are only available for East Coast areas south of Virginia.

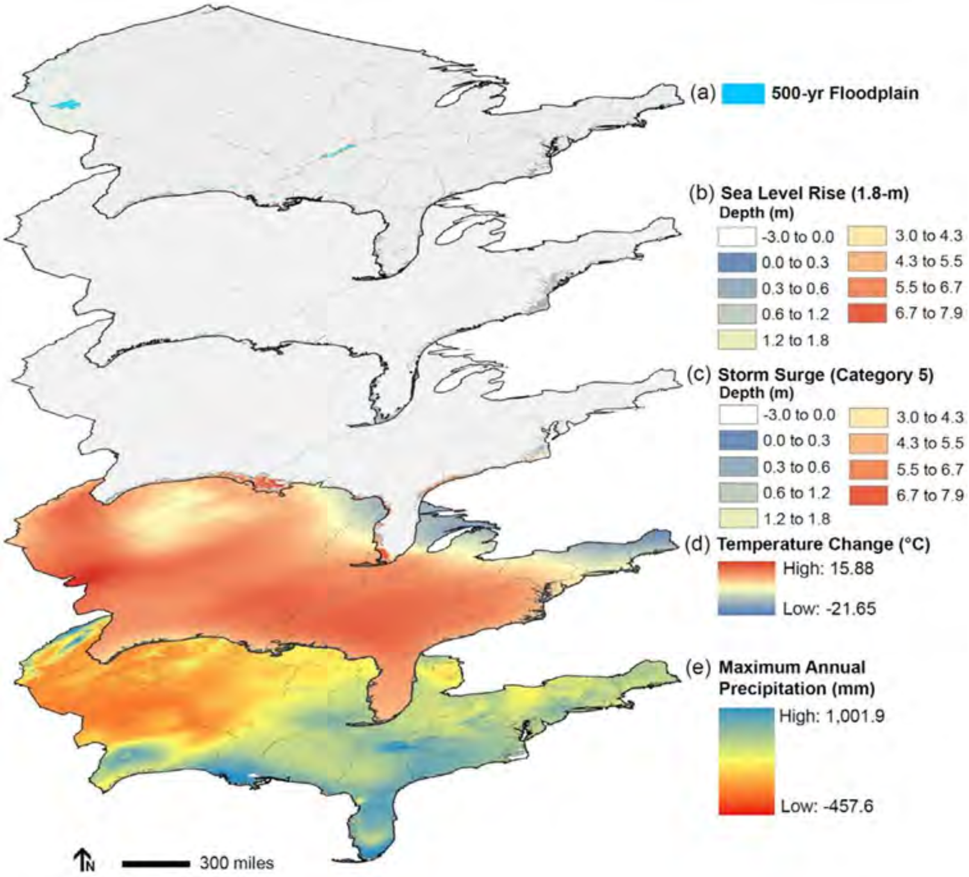

Fig. 3. Mapping of climate risk factors such as (a) 500-year floodplains, (b) 1.8-m sea level rise scenario (m), (c) category 5 storm surge (m), (d) future temperature change values (°C), and (e) future maximum annual precipitation (mm) parameters. Future annual maximum summer temperature (rcp 85, 2070) was subtracted from future annual minimum winter temperature (rcp 85, 2070) to create future temperature change. As shown in (d), for example, the northern portion of the United States is likely to experience more projected winter warming than summer warming. In (e), the eastern United States may be exposed to more annual precipitation than in western parts.

surge plus sea level rise (Table 3). In general, archives were at greater risk of flood inundation due to storm surge (22.1%) than sea level rise (1.8-m scenario) (4.3%) (see Table 2, Fig. 3b and c). Archives on the eastern seaboard were most likely to be exposed to future sea level rise with only one archive location at risk of inundation on the west coast. Projected maximum flood inundation (category 5 storm surge plus 1.8-m sea level rise) by 2100 was most prominent for archival repositories located in Connecticut (7.0-m), Florida (6.7-m), Massachusetts (5.8-m), South Carolina (5.8-m), Georgia (5.2-m), Louisiana (4.9-m), and Texas (4.6-m) (Fig. 4).

More than 90% of archives were estimated to have a temperature change greater than 1 °C (in either positive or negative direction), with 7.5% of sites greater than or equal to a change of 10 °C. Disparities between future annual minimum winter and annual maximum summer temperatures were most prevalent for archives located in Texas (15.59 °C change) and New Mexico (15.50 °C change) regions (Fig. 3d). For annual maximum precipitation, results showed 69.5% of sites with projected greater than 152 mm annual maximum rainfall, and 16 archive locations likely to receive an additional 300 mm of annual precipitation over present day averages. Highest precipitation increases were observed for archives located in parts of Louisiana (358-mm), Florida (336-mm), and South Carolina (300-mm) (Fig. 3e).

A cumulative risk assessment confirmed the need to understand the compounding effects of climate change on archival repositories using an evaluation process that allowed for cross-comparison. Approximately 98.8% of archives were likely to be affected by at least one climate risk factor, though on average, most archives were at low risk of exposure (90%) when risk factors were combined. Thirteen archives demonstrated high or extremely high levels of combined risk (Table 3). A high and extremely high level of risk indicated that a disaster management plan was critical for archives that did not already have an existing plan. Of these archival repositories identified as high-risk, more than half were located in Massachusetts with the remainder in Florida, North Carolina, South Carolina, New York, Rhode Island, and Louisiana.

Table 3

Sea level rise 1.8-m scenario plus storm surge, 500-yr floodplain, future annual temperature change (°C), and future annual maximum precipitation (mm) were categorized by level of risk with corresponding values designated for each variable value range. The number of archival repositories exposed to climate change and climate-triggered phenomena were included within each level of risk exposure.

Storm Surge (SS) + Sea Level Rise (SLR 1.8-m)

Risk Level	*Number of Sites*	*Range of Values*
High	**6**	**WSS + SLR = 6.13–9.45 m**
No SLR Impact	2	6
SLR Low Confidence	2	7
SLR High Confidence	2	8
Moderate	**24**	**WSS + SLR = 3.05–6.12 m**
No SLR Impact	9	4
SLR Low Confidence	9	5
SLR High Confidence	6	6
Low	**189**	**WSS + SLR = 0.03–3.04 m**
Flow Inundation	130*	1
No SLR Impact	55	2
SLR Low Confidence	3	3
SLR High Confidence	1	4
None	**1013**	**WSS + SLR = 0.0 m**
No SS or SLR Impact	1013	0

Floodplain (500-yr)

Risk Level	*Number of Sites*	*Range of Values*
High	30	In a Floodplain = 2
None	1202	Not in a Floodplain = 0

Temperature Change (rcp85, 2070)

Risk Level	*Number of Sites*	*Range of Values*
High	92	(−15.60)–(−10.00) °C OR 10.00–15.60 °C = 1.5
Moderate	428	(−9.99)–(−5.00) °C OR 5.00–9.99 °C = 1.0
Low	624	(−4.99)–(−1.00) °C OR 1.00–4.99 °C = 0.5
None	88	(−0.99)–0.99 °C = 0.0

Annual Maximum Precipitation (rcp85, 2070)

Risk Level	*Number of Sites*	*Range of Values*
High	93	253.1–358.0 mm = 1.5
Moderate	304	202.1–253.0 mm = 1.0
Low	459	152.1–202.0 mm = 0.5
None	376	0.0–152.0 mm = 0.0
Total Number of Sites	**1232**	

Risk Assessment (management plan)

Risk Level	*Number of Sites*	*Range of Values*
Extremely High (Critical)	3	8.5–10.0
High (Potentially Critical)	10	7.0–8.4
Moderate (Necessary)	19	5.0–6.9
Medium (Highly Recommended)	90	3.0–4.9
Low (Suggested)	911	1.0–2.9
None	199	0.0–0.9

* Includes sites not accounted for in SS + SLR (1.8-m scenario).

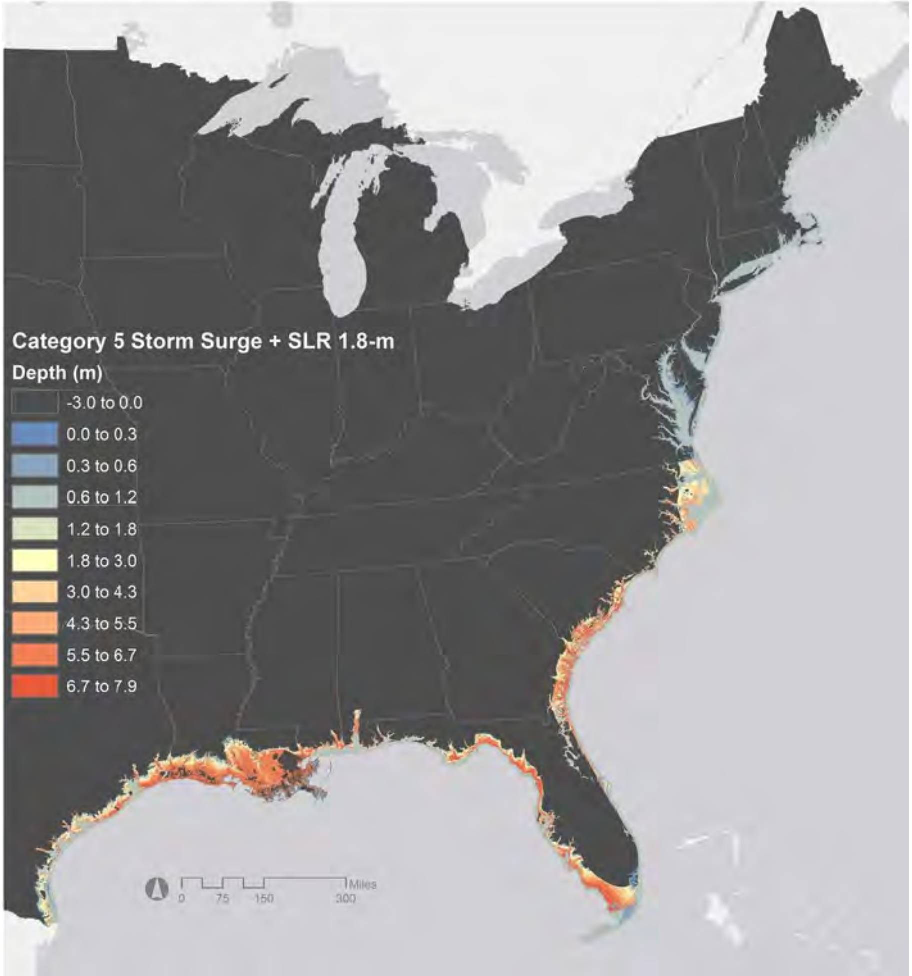

Fig. 4. Sea level rise 1.8-m scenario plus category 5 storm surge is shown for east coast areas south of Virginia, United States. Since category 5 storm surge data was unavailable for areas north of North Carolina, only sea level rise 1.8-m scenario was depicted in this area.

5. Discussion

This study suggested that most archival locations are currently or could be at risk of exposure to at least one type of climate change effect or climate-triggered phenomena by 2100. Less significant events such as periods of intense rainfall or higher summer temperatures can also threaten documentary cultural heritage and undermine the ability of archivists to successfully steward these important cultural resources into the future. This study can help to raise awareness of the possibility of extreme weather events that can lead to collection losses in archives. One example of the application of climate risk information for adaptation planning can be found in the Smithsonian Institution's 2015 strategic sustainability plan, which recommended that administrators do not build or acquire new facilities within FEMA 500-year flood zones (Smithsonian Institution, 2015). Notably, this is a more stringent criteria than is applied by the federal housing administration, which requires residential homeowners to carry special insurance when their home falls within a FEMA designated 100-year flood zone[4].

This study recommends that all archival repositories, regardless of risk exposure, take steps to develop pre-disaster institutional mitigation and ensure implementation of basic environmental monitoring controls. Disaster planning is a core function of archival preservation, yet surveys have shown large numbers of archival repositories without disaster plans or adequate disaster training for staff (Muir and Shenton, 2002; Heritage Preservation and IMLS, 2004). As well, some archives at smaller institutions lack proper environmental storage conditions, which increases the threat of even low risk climate change effects (Kenney and Stam, 2002;

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[4] Subsequent Smithsonian sustainability plans have not included this floodplain recommendation, and it is unclear whether it has become formal practice, or alternatively has been discarded. Nevertheless, this directive is an example of how an understanding of the risks associated with climate change can be incorporated into the management and planning activities of archive facility managers and professional archivists.

Tansey, 2015). Undertaking these planning efforts will help archival institutions guard against all levels of future climate risk. Archival repositories with existing post-disaster response plans should consider developing pre-disaster mitigation strategies to account for local risks associated with our most recent understanding of likely climate change effects. For example, low elevation and proximity to the low-relief coastlines both play a large role in climate risk exposure, so archives in such areas might focus disaster preparation on the likelihood and projected magnitude of oceanic and surface freshwater flooding. With appropriate environmental controls in place, archives exposed to high risks of temperature change can explore more creative methods for managing the environmental settings of collections storage to keep energy costs under control and/or prepare financially for higher operating costs in the future (Hong et al., 2012). Unlike many other measures which are considerably resource-intensive, many disaster planning tools and models exist within the archival profession which can be easily adapted by virtually all institutions.

For archival institutions with medium or higher levels of risk exposure, institutional disaster planning should be supplemented with cooperative planning at the local or regional level. The spatially-explicit results of this study can inform the formation of cooperative planning efforts by both identifying archival repositories that are geographically in close proximity to one another, as well as those that will likely face similar challenges under future climate change. This study recommends forming (or enhancing) dedicated disaster-response regional archival networks and strengthening relationships with regional and state emergency management officials in order to develop collaborative emergency response planning resources. COSTEP (Coordinated Statewide Emergency Preparedness) is a framework developed by cultural heritage professionals that outlines how archives can build and sustain emergency response networks at the state level, and has been used to successfully develop at least one network, COSTEP Massachusetts (NEDCC, 2009). In light of the risks posed by future climate change, more archives should consider undertaking initiatives similar to COSTEP. This work might be integrated within the context of existing regional archival associations, such as the Midwest Archives Conference or the Society of Southwest Archivists.

Locally, archives at medium or moderate levels of risk should also consider planning for disaster by carefully reviewing collections storage locations. Though potentially costly and time-consuming, projects can be developed to shift collections between buildings, to offsite storage locations, or even moved within existing structures to minimize the impact of climate and climate-triggered risks.

Archives with high or extremely high levels of risk may need to consider more aggressive climate adaptation measures. Institutions in geographically high risk areas that are considering new storage facilities or architectural updates to existing ones should make climate change impacts a key factor in planning and infrastructure design. But even those institutions not planning new buildings may need to consider architectural enhancements in order to protect collections (Hong et al., 2012). Institutions in high-risk areas should strongly consider landscape and engineering assessments that will help them most effectively determine how to strengthen, upgrade, or completely re-think the integrity of the building in the coming decades. Though it likely seems financially impractical, some institutions may need to give serious consideration to moving entire facilities to less vulnerable locations because the risk of substantial collection loss or damage is too high (Gordon-Clark, 2012) (Table 4).

Table 4
Management plan recommendations for archive managers based on level of risk exposure.

	Level of Risk Exposure		
Recommendations	*Low*	*Medium-Moderate*	*High-Extremely High*
Develop Institutional Pre-disaster Mitigation Strategies	✓	✓	✓
Implement Environmental Monitoring Tools	✓	✓	✓
Strengthen Relationship with Regional and State Emergency-Management Officials		✓	✓
Consider Shifting Selected Collections to Different Storage Environments Locally		✓	✓
Develop Regional Response Network for Other Archives that can assist in emergencies		✓	✓
Undertake Landscape and Engineering Assessments to Determine Future Environmental Risks to Building			✓
Consider Building Upgrades to Enhance Adaptation to Extreme Weather Events			✓
Consider Moving Entire Facility to Less-Vulnerable Location			✓

This study acknowledges that even the best-resourced archival institutions are unlikely to start receiving significant increases in resources to retrofit or move existing infrastructure, and some collections may remain exposed despite known risks. In addition, a major challenge for archives is that many exist within larger parent institutions such as universities, governments, or corporations in which top-level decision makers may not take risk to archival records as seriously as archivists themselves. Alongside mitigating risks, the American archival profession should also undertake efforts to embed sustainability and adaptation into existing archival practice (Tansey, 2015). This would require that the Society of American Archivists and other regional supportive professional organizations begin to more deeply embed climate change as part of advocacy and policy efforts (SAA, 2016b). With a better understanding of the potential effects of climate change on archives, new recommendations can be incorporated into existing materials, such as the Society of American Archivists' facilities standard. As well, the archival profession can begin to embed adaptation into formal advocacy and outreach initiatives. Such advocacy might, for example, focus on the role of funding agencies that engage in grant-making for archival organizations, or the possibility of restructuring grant programs to help archives develop infrastructure and planning for climate change resiliency.

6. Conclusion - archive community response

Understanding the impacts of water-related climate change and climate-triggered phenomena to archival repositories is imperative for the present and future security of American cultural resources. There is an increasingly pressing need to establish strategic disaster planning initiatives that are appropriate for each archival repository and suite of local risk exposure factors. Archival records are inherently unique, and therefore not easily assigned a monetized value for insurance purposes. In other words, archives are priceless. Better coordination and cooperation between and among archival facilities will likely be required. The complete listing of American archival repositories, their locations and the potential climate change impact risks that they face (generated by the present study), could serve as a starting point for coordination and cooperation efforts organized around either geographic proximity, or similarity in risks faced. The consequences of inaction could lead to damage to national archival infrastructure and degradation and loss of the precious cultural heritage materials housed within them.

Determining the nature and potential scope of climate change and climate-triggered phenomena that threaten documentary heritage found in archives is merely a first step in a potentially lengthy process of developing management interventions and adapting professional practices. It is the hope of the authors that our analysis motivates the archival profession to consider the ways that water-related climate change impacts may increase future risk of exposure to extreme or incompatible climate and weather, and empowers practicing archivists to consider climate change in the management of archival collections. Furthermore, our conceptual framework and mapping methodology may serve as a template for future research both within and outside of the continental U.S. study area. In other regions of the world where risk data exist, careful and spatially explicit study of the potential impacts to archival facilities can be carried out in similar ways to the present study. As more and better climate change risk data become available, the present study can be repeated as part of an iterative process of learning and updating archival management and pre-disaster planning.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2018.03.005.

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