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Subtask 2.5: Future Flood Hazards Gap Analysis

North Carolina Flood Resiliency Blueprint

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Definitions

A comprehensive list of definitions applicable to multiple Flood Resiliency Blueprint documents is provided in a separate document.

Acronyms

AR5/6 – Fifth or sixth Assessment Report (Climate Change)

BCCA – Bias Corrected and Constructed Analogs

BCSD – Bias Correction and Spatial Downscaling

CHAT – Climate Hydrology Assessment tool

CONUS – Conterminous United States

DEM – Digital Elevation Model

EPA – Environmental Protection Agency

FEMA – Federal Emergency Management Agency

FOR-SCE – USGS Forecasting Scenarios of Land-use Change model

GCM – General Circulation Model

GDDP – Global Daily Downscaled Projections

ICLUS – Integrated Climate and Land Use Scenarios

IDF – intensity-duration-frequency

IPCC – Intergovernmental Panel on Climate Change

LISCOAST – Large Scale Integrated Sea Level and Coastal Assessment Tool

LOCA – Localized Constructed Analogs

MACA – Multivariate Adaptive Constructed Analogs

NASA – National Aeronautics and Space Administration

NEX – NASA Earth Exchange

NOAA – National Oceanic and Atmospheric Administration

RCP # – Representative Concentration Pathways (value at the end refers to radioactive forcing in Watts per square meters (W/m^2) in the year 2100)

SLAMM – Sea Level Affecting Marshes Model

SFINCS – Super-Fast Inundation of Coasts

SLR – Sea level Rise

SSP – Shared Socioeconomic Pathways

US – United States

USACE – United States Army Corps of Engineers

USGS – United States Geological Survey

USGS FOR-SCE – United States Geological Survey Forecasting Scenarios of Land-Use Change

1 Introduction

Purpose: Subtask 2.5 – Identify scientifically defensible data necessary to analyze future flood hazards: future land use, climate, etc. List of datasets (including datasets that exist and those that would need to be created) required for assessing future flood hazards. For the purposes of this analysis, “future” can be defined as 10, 20, 30, 50, 60, and 70 years in the future. The Department of Environmental Quality must approve other definitions of “future.”

This document aims to identify scientifically defensible data necessary to analyze future flood hazards for North Carolina and use this information to identify potential projects to reduce the effects of flooding as part of the North Carolina Flood Resiliency Blueprint (Blueprint). Specifically, this document is intended to provide a Gap Analysis for flood projections datasets (including relevant climate change information), future land use maps, and any data that contribute to the generation of future flood hazard information so that the implemented strategies under this program are climate robust and flexible to accommodate different future hazard conditions under changing land use scenarios. This document will provide an overview of the data sources identified in this effort, and note gaps within the datasets pertaining to age, scale, level of detail, potential use, and other shortcomings.

2 Background on future flood hazards

Many flood hazard modeling and mapping studies have relied on historical observations, and failed to account for increasing threats under future climate change and changing land use as a consequence of development (Wing, et al., 2022). It is necessary to account for these future threats if flood mitigation projects are going to be implemented in the near-, mid-, and long-term future considering the investments required for any type of flood mitigation strategy. Moreover, to ensure wise investments, potential flood mitigation strategies ideally shall be robust and flexible to account for a range of different future scenarios. This can be done either by over-designing solutions (going beyond the standard design criteria and construction code standards and considering higher loads or conditions), or by leaving enough space to implement modifications when the circumstances change.

Both observed historical records and complex global and regional climate modeling indicate that an increase in temperature is leading to an intensification of the hydrological cycle, which results in increased intensity and frequency of extreme precipitation events, and therefore more severe flooding, especially in cases where no additional flood reduction measures are set in place (Gudmundsson, et al., 2021). Similarly, higher temperatures lead to changes in patterns of snow melt, rain on snow events, and increased runoff leading to potential increased fluvial[1] flooding (Graybeal & Leathers, 2006). Likewise, rising temperatures increase evaporation, which can reduce surface water and dry out soils, which can increase the likelihood of flash floods (by reducing the infiltration capacity of soils), especially during drought conditions when water availability is already scarce. In addition, rising air and ocean temperatures lead to higher sea levels and an increase in the frequency and magnitude of coastal[2] flooding, which can also be exacerbated by more frequent windstorms. Moreover, sea level rise can push up the shallow groundwater table in coastal areas, causing inland ponding due to emergent groundwater. It is important to note that increased development, human interventions in natural systems, aging infrastructure, and lack of maintenance, and factors such as increased land subsidence (due to sediment diversions, over-pumping of groundwater resources, and increased construction in coastal cities) lead to even higher risks related to flooding.

The Atlantic and Gulf Coasts of the United States (US) are prone to tropical storms and hurricanes, which can trigger both coastal and pluvial[3] flooding. This co-occurrence of hazards leads to exacerbated flooding conditions (also known as compound flooding), which usually is not being captured by modeling coastal or pluvial flooding independently (see (Wahl, Jain, Bender, Meyers, & Luther, 2015), (Wing, et al., 2018)). Those joint events (compound flooding) with climate change can become even more frequent; therefore, there is a need to account for compound flooding in future flood analysis and mapping.

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[1] Fluvial flooding occurs when streams and rivers exceed the capacity of their natural or constructed channels to accommodate water flow, and water overflows the banks, spilling out into adjacent low-lying, dry land (definition from Hazards FEMA).

[2] Coastal flooding is when ocean or estuarine water inundates or covers normally dry coastal land as a result of high or rising tides or storm surges (definition from Hazards FEMA).

[3] Pluvial flooding occurs when the amount of rainfall exceeds the capacity of urban stormwater drainage systems or the ground to absorb it. This excess water flows overland, ponding in natural or man-made hollows and low-lying areas or behind obstructions (definition from https://www.floodinfo.ie/).

Flood mapping (which depicts the spatial extent of water on normally dry land and its associated water depth) is performed by constructing and running flood models[4] using inputs such as topographic and bathymetric data, land use and land cover information, relevant infrastructure features, and appropriate upstream and downstream hydraulic boundary conditions. Boundary conditions may include meteorological conditions, water levels, waves, discharges, precipitation, and sea level rise, which can be derived from projections of historical trends or climate projections from climate modeling experiments (e.g., Coupled Model Intercomparison Project Phases 5 and 6: CMIP5, CMIP6, etc., or other sources). Those experiments simulate past and future climatic conditions according to a set of scenarios that describe how the atmosphere might change under future greenhouse gas emission scenarios, referred to as Representative Concentration Pathways (RCP). Those climate model results are downscaled to a regional level so that they can be useful at, for example, the county level. In the US, the National Oceanic and Atmospheric Administration (NOAA) is the institute leading the development of this type of information; and nationwide, there are different guides on how to use these data according to the geographical region.

Another type of data (as mentioned before) that play a role in assessing future flooding is land use and land cover information. Depending on the land use, ground cover, and type of soil or ecosystem (e.g., wetlands, forest, marshes), water can more easily infiltrate into the subsoil, where it can travel slowly into streams or recharge natural aquifers. An increase in impervious surfaces[5] leads to increased pluvial flooding because rainwater cannot properly infiltrate—instead, it accumulates and flows rapidly into storm drains. This is often the pattern seen in growing cities and developing areas where hard surfaces for commercial, residential, or industrial purposes are replacing agricultural land or greener areas. North Carolina's continued growth[6] is accompanied by increased impervious surfaces, which can have as much or greater impact as climate change on flooding, depending on the watershed. Future scenarios on how land use patterns will change can allow modelers to infer infiltration rates and runoff patterns that influence flood extents. Moreover, land use will inevitably change in coastal areas due to ongoing shoreline retreat and habitat migration. Therefore, capturing those changes in any future flood model mapping efforts is important.

The descriptions below review potential datasets necessary to assess future flood hazards (pluvial, fluvial, and coastal) in North Carolina. When needed datasets are unavailable, a recommendation is given on potential methods and approaches to develop that dataset for use in future flood hazard analysis and mapping. Current hazard information available for the state is not addressed in this specific subtask but is included in the report for Subtasks 2.2 and 2.4.

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[4] Typical examples of flood models include hydrological, hydraulic, and hydrodynamic models that simulate the physics of inundation directly using applicable governing equations, or through the application of empirically derived relationships to estimate water surface elevations, water depths, flow velocities, and other parameters.

[5] Impervious surfaces refer to hard surfaces like paved roads, parking lots, roofs, or highly compacted soils that prevent the natural soaking of rainwater into the ground.

[6] North Carolina is one of the fastest growing states in the United States. According to the US Census, North Carolina had the 4th highest overall state population growth between 2000 and 2019. The state's population grew by a total of 2,406,470 persons, trailing only the population growth in Texas, California, and Florida (see report of North Carolina's Department of Transportation). The growth in population increases the demand for public utilities, road infrastructure, residential areas, etc., which are all land uses associated with impervious materials.

3 Future projections

3.1 Pluvial and fluvial flooding

For future pluvial and fluvial flooding, it is necessary to have hydrologic projections at spatial and temporal scales and use those to set up hydrological and hydraulic models that can translate precipitation and runoff estimates for input to inland flooding analyses. Hydrologic projections are based on global projections coming from general circulation models (GCM; such as the CMIP suite of models), which are later downscaled using different techniques to produce regional information that can be used by decision-makers to address climate change and its associated challenges.

3.1.1 Future projections based on CMIP6 Data

The latest climate models are those of CMIP6, which are used for the latest Intergovernmental Panel on Climate Change (IPCC) publication on climate change (AR6). Based on these projections, the National Aeronautics and Space Administration (NASA) published the Earth Exchange Global Daily Downscaled Projections (NASA Earth Exchange [NEX]-GDDP-CMIP6 (Thrasher, et al., 2022)), which applied GCMs and Bias Correction and Spatial Downscaling (BCSD) methods to obtain daily climate projections at 0.25 degree resolution for the period from 2015 to 2100 for 35 GCMs, and four Shared Socioeconomic Pathways (SSP), as provided in Table 1. Variables relevant for flooding included in the dataset are:

- Near-surface relative humidity
- Near-surface specific humidity
- Mean daily precipitation rate (including liquid and solid phases)
- Surface wind speed
- Surface downwelling longwave radiation
- Surface downwelling shortwave radiation
- Near-surface air temperature
- Minimum near-surface air temperature
- Maximum near-surface air temperature

Table 1. Data Inventory NASA Downscaled Projections

NASA Earth Exchange – Global Daily Downscaled Projections (NEX-GDDP-CMIP6)	
Source of Information	NASA Source Link
Data viewer	N/A
Link to Online Data	Online Data Link 1 Online Data Link 2
Data owner	NASA NEX
Date created	August 2022
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

3.1.2 Future projections based on CMIP5 or CMIP3 Data

There are also downscaled CMIP3 and CMIP5 climate and hydrology projections that have been more frequently used in the US. These data are stored in a general archive for the US; the archive compiles the climate projections developed using different downscaling techniques (e.g., BCSD (monthly), Bias Corrected and Constructed Analogs [BCCA] (daily), and Localized Constructed Analogs [LOCA] (daily)). The latest update to the archive[7] was on June 2020, which included additional LOCA CMIP5 data. All datasets are available for daily (LOCA and BCCA) or monthly (BCCA) projections starting from 1950 through 2099. Differences in the downscaling methods (BCSD versus LOCA) are most noticeable for certain statistics (extreme precipitation and runoff) in mountainous environments. LOCA data in general allow precipitation and runoff values to vary more in a location, while BCSD presents less variation in the values, but in general, higher precipitation than LOCA. LOCA data are being used more frequently than climate projection using BCSD. In addition, LOCA also projects change in the number of wet days in the future, which can affect variables such as evapotranspiration and runoff, which are relevant for inland flooding. This technique attempts to better preserve extreme hot days and heavy rain events than the previous generation of downscaling approaches. The LOCA downscaled climate projections provide temperature and precipitation on a grid of 6km. According to University of California (U.C.) San Diego, Version 2 of the dataset already uses CMIP6 data instead of CMIP5 (only for three variables, but not the entire dataset). The updated CMIP6 data used the same spatial resolution of 6km as the CMIP5 version. The updated variables were minimum and maximum temperature (T_{min} and T_{max}) and precipitation values for the entire North American domain. A final date on the full release of LOCA data using CMIP6 data has not been confirmed by U.C. San Diego.

Datasets relevant for pluvial and fluvial future conditions flooding included in the LOCA CMIP5 dataset are:

- Precipitation (mm/day)
- Rainfall Rate (mm/day)
- Average Air Temperature (degrees Celsius)
- Wind Speed (m/s)
- Soil Moisture (layer 1) (mm)
- Soil Moisture (layer 2) (mm)
- Soil Moisture (layer 3) (mm)
- Snow Water Equivalent (mm)
- Change in Snow Water Equivalent (mm/day)
- Baseflow (mm/day)
- Runoff (mm/day)
- Evapotranspiration – Actual (mm/day)
- Evapotranspiration – Potential, natural veg (mm/day)
- Absolute Humidity (kg/kg)
- Relative Humidity (percent)
- Dew Accumulation (mm/day)
- Albedo (fraction)
- Latent Heat Flux (W/m^2)
- Longwave Net Heat Flux (W/m^2)

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[7] Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

- Sensible Heat Flux (W/m^2)
- Shortwave Down Heat Flux (W/m^2)
- Shortwave Net Heat Flux (W/m^2)
- Snow Melt Rate (mm/day)
- Snowfall Rate (mm/day)
- Sublimation (mm/day)

Summary LOCA variables are available for a historical time period (1976-2005) for three emissions scenarios (lower – RCP 4.5, higher – RCP 8.5, upper-bound[8] – RCP 8.5) and three different time horizons: Early (2016-2045), Mid (2036-2065), and Late century (2070-2099), as described in Table 2.

Table 2. Data Inventory CMIP3 and CMIP5 Climate and Hydrology Projections

Downscaled CMIP3 and CMIP5 – Climate and Hydrology Projections	
Source of Information	Multiple agencies (Archive collaborators) – Bureau of Reclamation, California-Nevada Climate Applications Program, Climate Analytics Group, Cooperative Institute for Research in Environmental Sciences, Lawrence Livermore National Laboratory, National Center for Atmospheric Research, Santa Clara University, Scripps Institution of Oceanography, Southwest Climate Adaptation Science Center, US Army Corps of Engineers, and US Geological Survey). Source Link
Data viewer	Data Viewer
Link to Online Data	All BCSD, BCCA, and LOCA downscaled data Online Data Link Only LOCA Data: Online Data Link
Data owner	Archive collaborators
Date created	From July 2014 to June 2020
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

Alternatively, another source for climate projections in the US is the Multivariate Adaptive Constructed Analogs (MACA) CMIP5 statistically downscaled climate projections as shown in Table 3, as discussed in Table 3. This dataset contains outputs from 20 GCMs from CMIP5 for the contiguous United States and provides projections for the historical record and for two future RCP (RCP 4.5 and RCP 8.5) scenarios for 2006–2100. Data can be downloaded on a daily or monthly basis. The resolution

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[8] Both lower and higher emission scenarios are averages from 32 model simulations under their respective RCP scenarios, while the upper bound in the average of the three wettest model simulations under RCP 8.5.

is either 4 or 6km, and it offers the following variables relevant for pluvial and fluvial future conditions flooding:

- Maximum daily temperature near surface
- Minimum daily temperature near surface
- Maximum daily relative humidity near surface
- Minimum daily relative humidity near surface
- Average daily specific humidity near surface
- Average daily precipitation amount at surface
- Average daily downward shortwave radiation at surface
- Average daily wind speed near surface
- Average daily eastward component of wind near surface
- Average daily northward component of wind near surface

According to (Wang, et al., 2020), both MACA and LOCA data can be used for adaptation planning for flood risk and climate change assessments. LOCA data have been used, for example, in the Fourth US National Climate Assessment, and MACA data have been used in the US Forest Service Resources Planning Act Assessment. However, the two datasets present differences due to the downscaling methods and the training data used. LOCA data in general present significantly less intense and less frequent precipitation extremes than MACA; therefore, when extreme events are relevant (such as in emergency planning and infrastructure design), using MACA data can result in more robust measures.

In 2022, with the approval of the Bipartisan Infrastructure Law, the Office of Water Prediction of NOAA received direct federal funding to update the NOAA Atlas 14 Precipitation frequency atlas of the United States while accounting for climate change (NOAA Atlas 15). The NOAA Atlas 14 provides precipitation frequency information for the US states and territories, and this information serves as the de facto standard for designing, building, and operating infrastructure to withstand the forces of heavy precipitation and floods, but it has been traditionally based on historical records, and assuming a stationary climate. The NOAA Atlas 15 project will be presented in two volumes: the first will account for temporal trends in historical observations, and the second will use future climate projections to generate adjustment factors applicable to the data published in volume 1. This update will provide critical information to support the design of state and local infrastructure under a changing climate[9]. The storm durations in the atlas will range from 5 minutes to 60 days and span average annual recurrence intervals of 1 to 1,000 years. According to NOAA, it is expected that a pilot study for the region of Montana will be published in 2024 and in 2026 for the rest of the conterminous United States (CONUS). The official launch of the complete dataset is planned to occur in 2027.

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[9] https://hdsc.nws.noaa.gov/pub/hdsc/data/papers/NA14_Assessment_report_202201v1.pdf

Table 3. Data Inventory MACA Downscaled Climate Projections

MACA CMIP5 Statistically Downscaled Climate Projections	
Source of Information	U.S Government Source Link
Data viewer	Data Viewer
Link to Online Data	Online Data Link 1/ Online Data Link 2
Data owner	U.S Government
Date created	2012 – 2016
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

Finally, directly for discharge data, the Climate Hydrology Assessment Tool (CHAT) dataset provides RCP 4.5 and RCP 8.5 discharge predictions at the HUC8 watershed level, as described in Table 4. Output data from this dataset provide annual information for both a historical period (1951-2005) and a future period (2006-2099). The tool uses CMIP5 LOCA data, and it performs a trend analysis for annual time series for the historical and the future time periods. The data provide a visualization of epoch-based differences in simulated, monthly, and annual historical versus future-period streamflow, precipitation, and temperature model outputs.

Table 4. Data Inventory for Stream Discharge

CHAT Dataset	
Source of Information	US Army Corps of Engineers (USACE) Source Link
Data viewer	Data Viewer
Link to Online Data	Online Data Link 1
Data owner	USACE – Climate preparedness and resilience
Date created	Latest update January 2023
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

3.2 Land use and land cover change

Climate change affects land use and ecosystems; similarly, changes in land use (due to anthropogenic factors) have a direct effect on amplifying or dampening certain natural hazards (USGS, 2023).

To quantify future flooding more accurately, it is important to have projections of future land cover, as provided in Table 5. In the US, this is a known data gap, but there are a few datasets that have been used to address that gap whenever there are limited resources to model those changes. One of these datasets is the United States Geological Survey (USGS) Forecasting Scenarios (USGS, 2018) of Land-use Change model (FOR-SCE) that gives annual land cover projections from 1992 through 2100 for the CONUS at a resolution of 250m using land uses classes similar to the ones of the National Land Cover Database. The dataset was published in 2014. The model uses IPCC AR4 report scenarios (which have since been superseded by two more recent publications [AR5 and AR6]). This dataset has updated some regions of the US to include newer IPCC scenarios, but the North Carolina region has not been part of those updates.

The 250m resolution of this specific dataset might not have enough detail for certain flood mapping; for example, at the coast the dataset might not cover changes induced by sea level rise, such as changes in wetland area and shoreline retreat. For those type of changes, the SLAMM model (Sea Level Affecting Marshes Model) by Warren Pinnacle Consulting, Inc. has produced projections for thousands of miles of the US Atlantic Coast. As an output, the SLAMM model gives changes in tidal marsh area and habitat type in response to sea level rise. The model accounts for the dominant processes involved in shoreline modifications during long-term sea level rise (inundation, erosion, accretion, overwash, and saturation). SLAMM results for North Carolina may be available from the North Carolina Sea Level Rise Impact Study (North Carolina Emergency Management , Geospatial and Technology Management, 2014); however, data availability could not be confirmed as part of this data review.

Table 5. Data Inventory for US Land Cover Projections

Conterminous United States Land Cover Projections – 1992 to 2100	
Source of Information	USGS Conterminous United States Land Cover Projections - 1992 to 2100 - Science Base-Catalog
Data viewer	N/A
Link to Online Data	Conterminous United States Land Cover Projections – 1992 to 2100 – Science Base-Catalog
Data owner	USGS
Date created	2018
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon new scientific evidence

Another alternative source for land use changes that focuses more on impacts on land cover induced by population growth is the land use and population projections in the Integrated Climate and Land-Use Scenarios (ICLUS) project Version 2.1.1. This dataset produced spatially explicit projections of population and land use that are based on the IPCC's scenarios and pathways. The changes in land use in the dataset focus on the new demand for residential lands. The data are provided for two SSP trajectories, and land use projections are provided every decade through 2100; see Table 6.

Table 6. Data Inventory for US Land Cover Projections Focusing on Population Trends According to SSP Scenarios

Integrated Climate and Land Use Scenarios (ICLUS)	
Source of Information	US Environmental Protection Agency (EPA) Source Link
Data viewer	Data Viewer
Link to Online Data	Online Data Link
Data owner	EPA
Date created	2020
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

Two additional resources relevant for the North Carolina Region related to landscape change are the FUTURES (FUTure Urban-Regional Environment Simulation) model developed by North Carolina State University and the Nature Conservancy's Resilient Coastal Sites Assessment. The first resource, FUTURES, is an open-source land change model that uses demand for development, local development suitability factors, and a stochastic patch growing algorithm for projecting alternative futures of urban form and landscape change (Van Berkel, et al., 2019). The model has been already used to project future land use change and urbanization at a large scale (all US South Atlantic States region, which includes North Carolina (Van Berkel, et al., 2019)). The second resource is a 2-year project that studied over 1,200 coastal sites in the South Atlantic (including North Carolina coastal regions) and assessed their capacity to sustain biodiversity and natural services under sea level rise (1.5, 3, 4, and 6.5 feet of sea level rise [SLR]). The project generated multiple datasets, including geospatial data showing areas with potential for marsh migration under different SLR scenarios that can be used for future conservation and nature management programs, and in the implementation of green or nature-based solutions to reduce climate impacts.

3.3 Sea level rise

The latest SLR dataset for the US comes from the "2022 Sea Level Rise Technical Report" (NOAA 2022), which provides updated projections for the entire US coastline through 2150 for every decade starting from 2020. The dataset was developed by NOAA, NASA, Environmental Protection Agency (EPA), USGS, Department of Homeland Security, Federal Emergency Management Agency (FEMA), US Army Corps of Engineers (USACE), and Department of Defense, and updated the 2017 projections based on new scientific evidence coming from multiple sources including the sixth assessment report (AR6) from the IPCC. The SLR scenarios are provided by decade, and they include estimates of local vertical land motion. The projections also include a set of extreme water-level probabilities for various heights along the US coastline. The estimates are available at 1-degree grids spatially, and they were downscaled specifically at NOAA tide-gauge locations. These data are discussed in Table 7.

This information can be used to adjust downstream boundary conditions for riverine flood models, and also to account for increased water levels in coastal flood modeling (e.g., extreme sea levels including sea level rise, tides, storm surge, and waves). There are other similar global datasets such as the Large-Scale Integrated Sea Level and Coastal Assessment Tool (LISCOAST) collection[10] (European Commission, Joint Research Center) which also provides extreme sea level projections until 2100 for every decade since 2000, but the 2022 SLR technical report includes information adjusted for the US, and therefore is the primary source to use in cases where more local projections are not available.

The final installment of the IPCC's AR6 is scheduled to be released in March 2023. According to the United Nations Foundation, the next report (AR7) will likely conclude around 2030 and will likely include a new update to this dataset. By 2030, it is expected that scientists will gain more certainty on the range of potential future warming that may occur, and this will reduce the uncertainty in future climate projections. NASA and NOAA are continuing monitoring efforts to assess potential divergence between observational measurements and the projected climate scenarios. It is recommended that North Carolina tracks the next generation of interagency reports and data to enable informed climate adaptation.

Table 7. Data Inventory Sea Level Rise

2022 Sea Level Rise Technical report and Data	
Source of Information	2022 Sea Level Rise Technical Report and Data Source Link
Data viewer	Data viewer
Link to Online Data	Online data Link (Data for download includes different sea level rise maps for different scenarios, associated water depths, DEM, and information of sea level rise scenarios at tidal gauges. In the first link, data of marsh migration can also be downloaded.)
Data owner	NOAA Office for Coastal Management
Date created	February 2022
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

3.4 Coastal hazard maps

The USGS recently (January 2023) released a dataset that provides future coastal flooding and erosion hazards due to SLR and storms along the North Carolina and South Carolina coast (Barnard, et al., 2023), as provided in Table 8. The dataset includes:

- Projected flood hazards (28 scenarios representing combination of seven SLR amounts in combination with three storm events and daily conditions);

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[10] LISCOAST Dataset portal

- Storm surge and astronomical tide time-series in the nearshore region for projected future storms (showing information on how water levels are expected to change from 2020-2050);
- Shoreline change time-series (2020-2100), which show changes in shoreline positions along transects, considering sea level, wave conditions, along-shore/cross-shore sediment transport, long-term trends due to sediment supply, and estimated variability due to unresolved processes (as described in (Vitousek, et al., 2021));
- Depth to water table (associated with seven SLR scenarios that give maps with groundwater emergence and shoaling – see example in Figure 1); and
- Vertical land motion (13 years of historical observations).

The resulting data products include detailed flood hazard maps along the North Carolina coast due to sea level rise and plausible future storm conditions that consider the changing climate, hurricanes, and natural variability, which makes it the latest future coastal flooding and erosion dataset for the region. Different from other coastal modeling efforts, not only was SLR included, but also dynamic contributions from tide, storm surge, wind, waves, river discharge, precipitation, and seasonal sea level fluctuations. Outputs include impacts from combinations of SLR scenarios (0, 0.25, 0.5, 1.0, 1.5, 2.0, and 3.0m) storm conditions including 1-, 20-, and 100-year return interval storms and a background condition (no storm – astronomic tide and average atmospheric conditions). Flood maps are available at 10m resolution and include each SLR scenario and flood frequency (1-, 20-, and 100-year return periods).

It is important to mention that the flood modeling scheme (using the SFINCS[11] model) includes future estimates for river discharge. The future time-series data of river/fluvial discharge were derived for 48 rivers in the study area. The discharge time-series was computed using the relationship between historical North America Land Data Assimilation System precipitation and NOAA National Water Model reanalysis data, and applying it to future GCM precipitation (2020-2050) output (Nederhoff, et al., 2023). Although both precipitation and river discharge were included, only flood depths for areas identified as coastal flooding were calculated. Nonetheless, flood extents (for all flood drivers) for the same return periods and SLR scenarios are included in the public data release.

This dataset will be expanded to include other states along the Atlantic coast, including Florida, Virginia, and Georgia, using the same methodology. This USGS effort decreases the need to perform additional coastal flood modeling because the maps are already available and can be used directly for planning purposes. The main downside is that the flood frequencies do not cover more severe coastal flood events, such as the 500-year flood event.

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[11] https://sfincs.readthedocs.io/en/latest/overview.html

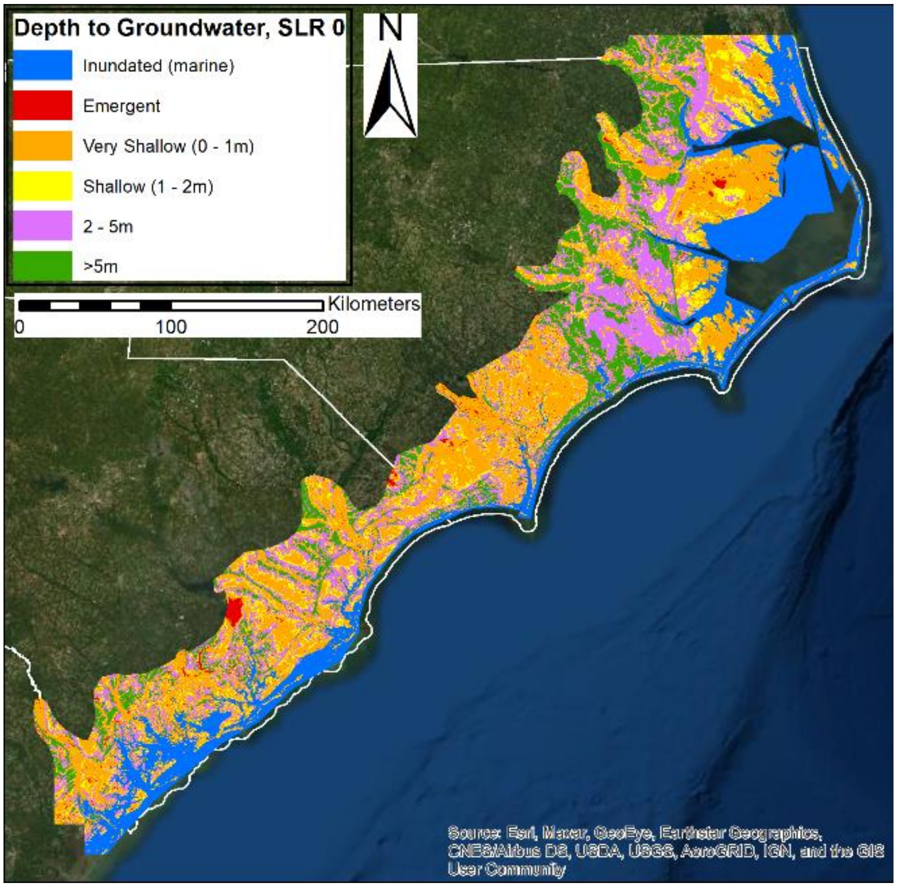

Figure 1. Depth to groundwater under current conditions (no SLR). Emergent and inundated areas do not have an associated depth. All other classifications indicate depth in meters below ground level.

Table 8. Data Inventory Future Coastal Hazards

Future coastal hazards along the US North Carolina coasts	
Source of Information	USGS projection of coastal flood hazards, coastal water depth and flood potential in North Carolina
Data viewer	–
Link to Online Data	Online Data Link/
Data owner	USGS
Date created	January 2023
Frequency of updates	N/A
Update Needed	Yes, upon receipt of new scientific evidence, new DEM, etc.

3.5 Global datasets (flood maps)

There are numerous initiatives that map flood hazards at a global scale. Some are commercial products, while some are publicly available data sources. Relevant examples of each of those products are the FATHOM hazard maps (commercial) and the Aqueduct datasets (public).

Fathom-Global 3.0 maps estimate pluvial, fluvial, or coastal flooding at a 30m resolution for the current climate (2020), and future climate scenarios including combinations of different time horizons (yearly from 2011 to 2100). Climate scenarios in FATHOM align with the IPCC AR6 report showing SSP in combination with RCPs, but also individual RCP scenarios. They provide the associated uncertainty as well (17th, 50th, and 83rd percentiles). These types of commercial hazard maps, as described in Table 9, have been used by insurance companies, the banking sector, engineering companies, and state agencies such as the Texas Water Development Board and international non-governmental organizations such as The Nature Conservancy. Fathom also has a US detailed dataset (10m resolution), but it is only available for the current climate (2020) according to their website (accessed March 23, 2023).

Table 9. Data Inventory Commercial Flood Maps for Future Climate Conditions

FATHOM Global 3.0 Maps and FATHOM US flood map	
Source of Information	FATHOM Contact US – Fathom
Data viewer	The Making of Fathom's Climate Dynamics Framework | Webinar
Link to Online Data	N/A
Data owner	Fathom
Date created	2020
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

Within the public realm, coarser datasets are available such as the Aqueduct data, as indicated in Table 10. This dataset provides fluvial and coastal risks under baseline conditions and future projections (RCP 4.5 and 8.5) in 2030, 2050, and 2080 at a grid size of 1km. These datasets offer a high-level overview of flood hazard and risk, but they are not at sufficient detail for local assessment. If there is not additional flood hazard data available and it is too costly to derive new information, this could be a first alternative to fill in data gaps.

Table 10. Data Inventory Publicly Available Flood Maps for Future Climate Conditions

Aqueduct Floods	
Source of Information	World Resources Institute Aqueduct Floods Methodology | World Resources Institute (wri.org)
Data viewer	Aqueduct Floods (wri.org)
Link to Online Data	Aqueduct Floods Hazard Maps Version 2
Data owner	World Resources Institute
Date created	Last update October 2020
Frequency of updates	Depending on IPCC and local monitoring
Update Needed	Yes, upon receipt of new scientific evidence

3.6 Other data

Accurate flood hazard modeling and mapping will always rely on good and updated bathymetric and topographic data. In North Carolina, many estuarine regions where coastal waters meet inland waters experience compound flood hazards (e.g., the Neuse River). Some of these areas have limited or no detailed bathymetric data, which introduces uncertainties in flood hazard modeling in these critical areas. If flood model results are questionable, then identification and evaluation of effective flood reduction measures may not be possible. For future modeling and mapping of flood hazards, this remains equally important. Therefore, it is recommended that the state invests in both bathymetric and topographic surveys at key locations so that modelers can have access to high-resolution topographic and bathymetric data that improve flood mapping. This information will need to be updated at regular intervals to reflect changes in natural conditions and anthropogenic alterations.

3.7 Methodologies (no datasets)

There are several papers that highlight methodologies on how to compute future climate conditions (mainly precipitation). Examples of this include:

- Estimation of future peak riverine flows (Kollat, Kasprzyk, Thomas, Miller, & Divoky, 2012);
- Estimation of relative changes in extreme daily precipitation for different return periods and different time horizons (Coelho, et al., 2022);
- Projecting flood frequency curves (until 2100) under near-term climate change using a sophisticated regression that includes precipitation and temperature (Awasthi, Archfield, Ryberg, Kiang, & Sankarasubramanian, 2022);
- Adapting or projecting intensity-duration-frequency (IDF) curves considering climate change (see example of publications in (Martel, Brissette, Lucas-Picher, Troin, & Arsenault, 2021) and (Irizarry-Ortiz, Stamm, Maran, & Obeysekera, 2022));

- Studying the effect of imperviousness in annual flooding through the panel regression method, which concluded that for the United States, on average, a 1 percent increase in impervious area leads to a 3 percent increase in annual flood (Blum, Ferraro, Archfield, & Ryberg, 2020); and
- Using peak over threshold methods in flood frequency analysis to better characterize changes in seasonality (Dickinson, Harden, & McCabe, 2019).

In addition, there are several publications that have examined hypotheses behind historical changes in flood frequency and annual peak streamflow in the CONUS Southeast region (Ryberg, 2022). These studies have found that anthropogenic factors such as changes in land use, reservoir construction, and water use are more dominant causes for changes in flood patterns than solely increases in precipitation due to climate change.

The use of certain assumptions, methodology, or the direct use of hydrological projections in detailed rainfall-runoff models or hydraulic/hydrodynamic model to obtain flood extents depends on several considerations that can include cost effectiveness reasons, technical capacity, and time and effort needed to modify pre-existing models, among other reasons.

In general, there are still knowledge gaps in terms of understanding the interaction of precipitation and temperature in future climate predictions, but also in modeling changes in seasonality associated with temperature increases. In addition, gaps in translating theoretical methods into information and data that can be used by practitioners to incorporate climate change insights into future planning and retrofitting of existing infrastructure remain a challenge. Apart from filling scientific gaps, it is also important to be able to make decisions in terms of climate mitigation and adaptation under deep uncertainty. Methods such as adaptation planning[12] should be prioritized alongside data collection and monitoring programs that enable correcting or implementing actions in time to reduce harmful effects of climate change.

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[12] Also described as Dynamic Adaptive Policy Pathways (see concept at link)

4 Key Data Gaps and Recommendations

In the previous sections, an overview was provided of the existing datasets and methodologies available to analyze future flooding, with emphasis on climate projections and other necessary data to use as input in future hazard modeling schemes. Most of the datasets listed in this document will require an update every time there are new scientific insights (for example, the IPCC publishes new scientific information every 5 to 7 years). Therefore, it is important that the State of North Carolina remains up-to-date with the latest information and evaluates if those changes would generate a substantial modification in flood hazard maps created with older climate projections.

Strategies such as working with “what-if?” scenarios or sensitivity studies that cover multiple possibilities of future change can be beneficial to reduce the risk of having to redo flood hazard analyses as future climate projections evolve. In addition, including adaptation planning together with monitoring programs that collect information about how certain parameters are changing (e.g., sea level rise or subsidence rates) can be more beneficial than static plans that are only designed to accommodate one future scenario.

For the current purpose of guiding the state’s efforts on flood planning processes to increase community resiliency, aside from using the existing datasets to estimate future hazards, there is also the need to invest in creating additional datasets for future flood hazard analysis. Those datasets are listed below as identifiable data gaps.

4.1 Pluvial and fluvial flooding

- Create adjusted curves for hypothetical storms (Soil Conservation Services storms) that reflect the future changes in rainfall patterns in North Carolina. These curves are traditionally used for estimating both peak flow rate and runoff volume from precipitation of a "critical" duration. Another approach can be to generate updated IDF curves to reflect future climate changes. The creation of any of those adjusted curves can be directly used as input in hydraulic models that use such information as boundary conditions to force the flood model.
- Estimate future frequencies for storms using extreme value analysis on synthetic storm data (including hurricanes) that accounts for changing precipitation/discharge patterns. Methods such as the one used by (Bates, et al., 2021) in which precipitation change factors between historical and current/future conditions were computed could be used to define future boundary conditions for flood hazard modeling.
- Use the NOAA Atlas 15 dataset when available (after 2027) to support the design of state and local infrastructure under a changing climate (incorporate findings into legislations for construction codes, planning regulations, watershed management policies, etc.).

4.2 Coastal flooding

- The recently published (2023) USGS coastal flood maps, including compound flooding, are a great source for statewide information on future flooding driven by extreme sea levels and inland flooding. It is important that monitoring activities related to vertical land motion and sea level change are continued to have longer observed records and local information about sea level trends.
- It is also suggested that the dataset of groundwater emergence and shoaling from USGS is used in any coastal district or county for future planning processes to increase public safety, mitigate

physical damages, and more effectively manage and allocate resources in complex coastal settings. Sea level rise will also cause the rise of shallow groundwater underneath low-lying coastal communities, so the focus cannot be solely at impacts near the shoreline, but also further inland.

4.3 Other input information

- Invest in high-resolution topographic and bathymetric data. Reliable elevation datasets are crucial for flood hazard analysis. Is important to have better bathymetry datasets, not only at the coastal boundaries, but also at inland river sections. Is also recommended that proper attention is given to the transition between submerged and dry land to have seamless elevations that do not cause any inaccuracies in flood mapping.
- Terrain characteristics coming from land use and land cover maps are very relevant, especially around waterbodies. From such maps, effective roughness values are derived to be later incorporated in flood modeling. To develop future flood mapping products, it is important to not only have future land use scenarios that can be retrieved from the existing datasets and methods described in this report (FORE-SCE model (Dornbierer, Wika, Robison, Rouze, & Sohl, 2021)), but also by exploring new methodologies such as machine learning techniques and agent-based modeling, because both approaches can have promising results in showing, for example, effects of urbanization and population growth in natural systems.

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