CLIMATE RISK ASSESSMENT

Kentucky River Area Development District

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Woodwell Climate Research Center

Introduction

The impacts of climate change on the frequency and severity of physical hazards have already put communities at significant risk. As the threat of climate change intensifies, the need for accessible information, tools, and expertise to support climate-resilient decision-making grows more urgent. From local communities to entire countries, effective planning and response are crucial. Woodwell Climate Research Center collaborates with local government leaders to tailor and localize climate risk assessments. Despite the critical importance of this information for informed planning decisions, it remains largely inaccessible to many local government leaders. Woodwell advocates for the free and widespread availability of this vital science. To bridge this gap, Woodwell partners with communities worldwide, including the Kentucky River Area Development District (KRADD), providing comprehensive community climate risk assessments at no cost.

Results summary

As a result of climate change, flood risk is projected to increase in KRADD. The probability of the present-day 100-year rainfall event, a useful indicator of flood risk, is expected to be five times greater by midcentury and ten times greater by the end of the century. Heavier rainfall will translate into greater flood depths and extent for KRADD. Here we present our findings on extreme precipitation and flooding to help KRADD in its plans to create a more resilient future for all residents.

Extreme rainfall

The Fifth National Climate Assessment shows that the U.S. Southeast region has already seen a 37% increase in annual precipitation occurring from the heaviest 1% of events[1]. Future warming is expected to continue this trend of intensification, meaning more frequent and severe rainfall events. Here we use localized future precipitation data from a downscaled global climate model to calculate the change in probability of extreme rainfall events. A detailed explanation of the precipitation data processing can be found in the methodology section of this document. In Figure 1, we show the changes in the return period of the present-day (2000-2020) 100-year rainfall event for midcentury (2040-2060) and late century (2070-2090). By midcentury, the present-day 100-year event will occur with a return period of roughly 1-in-20 for all counties except for Owsley and Letcher which are closer to 1-in-50. By late century, the present-day 100-year event will become a roughly 1-in-10 year event for all counties except Owsley which is a 1-in-15 and Letcher which is closer to 1-in-20.

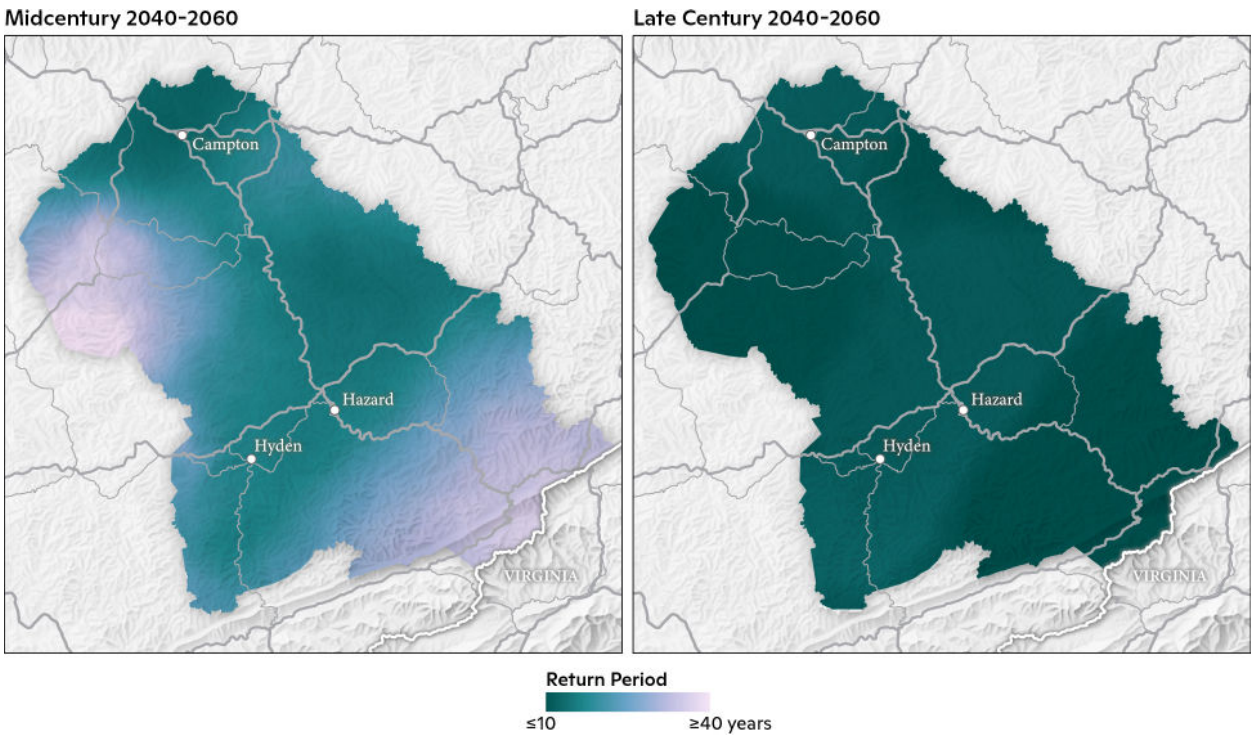

Figure 1: Mid- and late-21st century change in present-day 100-year return period. The future return period of the present 100-year rainfall events in midcentury (left) and late century (right) with the darker the hue, the smaller the return period (greater frequency of occurrence). By midcentury, the present-day 100-year rainfall event is expected to become between a 1-in-20 year event for all counties except Owsley and Letcher, which are closer to a 1-in-50 year event. By late century, the present-day 100-year rainfall event is expected to become a 1-in-10 year event everywhere except for Owsley County which is 1-in-15 year event and Letcher County which is close to 1-in-20 year event.

[1] Marvel et al., 2023: Ch. 2. Climate trends. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH2

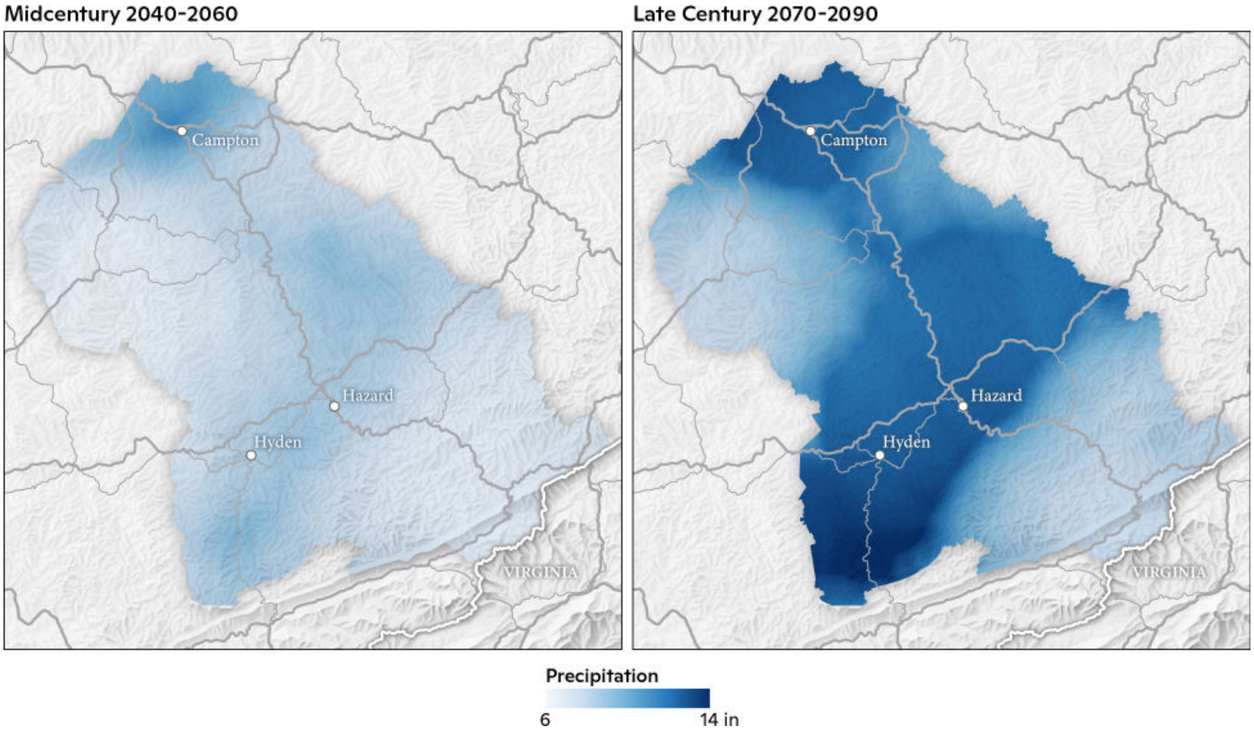

Figure 2: Mid- and late-21st century change in historical 100-year rainfall. The future rainfall amounts in inches for mid-century (left) and late-century (right) 100-year rainfall event with the darker the blue, the greater the rainfall amount. By midcentury and late century, the 100-year rainfall event is expected on average to drop 7.8 inches and 10.79 inches respectively across KRADD, see Table 1 for specific locations.

According to the National Atlas 14 published by the National Oceanic and Atmospheric Administration (NOAA), the 100-year rainfall amount, based on present-day rainfall records, for KRADD is between 5.42 inches (137.67 mm) and 6.48 inches (164.59 mm)[2]. For reference, the present-day annual average rainfall for Jackson, KY is 51.89 inches (1318.01 mm)[3]. By midcentury, the 100-year amount increases to between 6.25 inches (158.75 mm) and 11.34 inches (288.04 mm) and by late century this further rises to between 7.51 inches (190.75 mm) and 14.58 inches (370.33 mm; Figure 2). Table 1 shows the 100-year rainfall events for the eight county seats in KRADD and the average value across KRADD.

[2] NOAA calculates extreme rainfall frequencies with all available station data. Across KRADD, several locations have station data with daily rainfall records. For a list of all locations see: NOAA Atlas 14 Precipitation-Frequency Atlas of the United States Volume 2 version 3.0 revised 2006.

[3] National Weather Service Jackson, KY Climatological Annual Report https://forecast.weather.gov/product.php?site=JKL&product=CLA&issuedby=JKL

	Present	Midcentury	Late Century
Hazard	5.71 in (145.03 mm)	8.45 in (214.63 mm)	12.63 in (320.80 mm)
Jackson	5.72 in (145.29 mm)	8.26 in (209.80 mm)	11.89 in (302.01 mm)
Beattyville	5.8 in (147.32 mm)	6.6 in (167.64 mm)	8.42 in (213.87 mm)
Hyden	5.74 in (145.80 mm)	8.39 in (213.11 mm)	12.62 in (320.55 mm)
Whitesburg	5.58 in (141.73 mm)	6.6 in (167.64 mm)	7.6 in (193.04 mm)
Booneville	5.76 in (146.30 mm)	6.5 in (165.10 mm)	8.24 in (209.30 mm)
Campton	5.78 in (146.81 mm)	10.89 in (276.61 mm)	12.47 in (316.74 mm)
Hindman	5.51 in (139.95 mm)	7.63 in (193.80 mm)	11.12 in (282.45 mm)
Area Average	5.73 in (145.54 mm)	7.8 in (198.12 mm)	10.79 in (274.07 mm)

Table 1: Mid- and late-21st century change in present-day 100-year rainfall. The rainfall amounts in inches and millimeters for the county seats in the eight counties of KRADD along with an area average of the present-day, mid-century, and late-century 100-year rainfall events.

Flooding

For a detailed explanation of the flood model input data and flood modeling procedures, please refer to the methodology section of this document.

Flood extent comparison

Before estimating future flood risk, we compare the present-day flood risk results against the Federal Emergency Management Agency (FEMA) flood maps as a validation exercise. FEMA maps are not ground truth data, but it is useful to compare various model results given the lack of appropriate reference data. Several patterns emerge when comparing the extents visually. The risk of rivers overflowing their banks, also known as fluvial or riverine flooding, estimated by Woodwell is greater than FEMA estimates, particularly along tributaries to the different segments of the Kentucky River. This is a result of FEMA simulations indirectly accounting for rainfall because they use stream gauges or hydrologic models. Finally, FEMA shows no flood risk in areas disconnected from rivers, while Woodwell demonstrates extensive non-riverine areas are vulnerable to flooding. This is because FEMA does not account for direct rainfall across the entire domain, also known as pluvial flooding. Finally, comparing the flood extents in some counties is challenging, because the FEMA analyses used to generate the flood zones are out-of-date or they don't contain any in-depth studies. While the effective year of the FEMA Flood Insurance Study for Lee County is 2022, the riverine modeling for the Kentucky River and its tributaries in Beattyville was completed in 1976[4]. Breathitt County was also completed in 2022; however, the riverine modeling for Panbowl Lake was done in 1991 and the North Fork Kentucky River in the city of Jackson was completed in 1990[5]. The counties of Owsley and Wolfe have no flood zones where studies were completed.

[4] *Flood Insurance Study Lee County, Kentucky Volume 1*. Federal Emergency Management Agency. Preliminary October 27, 2022.

[5] *Flood Insurance Study Breathitt County, Kentucky Volume 1*. Federal Emergency Management Agency. Preliminary October 27, 2022.

Present and future flood risk

The primary flood risk in KRADD is riverine flooding. Major riverine flooding is associated with the North Fork Kentucky River, the South Fork Kentucky River, and the Middle Fork Kentucky River. In Figure 3, we show the depth of the 100-year flood for select locations around KRADD. In Hazard, flooding along the North Fork Kentucky River is quite extensive. Several structures along the North Fork Kentucky river are inundated during a present-day 100-year flood, particularly along Main Street (roughly 9.8–13.1 feet; 3–4 meters), and approximately 20 homes between Kentucky Boulevard and Parkway Street (about 9.8 feet; 3 meters). Campton also has flooding along Swift Camp Creek that goes through downtown. Approximately 1.64 feet (0.5m) to 3.28 feet (1m) of flooding occurs along Main Street and near Washington Street. Lastly, Hyden shows extensive flooding from the Middle Fork Kentucky River and Rockhouse Creek. This causes flooding along Main Street/ US HWY 421 which inundates several locations such as Hyden City Park (36.1 feet; 11 meters), Kentucky School of Bluegrass and Traditional Music (11.5 feet; 3.5 meters), and flood waters approaching Mary Breckinridge ARH Hospital on the west side (6.2 feet; 1.9 meters). We mask wetland areas to focus the analysis on locations where human life and property are at risk.

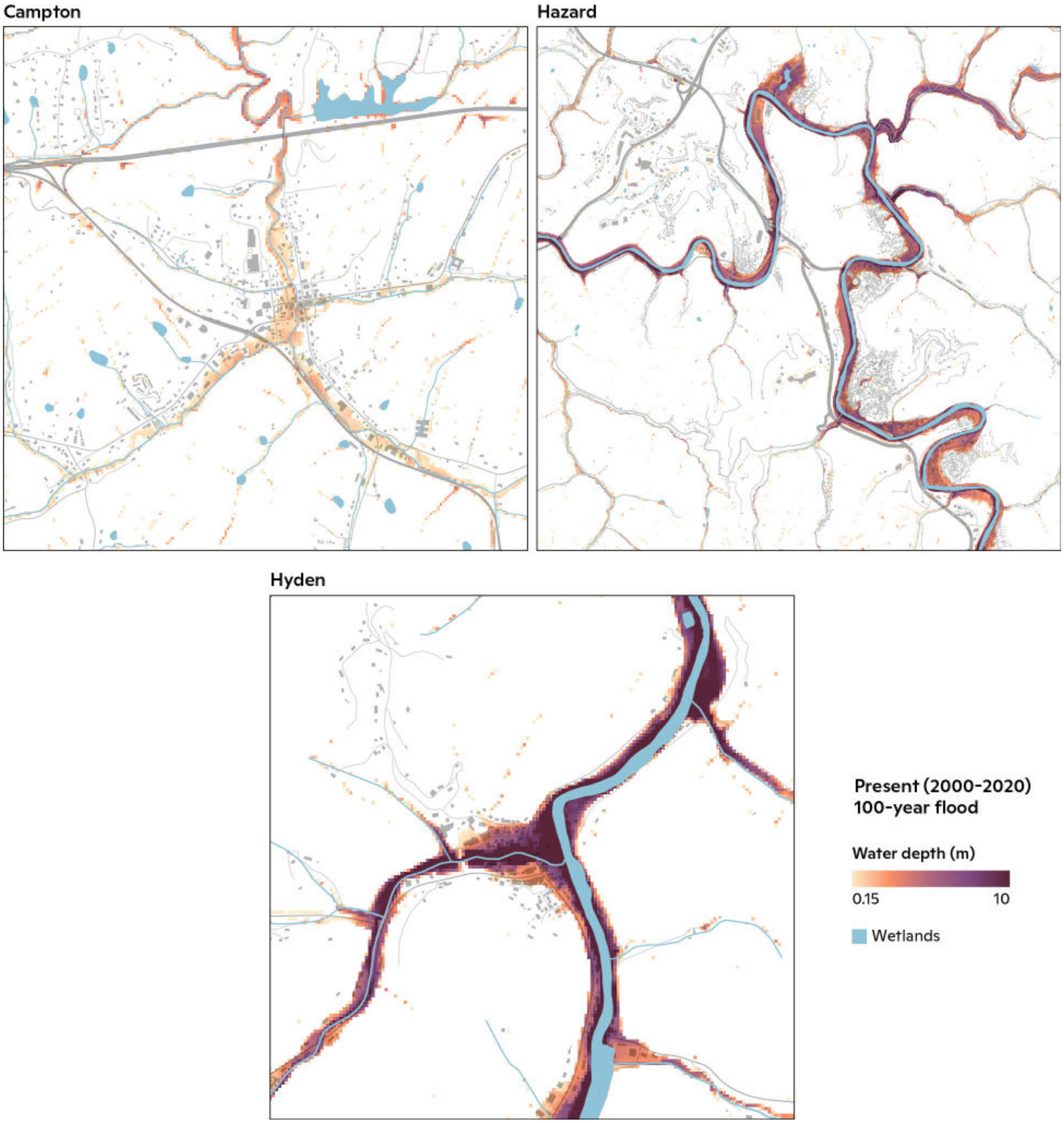

Figure 3: Present-day 100-year flood. The flood depth for select cities (Campton, Hazard, and Hyden) around KRADD. The maximum depth from the 100-year pluvial/riverine flood is shown. Darker hues indicate deeper flood waters. Gray polygons are buildings.

Future flood risk is most notably seen along various branches of the Kentucky River. We focus on Hazard, Campton, and Hyden where flood depth and extent expand throughout midcentury and late century (Figure 4). Most notably the Mary Breckinridge ARH Hospital in Hyden is inundated with 16.4 feet (5 meters) by late century. This change in riverine and pluvial flood risk is due to projected increases in rainfall on average between 2 and 5 inches (50.8 to 127 mm), as shown in Table 1. We also present several flood risk metrics in Table 2. Presently, just over 31% of the structures in KRADD are vulnerable to the 100-year flood. That number increases to about 36% by midcentury and then 40% by late century. The average flood depth in KRADD increases by 2.33 ft (0.71 meters) through the 21st century while the area flooded increases from 5.1% in the present day to 6.1% by late century.

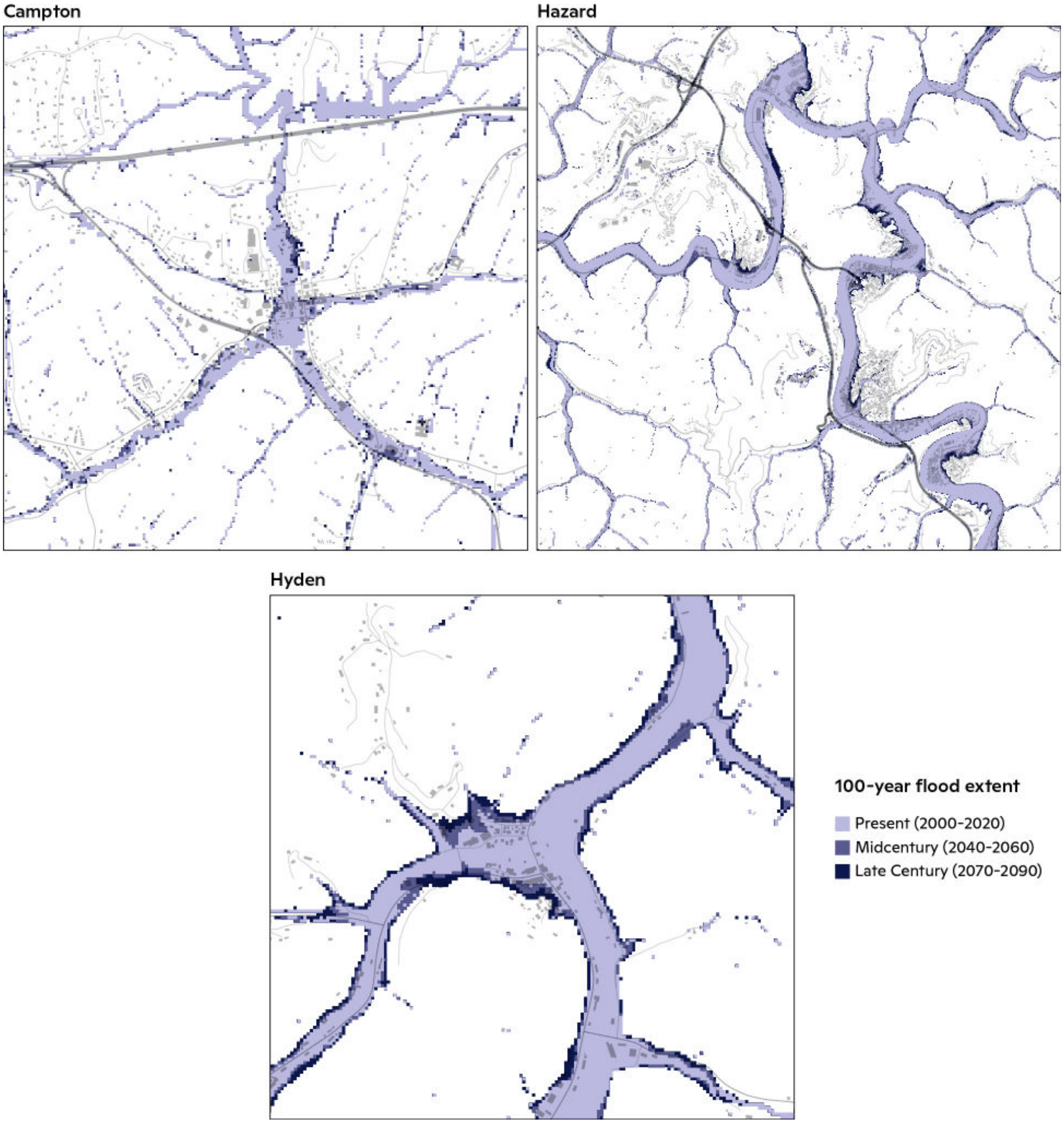

Figure 4: Present-day and future 100-year flood KRADD. The flood extent, quantified as having a depth of at least 0.5 ft (0.15 m), for select cities (Campton, Hazard, and Hyden) around KRADD. The maximum extent for the 100-year pluvial/riverine is shown. Gray polygons are buildings.

	Present	Midcentury	Late Century
Area Flooded	5.1%	5.5%	6.1%
Average Depth	6.20 ft (1.89 m)	7.02 ft (2.14 m)	8.53 ft (2.6 m)
Structures Flooded	21,070 (31.7%)	23,831 (35.8%)	26,568 (40%)

Table 2: Flood risk metrics for mid- and late-21st century in KRADD. The percent of land area (excluding wetlands) flooded and the number of buildings (and percent of total structures) flooded for KRADD of the present-day, mid-century, and late-century 100-year rainfall events.

Conclusion

KRADD is currently at high risk from flooding, and this exposure will only increase under climate change. The results presented in this study were compared to FEMA's flood maps, revealing significant discrepancies primarily due to the exclusion of pluvial flooding in FEMA's analysis and dated studies. The results of this research indicate an expected increase in the frequency and intensity of heavy rainfall with the probability of the present-day 100-year rainfall event to be five times higher by midcentury and ten times higher by late century for most counties. This report provides insight into the vulnerability of KRADD, where an increasing number of buildings and areas will be exposed to flood waters by late century.

Methodology

To simulate flood risk, we use the LISFLOOD-FP v8.1 flood model (LISFLOOD-FP developers, 2022; Shaw et al., 2021). LISFLOOD-FP is a two-dimensional raster hydrodynamic model that solves an approximation of the shallow water equations. LISFLOOD-FP has been extensively used from the river reach scale to continental simulations and we refer the reader to Shaw et al. (2021) for a detailed explanation of LISFLOOD-FP.

All flood model results show flooding above ~0.5 ft (15 cm) as this is an average curb height and any flooding above this threshold would likely result in flood damages. All areas that are wetland and permanent water cover as determined by National Wetland Inventory (https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper).

Three time periods were used for this study: 2000-2020 (present), 2040-2060 (midcentury), and 2070-2090 (late century). These time periods can also be interpreted as warming levels in the context of climate policy. The 2000-2020, 2040-2060, and 2070-2090 periods correspond to 1, 2 and 3 degrees Celsius of warming respectively. For each time period, a pluvial/riverine flooding run was performed.

Any analysis involving structures used the USA Structures dataset (https://gis-fema.hub.arcgis.com/pages/usa-structures). This dataset was created through a collaboration between DHS, FIMA, FEMA's Response Geospatial Office, Oak Ridge National Laboratory, and the U.S. Geological Survey.

1 Rainfall

A | Present-day rainfall

The 24-hour 1-in-100 year rainfall event was used from NOAA Atlas 14 precipitation frequency estimates for KRADD (Bonnin et al., 2004). The precipitation frequency GIS grids were used to obtain spatially varying rainfall values across the entire domain. The temporal distribution, also from NOAA Atlas 14, of the 24 hour rainfall is taken from the combined cases of the four quartiles and uses the 90% cumulative probability.

B | Future rainfall

CMIP6 climate model data were bilinearly interpolated to a 1-km grid and then bias-adjusted using phase 3 of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) version 2.5 methodology (ISIMIP3BASD v2.5) (Lange, 2019; Lange, 2021). High-resolution, 1-km Daymet reanalysis data (Thornton et al., 2022) were selected as the observation dataset for bias adjustment. Precipitation annual maxima were then extracted for three time periods, 2000-2020, 2040-2060, and 2070-2090 using the SSP5-8.5 scenario from the downscaled data. The Akaike Information Criteria (AIC) was used to determine the best Generalized Extreme Value (GEV) distribution between the L-moments method (Hosking, 1990) and the Maximum Likelihood Estimation (MLE) (Prescott and Walden, 1980). The annual maxima data for each pixel across all models were fitted to a GEV distribution using the MLE method as it was the best fit for KRADD. The future return period of the present day (2000-2020) 1-in-100 year event is determined by finding the percentile in the future GEV distribution that corresponds with the present-day rainfall amount. Rainfall amounts for the future 1-in-100 year events were estimated by determining what percentile in the present-day period corresponds to the future 100-year amount, according to the future

GEV. The percentile (analogous to a return period) was then converted to a rainfall amount using the rainfall distributions from the NOAA NA14 dataset. This was done across KRADD to have spatially varying rainfall input values.

2 Digital Elevation Model

The DEM obtained through KYFromAbove was used to create the KRADD elevation domain. The resolution of the raw data was 5 feet. The final DEM resolution was set to 15 meters to allow for faster simulation times while keeping results as accurate as possible due to the large domain size.

3 Friction coefficients

Friction coefficients, or Manning N values, were determined based on the land cover type of the area. The 2019 land cover was used for this from the National Land Cover Database (NLCD). Based on each classification of land cover, an associated friction coefficient is provided. See table here: https://rashms.com/wp-content/uploads/2021/01/Mannings-n-values-NLCD-NRCS.pdf

4 Infiltration

To calculate soil infiltration rates, the USDA Soil Survey Geographic Database (SSURGO) for Kentucky was used to obtain the soil hydrologic groups. These hydrologic groups have defined infiltration rates depending on the type of soil. Infiltration values per hydrologic group were used from Musgrave (1955). These rates in combination with the NLCD impervious surface percentages were used to compute more accurate infiltration rates. The impervious surfaces take into account built-up areas where rainfall will not be able to infiltrate. Based on previous FEMA flood studies that had been conducted, it was determined that the infiltration rates were too high leading to a reduced flood zone. The FEMA flood reports were examined for each county of KRADD to see which ones had detailed flood studies. The FEMA reports have areas that are labeled as 'AE' along sections of the river to indicate that a detailed study was done for that specific location. The counties of Perry, Letcher, and Knott had studies[6] completed in 2022 so those were used as a comparison to our flood extent. Infiltration rates were decreased to get the closest match in those three counties specifically, which resulted in the original infiltration rates being reduced by 75%.

5 Streamflow

We use the USGS StreamStats to determine the streamflow entering the model domain. The available 1-in-100 year streamflow data that was the furthest upstream in the modeled domain was used. At the confluence of Lick Fork and the Red Bird River, which is north of Beverly, KY along highway KY-66, a 1-in-100 year value of 6,900 ft^3/s. That streamflow value is to account for water that would be moving downstream from rain falling outside of the model domain into the domain. We do not change streamflows for the future time periods as such hydrologic modeling is outside the scope of this study.

6 Dam flow

There are quite a few dams in KRADD. The U.S. Army Corps of Engineers maintains the National Inventory of Dams that was used to obtain data on all the dams in KRADD. Most of them had been former mining sites or they had uncontrolled spillways, so no additional information was needed; however, Buckhorn dam has a controlled spillway with a gate, so this needed to be taken into account. It was found to have a discharge of 3,900 ft^3/s from Buckhorn Lake into the Middle Fork Kentucky

[6] *Flood Insurance Study Perry County, Kentucky Volume 1*. Federal Emergency Management Agency. Preliminary October 27, 2022; *Flood Insurance Study Knott County, Kentucky Volume 1*. Federal Emergency Management Agency. Preliminary October 27, 2022; *Flood Insurance Study Letcher County, Kentucky Volume 1*. Federal Emergency Management Agency. Preliminary October 27, 2022.

River. The streamflow value was added to the Middle Fork Kentucky River, while the infiltration rate of one grid cell in Buckhorn Lake near the dam was greatly increased to equal the discharge rate.

7 Water depth Startfile

Due to the DEM containing bathymetry elevations that were too low in the Buckhorn Lake and Carr Creek Lake, the model was initialized with starting water elevations representing the seasonal summer pool level[7]. First, a permanent water mask was used to locate pixels that possibly should be initialized with water elevations. Then, if the elevation of a pixel was less than the seasonal summer pool level, 782 feet NAVD88 for Buckhorn Lake and 1,028 feet NGVD29 for Carr Creek Lake in this case, then the starting water elevation for the pixel would be the lake level minus the DEM value.

[7] Buckhorn Lake Draft Master Plan with Integrated Environmental Assessment 2023. https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/23339; Carr Creek Lake Master Plan 2022. https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/21675

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Front cover: A view of Beattyville, Kentucky from Happy Top Park. / photo by Karen Roussel, CC BY 2.0, via Wikimedia Commons

Back cover: Intersection of Main and Lovern Streets in Hazard, Kentucky. / photo by Nyttend, Public domain, via Wikimedia Commons

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