Current and future flood risk under climate change in

Decorah, Iowa

NOVEMBER 2020

https://doi.org/10.5281/zenodo.15586419

For more information about this analysis, or Woodwell's other climate risk assessments, please contact us at policy@woodwellclimate.org.

To learn more about Woodwell, please visit our website at woodwellclimate.org.

Woodwell
Climate
Research
Center

Summary

Inland floods are some of the most devastating natural disasters and are expected to worsen under climate change due to the intensification of extreme precipitation. In this study, present and future flood risk in Decorah, IA, is examined through changes in the 1-in-100 year and 1-in-500 year flood events. Future rainfall and streamflow are estimated for two time periods, 2041–2060 and 2071–2090 representing the mid and late 21st century, respectively, using a regional climate model and river-reach scale hydrologic model.

The output of these simulations show that the historical 100-year rainfall event is 3.6x and 5.6x as likely in 2041–2060 and 2071–2090, respectively. The historical 100-year streamflow event is 1.2x and 0.87x as likely in 2041–2060 and 2071–2090, respectively. Greater changes in frequency were calculated for the 500-year rainfall and streamflow events.

Using these estimates as inputs into a flood model reveal minimal changes in flood risk across Decorah due to the levee system reducing. The total inundated area for the 100-year event within the flood model domain changes by 0.83% and -0.24% by mid and late 21st century, respectively. The number of structures inundated by the 100-year event increases by 4.2% and -0.7% by the mid and late 21st century, respectively. These metrics show relatively similar changes in the future periods for the 500-year event.

The main Decorah levee system along the Upper Iowa River is estimated to protect against a flood with a return period slightly less than a 500-year event. The area near the College Drive bridge is identified as a weak point since this area is overtopped by a few inches during the 500-year flood. The recent improvements to the Luther College levee and berm have increased the flood protection level to more than a 500-year event.

Introduction

Combustion of fossil fuels, deforestation, and other human activities release greenhouse gases (GHGs). These, in turn, have increased global average temperature at unprecedented rates. From 1901–2016, global average temperatures have already risen by 1°C (1.8°F) (Hayhoe et al., 2018). The rate of warming is not attributable to natural variability and has no natural explanation.

United Nations Framework Convention on Climate Change goals aim to prevent the most catastrophic impacts of climate change by limiting global warming to 2°C (3.6°F). The way that Earth's natural systems respond to the rapidly warming climate and human disruption will impact our quality of life for generations to come. Understanding and preparing for these changes is critical.

The impacts of climate change on frequency and severity of physical hazards will put many communities at risk. Physical hazards include extreme precipitation events, severe storms, extreme heat events, and flooding. Socioeconomic consequences include adverse public health outcomes, loss of critical infrastructure, and agricultural yield reduction.

In this report, we examine climate change driven flood risk for Decorah, IA. Due to climate change, Decorah and much of the Midwest is expected to see an intensification of extreme precipitation events and therefore, flood events (Angel et al., 2018). Floods can lead to temporary displacement, infrastructure damage, and worsened economic/social inequalities. Already, in the last quarter-century, the Midwest has seen three billion-dollar flood events (Angel et al., 2018). It is estimated that $500 million will be required to adapt infrastructure, such as drainage and sewer systems, in the Midwest for the more intense rain events by the end of the 21st century (Angel et al., 2018).

Flooding is the costliest and deadliest natural disaster in the United States (Perry, 2000; Miller et al., 2008). Flood risk is composed of three components: hazard, exposure, and vulnerability. Hazard refers to a destructive event (i.e. flooding), exposure represents the local community elements (e.g. people, buildings, infrastructure) that could be impacted by flooding, and vulnerability is the susceptibility of those community elements to be damaged by flooding (e.g. lack of resilient planning). This report will focus on flooding in Decorah, Iowa and will examine how flood events will be different in the future under climate change. The report will also discuss structure exposure and general exposure across the area of interest.

There are three different types of flooding: fluvial, pluvial, and coastal. Fluvial (also known as riverine) flooding occurs when rivers exceed the boundaries of the river channel. Pluvial flooding takes place during extreme precipitation events and is not associated with riverine flooding. This usually occurs when a stormwater system or soils cannot effectively drain or infiltrate rainfall leading to standing water. Coastal flooding occurs during storm surge or high tide events. Decorah is vulnerable to the first two: fluvial and pluvial. The main riverine flood risk in Decorah is from the Upper Iowa River that runs directly adjacent to the downtown area; however, fluvial flooding also occurs in streams and creeks within the watershed. Pluvial flood risk exists in urbanized areas where the stormwater system cannot properly convey a rainfall event and in natural depressions where soil drainage is poor. Areas surrounding the culverts that drain into the Upper Iowa River are prone to pluvial flooding because the culverts are forced shut when the water levels of the Upper Iowa River rise. Heavy rainfall falling when the culverts are closed becomes trapped behind the levee and begins to pond.

Late spring is often a time of severe flooding due to snowmelt coinciding with heavy rainfall as well. Convective storms that form during summer and early fall are also important sources of heavy rainfall. Decorah has experienced several devastating flood events, the most recent being in 2016 when 8.1 inches of rainfall were recorded at the Decorah Municipal Airport. In 2008, 6 to 8 inches of rainfall fell in the Upper Iowa River watershed causing the Upper Iowa River to reach its record peak discharge, 34,100 ft3/s, since data keeping began in 1914 (Fischer and Eash, 2010). The event is considered to have a return interval between 100 and 500 years. The previous record occurred in 1941, several years before the current levee system was built which protects the majority of Decorah (USGS, 2020). The left and right banks of the main Decorah levee system are currently classified as having a low risk of failure according to the United States Army Corps of Engineers (USACE) (USACE, 2020).

Project Overview

This study first explores the present flood risk in Decorah using historical (also referred to as present) streamflow data. The focus of the study will be the section of the Upper Iowa River that flows through Decorah because the river is the largest source of flood risk to the community. We focus on the 1-in-100 year (1% annual chance event) and the 1-in-500 year (0.2% annual chance event) due to the importance of these events in regulation. The Federal Emergency Management Agency (FEMA) determines flood risk and properties required to purchase flood insurance mainly through delineating the extent of the 100-year event. A comparison is made between the flood modeling results generated in this study to the currently effective FEMA flood maps, which are based on previous work by the United States Geological Survey (USGS), to showcase the deficiencies in the present federal flood mapping methodology. An additional analysis involving the levees in Decorah was conducted to identify important flood thresholds.

As mentioned previously, climate change is expected to exacerbate current flood risks across the United States. To provide Decorah a window into how these changes will manifest locally, we use climate model simulations to calculate future streamflow and rainfall in two future periods: 2041–2060 and 2071–2090 each centered on 2050 and 2080, respectively. The first time period represents the mid-21st century climate, and the second represents the late 21st century climate.

The results from the streamflow analysis are used as an input into a flood model to simulate future flood events. We present results from the late 21st century as this is relevant for large infrastructure projects; the design life of many infrastructure systems such as rail tracks, bridges, transmission lines, generating plants, water treatment and wastewater treatment plants, and stormwater systems usually have a 50-year or longer design lifetime (Gibson, 2017).

Furthermore, many of these installations are often used beyond their design period, which means it is likely that infrastructure built in 2020 will still be in use by the late 21st century. Presenting projected flood risks in the 2071–2090 timeframe allows planners to incorporate information on future flood risks in policy choices and the chance to mitigate flood losses.

Methodology

Present and future flood risk in Decorah is estimated using the LISFLOOD-FP flood model version 5.9 (Bates et al., 2000). LISFLOOD-FP has been tested extensively and produces comparable results to several localized and detailed flood studies conducted by the USGS (Neil et al., 2012; Coulthard et al., 2013). Wing et al. (2017) compared the output of a continental United States LISFLOOD-FP model run at a 30-meter resolution to USGS flood risk estimates that utilized elevation data with resolutions between 1 and 10 meters. The LISFLOOD-FP model was able to achieve a consistent hit rate of at least 80% across nine USGS flood studies that estimated the 1-in-100 year flood event.[1] The critical success index was between 60% and 90% for all but one USGS flood benchmark study. Therefore, LISFLOOD-FP was chosen to model flood risk for Decorah because of its computational efficiency when run at high spatial resolutions and its ability to accurately estimate flood risk at large spatial scales.

Finally, only grid cells with a water depth greater than or equal to 0.15 meters (6 inches) are shown in the final maps. We apply this threshold because water depths above this level have the potential to cause property damage (EA, 2019).

Several inputs are required to run the model which are described in detail below:

1) *Elevation data*: The 3-meter horizontal resolution Digital Elevation Model (DEM) created from LiDAR (Light Detection and Ranging) data for Iowa was resampled to a 7-meter resolution DEM (Iowa Geodata, 2018). Streambed elevations were extracted from the Preliminary FEMA Flood Insurance Study (FIS) and burned into the DEM (FEMA, 2019). The Dry Run left and right bank levee elevations were extracted from the National Levee Database and burned into the DEM (USACE, 2020). The Valley Drive and Highway 9 levee elevations were extracted from the 3-meter DEM. The Dike Road levee elevations were provided by Jay Uthoff and burned into the DEM (Uthoff, 2020). The berm extension of the College levee was not included into the DEM for the FEMA comparison given that there is no evidence the berm was included in the FEMA FIS and from reviewing the FEMA flood elevations. The berm was included in all other analyses. We assume the levees will operate as designed and no structural failures occur. The culverts identified through Google Maps imagery were burned into the final DEM.

[1] The hit rate measures how well the model predicted the number of wet cells in the benchmark data. Essentially, the hit rate gives an indication of how much the model underpredicted the validation data. The lower the hit rate, the greater the underprediction. The critical success index accounts for both underprediction and overprediction and so will usually be lower than the hit rate.

2) *Streamflow*:
   a. *Present streamflow*: The present 100-year and 500-year streamflow were estimated using the peak gage height data available at the Upper Iowa River USGS stream gage station at Decorah (ID: 05387500) (USGS, 2020). Peak river stage data for 67 water years (1952–2019) used as input into the PeakFQ software that utilizes the methodology outlined in Bulletin 17C (England et al., 2019; Veilleux, 2014). Because the stream gauge is not located at the upstream boundary of the flood model domain, the same ratios from the 2008 flood study between upstream and gauge streamflow were used in this study. The hydrograph input was created by using the most recent extreme flooding event which occurred on June 8th, 2008. The difference between the peak and 12 hours before and 12 hours after were used to estimate the starting and ending river stage heights, respectively, for the 100-year and 500-year events. The starting height was lowered further to avoid numerical instabilities in the flood model. The hydrograph peaks for 2 hours similar to the 2008 flood event.

   b. *Future streamflow*: As was done for future rainfall estimates, all future streamflow analyses were completed assuming the RCP8.5 scenario. To calculate the change in probability of the historical 100-year and 500-year streamflow events, river reach streamflow data from Wobus et al. (2017) modeled through 2100 was used. The full model ensemble (29 GCMs) data for the Upper Iowa River reach closest to Decorah was fit to a GEV distribution (as was done in Wobus et al., 2017) using the maximum likelihood estimator (MLE) method, justified through a Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) analysis. The future streamflow amount was then assigned to the future 100-year and 500-year events using the historical GEV distribution discussed previously.

3) *Floodplain friction values or Manning's n values*: Each pixel in the model domain was assigned a friction value based on land cover from the National Land Cover Database 2016 (Yang et al., 2018). The friction values come from an analysis completed by the United States Department of Agriculture (NRCS, 2016).

4) *Infiltration Rates*: Soil infiltration rates were assigned using the hydrologic group attribute in the SSURGO database and the infiltration rates from the Minnesota Stormwater Manual (Soil Survey Staff; MSSC, 2020). While the stormwater system is important for estimating pluvial flooding, the Decorah stormwater system has not been fully mapped nor the capacity analyzed and therefore it is not possible to incorporate the stormwater system in the flood model. According to the Decorah's Comprehensive Plan, "new storm sewers have been developed as part of new subdivisions to convey runoff from a 10-year storm event, although the existing city subdivision ordinance does not address a storm sewer requirement" (City of Decorah, 2019).

We also estimate the change in probability of the 100-year and 500-year precipitation events in the 2041–2060 and 2071–2090 future periods in reference to the historical (2001–2020) under the Representative Concentration Pathway (RCP) 8.5 scenario. We use RCP8.5, the most aggressive emissions scenario, because it most closely matches historical emissions from 2005 to 2020 (within 1% for total carbon dioxide emissions) compared to other pathways (Schwalm et al., 2020). We use output from a regional 0.22º resolution climate model, REMO2015, which was forced by 3 general circulation models (GCMs) to calculate the change in probability (Remedio et al., 2019). A regional frequency analysis method was used to fit a generalized extreme value (GEV) distribution by the method of L-moments to the full model ensemble output using the Bukovsky regions (Hosking et al., 2005; Bukovsky, 2011). The full ensemble was used to maintain consistency with the streamflow analysis.

Finally, we note sources of uncertainty in this study that have not been previously mentioned. The first being that the uncertainty in climate model output increases with spatial resolution since climate models are estimating some atmospheric processes that occur at spatial resolutions higher than the model resolution. Within a flood model, there is some uncertainty regarding antecedent moisture conditions as these can impact the ability of soils to infiltrate rainfall and thus flooding. Sensitivity tests regarding antecedent moisture conditions were not completed as part of this study. Additionally, there is uncertainty in pluvial flood estimates in urban areas where stormwater systems are not adequately represented.

Results

A. Present Flood Risk and Comparison to FEMA Flood Maps

To establish the comparability between the FEMA/USGS flood studies and this study, we first show the similarity between FEMA's 100-year flood extent and the flood extent generated with LISFLOOD-FP using the streamflow boundary conditions from FEMA's FIS (FEMA, 2019). The two extents are compared in Figure 1. The results are identical except for a few small areas indicating that using the same inputs and only modeling riverine flooding, the quality of results generated from the model utilized by Woodwell are comparable, if not better, than those of FEMA. Areas of interior ponding in the FEMA 100-year floodplain are not considered in this study since the focus is on the Upper Iowa River.

FEMA's preliminary flood maps, released in 2019, for the Upper Iowa River floodplain near Decorah are based on the USGS study completed in 2008. The study was completed before the June 8th-9th, 2008 flood and so does not incorporate the streamflow data from that year. Although the FEMA flood map was released more than a decade later, the 100-year and 500-year discharges for the Upper Iowa River were not updated from the USGS 2008 study according to FEMA FIS (FEMA, 2019; Christiansen, 2008). A comparison of streamflows used in the FEMA FIS and this study for the Upper Iowa River stream gauge at Decorah is shown in Table 1. The updated streamflow calculated by Woodwell is 26% and 28% greater for the 100 year and 500-year events, respectively, compared to the FEMA values. While these are significant increases in streamflow, the increases in flood extent are not as large because of the channelization of the Upper Iowa River from the levees. Finally, FEMA also only shows historical flood risk and does not incorporate future changes in the climate (Pralle, 2019).

Table 1. Streamflow inputs for FEMA and Woodwell flood studies (cubic feet per second).

	FEMA	Woodwell
1-in-100 year	23,400	28,210
1-in-500 year	30,400	39,030

B. Shifting Return Periods of Extreme Rainfall and Streamflow

To give an initial indication of how the frequency of historical extreme rainfall and streamflow events will change in the 21st century, the future return periods of the historical (2001–2020) 100-year and 500-year in the 2041–2060 and 2071–2090 time frames are shown in Tables 2 and 3. The historical 100-year rainfall event is 3.6x and 5.6x as likely in 2041–2060 and 2071–2090, respectively. The historical 500-year rainfall event is 4.9x and 7.4x as likely in 2041–2060 and 2071–2090, respectively. The historical 100-year river stage event is 1.2x and 0.87x as likely in 2041–2060 and 2071–2090, respectively. The historical 500-year river stage event is 1.4x and 0.8x as likely in 2041–2060 and 2071–2090, respectively. We note that the future return periods differ between streamflow and rainfall as well as between future time periods.

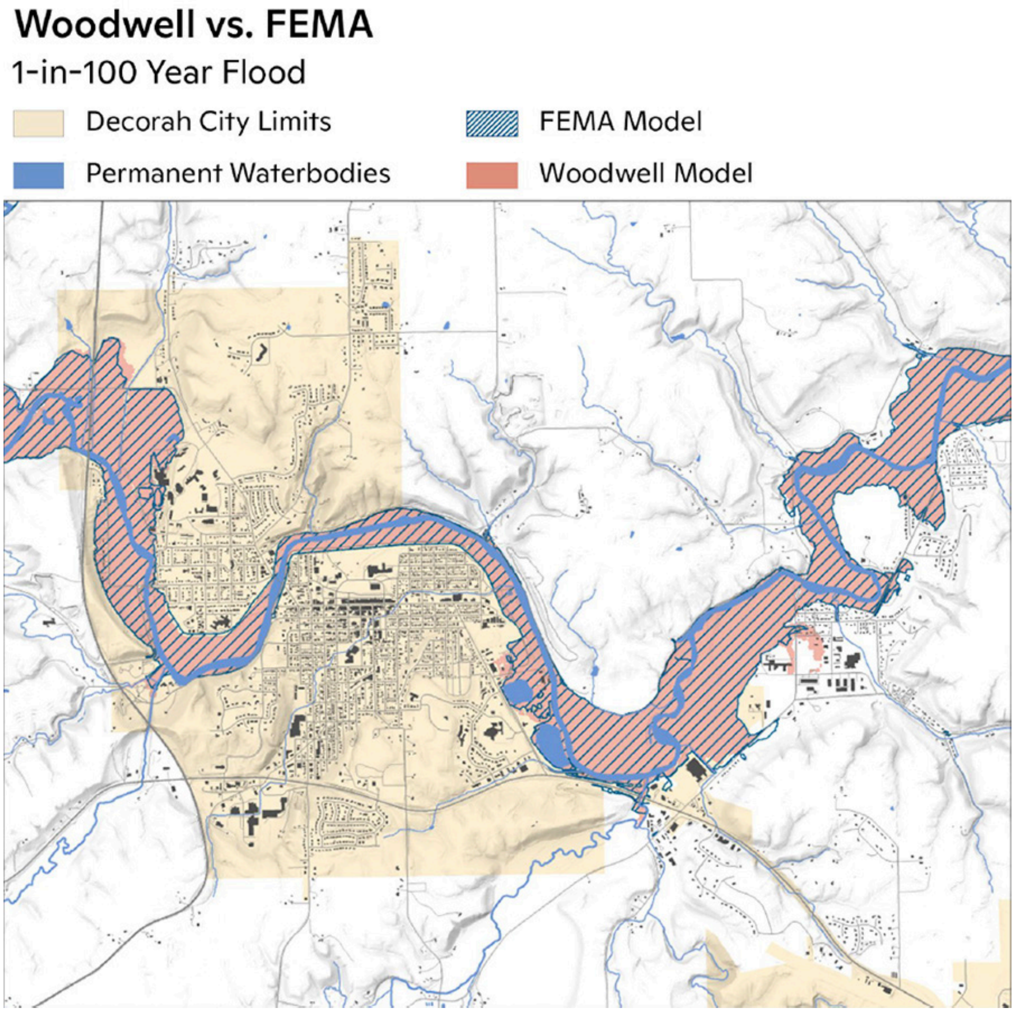

Figure 1. The 1-in-100 year flood extent for Decorah generated by Woodwell and FEMA.

There are several possible reasons for this phenomenon. The first is that we use different models to analyze changes in rainfall versus streamflow. The second is that we are using a 20-year time period to estimate extreme events with return periods several times greater than the time period length (e.g. 100-year). While using the full ensemble of models allows for robust statistical estimates, there are still uncertainties in the model output. Steamflow intensifies through the middle of the 21st century but the trend reverses as we approach the end of the 21st century. A possible explanation for this is the reduction in snow accumulation by the end of the 21st century (Dankers et al., 2014). As temperatures rise, more precipitation falls as rain instead of snow which would decrease the chances of late spring floods due to snowmelt and heavy rains occurring simultaneously.

A 100-year event and 500-year event have a 26% and 5.8% chance, respectively, of occurring over a 30 year period. The probability of each event occurring in the future at least once over a 30 year period (average length of a mortgage) is also shown to provide a more realistic view of the risk in the future. An extreme event only needs to occur once to severely damage a building which can be devastating, especially if the structure is not properly insured. We see significant increases in the rainfall probabilities. A historical 100-year rainfall event has an 82% chance of occurring at least once in a 30-year period by 2071–2090.

Table 2. Historical (2001–2020) return period and probability of occurring in a 30 year period of future rainfall events.

	2041–2060		2071–2090	
	Return period	30yr probability	Return period	30yr probability
1-in-100 year	1-in-28 year	66.4%	1-in-18 year	82%
1-in-500 year	1-in-103 year	25.4%	1-in68 year	35.9%

Table 3. Historical (2001–2020) return period and probability of occurring in a 30 year period of future streamflow events.

	2041–2060		2071–2090	
	Return period	30yr probability	Return period	30yr probability
1-in-100 year	1-in-84 year	30.2%	1-in-66 year	23%
1-in-500 year	1-in-364 year	7.9%	1-in-27 year	4.7%

C. Future Flood Extents and Risk

Using the future streamflow return periods shown in Table 3 as inputs into the flood model, future flood extents are generated for the 100-year and 500-year riverine flood events in 2041–2060 and 2071–2090. The percent change in flood depth is then calculated from the baseline period. These results are shown in Figures 2, 3, 4, and 5. Changes in flood extent in these maps can be identified in dark orange areas where the percent change in flood depth

exceeds 5%. By the mid-century 21st century, flood extent and depth increase, but then decrease by the late 21st century. Flood extents and depths do not shift dramatically along the Upper Iowa River due to the steep topography that defines the floodplain and the channelization of the Upper Iowa River near Decorah due to the levees. However, in areas with higher flood waters come greater flood damages. Even buildings with flood defenses in place and elevated structures may be at risk of flooding in the future because of these higher water levels. Changes in total inundated area and average water depth within the flood model domain are shown in Table 4 to provide a high-level view of the changes in flood risk. There are minimal changes in flood area and average water depth between the present and future periods; however, the overall finding of these results is how important the levee system is for keeping Decorah safe from the Upper Iowa River floods. Therefore, an analysis on important thresholds for the levee system is presented later in this study.

Table 4. Changes in flood extent and average flood depth from present period (2001–2020).

	% Change in Flood Area	Change in Average Water Depth in cm (ft)
2041–2060 100-Year	+0.83%	+7.2 (0.24)
2071–2090 100-Year	-0.24%	-1.9 (0.06)
2041–2060 500-Year	+0.63%	+4.2 (0.14)
2071–2090 500-Year	-1.16%	-8.7 (0.28)

Several areas in and around Decorah are currently at risk from the 100-year and 500-year flood events. The homes on Valley View Drive are expected to experience approximately 1 meter (3.3 ft) during the 100-year event. The depth increases to more than 1.5 meters (~5 ft) for the 500-year event. Areas in Decorah between College Drive and the Upper Iowa Speedway on the east side of Decorah have no flood risk from the 100-year event; however, the 500-year flood does pose a danger to downtown Decorah because of a low point in the levee around College Drive. This weak point is discussed further in the subsequent levee analysis. The levee ends at the Upper Iowa Speedway, which exposes the commercial and industrial area just south of the speedway to both the 100-year and 500-year floods. Not only is the Bruening Rock Products quarry significantly at risk from both events, but the flood extent of the 100-year flood abuts the Interstate Power and Light substation located on the river side of the Goodyear store. The 500-year flood causes portions of the substation to be under 0.3 meters (1 ft) of water. Further downstream, the Freeport community also faces risk from just the 100-year flood. Several homes between River Road and 252nd Street lie within the floodplain modeled in this study. The estimated 500-year flood causes substantially more damage. Freeport park becomes entirely inundated and the floodwaters reach the Collins Aerospace building in addition to more homes in the northern area of Freeport. Flood risk for Luther College is explored in the additional levee analysis below given the recent changes to the Dike Road levee and berm.

An additional analysis was completed to estimate the number of structures in the model domain affected by at least 15 cm (6 inches) of flooding. Structure outlines were taken from the High Resolution Land Cover of Iowa in 2009 (Iowa Geodata, 2019). The results are shown in Table 5 for both the 100 and 500 year events and each time period. Percent changes for future periods compared to the present are shown in parenthesis. Minimal changes occur for the two future periods since the floodplain in Decorah is mostly confined by the levee system.

Table 5. Number of structures (% change) in model domain flooded (water depth greater than 15 cm).

	Present	2041–2060	2071–2090
1-in-100 Year	141	147 (4.2%)	140 (-0.74%)
1-in-500 Year	203	214 (3.8%)	188 (-7.4%)

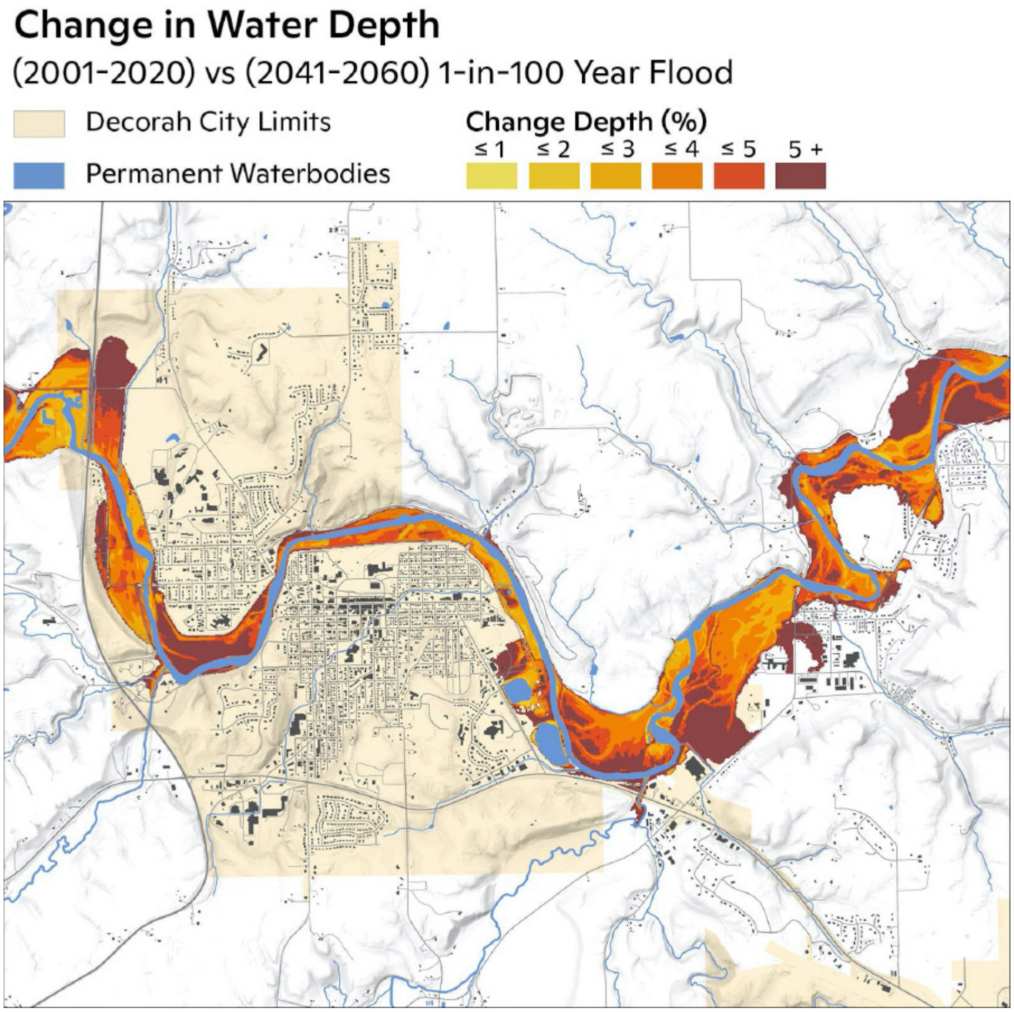

Figure 2. Percent change in water depth between 2041-2060 and present 1-in-100 year event.

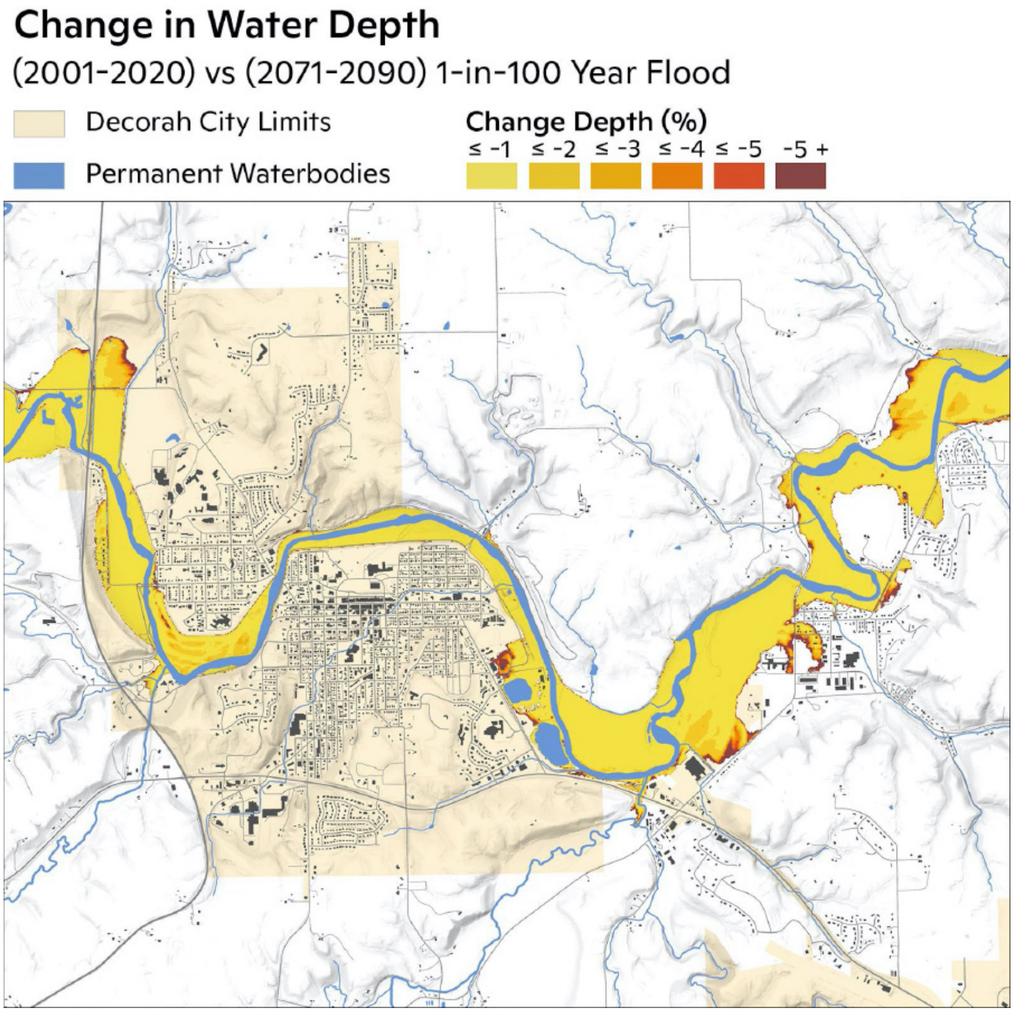

Figure 3. Percent change in water depth between 2071–2090 and present 1-in-100 year event.

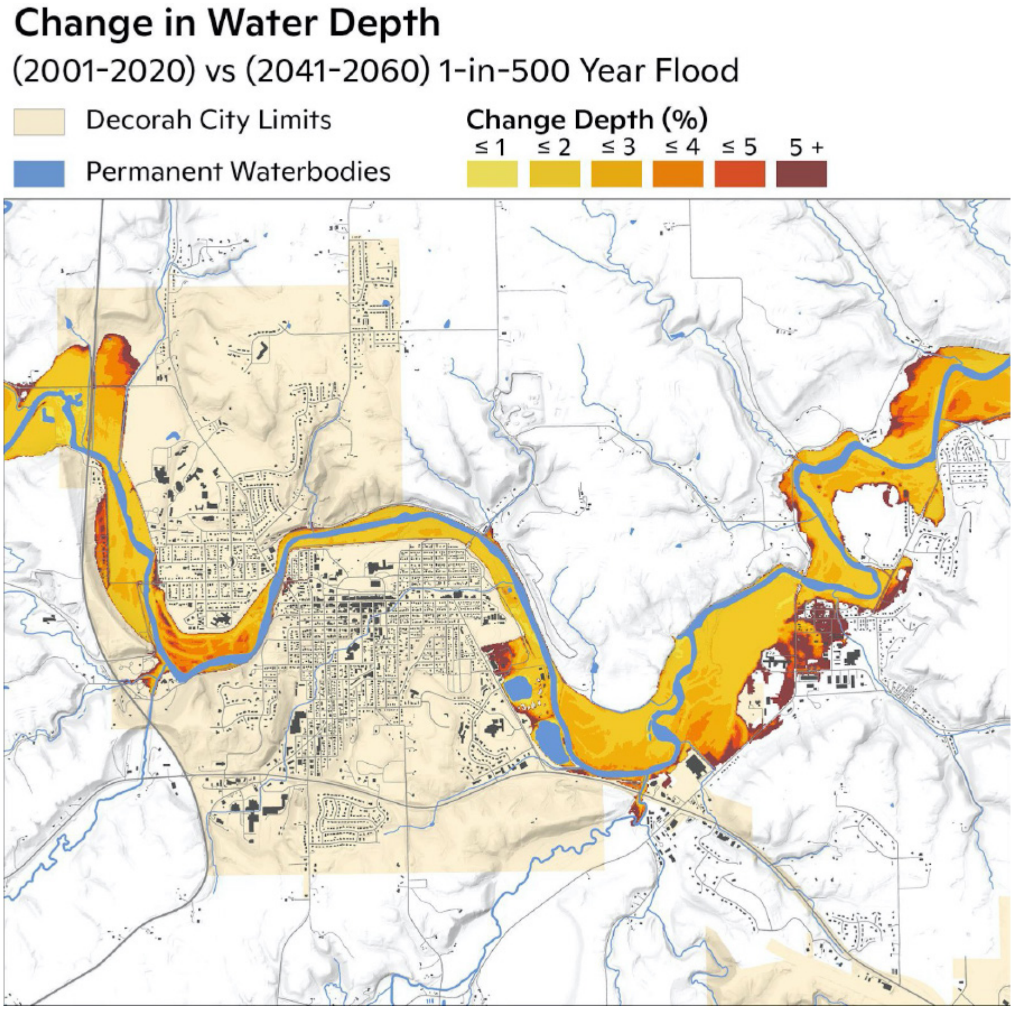

Figure 4. Percent change in water depth between 2041-2060 and present 1-in-500 year event.

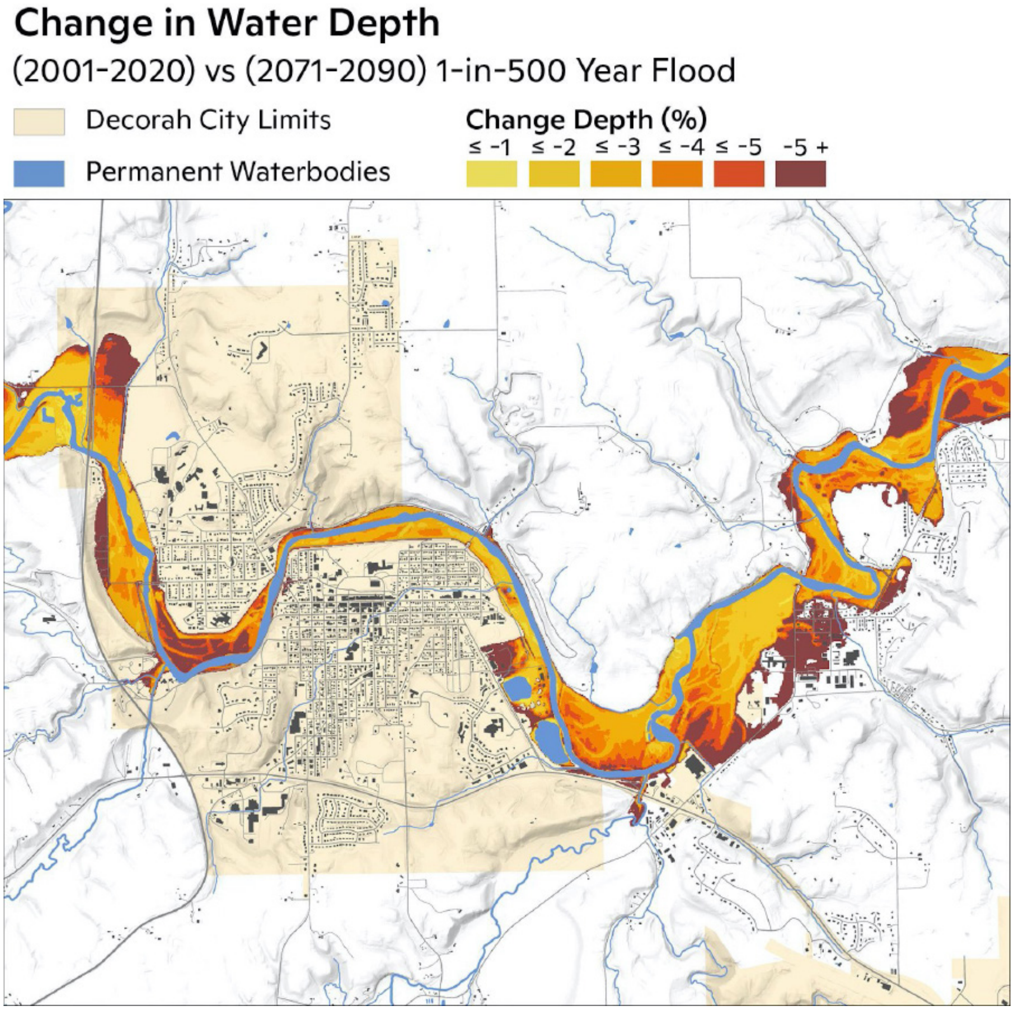

Figure 5. Percent change in water depth between 2071–2090 and present 1-in-500 year event.

D. Levee Analysis

The main levees in Decorah, placed along the Upper Iowa River and hereafter referred to as the Upper Iowa River Left and Right Bank levees, were completed in 1950 by the USACE (City of Decorah, 2019). The Left Bank protects the western part of Decorah and the Right Bank protects the eastern, downtown portion of Decorah as shown in Figure 6. Using the updated historical 100-year and 500-year streamflow amounts, an analysis of the levee system in Decorah was completed to identify vulnerable areas along the levee and the return period thresholds of the levee. Figures 7 and 8 show the profile of both the Left and Right Bank levees as well as landmarks. The levee IDs along the x-axis correspond to the IDs shown in Figure 6. The area near the College Drive bridge along the Upper Iowa River Right and Left Banks were identified as weak points. The levee on the Left Bank is two inches higher than the 500-year water level. The levee on the Right Bank does in fact become overtopped by the 500-year flood by approximately 4 inches at the College Drive bridge. Current emergency management plans detail procedures to deploy sandbags at this point along the levee during extreme floods to prevent the Upper Iowa River from reaching the downtown area. However, because of this deficiency in the levee, the Upper Iowa River Left Bank levee was classified as having a return level threshold of a 1-in-500 year event and the Right Bank levee was classified as having a return level threshold of slightly below a 1-in-500 year event.

The recently raised Luther College Dike Road levee and berm also protect against the 100-year event but by less than the engineered freeboard. Elevation profiles of the levee show the top of the levee was designed to be four feet above the 100-year water level; however, this analysis shows that most of the levee falls short of that amount and the smallest difference between the top of the levee and the 100-year water level is 1.8 feet. The 500-year water level is only 0.2 feet below the levee elevation at levee ID 110. The Luther College levee is currently not accredited by FEMA and therefore is not represented in the federal flood maps but once it gains accreditation, the 100-year floodplain area near Luther College in the FEMA maps should decrease dramatically.

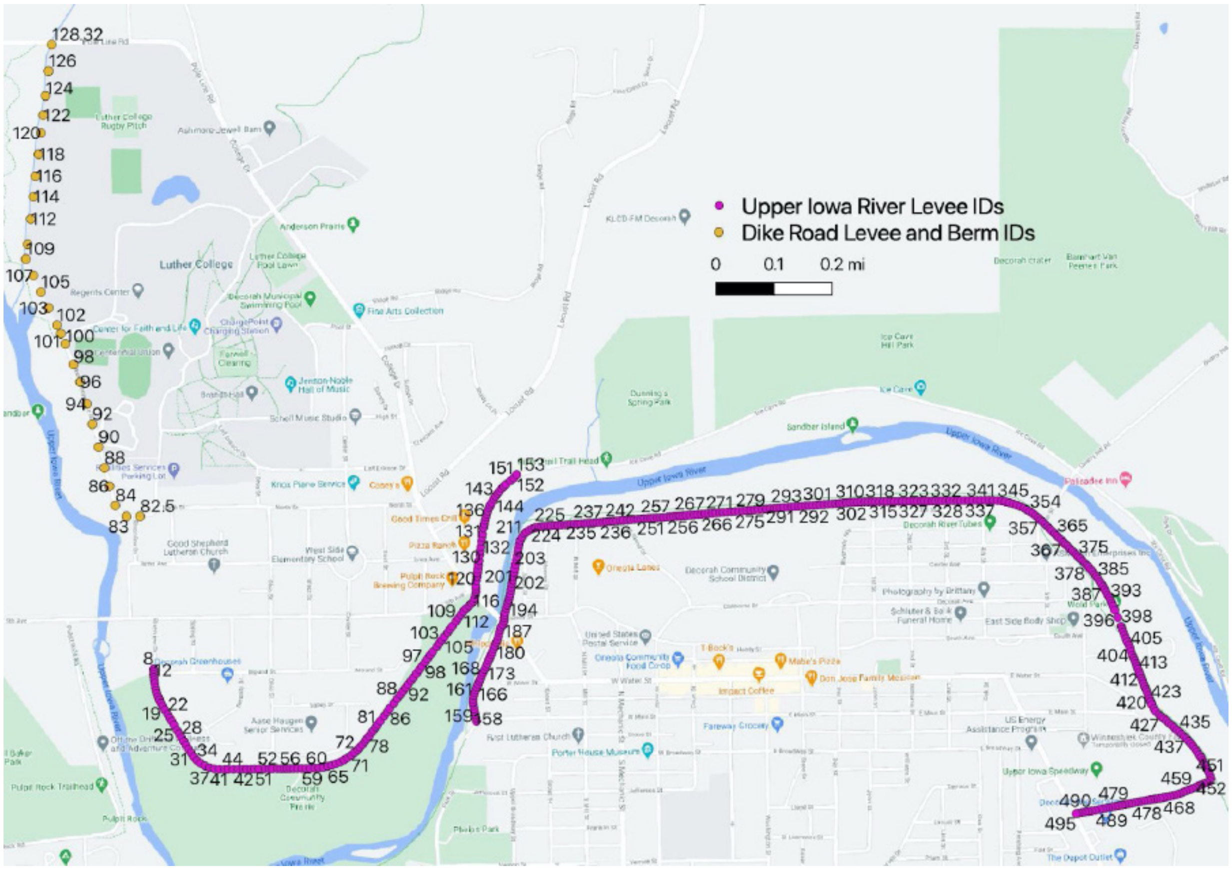

Figure 6. Upper Iowa River and Luther College levee locations and IDs.

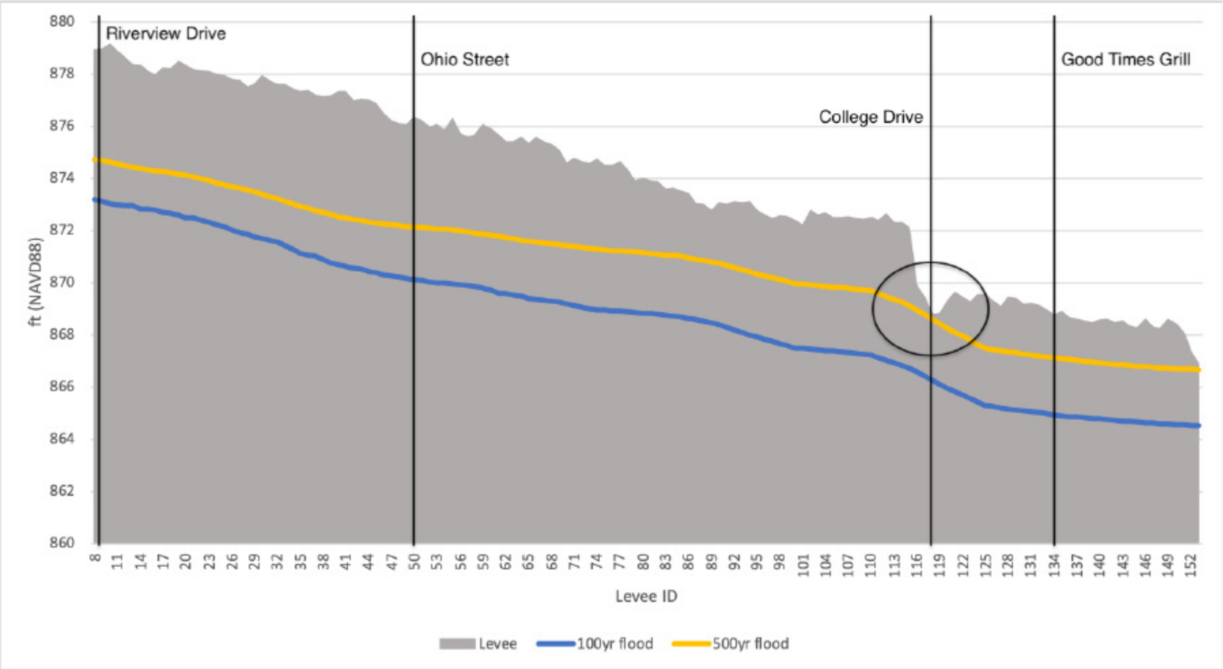

Figure 7. Upper Iowa River Left Bank levee profile and flood elevations.

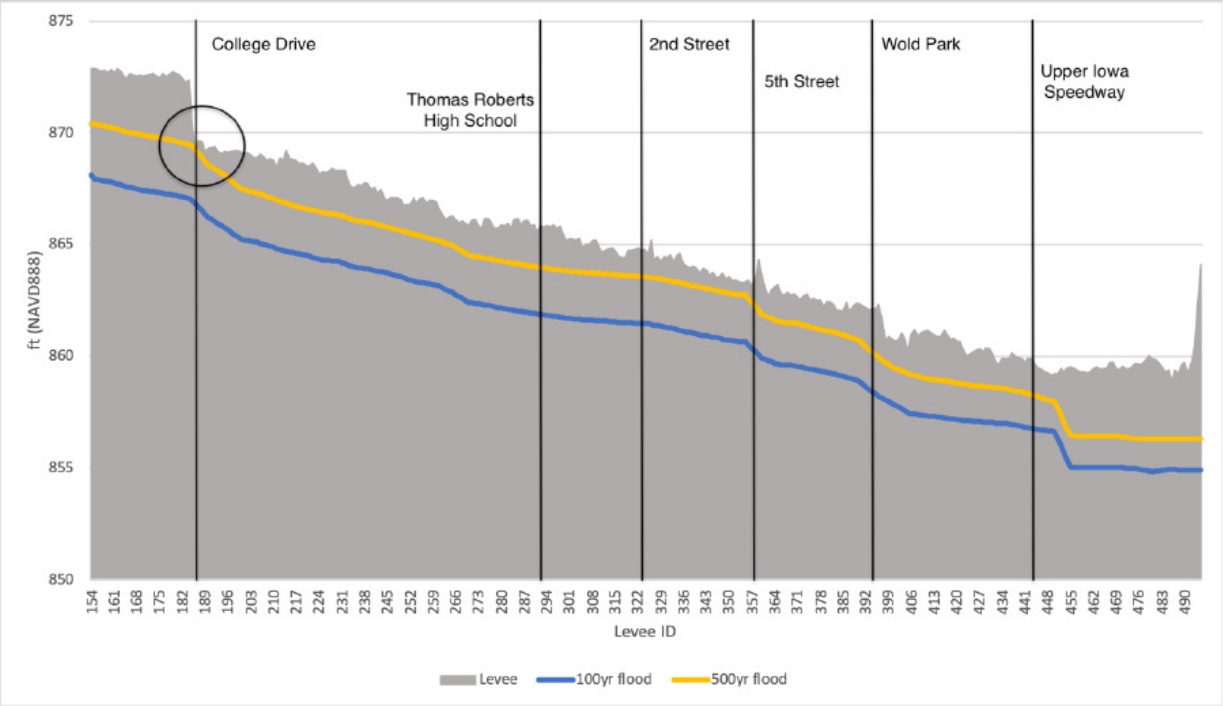

Figure 8. Upper Iowa River Right Bank levee profile and flood elevations.

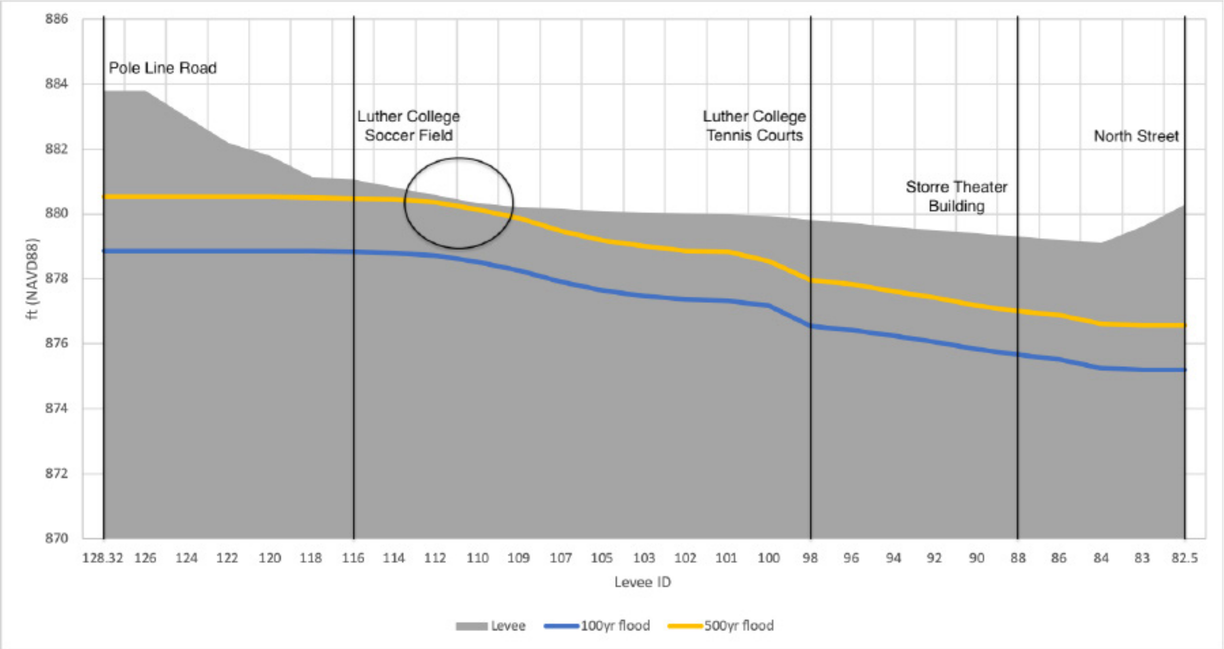

Figure 9. Luther College/Dike Road levee and berm profile and flood elevations.

About Woodwell Climate Research Center

Woodwell Climate Research Center (“Woodwell”) is an organization of researchers who work with a worldwide network of partners to understand and combat climate change. We bring together hands-on experience and 35 years of policy impact to find societal-scale solutions that can be put into immediate action, including with municipalities that are so often on the front lines of the climate crisis.

We were founded in 1985 as the Woods Hole Research Center by George Woodwell, a visionary ecologist. Today, we work around the globe, conducting research in collaboration with policymakers and decision makers in more than 20 countries. We conduct research on a range of strategies to immediately address climate change, from carbon sequestration solutions using Earth’s forests and soils, to climate risk assessments that seek to shift public perception and corporate behavior. Our scientists are widely published in leading scientific journals, testify to lawmakers around the world, and are regularly quoted in media outlets from the *New York Times* to *CBS Evening News*. They have contributed to every Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and shared the 2007 Nobel Prize awarded to the IPCC.

References

Angel, J., Swanston, C., Boustead, B.M., Conlon, K.C., Hall, K.R., Jorns, J.L., ... , & Todey, D. (2018). Midwest. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 872–940. doi: 10.7930/NCA4.2018.CH21

Bates, P. D., & De Roo, A. P. J. (2000). A simple raster-based model for flood inundation simulation. *Journal of Hydrology*, 236(1–2), 54–77. https://doi.org/10.1016/S0022-1694(00)00278-X

Bukovsky, M. S. (2011). *Masks for the Bukovsky regionalization of North America*, Regional Integrated Sciences Collective, Institute for Mathematics Applied to Geosciences, National Center for Atmospheric Research, Boulder, CO. Accessed 9/2020. http://www.narccap.ucar.edu/contrib/bukovsky/

Center for International Earth Science Information Network (CIESIN), Columbia University. (2019). Building data for climate change adaptation: filling data gaps and characterizing storm surge impacts in the Hudson River Valley and Long Island. Palisades, NY. Accessed 1 September 2020. https://www.nysgis.net/Docs/NYGeoCon2019/Building-Data-for-Climate-Change-Adaptation.pdf

City of Decorah. (2019). Decorah Comprehensive Plan. https://www.decorahia.org/reminders-and-notices/2012/decorah-comprehensive-plan

Cornell University. (2020). Aquatic Connectivity and Barrier Removal. https://wri.cals.cornell.edu/hudson-river-estuary/watershed-management/aquatic-connectivity-and-barrier-removal-culvert-dams/

Coulthard, T. J., Neal, J. C., Bates, P. D., Ramirez, J., de Almeida, G. A., & Hancock, G. R. (2013). Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. *Earth Surface Processes and Landforms*, 38(15), 1897–1906. https://doi.org/10.1002/esp.3478

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., ... & Stacke, T. (2014). First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences*, 111(9), 3257-3261. https://doi.org/10.1073/pnas.1302078110

Christiansen, D. E., & Eash, D. A. (2008). Flood-Plain Study of the Upper Iowa River in the Vicinity of Decorah, Iowa. US Geological Survey. https://doi.org/10.3133/sim3005

England Jr, J. F., Cohn, T. A., Faber, B. A., Stedinger, J. R., Thomas Jr, W. O., Veilleux, A. G., ... & Mason Jr, R. R. (2019). Guidelines for determining flood flow frequency—Bulletin 17C (No. 4-B5). US Geological Survey. https://doi.org/10.3133/tm4B5

Environment Agency (EA), United Kingdom. (2019). What is the Risk of Flooding from Surface Water map? https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/842485/What-is-the-Risk-of-Flooding-from-Surface-Water-Map.pdf

Federal Emergency Management Agency (FEMA). (2019). Flood Insurance Study for Winneshiek County, Iowa. https://www.federalregister.gov/documents/2019/08/01/2019-16414/proposed-flood-hazard-determinations

Feldman, A. D. (2000). Hydrologic Modeling System HEC-HMS: Technical Reference Manual. US Army Corps of Engineers, Institute for Water Resources, Hydrological Engineering Center. https://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Technical%20Reference%20Manual_(CPD-74B).pdf

Fischer, E. E., & Eash, D. A. (2010). Flood of June 8-9, 2008, Upper Iowa River, Northeast Iowa. US Geological Survey. https://doi.org/10.3133/ofr20101087

Gibson, J. R. (2017). *Built to Last*. Union of Concerned Scientists. https://www.ucsusa.org/climate-smart-infrastructure

Hayhoe, K., Wuebbles, D. J., Easterling, D. R., Fahey, D. W., Doherty, S., Kossin, J. P., Sweet, W. V., Vose, R. S., & Wehner, M. F. (2018). Chapter 2: Our Changing Climate. Impacts, Risks, and Adaptation in the United States: *The Fourth National Climate Assessment, Volume II*. U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.CH2

Hosking, J. R. M., & Wallis, J. R. (2009). *Regional Frequency Analysis: An Approach Based on L-Moments*. Cambridge University Press. https://doi.org/10.1017/CBO9780511529443

Iowa Geodata. (2018). Three Meter Digital Elevation Model of Iowa, Derived from LiDAR. https://geodata.iowa.gov/dataset/three-meter-digital-elevation-model-iowa-derived-lidar.

Iowa Geodata. (2019). High Resolution Land Cover of Iowa in 2009. https://geodata.iowa.gov/dataset/high-resolution-land-cover-iowa-2009.

Kemble, W. J. (2011). "IRENE: Region's farms ravaged by flooding (video)." *Daily Freeman*. https://www.dailyfreeman.com/news/irene-regions-farms-ravaged-by-flooding-video/article_1b6 89880-9365-5a7a-8ee6-67f6f053e185.html

Minnesota Stormwater Steering Committee (MSSC). (2020). The Minnesota Stormwater Manual. Minnesota Pollution Control Agency. https://stormwater.pca.state.mn.us/index.php/Design_infiltration_rates

National Resource Conservation Service (NRCS), United States Department of Agriculture. (2016). Manning's n Values for Various Land Covers to Use for Dam Breach Analyses by NRCS in Kansas. https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/HecRAS/NEDC/lectures/docs/Manning%92s%20n-values%20for%20Kansas%20Dam%20Breach%20Analyses%20-%20Adopted%2007121 6.pdf

Neal, J., Villanueva, I., Wright, N., Willis, T., Fewtrell, T., & Bates, P. (2012). How much physical complexity is needed to model flood inundation? *Hydrological Processes*, 26(15), 2264–2282. https://doi.org/10.1002/hyp.8339

Perica, S., Pavlovic, S., Laurent, M. S., Trypaluk, C., Unruh, D., Martin, D., & Wilhite, O. (2019). NOAA Atlas 14: Precipitation Frequency Atlas of the United States Volume 10: Northeastern States. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume10.pdf

Perry, C. A. (2000). Significant Floods in the United States during the 20th Century: USGS Measures a Century of Floods. US Department of the Interior, US Geological Survey. https://doi.org/10.3133/fs02400

Pralle, Sarah. (2019). Drawing lines: FEMA and the politics of mapping flood zones. *Climatic Change*, 152, 227–237. https://doi.org/10.1007/s10584-018-2287-y

Remedio, A. R., Teichmann, C., Buntemeyer, L., Sieck, K., Weber, T., Rechid, D., ... & Jacob, D. (2019). Evaluation of New CORDEX Simulations Using an Updated Köppen-Trewartha Climate Classification. *Atmosphere*, 10(11), 726. https://doi.org/10.3390/atmos10110726

Schwalm, C. R., Glendon, S., & Duffy, P. B. (2020). RCP8.5 tracks cumulative CO_2 emissions. *Proceedings of the National Academy of Science*s, 117(33), 19656-19657. https://doi.org/10.1073/pnas.2007117117

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Ulster County, New York. Accessed 9/1/2020. https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

U.S. Army Corps of Engineers (USACE). (2020). National Levee Database data available on the World Wide Web, assessed November 1, 2020 at https://levees.sec.usace.army.mil/#/levees/search/in=@county%20state:Winneshiek,%20Iowa&v iewType=map &resultsType=systems&advanced=true&hideList=false&eventSystem=false

U.S. Geological Survey (USGS). (2020). National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), accessed September 29, 2020, at https://nwis.waterdata.usgs.gov/nwis/peak?site_no=05387500&agency_cd=USGS&format=html

Uthoff, J. (2021). Personal communication.

Veilleux, A. G., Cohn, T. A., Flynn, K. M., Mason Jr, R. R., & Hummel, P. R. (2014). Estimating magnitude and frequency of floods using the PeakFQ 7.0 program. U.S. Department of the Interior, U.S. Geological Survey. https://doi.org/10.3133/fs20133108

Wing, O. E., Bates, P. D., Sampson, C. C., Smith, A. M., Johnson, K. A., & Erickson, T. A. (2017). Validation of a 30 m resolution flood hazard model of the conterminous United States. *Water Resources Research*, 53(9), 7968-7986. https://doi.org/10.1002/2017WR020917

Wobus, C., Gutmann, E., Jones, R., Rissing, M., Mizukami, N., Lorie, M., ... & Martinich, J. (2017). Climate change impacts on flood risk and asset damages within mapped 100-year floodplains of the contiguous United States. *Natural Hazards and Earth System Sciences*, 17(12), 2199-2211. https://doi.org/10.5194/nhess-17-2199-2017

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., ... & Xian, G. (2018). A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. *ISPRS Journal of Photogrammetry and Remote Sensing*, 146, 108-123. https://doi.org/10.1016/j.isprsjprs.2018.09.006

Cover: Aerial view of Decorah, Iowa over the crater area. / photo by Wikideas1, CC BY-SA 1.0

Back: Water Street, downtown Decorah, Iowa. / photo by Bobak Ha'Eri, CC BY-SA 3.0

WOODWELL CLIMATE RESEARCH CENTER conducts science for solutions at the nexus of climate, people and nature. We partner with leaders and communities for just, meaningful impact to address the climate crisis. Our scientists helped to launch the United Nations Framework Convention on Climate Change in 1992, and in 2007, Woodwell scientists shared the Nobel Prize awarded to the Intergovernmental Panel on Climate Change. For over 35 years, Woodwell has combined hands-on experience and policy impact to identify and support societal-scale solutions that can be put into immediate action. This includes working with municipalities on the frontlines of the climate crisis.

149 Woods Hole Road, Falmouth, MA 02540 ▪ 508-540-9900 ▪ **woodwellclimate.org**