Iowa Flood Frequency and Projections: Analysis and Web-Tool

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Introduction

Climate change presents a significant challenge to water resource engineers and planners as it is expected to increase the likelihood of hydrometeorological extremes such as extreme precipitation and temperature (IPCC, 2021). For many watersheds within the United States, this means that the annual maxima discharges are expected to increase over time creating a nonstationarity component. Currently federal guidelines for flood frequency analysis (see Bulletin 17C) do not provide guidance on how to account for projected changes in the climate system and new tools and approaches are needed.

In Iowa, the need for understanding changes in design flows due to climate change is especially important as increases in temperature and precipitation are expected to increase the magnitude of annual maxima discharges. Currently guidelines provided by the U.S. Geological Survey (USGS) (East et al. ,2013) for design flows are limited in designing for the future. Currently, regional flood frequency for Iowa is established by a relationship between maximum discharge and drainage area through statistical regression. Parameters consisting of catchment physical properties are selected based on minimization of residuals. However, only one-third of the developed regional equations have a climatic parameter (rainfall) which is an important driver of hydrologic processes. These methods cannot provide projections for design flows, highlighting limitations of available tools. These guidelines are implemented in a web-tool provided by the USGS called Streamstats to obtain estimates anywhere in Iowa. However, the tool is limited in its ability to provide information about the future change in annual maximum discharge as no projections are available.

Due to these reasons and lack of available online resources, we created the Iowa Flood Frequency and Projections Tool (IFFP, https://iowafloodfrequency.iihr.uiowa.edu/) which incorporates climate change projections. We use the Iowa Flood Center's Hillslope-Link Model (HLM) to estimate discharge projections utilizing forcings derived from global climate models (GCMs) part of the Coupled Model Intercomparison Projected Phase 5 (CMIP5, Taylor et al. 2012) and Phase 6 (CMIP6, Eyring et al. 2016). This tool addresses two specific objectives. First, it provides flood frequency estimates based on default settings. Specifically, the approach provides estimates by fitting a subset of discharge projections to a nonstationary generalized extreme value distribution. These settings cannot be edited and would reflect our best assessment of the projected changes in flood frequency. The second objective is to provide a service which allows users to explore how the selection of the CMIP suite, emission scenario, climate models, time period, and distribution type impact projected annual exceedance discharges. For this paper, we briefly summarize the hydrologic dataset used for flood frequency analysis, highlight the features of the IFFP and For Research pages, and give a brief discussion on the tool.

IFFP Components

Hydrologic Simulations

For the IFFP tool we simulated annual maximum discharges from either 1950 (CMIP5) or 1981 (CMIP6) to the end of the 21st century at every stream segment in Iowa using the HLM developed by the Iowa Flood Center (IFC). These periods are utilized as they are the periods utilized for the global climate model forcings utilized as input to the HLM. The simulations are conducted offline as they require high-performance computing, and the final results are stored in an SQL database on our server. All calculations with the tool are conducted with these simulations.

For the simulations we specifically utilized the TETIS-version of the HLM (see Quintero and Velasquez (2022) for more details). The theoretical background and conceptualization of the HLM is comprehensively described in Mantilla et al. (2022). The TETIS version of HLM is a fully distributed hydrologic model structure, which is based on the decomposition of the landscape into hillslopes and channels. The model estimates runoff generation at the hillslope by simulating different processes. Snow accumulation and melting rates are derived from precipitation and temperature data, based on the degree-day method. The model simulates precipitation losses in vegetation and soil pore macrostructure. Surface infiltration considers the hydraulic soil properties of the hillslope, and the conditions of frozen ground during the cold season. Deep percolation and groundwater losses are also modelled, considering the hydraulic conductivity of soil at the subsurface. Total hillslope runoff is aggregated in the river channel from the contribution of overland flow, interflow, and base flow. A nonlinear hydrologic routing model transports flow in the channels and considers the geomorphologic characteristics of the river network. The model equations are written as ordinary differential equations. HLM integrates a numerical solver that benefits from the binary tree structure of the river network to solve the system of differential equations in an asynchronous manner, suitable for high performance computing environments. In our implementation, the HLM provides hourly streamflow data, and the annual maximum discharge is obtained for all channel links in the river network. Projections of precipitation, temperature, evapotranspiration, and frozen ground conditions are used as forcings into the hydrologic model. The spatial and temporal resolution of these inputs are key for the performance of the model (see Quintero and Velasquez (2022) for more details). Simulations are conducted under naturalized flow conditions where stream regulation (i.e., dams) is ignored due to the lack of available data on future operating procedures. However, in Iowa stream regulations by dams are not a primary factor in simulating flood peaks across the state. Finally, the model does not consider ice formations within rivers but the period in which annual flood peaks occur in Iowa are in the spring and summer months, so this is not of concern for our simulation set.

The simulations are conducted from 1950 to 2100 utilizing climate model forcings (i.e., precipitation, temperature, and evapotranspiration) from the CMIP5 and CMIP6 suites. The CMIP5 precipitation and temperature are provided at a daily scale and are bias-corrected and statistically downscaled using constructed analogues (BCCA; Maurer et al., 2010) with a spatial resolution of 1/8° by 1/8°. Evapotranspiration is taken at the monthly scale. The CMIP5 suite contains two emission scenarios or representative concentration pathways, RCP45 and RCP85. RCP45 represents a scenario in which the peak emissions occur near 2040 and then decline to the end of the century. RCP85 is a scenario in which emissions continue to rise through 2100. The values 45 and 85 represent the radiative forcing level in 2100 (W/m^2) indicating 4.5 and 8.5 W/m^2, respectively. The hydrologic simulations are conducted with 19 GCMs from the CMIP5 suite. A full analysis of these simulations with this dataset can be found in Michalek et al. (2022). The CMIP5 suite is used in the For Research page of the tool.

The second set of annual flood peak projections incorporated in our tool utilizes forcings from GCMs within the CMIP6 suite. The CMIP6 suite provide climate projections for four emission or shared socio-economic pathways (SSP). Each SSP represents a corresponding emission and land-use scenario. We incorporate SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 into our tool, which represent end of century radiative forcings of 2.6, 4.5, 7.0, and 8.5 W/m^2, respectively. We utilize precipitation and temperature forcing data at the daily-scale which has been bias-corrected and downscaled to a spatial resolution of $1/16^{th}$ degree as input to the HLM. The evapotranspiration is used directly from the climate models with only a statewide bias-correction. These simulations are utilized under the IFFP page of the tool.

Web-Tool Components

The user interface of the IFFP was developed using HTML, which is the standard markup language for documents designed to be displayed in a web browser. JavaScript is utilized is the primary scripting language for dynamically updating content such as graphs, tables, and maps. The Google JavaScript library is utilized to provide line plots. Leaflet's JavaScript library is utilized to create an interactive map for users. PHP scripting is utilized to query our hydrologic dataset from the SQL databases. The primary function of the web tool is to fit simulated data to a distribution and return discharge for different annual exceedance probabilitis (AEPs) over time. The distribution fitting is conducted with the gamlss and extRemes library in R and is accessed through an API which is hosted on the web server. Figure 1 provides a schematic on the framework of the IFFP.

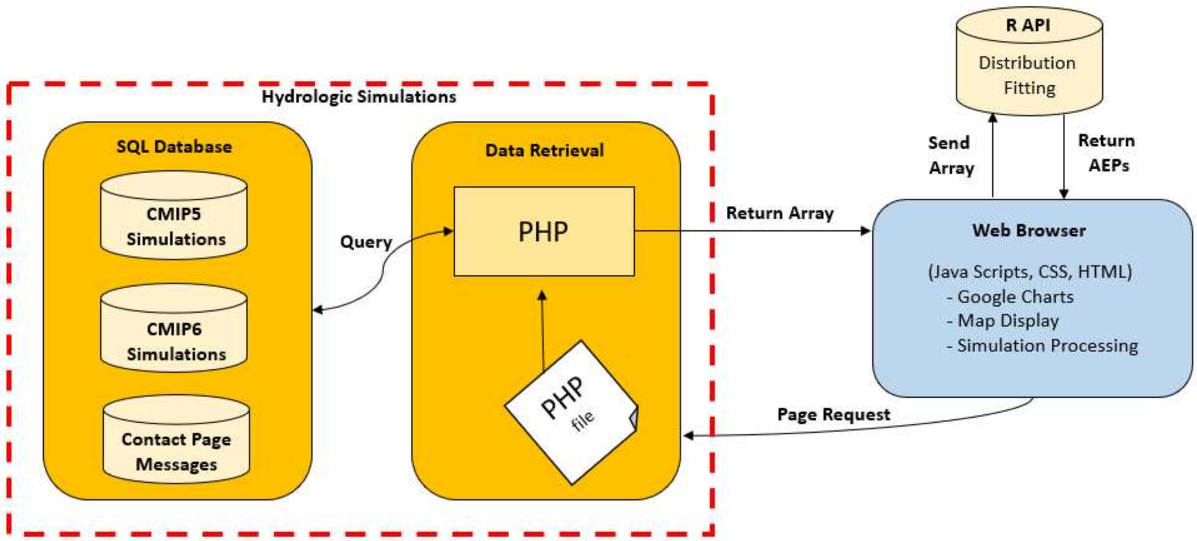


Figure 1. IFFP web framework showing how client-side requests are managed.

IFFP Page

With the background of the web-tool complete we now shift our focus to demonstrating the capabilities of the main page (IFFP tab). The IFFP tab focuses on projections in annual maximum discharge at all major streams in Iowa which drain into the Mississippi and Missouri Rivers. For most streams greater than 50% of the streamflow originates in Iowa. It is the primary page and provides stakeholders with our best assessment of the projected changes in flood frequency. The annual maximum discharge simulations utilized are from the CMIP5 suite for a select number of GCMs that we deemed to perform well in the historical period. We allow the user to select two emission scenarios (RCP4.5 and RCP8.5) to generate flood frequency projections at a location. The approach used in this page is based on the fitting of a nonstationary generalized extreme value (GEV) distribution to the annual maximum daily discharge. The GEV distribution fitting utilizes the Bayesian Information Criterion (BIC) to select a model with no parameters varying on time (if no trend is detected), location varying on time, scale varying on time, and location and scale varying on time. The AEP discharges are returned varying over time, with cases with no trend being shown as a constant value. Trend is determined based on the Mann-Kendall trend test at the 5% level. To utilize the tool, the user selects a stream link on the map and the flood frequency estimates over time are provided for a selected emission scenario. The results are provided for discharge values with an AEPs of 0.5, 0.2, 0.1, 0.04, 0.02, 0.01 and 0.004. The users can then click the button to generate a report with the location of interest, drainage area, and a table of AEP estimates overtime.

To demonstrate the capability of the tool, we will briefly examine the results for river section at the Cedar River near Cedar Rapids, Iowa. Figure 2 shows the results when a user selects the river link (highlighted in yellow). A display is returned providing the AEP projections for RCP4.5 from 1950 to 2100 with the drainage area of the basin (6492 sq. mi.). The plot shows that the annual maximum discharges have a trend, so the distribution also varies over time. If the user selects the "Build Report" button, a table of the AEP values will appear along with a map of the selected point and the ability to download the simulation and AEP parameters (Figure 3). For the 50% AEP a stakeholder would be able to see that from 1950 to 2100 the discharge value would increase from 24,262 ft^3/s to 25,594 ft^3/s. This change could be incorporated into a design or plan to help account for future conditions. Figure 3 shows the top and bottom screenshot of the report that can be built from this page. It provides the AEP estimates in tabular format as well as the ability to download the estimates and the simulation discharge data to csv.

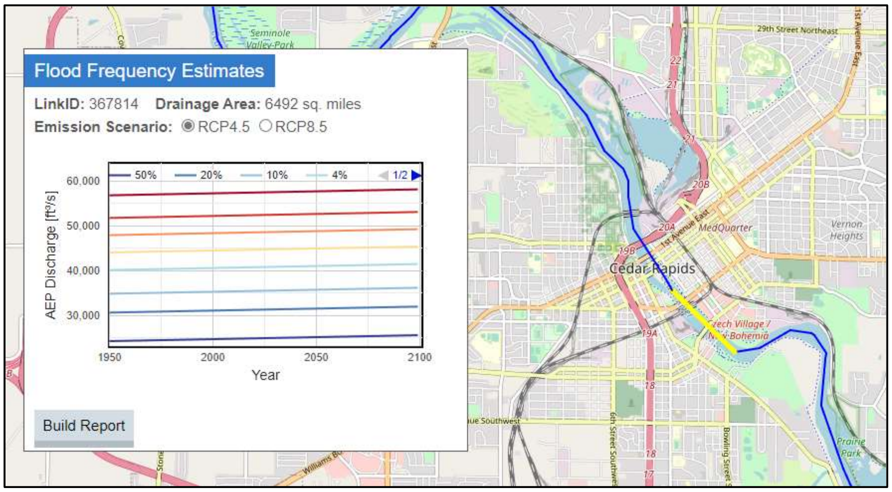
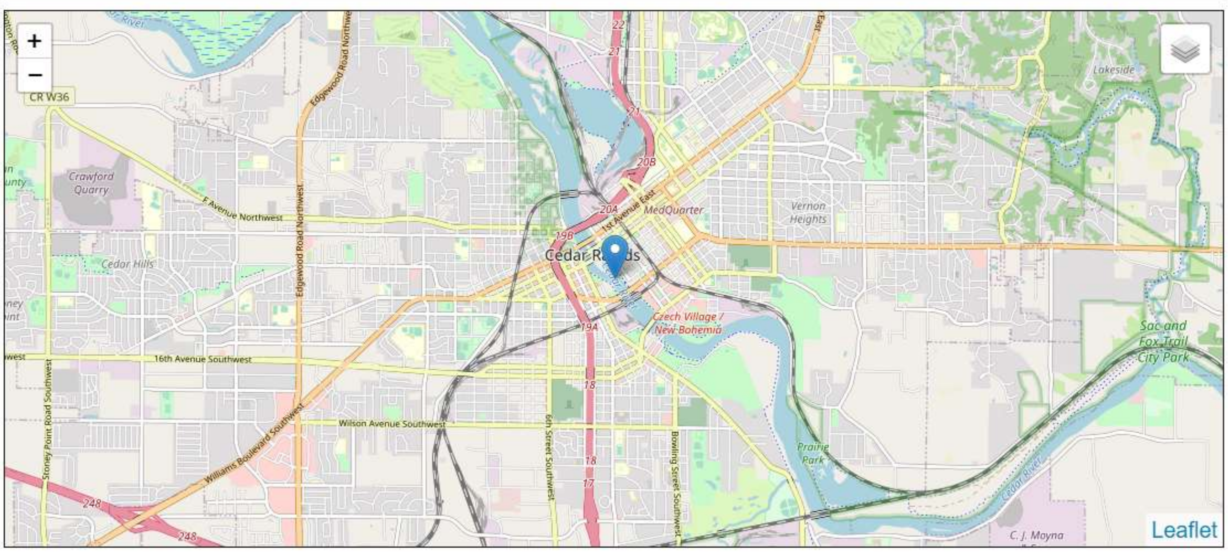


Figure 2. Screenshot showing test case when selecting a link (yellow) at the Cedar River at Cedar Rapids, Iowa, and the returned AEP discharges under emission scenario RCP4.5.

IFFP Report (RCP45)

LinkID: 367814
Longitude/Latitude: -91.67, 41.97
Upstream Area: 6492 sq. miles
Time: Tue Nov 22 2022 17:07:52 GMT-0600 (Central Standard Time)



IFFP Estimates [ft³/s]:

Year	50%	20%	10%	4%	2%	1%	0.5%	0.2%
1950	24262	30649	34858	40155	44070	47942	51787	56841
1951	24271	30658	34867	40164	44079	47951	51796	56850
1952	24280	30667	34876	40173	44088	47960	51805	56859

2096	25567	31954	36164	41461	45375	49247	53093	58146
2097	25576	31963	36173	41470	45384	49256	53102	58155
2098	25585	31972	36182	41479	45393	49265	53111	58164
2099	25594	31981	36191	41488	45402	49274	53119	58173

Print Report | Download Simulation Data | Download Selected AEP

Figure 3. The top and bottom of the report bult when selection the “Build Report” button in Figure 2. It provides the AEP projections in tabular format along with a map of the area selected, and buttons to download the data.

For Research Page

The second tool we provide is under the “For Research” tab which provides a higher degree of flexibility to the users compared to the “IFFP” Page. The biggest difference between the two pages is that the calculations and selection of model parameters are up to the user. Furthermore, here are two ways of performing the analyses by: 1) modeling the annual maximum discharge using different statistical distributions for a selected period of interest; and 2) computing a scaling factor that allows the comparison of the median annual maximum discharge values between two user-selected periods. The user has the capability to select any GCM or a subset of them among those analyzed. The plotting of AEP values allows selecting either individual GCMs or their average. The available distributions a user can select consist of the generalized extreme value, Gumbel, and lognormal distributions. When performing a distribution fitting analysis, it provides the results of the Mann-Kendall test for trend analysis, and summary statistics for the selected distributions (e.g., values of the fitted parameters, the Bayesian Information Criterion). The goal of the tool is allowed users to explore how different climate models and scenarios impact projections.

To demonstrate the capability of the tool, we will now demonstrate a simple example. Figure 4 shows a user case where the stream link (yellow) near the Cedar River at Cedar Rapids, Iowa is selected for a distribution analysis. The selected climate model suite is CMIP5 with RCP4.5 emission scenarios, and three models (access1-0, canesm2, cmcc-cm) selected. The start year and end year for the period of interest can be specified and for this example is selected as 1950 and 2020, respectively. Finally, the user selected a Lognormal distribution to be fit over time using imperial units. The output provides the AEP discharges over time as on the first page except the user can toggle through each individual model. In Figure 4 the access1-0 climate model simulation results are displayed and no trend in the data is detected ($p>0.05$), hence a static lognormal distribution is fit. The results boxes highlights the respective parameters selected, trend test results, BIC, and distribution parameters. In the final line of the results box, the “-999” indicates parameters not used in the distribution fit. Here the log-mean (mu1) is 9.63 ft^3/s with a variance (sigma1) of 0.68. These statistics are displayed when selecting a different chart to display as well.

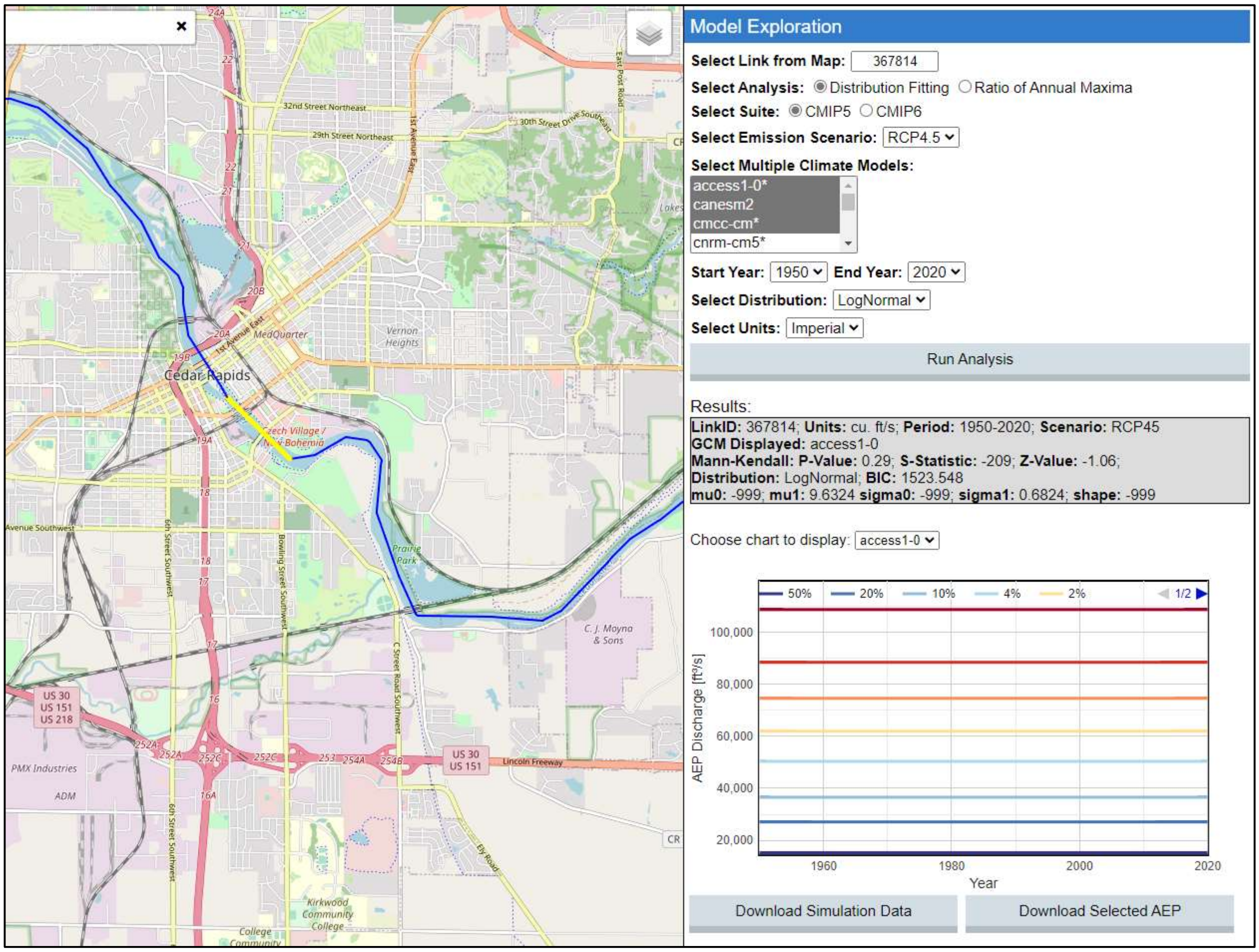


Figure 4. Screenshot of distribution fitting of Lognormal distribution from three selected CMIP5 climate models from 1950 to 2020 under RCP4.5. at the Cedar River at Cedar Rapids, Iowa (yellow highlight) The Results box show the distribution parameters with the Mann-Kendall statistic and an AEP discharge plot over time for the average of the models.

Next, we will display the capability of the second tool in this page which allows the users to see the ratio of future to present median annual maximum discharges to obtain a scaling factor for analyses. Figure 5 shows a simple example at Cedar Rapids where a user selects the same climate model scenario as in Figure 4 and is interested in the ratio between the median annual maximum discharge computed during the 1950-1980 and 2070-2100 periods. The "Results" box provides the ratio (future over reference) of the medians of the periods for each model and the average. The results show that, for the models selected, the annual maximum medians are expected to increase by 13% for this situation. This tool allows for users to explore a simple metric to understand how flood peaks are expected to change and how they vary between simulations with difference climate models.

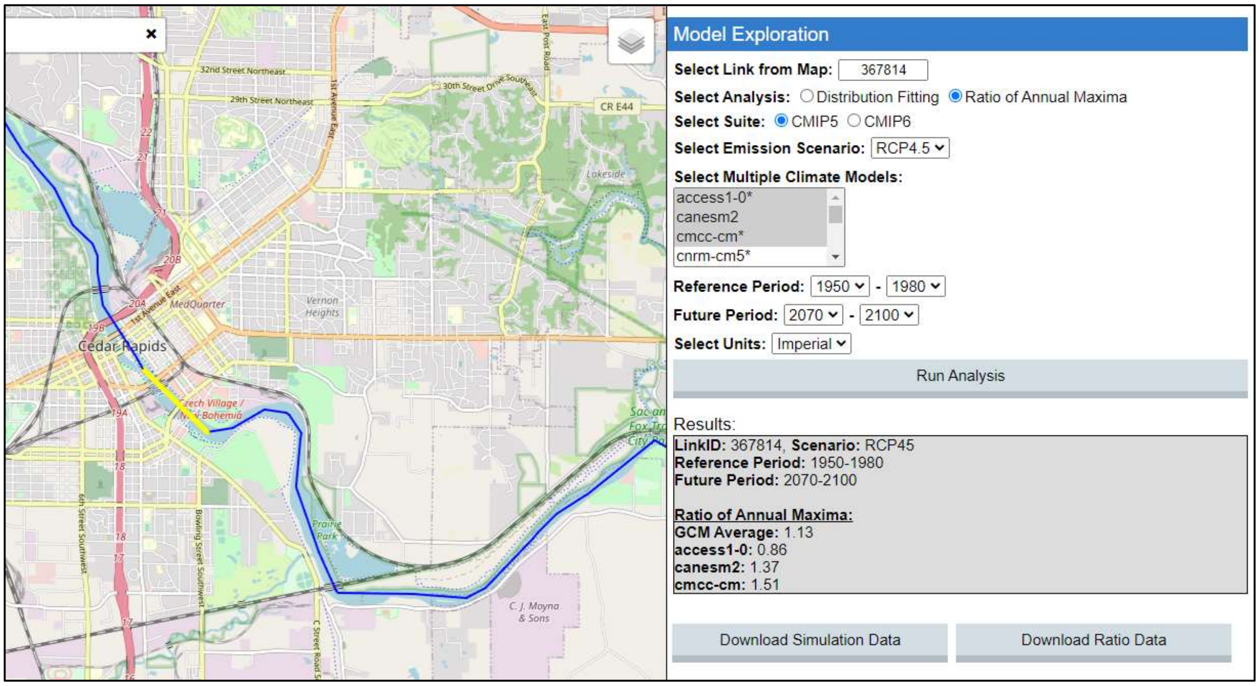


Figure 5. Screenshot of ratio of median annual maxima between periods of 1950 to 1980 and 2070 to 2100 for three selected CMIP5 climate models from 1950 to 2020 under RCP4.5. at the Cedar River at Cedar Rapids, Iowa (yellow highlight) The results box provides the user selections as well as the ratio of median annual maxima between periods for the models.

Discussion and Conclusions

In this paper, we present the IFFP web-based tool which provides flood frequency projections for Iowa and allows for exploration of future changes in flood peaks. We provide simple use cases to demonstrate its ability, which can be efficiently utilized by stakeholders across Iowa. It fills a current software gap for stakeholders as current tools do not provide flood projections for end-users. The main function of the tool provides users with AEP discharge estimates over time from 1950 to 2100 by fitting a generalized extreme value distribution with parameters that can vary on time. It provides users the ability to download the simulation data, AEP data, as well as provide a pdf report for a specific river link anywhere in the state. Furthermore, it easily allows users to search a location with a simple geographical interface. The research page expends on the ability of the main tool by allowing users to explore how climate model selection, time period, emission scenario, and distribution type impact flood frequency projections. Additionally, it provides users the ability to see the median change between two periods based on the scenario selected. A wiki page on the main page of the web site provides guidance on how to utilize the tool and a manuscript is in preparation for the web tool. To generalize the web-tool for the entire United States, further development of web-tools for flood frequency projections should be developed and integrated.

References

Claudia Tebaldi et al. 2021. “Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6,” Earth Syst. Dynam., 12, 253–293. https://doi.org/10.5194/esd-12-253-2021

Eash, D. A., Barnes, K. K., and Veilleux, A. G. 2013. "Methods for estimating annual exceedance-probability discharges for streams in Iowa, based on data through water year 2010." Retrieved from http://pubs.usgs.gov/sir/2013/5086/

England Jr, J. F., Cohn, T. A., Faber, B. A., Stedinger, J. R., Thomas Jr, W. O., Veilleux, A. G., et al. 2019. Guidelines for determining flood flow frequency—Bulletin 17C (4-B5). Retrieved from Reston, VA: http://pubs.er.usgs.gov/publication/tm4B5

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. . 2016. "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization," Geosci. Model Dev., 9, 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Mantilla, R., Krajewski, W. F., Velasquez, N., Small, S. J., Ayalew, T. B., Quintero, F., et al. 2022. "The hydrological Hillslope-Link Model for space-time prediction of streamflow: Insights and applications at the Iowa Flood Center," in M. Astitha & E. I. Nikolopoulos (Eds.), Extreme Weather Forecasting: Elsevier.

Michalek, A., Quintero, F., Villarini, G., and Krajewski, W. 2022. "Advantages of Physically-based Flood Frequency Analysis with Long Term Simulations for Iowa," ASCE Journal of Hydrologic Engineering. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002230 .

Michalek, A., Quintero, F., Villarini, G., Krajewski, W. 2022. "Projected changes in annual maximum discharge for Iowa communities," Journal of Hydrology (submitted).

Quintero, F.and Velasquez, N. 2022. "Implementation of TETIS hydrologic model into the Hillslope Link Model framework," Water, 14(17), 2610.https://doi.org/10.3390/w14172610.

Quintero, F., Krajewski, W. F., Seo, B.C., and Mantilla, R. 2020. "Improvement and evaluation of the Iowa Flood Center Hillslope Link Model (HLM) by calibration-free approach," Journal of Hydrology, 584. https://doi.org/10.1016/j.jhydrol.2020.124686.

Taylor, K. E., Stouffer, R. J. and Meehl, G. A. 2012. "An overview of CMIP5 and the experiment design," Bull. Amer. Meteor. Soc. 93, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1