Flow Frequency Study of the Upper Mississippi River

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Extended Abstract

The U.S. Army Corps of Engineers (USACE) is working on a study effort targeted at updating flow frequency relationships and hydraulic profiles within the Upper Mississippi River (UMR) Basin. The Mississippi River flows from northern Minnesota to the Gulf of Mexico for a length of 2,340 miles with a total drainage area of 1,151,000 square miles. This study will focus on 189,800 square miles of drainage area, or approximately 16% of the total Mississippi River Watershed (Figure 1). The previous UMR System Flow Frequency Study (UMRSFFS) was completed in 2004 using UNET unsteady hydraulic modeling based on data collected through 1998 (USACE 2004). There are multiple reasons to update the 2004 UMRSFFS: the flow record includes additional, large flood events, flow frequency guidance has been updated to Bulletin 17C (England, J.F., Jr. et al. 2019), and advances have been made in modeling software. Future and concurrent flood risk management efforts, floodplain mapping, dam and levee safety assessments, and other applications will depend on reliable flood frequency analysis and corresponding hydraulic profiles. Concurrent flow-frequency efforts on the Lower Mississippi River, Missouri River, and Ohio River are all in different stages of completion with periodic coordination occurring between the study efforts.

Figure 1. UMR study watershed compared to entire Mississippi River Basin

Flow frequency relationships and corresponding hydraulic profiles will be updated on the UMR from Anoka, Minnesota to the confluence of the Ohio River (approximately 865 river miles) and on the Illinois River from Dresden Island Lock and Dam to the Illinois River's confluence with the Mississippi River (approximately 272 river miles). Analysis will not be generated for the Missouri and Ohio Rivers because these watersheds are being studied as part of concurrent USACE study efforts. This study consists of three phases spanning four to five years (Table 1). The study is to be a coordinated investigation conducted with input from USACE experts, other federal agencies and local stakeholders. Final study results will be compiled into a report and a web-based database.

Table 1. Phases and descriptions of the study

<table>
<tr><th colspan="2">Phase</th><th>Status</th><th>Description</th></tr>
<tr><td rowspan="3">Phase I
Years 1-2</td><td>Phase IA</td><td>Complete</td><td>Data Inventory</td></tr>
<tr><td>Phase IB</td><td>Complete</td><td>Initial Climate Change Assessment</td></tr>
<tr><td>Phase IC</td><td>Ongoing</td><td>Hydrologic Engineering Management Plan (HEMP)</td></tr>
<tr><td rowspan="2">Phase II
Years 2-4</td><td>Phase IIA</td><td>Future</td><td>Development of Hydraulic Routing Model</td></tr>
<tr><td>Phase IIB</td><td>Future</td><td>Homogenous Unregulated and Regulated Flow Timeseries</td></tr>
<tr><td rowspan="3">Phase III
Years 4-5</td><td>Phase IIIA</td><td>Future</td><td>Flow Frequency Analysis</td></tr>
<tr><td>Phase IIIB</td><td>Future</td><td>Development of Hydraulic Profiles</td></tr>
<tr><td>Phase IIIC</td><td>Future</td><td>Finalization of Climate Change Evaluation</td></tr>
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Phase IA of this study is complete and focused on developing inventories of available resources including hydrologic data, existing models, and reference information. The availability of observed flow and stage records, historic flood information, and paleoflood data was inventoried and documented. Water management structures within the UMR Basin were identified. Previous flow frequency analyses within the study area were inventoried to include descriptions of the approach taken and data used. Existing reservoir, precipitation-runoff, and hydraulic models that provide coverage of the study area were identified. References and datasets describing historic and present-day land use and land cover were consolidated and documented. These inventories were compiled to include geospatial information and are organized through mapbooks created with ArcGIS Pro.

Phase IB is complete and consisted of conducting a climate change assessment following USACE Engineering Construction Bulletin (ECB) 2018-14, *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Work Studies, Designs, and Projects* (USACE 2020), as well as USACE Engineering Technical Letter (ETL) 1100-2-3, *Guidance for Detection of Nonstationarities in Annual Maximum Discharges* (USACE 2017). ECB 2018-14 requires that climate change and variability analysis be conducted in support of USACE studies to identify and communicate climate change risk. Analysis serves to provide the context necessary to identify problems and risk reduction opportunities related to climate change impacts. Review of peer reviewed literature describing trends in observed and projected temperature and precipitation indicate a warmer, wetter future for the UMR basin. Extreme rainfall events are anticipated to increase in frequency and magnitude, while drought frequency and duration are also projected to increase. The region is expected to experience less snowfall and a longer frost-free season. Although there is some indication within the observed record that streamflow is increasing, little consensus exists regarding projections of future streamflow. The primary references used in support of this effort are The *Fourth National Climate Assessment* (NCA4) and the USACE *Civil Works Technical Report CWTS-2015-13,* as well as state climate summaries published by the National Oceanic and Atmospheric Administration (USGCRP 2018, USACE 2015, Kunkel et al. 2017).

Select observed temperature, precipitation and streamflow datasets were analyzed annually and seasonally for monotonic trends and nonstationarities using a series of R-based scripts developed to batch process hydrologic timeseries data using the statistical tests recommended by USACE ETL 1100-2-3 and incorporated into the web-based USACE Timeseries Toolbox. Twelve different statistical tests are applied to test for abrupt and smooth shifts in the statistical properties (mean, standard deviation, and overall distribution) of the datasets including non-parametric tests like the Petitt and Mann-Whitney tests. The t-test, Mann-Kendall and Spearman Rank-Order tests are applied to detect monotonic trends. Results are presented both tabularly and spatially via a series of mapbooks created in ArcGIS. Temperature and precipitation records were evaluated from the late 1800s or early 1900s through 2020, depending on the location. Trends and nonstationarities were not detected in many annual maximum 1-day or 3-day precipitation timeseries. There is more evidence of change in total precipitation, but the timing of when these nonstationarities are detected lacks consistency between locations. There is consensus across the UMR region that maximum temperatures are decreasing annually and in the summer and fall. There is corresponding evidence of nonstationarity circa the middle of the 20th century. In the UMR region, minimum temperatures are generally increasing both on an annual and seasonal basis. There is evidence of increasing trends in annual instantaneous observed (historic) peak streamflows throughout the entirety of the UMR region (HUC 07). The length of streamflow records analyzed varied between 65 years and over 110 years. Trends and nonstationarities detected were grouped by the length of record analyzed to aid in interpretation of results. Increasing trends are observed annually and for all seasons analyzed. There is more evidence of nonstationarity in the upstream portions of the UMR region relative to the downstream portions. The majority of nonstationarities detected are occurring between 1935-1945, 1965-1980 or circa 1990.

To assess comparisons between simulated historic and future, climate influenced streamflow, the USACE Climate Hydrology Assessment Tool (CHAT) was applied to evaluate changes in annual-maximum of mean, monthly streamflow simulated for 8-digit Hydrologic Unit Code (HUC) watersheds in the UMR Basin. The CHAT uses Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate model (GCM) meteorological data outputs that have been statistically downscaled using the Localized Constructed Analogs (LOCA) method. Projected, climate influenced streamflow data for 2006 to 2099 are produced using two future scenarios: representative concentration pathway (RCP) 4.5 and RCP 8.5. Simulated output representing the historic period of 1951 to 2005 is generated using a reconstitution of historic greenhouse gas emissions. To analyze runoff, LOCA-downscaled GCM outputs are used to force an unregulated Variable Infiltration Capacity (VIC) hydrologic model. Areal runoff from VIC is then routed through a stream network using MizuRoute (Mizukami et al. 2016). The CHAT fits trendlines to the average of the simulations for both the historic period (1951-2005) and the future period (2006-2099). Trends in projected maximum streamflow records are consistent with trends in the observed streamflow records analyzed. For the projected, future period all the 8-digit HUC watersheds downstream of HUC 0707 (the Wisconsin River) show strong evidence of increasing streamflow over the next century. Upstream of the Wisconsin River's confluence with the Mississippi River results are mixed, with over half of the watersheds showing no statistically significant evidence of change through water year 2099.

Finally, for Phase IB, the USACE Vulnerability Assessment (VA) Tool was utilized to look at how climate change could expose UMR Basin 04-digit HUC watersheds to climate change driven risk in the future. The VA Tool facilitates a screening level, comparative evaluation of climate change exposure in each 4-digit HUC watershed, for a specified USACE business line relative to the other 4-digit HUC watersheds within the continental United States (CONUS). USACE business lines include flood risk management, navigation, ecosystem restoration, hydropower, recreation, water supply, regulatory and emergency management. The VA Tool relies on a series of indicator variables are computed and aggregated into a vulnerability score using the weighted-order, weighted-average (WOWA) approach. The tool uses the CMIP5 GCM based BCSD (Bias Corrected, Spatially Disaggregated) VIC dataset (2014) to define projected hydrometeorological inputs to the tool's WOWA scores. It was found that most of the 4-digit HUC watersheds within the UMR region (HUC 07) are not relatively vulnerable to the effects of climate change for the flood risk management business line. The flood risk management business line includes projects such as dams and levees. For most of the 4-digit HUCs, the WOWA scores increase during the 2085 epoch, suggesting that higher risks may materialize later in the future.

The study is currently in Phase IC: Hydrologic Engineering Management Plan (HEMP) development. The HEMP will serve as a guide outlining the method applied to generate flow frequency profiles for the UMR and Illinois River. The HEMP will document the recommended methods and alternative approaches considered for defining the flow frequency curves and hydraulic profiles being produced. The goal of the document is to expand on and clarify any assumptions and unknowns identified by the Scope of Work (SOW). The key elements of the HEMP include defining study extents and period of record, establishing the strategy for hydrologic analysis, and establishing the strategy for hydraulic analysis.

The HEMP will describe which of the tributaries to the mainstem Mississippi and Illinois Rivers require detailed analysis (flow frequency analysis at most downstream gage, coincident frequency analysis, etc.) to aid in the development of hydraulic profiles on the mainstem rivers. The period of record will be determined based on availability of historic flood data, systematic streamflow, stage and precipitation records, as well as watershed changes through time (e.g. land cover and land use). The strategy for hydrologic analysis will address estimation of ungaged and missing flows, the approach to flow frequency analysis for mainstem and tributary gages, a preliminary evaluation of the need for mixed population analysis, an examination of how far downstream regulation impacts extend, and how coincidental flows will be analyzed. The strategy for hydraulic analysis will include the HEC-RAS modeling approach, levee breach assumptions, how hysteresis will be incorporated into the study approach, identification of areas of hydraulic complexity, and the overall approach to hydraulic profile development.

Phase IIA will focus on the development of the hydraulic routing model that will cover the study extents of the mainstem Mississippi and Illinois Rivers and represent today's conditions. USACE has recently developed detailed HEC-RAS modeling for the study's reaches (USACE 2018). The goal is to utilize these recently developed HEC-RAS models as a starting point for the development of a simplified hydraulic routing model that can be used for continuous simulation of flows between approximately the 1930s and present-day. The routing model will be used to generate homogeneous, daily flow records representative of regulated and unregulated conditions for points of interests on the Mississippi and Illinois rivers.

Phase IIB consists of the development of homogeneous, daily regulated and unregulated flow records. First, all observed (in situ) streamflow records will be verified and gaps in the streamflow records will be identified. Record extension will be performed by using either the Maintenance of Variance Extension (MOVE) technique as recommended by Bulletin 17C or by using a flow-duration curve-based algorithm as defined by D.A. Hughes and V. Smakhtin (1996). The record extension methodology will be chosen based on whether the gaged portion of the watershed is impacted by regulation. All sources of regulation which have a significant impact on mainstem Mississippi and Illinois River peak flows will be identified. The downstream extents of the effects of regulation on the Mississippi and Illinois River will also be evaluated to identify which gage locations experience significant regulation during high flow conditions and which locations can be considered unregulated.

To develop continuous, unregulated flow records for portions of the record impacted by regulation, reverse routing will be used to calculate the reservoir inflow records. To produce regulated flow records reflective of present-day reservoir operations, HEC-ResSim will be used to model reservoir outflows for portions of the period of record prior to when regulation went into place and/or to changes in operations. All available HEC-ResSim models have been inventoried along with pertinent metadata. As many of these models were used in past studies to produce regulated and unregulated flow records, this study will utilize these available models and results while augmenting and updating them as applicable, as well as creating new HEC-ResSim models as needed. Computed inflows (unregulated flows) or reservoir outflows (regulated flows) will be routed and combined with approximations of ungaged local flow using hydrologic routing in HEC-ResSim and/or HEC-HMS along the tributaries and headwaters reaches to the upstream extents of the HEC-RAS model. Flows along the mainstem of the Illinois and Mississippi Rivers will be approximated using the HEC-RAS model configured for continuous simulation. Ungaged local flow inputs will be computed using the optimized holdout method and/or output from precipitation-runoff models.

The final phase of the study will be focused on flow frequency computations, the development of hydraulic profiles, as well as the finalization of the study report and associated products. Phase IIIA will consist of developing annual peak flow frequency analysis at points of interest on the mainstem of the Mississippi and Illinois Rivers and for the downstream most gage on major tributaries. The list of major tributaries generated in Phase IC will be validated during Phases II and III using the HEC-RAS model to determine which tributary contributions to the UMR and Illinois River significantly impact the continuity of mainstem hydraulic profiles.

In accordance with Bulletin 17C, the Hydrologic Engineering Center's (HEC) Statistical Software Package (HEC-SSP) will be used to generate unregulated flow frequency curves and their 90% confidence intervals using the expected moments algorithm (EMA). The HEC-SSP software combines established statistical methods and new capabilities such as EMA into a unified suite of tools having a graphical user interface (GUI), separate statistical analysis components, data storage and management capabilities, mapping, graphics, and reporting features. The appropriate approach to defining mainstem skew will be evaluated as a part of this study. Consideration will be given to applying a regional skew value, a weighted skew value or station skew. For tributary locations, a weighted skew will be adopted incorporating regional skew information as published by the USGS. To define the portions of the curve associated with more frequent events (Annual Exceedance Probability (AEP) > 10%), a partial duration approach will be used. At locations impacted by regulation, flow frequency relationships will be defined graphically. Hypothetical flows exceeding the 2% AEP event will be developed to help define the upper portions of regulated curves. For the graphically defined relationships, confidence limits will be determined by first defining an equivalent period of record length based on the methodology/data sources used to generate the flows being analyzed. Then the ordered statistics approach will be used to compute the confidence interval for the observed/modeled portion of the period of record with asymptotic approximation being applied to extend the confidence band.

Major tributaries will require additional analysis to define coincidental tributary flows to mainstem peak flows. In these cases, coincidental flow analysis is necessary to accurately model hydraulic profiles tied to AEPs of interest. If significant flow occurs on both the tributary and the mainstem at the same time, but flows are not highly correlated, a coincidental peak flow frequency analysis will be carried out for the tributary. If the mainstem peak typically occurs independently of the tributary peak flow then a seasonal, daily duration curve analysis will be conducted to generate the coincident flows on the tributary. If the peak flows on the mainstem are highly correlated with peak tributary flows, then a Monte Carlo based approach will be applied to define coincidental tributary flows.

Phase IIIB will utilize unsteady HEC-RAS to produce flow profiles representative of the 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% AEPs. Hypothetical floods (ratioed from historic events) will be modeled to help define the hydraulic profiles associated with rare flood events. The proposed approach will use output from the period of record HEC-RAS simulation to develop peak stage-flow rating curves at every cross-section in the HEC-RAS model. Unregulated flow frequency results will be interpolated to every HEC-RAS model cross-section. A drainage area ratio will be used to interpolate the mean and standard deviation between locations where a Bulletin 17C flow frequency analysis was completed. Skew will likely be defined based on a regionalized value, a skew versus drainage area relationship or a relationship between mean and skew. Using the unique mean and standard deviation for each cross-section along with the estimated skew, an unregulated flow frequency curve will be developed for all cross-section locations throughout the hydraulic profile study extents. At locations impacted by regulation, the unregulated flow frequency results will be transformed to regulated flow frequency results using a regulated-unregulated rating curve established from the continuous HEC-RAS modeling results. Flows will be converted to elevations using the established annual peak stage-flow rating curves.

For certain reaches of the UMR and Illinois River, hydraulic profiles can't be developed from interpolated flow frequency results and peak stage-flow rating curves. In these reaches, hydrograph attenuation causes a decrease in peak flows as drainage area increases. Instead, the hydraulic profiles will be developed by explicitly modeling each specific flow frequency event using a synthetic hydrograph on the mainstem in conjunction with coincident tributary inflows.

Access to reliable flow frequency information is requisite for future water resources and flood risk mitigation works in the UMR basin by USACE and the engineering community. The objective of this project is to develop that information. In doing so, this project will incorporate updated flood records and leverage the latest advancements in flow frequency guidance and software. As Phase I of this project nears completion, the remaining two phases will proceed in coordination with partners at the agency, federal and regional levels.

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