Lower Mississippi River Probabilities: A Collaborative Investigation

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Abstract

In scoping an investigation of the Lower Mississippi River flow probabilities, the US Army Corps of Engineers (USACE) looked for existing, watershed-wide continuous simulation hydrologic models with established confident results covering several decades of simulation or forecasting. USACE and the National Weather Service (NWS) established a partnership where the NWS simulated two scenarios using the Community Hydrologic Prediction System and Flood Early Warning System (CHPS-FEWS) for the entire Mississippi River watershed.

The regulated simulation represents today's hydrology and an unregulated simulation "turned-off" most flood control reservoirs. The period simulated for the scenarios leveraged the NWS historic precipitation and temperature time series spanning from about 1952 to 2017. USACE prepared temperature and precipitation grids using the Livneh 1/16 resolution gridded daily datasets, that extended the simulation period back to 1915. The 2018 Mississippi River & Tributaries (MR&T) Flowline Assessment HEC-RAS model was leveraged to route and combine major tributaries to simulate the Lower Mississippi River from Cairo, Illinois to the downstream boundary condition at West Pointe a La Hache, Louisiana (River Mile 48.76). For the unregulated simulation, the three major M&RT diversions at Old River, Morganza and Bonnet Carre are removed to approximate the pre-project geometry

USACE developed an R script to compare simulated flows for the regulated simulation to the observed flow at a set of primary USGS gage locations for the last 20-30 years of modern record. Timeseries plots and statistical comparisons demonstrated the fit of the simulated data to observed. The R script exported a standardized report for each of the NWS River Forecast Centers (RFCs), and coordination meetings were held between USACE and the RFCs to verify the results.

The two simulated time series are used to initially prepare preliminary frequency curves at key gage locations in the Lower Mississippi River and major tributaries. The regulated simulation timeseries is a stationary data set for the modern-day condition and displays a picture of how the

flood control reservoirs would have impacted the watershed's response to floods that occurred before the construction of those major reservoirs in the system. The unregulated simulation is a unique dataset that can be used to help define the upper end of the frequency curves and is helpful in quantifying the impact of reservoirs throughout the watershed. This collaboration between the USACE and NWS Agencies provides unique datasets that will have numerous uses for watershed planning scenarios in the future.

Introduction

Background

The Mississippi River Watershed encompasses 1.2 million square miles and covers approximately 40% of the area of the United States (Figure 1). Within the downstream extents of this massive drainage system, the US Army Corps of Engineers (USACE) watershed management within Mississippi Valley Division (MVD) includes the maintenance of approximately 2800 miles of authorized embankments and floodwalls. Nearly 2220 miles of embankments and floodwalls protect the main stem of the Mississippi River. The extensive flood protection system is called the Mississippi River and Tributaries (MR&T) Project and is designed to protect the 36,000 square mile Lower Mississippi River Valley from periodic floods that move through the Mississippi River. The project was designed to convey the Probable Design Flowline (PDF) represented by a maximum event that has a "reasonable chance of occurring". The PDF was based on applying a sequence of hypothetical rainfall events that were derived from actual extreme rainfall events that occurred within the basin. The most recent update for the PDF and the development of a MR&T Flowline Model in HEC-RAS was completed in 2018. Tracking performance of the MR&T system and operational needs within the valley requires assessing the magnitude of annual exceedance probabilities. An updated probabilities assessment is a priority for the Lower Mississippi Valley.

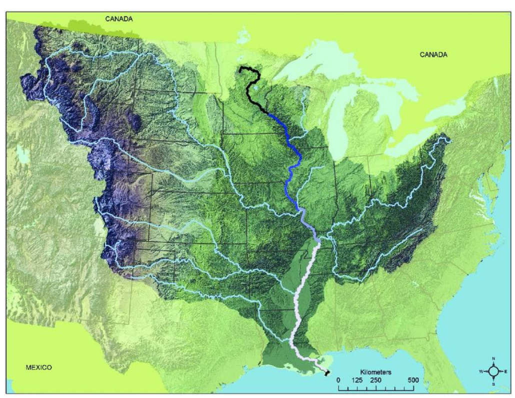

Figure 1. Mississippi River Watershed (Image Credit US Geological Survey, Upper Midwest Environmental Sciences Center)

Previous frequency assessments on the Lower Mississippi River are based on observed regulated discharges at key gages on the Mississippi River and frequency estimates for project sites are interpolated between the key gages. Development of frequency relationships were accomplished gage by gage. A rigorous analysis to update probabilities on an expansive watershed with such a high degree of regulation requires a unique and innovative approach for an updated probability investigation.

Agency Collaboration

Given the very large drainage area of the Mississippi River Watershed, the first task is to collect pertinent data and previous study information to form a picture of what existing data there was to work with. Although USACE has been developing real time water management system models for regulated tributaries in the watershed, the models are focused on short-term simulations for real time decision making. Looking beyond the USACE model inventory, the USACE and National Weather Service (NWS)discussed the options available to leverage the hydrology models presently used for forecasting across the Mississippi River Watershed. USACE and NWS established a partnership where the NWS generated two simulations using the Community Hydrologic Prediction System and Flood Early Warning System (CHPS-FEWS). The basin-wide hydrologic analysis was accomplished through the partnership across five River Forecast Centers (RFC): NCRFC (North Central), MBRFC (Missouri Basin), OHRFC (Ohio River), ABRFC (Arkansas/White/Red Basin) and LMRFC (Lower Mississippi River). The Tennessee Valley Authority (TVA) also offered to run the same precipitation forcings through their model system of the Tennessee Watershed to produce regulated and unregulated flows.

Meteorologic Forcing

Multiple sources of gridded precipitation and temperature data were used within this modeling effort. Some RFCs had meteorological boundary conditions that could be used starting in the early 1950s, while others had readily available data beginning in the late 1950s. To extend the precipitation data to a uniform start date, Livneh daily CONUS near-surface gridded meteorological and derived hydrometeorological data were used (https://psl.noaa.gov/data/gridded/data.livneh.html) (Livneh, et al., 2013).

The original Livneh data was available at a 1/16-degree spatial resolution from 01Jan1915 to 31Dec2011. However, only the period spanning 01Jan1915 to 30Sep1960 was used in this effort to supplement the available RFC data. The continental-scale datasets were projected to a coordinate reference system (CRS) using the Albers Projection and Geographic Coordinate System (GCS)_North_American_1983.

Precipitation Data: The Livneh precipitation grids were resampled to a 2 km grid size and then were clipped to the boundary of the Mississippi River watershed. The daily precipitation data was uniformly disaggregated to a 6-hr time step to match the computational time step of the RFC hydrologic models. Prior to 1940, there were few operating sub-daily gages that could help with patterning to an increment smaller than one day. Finally, the gridded precipitation data was converted to ASCII format (U.S. Army Corps of Engineers, 2022).

From the 1950's to present, the NWS RFCs developed quality-controlled precipitation time series for each of their operational subbasins which represents the average precipitation and temperatures for each 6-hour time step for a historic period. The historic RFC precipitation datasets are generated using the best available historical rain gage data along with more recent multi-sensor radar estimates. The NWS ingested the Livneh gridded data along with their quality controlled historic datasets into the CHPS-FEWS models to merge them together in to generate continuous records of rainfall for the period 1915 to 2019 for all basins in the greater Mississippi River watershed.

Temperature Data: The Livneh daily CONUS near-surface gridded meteorological and derived hydrometeorological data was also used to derive gridded temperature boundary conditions (Livneh, et al., 2013). Like the precipitation data, each RFC had readily available temperature data ready for use beginning in the 1950s. The Livneh data was used to generate gridded temperature boundary conditions from 01Jan1915 to 30Sep1960 within this effort.

The continental-scale datasets were reprojected to the previously mentioned CRS and resampled to a 2 km grid size. Then, the temperature grids were clipped to the boundary of the Mississippi River watershed. Unlike the precipitation data, the following logic was used to temporally disaggregate the temperature data. For 00:00 to 09:00 (UTC), the following equation was used:

$$Hourly\ Temperature = -\left(\frac{MAX1-MIN1}{2}\right) * cos\left(time * \frac{\pi}{9}\right) + \left(\frac{MAX1+MIN1}{2}\right) \quad (1)$$

For 10:00 to 23:00 (UTC), the following equation was used:

$$Hourly\ Temperature = -\left(\frac{MAX1-MIN2}{2}\right) * cos\left((time-10) * \frac{\pi}{13}\right) + \left(\frac{MAX1+MIN2}{2}\right) \quad (2)$$

Within the previously mentioned equations, *MAX1* is the daily maximum temperature for the current day, *MIN1* is the daily minimum temperature for the current day, and *MIN2* is the daily minimum temperature for the next day. The 6-hour temperatures represent an average temperature over the 6-hour period. Finally, the gridded temperature data was converted to ASCII format.

Regulated Condition Simulation

NWS Model Structure: The NWS RFCs utilize the Community Hydrologic Prediction System (CHPS) Deltares Flood Early Warning System (FEWS) model to simulate rainfall-runoff events and develop river forecasts throughout the United States. This suite of modeling tools is referred to as CHPS-FEWS.

The NWS RFSs executed their CHPS-FEWS model with the meteorological forcings spanning the period from 1915 to approximately 2019. The regulated condition is based on the current, calibrated operational hydrology models that were individually calibrated at each of the five RFCs over years of forecasting. In general, the models reflect today's conditions but there may be some approximations especially at dams and spillways, where regulating agencies manage and operate the structures on a daily or sub-daily basis. The NWS RFCs run a continuous hydrologic model that was initiated from a "cold-state" and noted that the first couple years of the CHPS -FEWS simulation should be considered a "warm up period". The regulated discharge time series were written out for "primary gage locations" that are desired by the team for comparisons and a subset of those gages will be used to generate frequency curves for the Lower Mississippi River.

CHPS-FEWS Reservoir Routing: Reservoirs are coded within the CHPS-FEWS model using a routing element, with inflow, storage and outflow relationships that have been approximated over time through calibration. During flood events, the NWS typically coordinates with the regulating agency to verify assumptions for reservoirs that have extensive regulation rules and downstream controls. In this simulation, where the time series ran continuously from 1915 through 2019, no adjustments were possible. The best fit approximation for the regulation were set in place and simulated through the period.

Hydraulic Routing: The incorporation of the runoff time series from the major tributaries flowing into the Lower Mississippi happens within a HEC-RAS model that was built as part of MR&T Flowline Study. The HEC-RAS model was updated to version HEC-RAS 6.3.1 and simulates the Lower Mississippi River from Cairo, Illinois to the downstream boundary condition at West Pointe a La Hache, Louisiana (River Mile 48.76). The model is a 1-dimensional RAS model with storage areas. The contributions from the various tributaries are imported from a database as a boundary condition within the unsteady flow file and linked to the appropriate cross section in the geometry. The primary dynamic tributaries included the Mississippi River at Chester, Big Muddy at Murphysboro, Ohio River at Smithland, Tennessee River at Kentucky Dam, Cumberland River at Barkley Dam, St Francis River, White River at Newport, Cache River, Arkansas River and Yazoo River. Other smaller tributaries and ungaged local flow are inserted into the Flowline model as lateral inflows to account for all runoff in the Lower Mississippi River watershed. The geometry of the channel and levees represent the modern condition. The extensive simulation period (1915-2019) was run in 10-year periods, saving the states and the end of each decade run, and using that as a hot start for the next 10-year simulation period.

Lower Mississippi Diversions: The Lower Mississippi River diversions at Old River, Morganza and Bonnet Carre are treated as negative outflows in the RAS model. Old River diversion flows were calculated based upon the Congressionally authorized 30% split of total latitude flow including the Mississippi, Red and Black Rivers and taken out using an unsteady flow time series (River station 319.16). The Morganza and Bonnet Carre diversion flow time series were computed based upon their respective max flow threshold exceedances of 1.5 MCFS and 1.25 MCFS, respectively.

Unregulated Condition Simulation

NWS Regulation Removal: The unregulated condition maintains the calibrated parameters from today's hydrologic calibration, but removes the storage and attenuation offered by the major reservoirs in the system. The NWS RFCs removed regulation from for both Corps Dams and Non-Corps dams. Not all projects are equally important as far as their significance on reducing flows to the Mississippi River, and each RFC determined which reservoirs it could deactivate or remove for the unregulated condition. A few reservoirs were left active where the lakes provided substantial storage or attenuation even in their natural state. No adjustment was made in the HEC-RAS model to remove levees.

Lower Mississippi Spillway Configuration: The Major spillways exist in the Lower Mississippi River Reach within the USACE New Orleans District. The Old River Control Complex (ORCC), Bonnet Carre and Morganza spillways were adjusted in the HEC-RAS model to approximate the "natural flows" hydraulic controls that included smaller channels and weirs. Design reports and as-built drawings were located for the Bonnet Carre and "natural" land surface elevations were extracted as much as possible. The levees coded within the HEC-RAS geometry were left as-is for the unregulated condition simulation.

Verification of CHPS-FEWS Simulations

Evaluation for the modern period (last 20-30 years) of the regulated condition was accomplished to verify the reasonableness of calibration. An innovative approach was needed to process the massive amount of output data for each of the RFC's primary gage points. The team chose to develop a script in the R Statistical Software (R) to compute quantitative goodness of fit statistics for USGS gage locations within each RFC and write out standardized results in a PDF report for each RFC. The goodness of fit that in the lower portions of major tributaries were the primary focus, as those would indicate the quality of the flows used as boundary conditions for the Lower Mississippi River routing.

R Script: The R script accomplished many tasks, including 1) creating contributing drainage area and gage site location maps, 2) importing average daily values from the USGS web page, 3) importing NWS simulation data from the Hydrologic Engineering Center's database, HEC-DSS 4) filtering and plotting daily, monthly and annual data, 5) developing two statistical plots (empirical cumulative distribution function and Weibull plotting positions) ,6) computing four goodness of fit statistics (percent bias, Nash-Sutcliffe Efficiency, coefficient of determination, ratio of root mean square error to standard deviation), and 7) generating a statistical report in PDF format for each RFC (Figure 2). When observed discharge records were not available from the USGS, data was collected from other agencies. At sites that published stage data, verified rating curves were used to convert observed stage to discharge to fill in missing data. These observed records were imported from HEC-DSS as observed data for comparison with the NWS simulation results. A few gages had uncertainties with their rating curves that are ear-marked for future investigation.

Statistical Insights: The statistical reporting provided valuable information to the NWS and study team related to the fit of the observed data to the simulated regulated results. Plots included a visual time series comparison, monthly average flow comparisons, cumulative distribution plots of flow, and a straight-forward period of record frequency plot and tabulation of Moriasi's goodness of fit statistics (Moriasi, 2007). It is a both the timing and volume of tributary peak inflows will impact how well the simulated period can be represented in the lower watershed for discharge frequency updates.

The goodness-of-fit statistics were pulled into a GIS map for visualization. Both the timeframe of the goodness of fit statistic and which statistic is spatially analyzed are important to the interpretation of the results. Precent Bias (PBIAS) compares the observed and simulated volumes; whereas the coefficient of determination (R2) focuses on shape and timing and Nash Sutcliffe Efficiency (NSE) looks at both the magnitude and timing of the peaks. Generally, systematic volume biases can be accounted for via statistics while timing issues suggest modeling problems. For example, representation of the precipitation in 6-hour blocks and computing a subbasin average depth may dampen peaks of smaller upstream watersheds and may affect the peak timing that are represented in the Nash Sutcliffe goodness of fit.

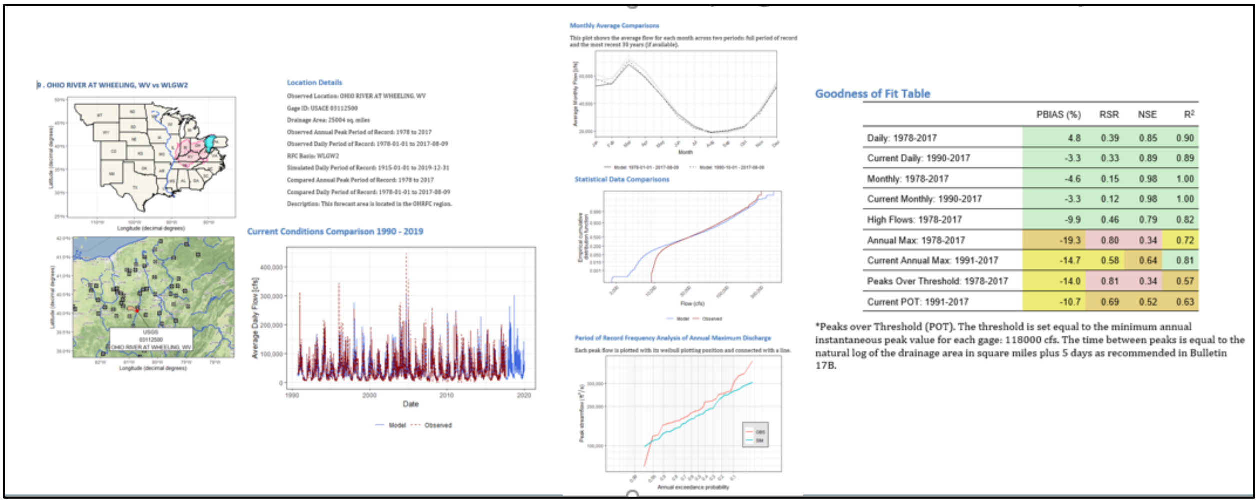

Figure 2. Example R-Stats Goodness of Fit Figures

In general, upstream tributaries that included less complexity with their reservoir operations had the better goodness of fit metrics. Watersheds that were highly regulated and had storage that could carry-over from year to year were more difficult to simulate with approximate storage and routing relationships within CHPS-FEWS. During real-time forecasting operations, the NWS and regulating agency coordinate with each other and the "regulated" discharges are incorporated into the models to capture the logic of the regulator in real time. For highly regulated tributaries, like some portions of the Missouri River Watershed, NWS time series will be substituted for an alternate time series generated through a USACE frequency study and rerouted through the HEC-RAS model. Similarly, with the complexity of the Tennessee Watershed regulation and hydropower decision criteria, the Tennessee Valley Authority (TVA) simulated their regulated and unregulated simulations with their modeling system.

Pilot Studies for Modeled Peak Adjustments

The Lower Mississippi River Probabilities investigation's focus is on gages where the drainage area is large (10,000+ square miles). The error imposed at subbasin runoff hydrographs caused by applying averaging precipitation depths at a 6-hour time step is dampened as the total drainage area accumulates downstream in the river valley as the hydrographs route and combine. A pilot will be conducted to explore a few tributaries to determine the impact of different precipitation temporal distributions on hydrograph response. This investigation will help inform the adjustment on the modeled peaks to the instantaneous peaks.

Lower Mississippi Flow Frequency Evaluation

This study provides a unique dataset across the watershed and will be used to create updated flow frequency estimates for a set of major gages on the Lower Mississippi and a few gages on major tributaries such as the Lower Ohio, White, Red, and Yazoo. The flow frequency development will follow Bulletin 17C guidance and updated frequency relationships will be coordinated with FEMA for approval as updated regulatory frequency estimates. Operational managers within the Lower Mississippi will have updated annual exceedance probabilities that can be used to inform maintenance decisions and project planning. A regional ECB 2018-14 climate assessment was completed for Lower Mississippi Region. The findings from the climate assessment will support the updated frequency estimates and be discussed in the final report.

This interagency collaboration and resulting datasets have opened the possibilities for future studies and analyses. For example, the unregulated time series for today's conditions could be used for sensitivity analyses or to evaluate the impacts of future projects, regulation scenarios and other innovative uses for the outputs. Once this study is completed and reviewed, the time series will be available at a location on the web where other agencies can access and use the study intermediate products.

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