SECTION 1. ADMINISTRATIVE INFORMATION:
Award recipient: US Geological Survey, Missouri Cooperative Fish and Wildlife Research Unit
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Project Title: Science to Inform Management of Floodplain Conservation Lands under Non-Stationary Conditions
Agreement number: G14AC00308
Date of the report: 31 December 2017
Period of time covered by the report: August 15, 2014 to September 30, 2017
Actual total cost of the project: $165,678

SECTION 2. PUBLIC SUMMARY:
Recent extreme floods on the Mississippi and Missouri Rivers have motivated expansion of floodplain conservation lands. Within Missouri there are more than 85,000 acres of public conservation lands in large-river floodplains. Floodplain lands are highly dynamic and challenging to manage, particularly as future climatic conditions may be highly variable. These lands have the potential to provide valuable ecosystem services like provision of habitat, nutrient processing, carbon sequestration, and flood-water storage that produce economic values in terms of recreational spending, improved water quality, and decreased flood hazards. However, floodplain managers may need tools to help them understand nonstationary conditions on conservation lands. This project worked with floodplain managers to identify the information most needed to understand nonstationary conditions, and to develop tools they can apply to conservation lands to improve decision making. Our survey revealed that time, funding, and a perceived disconnect between research and management limited the ability of managers to use new information. However, managers were willing to partner with scientists to identify science needs, relevant
spatiotemporal scales, and products useful for management decisions. Floodplain managers agreed that metrics of inundation, including depth, extent, frequency, duration, and seasonality are the most useful metrics for management of floodplain conservation lands. We developed an approach to derive digital spatial layers of these metrics of inundation from numeric flood inundation models under baseline and climate change scenarios. We applied this method to the lower 500 miles of the Missouri River, making 45 spatial layers available to aid in current and future management decisions of conservation properties. Patterns of floodplain inundation vary longitudinally, with channel incision acting as the dominant control. Annually, climate change is estimated to increase the duration, frequency, depth, and extent of floodplain inundation. However, these patterns vary seasonally, with inundation increasing in the spring and decreasing in the fall.

SECTION 3. PROJECT SUMMARY:
Purpose and Objectives:
Floodplain management is inherently difficult because of uncertainty in the spatiotemporal patterns of inundation due to constantly changing interactions of floodplains with their rivers, wide ranges of hydroclimatic variability, and anthropogenic modifications of in-channel conditions and throughout contributing drainage areas. Challenges of managing floodplains are compounded when hydroclimatic stationarity cannot be assumed, and changing climate, land use, and/or water use combine to alter the magnitude, duration, and seasonality of hydrologic events. Our objectives for this project were to: 1) identify science needs required to better manage conservation objectives and priorities under nonstationary conditions, i.e., climate change, through stakeholder queries and interactions, and 2) improve the management and scientific community understanding of the identified science needs through the development of tools and analyses.

Organization and Approach:
Objective 1. Identify science needs required to better manage conservation objectives and priorities under nonstationary conditions.
We developed a three-step interactive approach to document management priorities and science needs of floodplain conservation lands. Our target stakeholders were natural resource managers of floodplain conservation lands owned or managed by federal and state natural resource agencies; these agencies provide public access to lands for recreation, fishing, and hunting, as well as manage these lands for ecosystem benefits.

In the fall of 2014, an initial online survey was sent to ~80 resource managers from the Upper Mississippi River (Minneapolis, MN to St. Louis, MO), Middle Mississippi River (St. Louis, MO to Cairo, IL), and Lower Missouri River (Yankton, SD to St. Louis, MO) to identify and prioritize selected management objectives and conservation targets and to assess the relative information available to adequately manage those objectives and targets. We then hosted a two-day workshop in March 2015 in St. Charles, MO with 15 floodplain conservation land managers that took part in the initial online survey to identify high-priority science needs and tools that would assist complex decision making of floodplain lands in the face of environmental change. At this workshop, we discussed the findings from the initial online survey, presented historic climate trends and climate projections (U.S. Army Corp of Engineers, 2014; 2015a; 2015b; U.S. Bureau of Reclamation, 2014), and discussed how projections of climate change might influence management priorities on floodplain conservation lands. We also queried participants in the types of scientific information they currently use and the types of scientific information that would be informative to management, particularly in consideration of projections of climate change or other sources of nonstationarity.

In April 2015, a summary of the workshop and a follow-up online survey were emailed to all managers previously surveyed to solicit information from individuals not represented at the workshop on science needs and frequency of use and value of different types of scientific information in decision making. The follow-up survey also included questions on the way management agencies currently
incorporate climate change, a source of nonstationarity, into management plans and the types of scientific products and formats would be most useful for transferring knowledge to managers.

**Objective 2: Improve our understanding of the identified science needs through the development of tools and analyses.**

We developed a method for deriving identified metrics representing the patterns of floodplain inundation from large-scale 1-dimensional numeric hydrodynamic models under both baseline and climate change scenarios. We identified an available hydrodynamic model for the Lower Missouri River (U.S. Army Corps of Engineers, 2015). This model simulates daily discharge and water surface elevation at ~0.5-mile intervals for the lower 500 miles of the Missouri River (Figure 1) from 1930 to 2012, calibrated to the historical period of record from hydrologic gaging stations for the main channel and major tributaries. Using Python programming language (Python Software Foundation\(^1\), [https://www.python.org/](https://www.python.org/)), we generated daily grids (29,892) of water surface elevation at 30-m\(^2\) (98.4-ft\(^2\)) resolution for the entire 500 miles, encompassing the entire floodplain width (1475-miles\(^2\)). To generate daily grids of water depth, we calculated the difference between each daily grid of water surface elevation and a 30-m\(^2\) (98.4-ft\(^2\)) topographic layer. The topographic layer was derived from 1) a merged high-resolution digital elevation model (~1-m\(^2\) [3.3-ft\(^2\)], courtesy of the USGS Columbia Environment Research Center unpublished data; LiDAR points collected 2010-2014) of the floodplain and 2) a high-resolution channel and adjacent banks bathymetric digital elevation model (3-m\(^2\) [9.8-ft\(^2\]), courtesy of the U.S. Army Corps of Engineers; LiDAR and bathymetry points collected 2012-2014).

The spatial patterns of inundation from the model of baseline conditions were validated against two independent sources of data. First, we compared a grid of inundation on May 13, 2002 from our model to polygons of surface water on the floodplain on the same day for a unit of the Big Muddy Wildlife Refuge (Appendix 2). The polygons of ponded water were digitized from aerial videos of the floodplain flown by the Missouri Department of Conservation as part of the North American Wetlands Conservation Act (Missouri Department of Conservation, unpublished data). Second, daily inundation grids from our baseline model were compared to layers of floodplain inundation from a 2-dimensional hydrodynamic model for the same Big Muddy refuge unit (Erwin, et al., 2017).

For the climate change scenario, we accessed the monthly total runoff observations for 1950-1999 and monthly total runoff projections for 1950-2099 (using 29 different climate models and two climate scenarios [RCP 4.5 and 8.5]) for the 12 stream gages within our model domain from the ‘Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections’ archive at [https://gdo-dcp.uccllnl.org/downscaled_cmip_projections/](https://gdo-dcp.uccllnl.org/downscaled_cmip_projections/) (Maurer et al., 2007; U.S. Bureau of Reclamation, 2014).

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\(^1\) Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.
We calculated the percent change in monthly mean annual runoff between each of the streamgage records and the projected 2050-2059 scenario for each of the 29 models, and then averaged the percent change across the 29 models for this future time period. We created estimates of percent change to discharge for each day of the year by interpolating between the monthly values set to the middle of the month. We then applied the percent change to each of the 29,892 days to each gage location in the model, attributing percent changes between the gages by interpolating the percent change for each day based on river mile. The resulting daily grids of water surface elevation for the 2050s climate change projection were each differenced with the 30-m topographic layer. The assessment of climate change scenarios is intended as an exploration of sensitivity to climate inputs, as actual hydrologic changes will be highly dependent on land-use changes and water-management decisions in the highly impounded Missouri River basin.

From this matrix of daily depth grids for the Lower Missouri River floodplain under the baseline and climate change scenario, we developed queries to derive metrics representing the extent, depth, frequency, duration, and seasonality of inundation. The queries were based on collapsing the 82 years of daily depths for each pixel into annual averages for each decision criterion. In particular, we generated datasets that represent 1) areas inundated by annual flood return intervals, 2) total days inundated annually, during the vegetation growing season, and during the spring and fall waterfowl migrations, 3) longest consecutive period of inundation annually, during the vegetation growing season, and during the spring and fall waterfowl migrations, and 4) probability of a pixel being inundated based on depth criteria (Appendix 1).

Project Results, Analysis and Findings:

**Objective 1. Identify science needs required to better manage conservation objectives and priorities under nonstationary conditions.**

Full results of our interactive approach to identifying management priorities, information gaps and science needs can be found in Bouska et al. (2016). In assimilating the responses from the floodplain managers from the initial survey, the workshop, and the post-workshop survey, there was consensus among floodplain managers that metrics of inundation, including depth, extent, frequency, duration, and seasonality of inundation would be the most useful metrics for management of floodplain conservation lands with multiple objectives (Figure 2).

**Objective 2: Improve our understanding of the identified science needs through the development of tools and analyses.**

The baseline conditions inundation model over-predicts floodplain inundation relative to the aerial survey and 2-dimensional hydrodynamic model in the Lisbon Bottom and Jameson Island units of the Big Muddy Refuge. Compared to the Missouri Department of Conservation aerial survey from May 13, 2002, the estimated area inundated by the model is 0.35 miles$^2$, while area mapped from the aerial survey is 0.18 miles$^2$. Although the predicted area from the model is nearly double that from the survey, the agreement in spatial overlap is strong (Appendix 2). In the southern unit, most of the areas mapped as inundated from the aerial survey are also predicted to be inundated from the model. For in-channel flows, the baseline model and the 2-dimensional model have similar predictions of inundation (Figure 3).
However, starting at 150,000 ft$^3$/s, these predictions deviate from the 2-dimensional model as flows transition to the floodplain. As floodplain inundation increases with increasing discharge, the predicted inundation from the baseline model is nearly double that of the 2-dimensional model. The 2-dimensional model was only calibrated for in-channel flows, which may explain the poor match in floodplain inundation between the two models (Erwin et al., 2017).

Spatial patterns of floodplain inundation in both our model scenarios are strongly controlled by the degree of channel incision in the main channel, which varies longitudinally along the 500 miles of the Lower Missouri River. Incising reaches, likely caused by channelization and sand dredging, such as that near Kansas City, MO (blue dashed lines in Appendix 3), have fewer consecutive days inundated during the growing season for both the baseline and climate change model scenarios relative to stable and aggrading reaches, such as that near Columbia, MO (red dashed lines in Appendix 3) [Jacobson et al., 2011]. Under future climate change we may expect longer periods of consecutive inundation during the growing season across the entire river reach, including both the incised reach near Kansas City and a more connected reach near Columbia, MO. On average, for all pixels on the floodplain (outside the main channel mask) with a depth greater than 0, there is a projected increase of 2.4 days for the longest consecutive period of inundation during the growing season under the future climate projection relative to baseline conditions.

Longitudinal patterns of inundation vary during the spring and fall waterfowl migrations (Figure 4). Overall, the average longest period of consecutive days inundated during the spring migration is projected to increase by 4.4 days, but the pattern varies by location. Around Kansas City, MO (RM350) metric of inundation patterns change little under climate change due to channel incision in this reach. However, downstream of this incised reach between river miles 275 to 325 where there is not as much channel incision and the floodplain is at its widest within this 500-mile reach, we expect to see increases of a week or more for the longest periods of inundation in the spring. During the fall migration, there is a net loss of consecutive days inundated between the baseline and climate change scenarios. On average,
the Lower Missouri River floodplain will have 0.3 fewer consecutive days inundated during the fall migration, although patterns vary based on location. In the incised reach near Kansas City, MO, there are relatively few days of inundation lost to climate change. River miles 275 to 325 have the greatest potential for lost days of inundation during the fall migration, with an average of 0.5 days lost during within this reach.

Patterns of inundation vary by individual conservation properties and their style of management. For five Missouri Department of Conservation properties, the two (Eagle Bluffs and Bob Brown) that are leveed with active pumping of main channel water into floodplain wetlands (water pumping was not simulated in our model) have the largest increase in consecutive days inundated during the spring migration, while also showing the fewest days lost during the fall migration (Figure 5). The three passively managed properties (Plowboy Bend, Marion Bottoms, and Wolf Creek) have lower median values of consecutive days inundated during both the spring and fall migrations under both model scenarios relative to the actively managed properties.

**Conclusions and Recommendations:**

1. Floodplain conservation lands are managed for a variety of complex and competing purposes, yet our study found a consensus among resource managers that an understanding of inundation patterns is fundamental to manage multiple objectives and targets (Bouska et al., 2016). Our surveys provide evidence that managers recognize the linkage between inundation and ecological processes. In particular, depth, extent, frequency, duration, and seasonality of inundation were perceived as key metrics for improving management outcomes on floodplain conservation properties. The inundation metrics identified by managers are evidence for the need to understand key drivers, such as hydrology, of river-floodplain ecosystems. These inundation metrics are likely related to the various objectives and conservation targets for which floodplain conservation lands are managed. Therefore, our end products were focused on those manager-recommended metrics. The emphasis on inundation metrics supports the need for conservation agencies to invest in additional expertise in hydrology and geomorphology.

2. The majority of resource managers surveyed have interest in understanding how climate is likely to impact floodplain dynamics over time. Even with an understanding of the potential range of variability in river hydrogeomorphic conditions under climate change projections, managers still maintain that depth, extent, frequency, and duration of inundation are the top priorities to understand for long-term management of floodplain conservation lands.

3. Our survey also revealed that time, funding, and a perceived disconnect between research and management communities limited the ability of resource managers to use new scientific information.
in management decisions. The participating managers in our workshop were eager to help scientists understand the difficulties inherent to managing floodplains, and to aid in the identification of science products that meet their needs. This suggests that partnerships between managers and researchers can identify science needs, specify relevant temporal and spatial scales, and determine user-friendly product formats.

4. Additional information gaps may be limiting managers’ ability to effectively manage for objectives such as strategies for controlling invasive species, maintaining respectful relationships with neighboring landowners, managing native, nongame species, managing endangered and threatened species, and promoting nutrient cycling. There was limited information relative to priority ranking of several conservation targets including pollinators, marsh birds, reptiles, shore birds, aquatic invertebrates, and amphibians. These limitations suggest that monitoring and pilot studies may be needed to gain information on floodplain ecosystem functions, habitat needs, and the role of management actions on these objectives and targets.

5. Maintaining positive relationships with neighboring landowners was the highest scored priority across the study area. Several of our survey participants noted the importance of determining the needs and values of private landowners and using that information to better link public and private land conservation programs. Metrics that can capture spatiotemporal patterns of inundation on private lands as well as public lands under future climate change scenarios may aid floodplain managers in evaluating vulnerability of conservation properties and adjacent private properties, helping to maintain positive relationships into the future.

6. Hydrodynamic models can be used to create indices of floodplain inundation as spatial layers in GIS format. Based on recommendations by conservation managers, the most useful information for inferring biological endpoints in managing floodplain conservation is that which represents the spatiotemporal patterns of inundation. These spatial layers represent eight decades of hydrologic conditions collapsed into annual indices that represent depth, extent, frequency, duration, and seasonality of inundation on the floodplain for baseline and climate change conditions. By collapsing this long-term hydrologic datum into annual indices of inundation, these indices represent the full extent of hydrologic variability within our system. This information can be used to establish short-term and long-term criteria for management activities suited to specific locations based on the patterns of inundation and topography at those priority locations.

7. Spatial patterns of floodplain inundation are tied to the patterns of channel incision of the main channel. The more incised reaches have less floodplain connectivity, and the indices in these reaches show fewer days inundated and lower frequencies of inundation relative to the less incised or aggrading reaches. The incised reaches have relatively little changes in inundation frequencies between the baseline and climate change scenario. The most significant changes in inundation indices between the baseline and climate change scenario are immediately downstream of a highly incised reach along a stable reach with less channel incision and a wide floodplain.

8. Under climate change, we can expect higher frequencies of inundation and longer consecutive periods of inundation annually and during the growing season relative to the baseline scenario. However, these patterns vary seasonally and spatially. Large increases in inundation duration and frequency are expected during the spring waterfowl migration period and decreases in inundation duration and frequency are expected in the fall waterfowl migration. For waterfowl with a narrow fall migration window, the loss of inundation days may have a significant impact on their migration patterns.

9. This approach represents a relatively cost-effective approach for inferring floodplain restoration potential over a large area along a major river. Although alignment of the spatial patterns of inundation between the baseline model and the aerial survey and 2-dimensional model were imperfect, the relative differences between the inundation metric layers can be used to infer restoration potential of specific locations. In this approach, we used the best available data to provide physically-based scientific information in a cost-effective manner for the largest extent possible. Improvements to the approach presented here include specific representations of flow pathways onto within the floodplain, such as the effects of levees on the floodplain flows, or the influence of soil
properties, such as groundwater interactions with ponded floodplain water. However, the incremental costs in addressing these questions at the scale of this project become prohibitive, or the spatiotemporal coverage must diminish. Another limitation of this approach is the interpolation of daily climate change data from monthly projections, which removes intra-monthly streamflow variability. However, the climate projections used here were the best available for our project scope.

10. This approach is explicitly transferable to other large-river systems. However, those rivers of interest must have models that simulate long-term hydrologic variability in order to apply this approach. Collaborative partnerships with agencies, such as the U.S. Army Corps of Engineers, that are responsible for modeling large-river systems is an integral component for undertaking an interdisciplinary floodplain inundation mapping project of this scope. Based on a partnership with the U.S. Fish and Wildlife Service that developed from the project described here, we will be applying this same methodology to the Middle Mississippi River National Wildlife Refuge.

11. With the layers generated from this project hosted on a federal data portal, our intention is to reach out to those participants of our surveys and workshop and other interested constituents to inform them of the available products. To improve the ability of managers to make good use of these products, a fact sheet, along with the metadata in the spatial layers, will be made available to those participants and constituents. We have also informed our close working partners, such as those with the Missouri Department of Conservation, that we are willing to develop other layers not in the original archive to address their management priorities.

Outreach and Products:
We have developed or plan to develop several products from these efforts. There is one manuscript that was published in 2016 and another in preparation:


We have also disseminated this work at numerous professional society meetings:

- Lindner, G., E. Bulliner, K. Bouska, C. Paukert, R. Jacobson. 2016. Mapping flood patterns to address management needs on the Missouri River. USGS National Climate Science Centers Student and Early Career Training. Amherst, MA. (Best poster award)
- Bouska, K., G. Lindner, R. Jacobson, and C. Paukert. 2015. Identifying floodplain conservation land management priorities and science needs for the Lower Missouri River. Missouri River Natural Resources Conference, Nebraska City, NE.

Webinars, workshops, and invited seminars:
- We held a meeting with Missouri Department of Conservation biologists on May 30, 2017. The purpose of the meeting was to inform them of the products we were making available in support of their conservation efforts. They provided to us mapped water extents on the floodplain from 2001 to be used for validation of our model. We also made them aware that in the future we can derive other layers from our model to suit their specific needs, if those needs were to arise.
- Paukert, C. P. 2016. Climate Change Effects on Fish: What We Know and What We Can Do About It. Departmental Seminar, Iowa State University.
- We held a workshop in March 30-31, 2015 targeted to floodplain managers to discuss the project, and identify what management questions they have that can be answered by this project. A total of 15 people participated in the workshop form the US Fish and Wildlife Service, The Nature Conservancy, US Geological Survey, Army Corps of Engineers, Missouri Department of Conservation, the University of South Dakota, and the University of Missouri. The results of the workshop fed into the Bouska et al (2016) paper and helped us identify the metrics most important to these managers. One outcome of this workshop was that the managers were more focused on abiotic metrics (e.g., when and where will water be on the floodplain) rather than biological metrics (e.g., growth of fish, abundance of shorebirds, etc.). Although the original objective of the project was to provide biological metrics linked to floodplain conditions under nonstationary conditions, the feedback from this meeting changed our products to focus on the abiotic metrics, and the floodplain managers can use those metrics to infer biological responses of interest to their lands.
We provided numerous data products generated from this project, all at 30-meter resolution encompassing the full extent of the modeled Lower Missouri River valley bottom. Data are hosted on ScienceBase.gov at https://www.sciencebase.gov/catalog/item/5a0f755de4b09a898d09bc2.


This ScienceBase page consists of:

- LIDAR elevation/bathymetric survey dataset
- Links to two sets of inundation metrics, one for each of the baseline and climate change scenarios. Each set of inundation metrics includes 16 different raster layers. The metrics characterize total periods of inundation and consecutive periods of inundation within various seasons of interest to floodplain managers. Probability-based metrics of inundation are also included. For the full list of inundation products, see Appendix 1.
- We also host, for each scenario, two additional products based on flood-return interval as calculated from the model dataset. The first product is a per-pixel representation of minimum flood return interval for inundation. The second product is a series of raster grids which display water depth at each pixel for 11 flood-return intervals, from 1 to 500 years.

References


### Table 1: List of inundation metrics under the modeled Baseline Conditions

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>base_MeanSumAnnual.tif</td>
<td>Sum of days inundated during entire year, averaged across all years for the baseline scenario</td>
</tr>
<tr>
<td>2</td>
<td>base_MeanSumGrowing.tif</td>
<td>Sum of days inundated between DOY 91 and 273, averaged across all years for the baseline scenario</td>
</tr>
<tr>
<td>3</td>
<td>base_MeanConsecutiveGrowing.tif</td>
<td>Max consecutive period of inundation between DOY 91 and 273 per year, averaged across all years for the baseline scenario</td>
</tr>
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<td>Sum of days inundated between DOY 91 and 150, averaged across all years for the baseline scenario</td>
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<td>5</td>
<td>base_MeanSumFallMigration.tif</td>
<td>Sum of days inundated between DOY 196 and 273, averaged across all years for the baseline scenario</td>
</tr>
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<td>6</td>
<td>base_MeanConsecutiveSpringMigration.tif</td>
<td>Max consecutive period of inundation between DOY 91 and 150 per year, averaged across all years, for the baseline scenario</td>
</tr>
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<td>7</td>
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</tr>
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<td>13</td>
<td>base_RelProb0p5mPerYearGT.tif</td>
<td>Probability (relative) that a pixel will be inundated to a depth greater than 0.5m on any days when inundated past base threshold (0m) for the baseline scenario</td>
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<td>14</td>
<td>base_RelProb0p5mPerYearLT.tif</td>
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<td>Max consecutive period of inundation between DOY 196 and 273 per year, averaged across all years, for the climate change scenario</td>
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<td>Probability (relative) that a pixel will be inundated to a depth greater than 1m on any days when inundated past base threshold (0m) for the climate change scenario</td>
</tr>
<tr>
<td>32</td>
<td>cc_RelProb1mPerYearLT.tif</td>
<td>Probability (relative) that a pixel will be inundated to a depth less than 1m on any days when inundated past base threshold (0m) for the climate change scenario</td>
</tr>
</tbody>
</table>
Appendix 2:

Patterns of floodplain inundation on May 13, 2002 between the baseline inundation model (blue cross-hatched) and the digitized polygons of standing water from the Missouri Department of Conservation aerial survey (red) in the Big Muddy Wildlife Refuge Lisbon Bottom/Jameson Island unit.
Appendix 3:

Examples of products available for download, showing spatial patterns of A) elevation in feet, B) maximum consecutive days inundated during the growing season under the baseline conditions model, C) maximum consecutive days inundated during the growing season under the climate change scenario. Insets depict reaches near Kansas City, MO (left, blue dashes) and Columbia, MO (right, red dashes).