February 1, 2013

Hydroclimatic information and risk assessment methods for managing hydrologic extremes in the Missouri River Basin

A white paper for future studies
February 1, 2013

Executive Summary

Recent droughts and unprecedented flooding have highlighted the need for additional hydroclimatic information that would be relevant to a wide variety of water resource management issues, both along the mainstem of the Missouri River and throughout the basin. The Missouri River Basin is subject to extreme variability in hydroclimatic conditions. Management of the mainstem reservoir system historically has been affected more frequently by drought conditions than flood conditions, and managing for the two opposing extremes is especially challenging.

Observed streamflow and climate records generally are inadequate to accurately describe long-term variability in hydroclimatic extremes. This document provides an overview of conceptual approaches for developing additional datasets and scientific tools useful in managing for hydroclimatic extremes. The general objectives of the proposed study would be to (1) obtain comprehensive hydroclimatic information on timescales substantially exceeding observed records and (2) develop scientific tools for improving management capabilities, especially relative to hydrologic extremes. The proposed approach would consist of three primary study components: (1) compilation and characterization of observed hydroclimatic records; (2) various levels of hydroclimatic modeling focused on probability analyses relative to hydrologic extremes and improving predictive watershed modeling capabilities; and (3) paleoclimatic and paleoflood investigations, which would provide much longer-term context than is currently available relative to hydroclimatic extremes. For planning purposes, a time frame of about 5 years probably would be needed for completion of paleoclimatic and paleohydrologic investigations; however, the other primary study components could completed within several years.

It is envisioned that numerous Federal, Tribal, State, and local agencies would benefit from improved information regarding hydroclimatic extremes for the Missouri River Basin and thus could participate from various standpoints. Resources could be contributed by many agencies and in many forms including funding, staff time, relevant datasets, and so forth. A critical aspect will be coordination of research efforts, which could be facilitated by formulation of an advisory committee consisting of interested agencies working jointly to find applicable programmatic means for bringing resources to bear. Thus, it is envisioned that research needs would be addressed through a wide variety of individual projects that would be funded through numerous programmatic avenues appropriate to specific research projects.

Background/problem

Unprecedented flooding throughout the Missouri River Basin during 2011 has been bracketed by current (2012) drought conditions and the extended drought of the early 2000s. These conditions highlight the need for additional hydroclimatic information that would be relevant to a wide variety of water resource management issues, both along the mainstem of the

Missouri River and throughout the basin. The Missouri River Basin is subject to extreme variability in hydroclimatic conditions from both spatial and temporal standpoints. General climatic conditions transition from sub-humid in the southeastern part of the basin to semi-arid throughout the upper Great Plains to sub-alpine and alpine in the Rocky Mountain headwater reaches. Western parts of the basin are especially susceptible to severe long-term drought conditions, which can be offset by prolonged wet cycles. Management of the mainstem reservoir system historically has been affected more frequently by drought conditions than flood conditions, and managing for the two opposing extremes is especially challenging. Effects of potential climate change may create additional uncertainty regarding planning for future hydroclimatic conditions.

Observed streamflow and climate records generally are inadequate to accurately describe long-term variability in hydroclimatic extremes. A comprehensive program is needed to develop new datasets for characterizing hydroclimatic extremes and to develop sound scientific tools for informing the best possible decision-making processes for operational and management considerations throughout the Missouri River Basin.

Objectives, general approach, and proposed study area

This document provides an overview of conceptual approaches for developing additional data sets and scientific tools useful in managing for hydroclimatic extremes. The objectives of the proposed study would be to (1) obtain comprehensive hydroclimatic information on timescales substantially exceeding observed records and (2) develop scientific tools for improving management capabilities, especially relative to hydrologic extremes.

The proposed approach would consist of three primary study components: (1) compilation and characterization of observed hydroclimatic records, which would include various climatic datasets and streamflow records for selected locations along the mainstem and major tributaries; (2) various levels of hydroclimatic modeling focused on probability analyses relative to hydrologic extremes and improving predictive watershed modeling capabilities; and (3) paleoclimatic and paleoflood investigations, which would provide a much longer term context than is currently available relative to hydroclimatic extremes. The proposed study area would focus on the upper Missouri River Basin (upstream from Gavins Point Dam in South Dakota), which is heavily regulated by six large mainstem reservoirs and numerous relatively large reservoirs along many tributaries. Similar studies in several adjacent basins also could be beneficial, and efficiencies could be accomplished by expanding the study area, especially relative to items 1 through 3 above. An example is the lower Missouri River Basin (downstream from Gavins Point Dam), which has obvious related water management implications, but for which the large majority of regulation occurs in the upstream basin. Other examples include parts of several adjacent watersheds (Minnesota River, Red River of the North, Souris River, and Platte River) where substantial flooding also has recently occurred and for which extensive paleoclimatic datasets are already available, in some cases.

Specific study approaches

The following is a preliminary overview of conceptual approaches for the three primary study components. Additional details regarding proposed activities would be developed as the scope of the proposed study evolves through discussions with interested agencies.

1. Compilation and characterization of observed hydroclimatic records

Comprehensive compilation and characterization of observed climatic and streamflow records would provide an important foundation for other study components. In general, observed records would first be examined for accuracy and completeness, within an overarching goal of assembling consistent datasets relevant to key hydroclimatic circumstances, timeframes, or locations along the Missouri River mainstem and major tributaries. Minor manipulations to observed records (estimation of missing records, short-term record extensions, and so forth) would then be performed to develop consistent datasets for various key timeframes that could include (1) the current circumstance of Missouri River mainstem reservoir regulation; (2) a preceding period of major reservoir construction and filling of storage along the Missouri River mainstem and key tributaries; (3) a preceding period representing generally basin-wide availability of streamflow records (if sufficient preceding datasets are even available); and (4) preceding periods relating to the longest available datasets for key mainstem and tributary locations, which date back to the late 1800s and early 1900s for some locations. Characterizations of the resulting data sets would provide a comprehensive overview of observed hydroclimatic variability within the Missouri River Basin.

1A. Compilation and characterization of climatic data

Basin-wide climatic data (precipitation, snowpack, temperature, and evapotranspiration estimates) would be used for extension of streamflow records, numerous possible modeling applications, and as a starting point for extending climatic records on the basis of paleoclimatic data. At least three sources can be considered for climatic data: (1) ground-based measurements, such as the National Weather Service (NWS) climatic stations and cooperator observation network, Natural Resource Conservation Service SNOTEL observation network, etc.; (2) spatially distributed estimates derived from ground-based measurements and GIS data, with PRISM (parameter-elevation regressions on independent slopes model; http://www.prism.oregonstate.edu/) data being the prime example; and (3) spatially distributed estimates based on combination of remote sensing and ground-based data, with NCAR (National Center for Atmospheric Research) reanalysis data being the prime example. The PRISM data, developed at Oregon State University in cooperation with the U.S. Department of Agriculture, probably are the most stable, complete, and quality-controlled data for monthly precipitation and temperature. It is anticipated that much of the desired information can be derived using a monthly time step, and the PRISM data is well-suited for that analysis. When a smaller time step, such as daily, is required, the NWS climate division data (http://www.ncdc.noaa.gov/temp-and-precip/us-climate-divisions.php) would be used to disaggregate PRISM data, for example, by using a spatial interpolation technique such as Kriging to estimate the ratio of daily to monthly precipitation based on stations in the climate division database and multiplying monthly values by the daily ratios. The advantage of using PRISM and climate division data is that both are available for 1895-present, whereas SNOTEL data and remote sensing data generally are available for about 1980-present. The datasets derived from the PRISM and climate division data for the more recent period will be compared to SNOTEL and satellite-based data see how well the former represents spatial and temporal variability.

1B. Compilation and characterization of naturalized streamflow records

The Missouri River Basin is highly regulated by numerous large reservoirs (mainstem and tributaries) and by withdrawals for large-scale irrigation and other water uses. Thus, an initial need is to characterize streamflow for "naturalized" and "regulated" scenarios during the period of observed streamflow records, which generally extends to no earlier than about the late 1800s. Naturalized streamflow records would be developed for selected key locations on the mainstem Missouri River and major tributaries for a common base period that would be as long as possible, depending upon available records for streamflow, withdrawals, and climate and the applicability of appropriate statistical record-extension methods. The naturalized records would account for depletions and reservoir operations for both discrete time steps (probably primarily monthly) and peak-flow conditions (instantaneous maxima). Naturalized streamflow records (and the data used to naturalize the observed records) would then serve as the basis for calculating streamflow statistics for a regulated scenario that would apply "recent level-of-development conditions" to the naturalized records for the entire common base period. Depletion data for calculating naturalized streamflow records are available from the Bureau of Reclamation (2005), and the general approach for characterizing naturalized and regulated streamflows is well represented in a recent study for the Yellowstone River Basin (Chase, 2012) that was a coordinated effort between the U.S. Geological Survey (USGS), the Bureau of Reclamation (BOR), and the U.S. Army Corps of Engineers (USACE).

As part of this compilation process, estimates of historical flood magnitudes prior to the systematic streamflow records would be identified from USGS, BOR, USACE, or other reliable sources. Together with paleohydrologic information described later, these data would be used to evaluate how well the systematic record represents hydroclimatic extremes that may occur over a much longer period.

The naturalized streamflow records would provide the basis for linking streamflow variability during the period of observed streamflow records with potentially longer-term observed climatic records, paleoclimatic information, and paleoflood information (see item 4 that follows). Naturalized streamflow records also would be highly useful for calibration of various large- or small-scale watershed models that also could be very beneficial relative to management needs throughout the basin.

2. Hydroclimatic modeling

Climate in the upper Missouri River Basin and elsewhere in central North America is subject to complex, long-term (decadal- to century-scale) variation that is just beginning to be understood. This long-term variation, coupled with potential climate change, makes it particularly difficult to evaluate the risk of extreme hydroclimatic events such as the upper Missouri River drought of 2000-07, the great upper Missouri River flood of 2011, or even more extreme floods or droughts. Various modeling approaches could have immense utility for improving predictive capabilities and probability analyses relative to hydroclimatic extremes.

Based on historical climate and streamflow records for the upper Missouri River Basin, climatic conditions during the past two decades (1993-2012) have been more variable than at any time during the previous century. This increased variability simultaneously increases risk of both extreme floods and droughts and makes management of the reservoirs particularly challenging. This is illustrated in the figure 1, which shows seasonal discharges for two streamgages for water years 1934-2011. Discharge variability for the Yellowstone River near Sidney, MT is typical of the Rocky Mountain headwaters, and variability for the James River near Scotland, SD is more typical of downstream tributaries in North and South Dakota. Discharges for both rivers are subject to long-term persistence caused both by decadal to multi-decadal climate variability and basin memory. Although the record length is relatively long, because of long-term persistence the effective information content of the record is much less than it would be if the annual discharges were stationary and independent random variables.

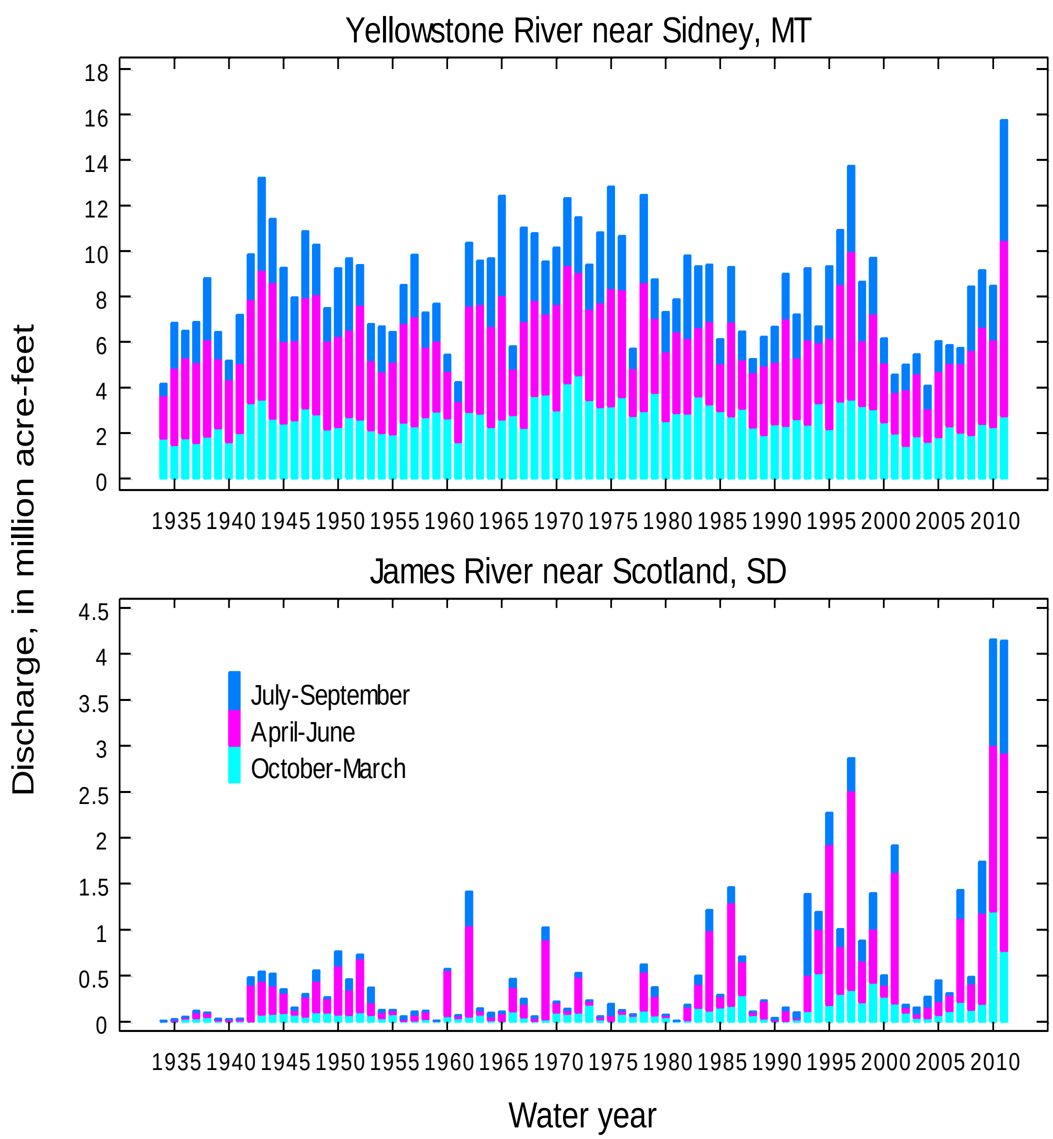

Figure 1. Seasonal discharges for 1934-2011 for the Yellowstone River near Sidney, MT and James River near Scotland, SD.

Limited paleoclimatic reconstructions from parts of the upper Missouri River Basin and elsewhere in the Northern Plains indicate that flood or drought conditions much more severe than any observed in the historical record were typical in previous centuries (Gray et al, 2004; Shapley et al, 2005; Murphy et al, 1997). For example, figure 2 shows reconstructed annual precipitation for Bighorn Lake on the MT/WY border for 1250-1975 (Gray et al, 2004). Precipitation was much more variable in previous centuries and several "mega-droughts" occurred in the 13th to 16th centuries.

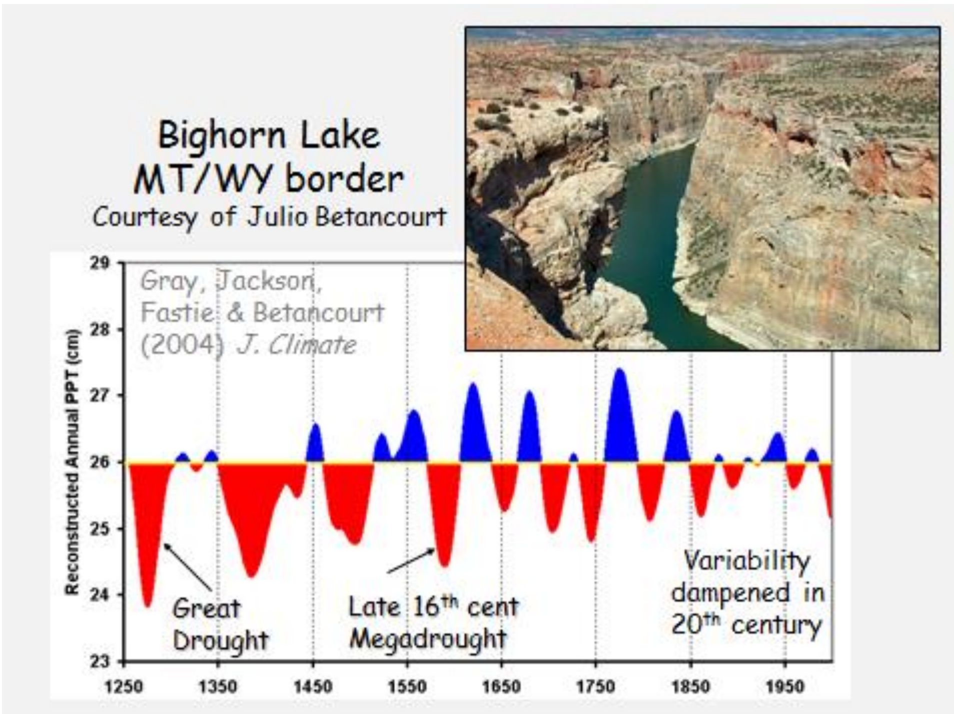

Figure 2. Paleoclimatic reconstruction for Bighorn Lake (from Gray et al, 2004)

Hydroclimatic modeling is crucial for evaluating the climatic conditions leading to extreme floods and droughts, evaluating the risk of future extremes, and helping improve reservoir operation to minimize the effects of severe floods and droughts. A monthly water-balance model will be developed to estimate unregulated monthly flows from major tributaries on the basis of monthly precipitation, evapotranspiration, and storage (both snowpack and soil moisture). A monthly water-balance model based on PRISM data (Gray and McCabe, 2010) has been shown to be successful for reproducing naturalized monthly flows for headwater streams in the upper Missouri River Basin, and a similar approach with some potential modifications will be used for reproducing flows for downstream tributaries. The water-balance model will be linked with a stochastic model for simulating future monthly climatic inputs and tributary flows that represent the full range of potential severe floods and droughts. Simulated unregulated flows can be used in reservoir operation models to evaluate the best operating contingencies for minimizing the effects of severe floods or droughts. These records are also critical for the screening and calibration of available paleohydrologic proxies used for long-term reconstructions of the Missouri main stem and tributaries (see section 3 below). The monthly water-balance model with stochastically generated inputs will be capable of reproducing both the statistical properties (means, variance, cross-correlations, etc.) of the historical streamflow records and the long-term (century-scale) variability inferred from paleoclimatic and paleohydrologic studies described in the next section. Just as the water-balance model is critical for screening and calibration of the paleohydrologic proxies, the paleohydrologic proxies are critical for ensuring the stochastic model correctly reproduces the frequency and magnitude of extreme floods and droughts that are outside of the extremes of the historical record. Examples of the robust capabilities of stochastic modeling for addressing hydroclimatic extremes are provided by frequency analyses conducted for Devils Lake (Vecchia, 2008), the Waubay Lakes Chain (Niehus and others, 1999), and a reservoir in Afghanistan (Vining and Vecchia, 2007; Vining and Vecchia, 2008).

In addition to the monthly water-balance models, various existing precipitation-runoff models, or watershed models, could be calibrated and compared. Watershed models can be used to simulate daily streamflow given inputs of daily temperature and precipitation. This effort would build upon watershed models (1) developed by USACE, BOR, and NWS for reservoir management or flood forecasting, and (2) developed by the USGS, USACE, and others for investigating the 2011 flood events. Considerations of major importance would include (1) a conceptual approach of nesting many sub-basin models within a larger basin-wide model; (2) utilization of standardized streamflow and climatic datasets (developed as part of the first numbered study component) for consistent input among models; and (3) comparisons of model capabilities and performance under a variety of circumstances such as different runoff scenarios (i.e. rainfall versus snowmelt), climate data (i.e., station data versus gridded data) and watershed characteristics (i.e., scale, geology, and topography). Development and comparison of these calibrated precipitation-runoff models could improve short- and long-term streamflow-simulation capabilities for numerous agencies involved with watershed management at many scales.

3. Paleoclimatic and paleohydrologic approaches

A powerful approach for examination of hydroclimatic extremes beyond observed records would be a combination of paleoclimatic and paleohydrologic investigations. Geologic and paleobotanical evidence can be used for developing proxy hydroclimatic records based on correlations between various surrogate parameters and observed climatic and hydrologic data, which can be extended substantially beyond the observed records. Here, long-term records generated from naturalizing historic flow records, or produced using a monthly water balance model or stochastic streamflow model (see sections 1 and 2 above) are critical for the screening and calibration of potential biological or chemical proxy records.

3A. Basin-wide paleoclimatic investigations: Basin-wide paleoclimatic investigations would consist first of a detailed literature search to compile existing information, followed by field studies to fill data gaps for critical locations, and updating proxy records originally collected in the 1970s and 1980s that should have time series extended to the present. A preliminary literature search has already been initiated to evaluate the availability of existing information, and a brief summary follows.

A well known paleoclimatic approach is dendrochronology, which can provide detailed annual and seasonal indications of wet and dry conditions on the basis of tree-ring growth characteristics, with record extensions achieved through crossdating of overlapping samples from living and dead trees. Recent studies have shown that chemical data from tree rings also can provide insights into stream discharge and localized precipitation amounts. Existing tree-ring records are fairly numerous across the headwaters region of the upper basin (fig. 3), but become increasingly sparse throughout the main and lower basin. The existing network of tree-ring chronologies within the upper basin has shown good potential for successful flow reconstruction throughout the headwaters regions, with trees providing critical information on winter snowpack, spring precipitation, and summer drought (Cook et al. 2004, Gray and McCabe 2010, and Pederson et al. 2011). The potential for successful reconstructions of flow in the main stem and lower Missouri from this network of chronologies is at present unknown. Recent work on reconstructing the historic flows of the Little Missouri River by Friedman et al. (2012) using plains cottonwood (*Populus deltoides*), however, suggests skillful tree-ring based streamflow reconstructions are indeed possible.

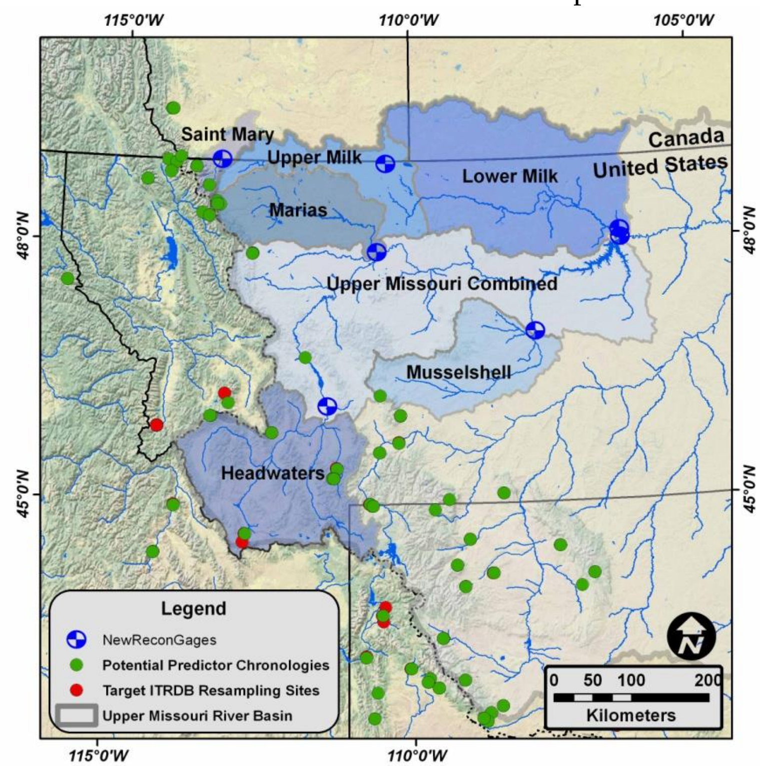

Figure 3. Upper Missouri River Basin study area showing streamgages and watersheds that exhibit good potential for paleohydrologic reconstructions of total water year, peak, and summer base-flow reconstructions using the existing network of tree-ring chronologies. Streamgages with trial reconstructions are labeled with blue dots. Upper Missouri River sub-basins are outlined and include the Marias, Milk (upper and lower), Musselshell, Missouri River headwaters, and Missouri River main drainage basins. Existing chronologies available for reconstruction model calibration shown (green dots) along with sites targeted for recollection (red dots). The Continental Divide borders the west side of the basins.

Lake sediments contain many physical and chemical indicators of past local and regional climatic conditions. Excellent records dating back thousands of years have been derived for many locations in northeastern South Dakota, and eastern North Dakota, with an increasing number of records now becoming available for western North Dakota and Montana. Cave formations, including stalagmites and cave sediments, can provide paleoclimate records that date back thousands of years, preserving evidence of long-term climate cycles and also evidence of episodic cave flooding. Some excellent studies have been completed along the periphery of the basin; however, more work needs to be conducted to locate and identify more sites for paleoclimatic reconstructions.

3B. Paleoflood investigations: In appropriate environments, definitive chronologies of especially large floods can be obtained using geologic and paleobotanical evidence to determine the ages and magnitudes of floods that occurred before collection of observed records (paleofloods). An excellent example is provided by recent paleoflood investigations for the Black Hills area of western South Dakota (Harden and others, 2011), which provided evidence of numerous large floods over the past several thousand years that substantially exceeded magnitudes of the devastating 1972 floods in and near Rapid City. For this study, the primary paleoflood evidence consisted of stratigraphic records from fine-grained sediment deposits preserved in slack-water environments. These deposits accumulate and can record multiple floods where (1) velocities are relatively low, allowing deposition of suspended sediment; and (2) conditions are suitable for preservation. Paleoflood investigations are most successfully conducted in specific geologic and topographic settings where river channels and valleys are constrained by bedrock outcrops, providing conditions amenable for hydraulic analyses. The presence of overhanging ledges, alcoves, or small caves flanking the rivers also is a key factor, as these provide excellent environments for deposition and preservation of stratigraphic sequences slack-water flood deposits.

A general study approach could first employ a reconnaissance-level study to identify locations suitable for detailed site investigations. This would allow scoping for a subsequent implementation-level study, which presumably would focus on relatively large headwater basins that would provide perspectives relative to basin-wide flood conditions. Collective consideration with results of paleoclimatic investigations would be key to transitioning from records of stage/discharge to broader evaluations regarding basin-wide conditions. Additionally, an extensive paleoflood record would provide information on extreme events and sustained wet conditions, which are often missed completely or underestimated (respectively) by the more conventional paleohydrologic proxies.

<u>Accomplishment of research needs</u>

It is recognized that a single research project probably cannot be realistically formulated and funded to accomplish the multiple basin-wide research needs identified within this concept paper. A more realistic approach would consist of coordinated efforts involving many entities working towards a common end point. It is envisioned that numerous Federal, Tribal, State, and local agencies would benefit from improved information regarding hydroclimatic extremes for the Missouri River Basin and thus could participate from various standpoints. Resources could be contributed by many agencies and in many forms including funding, staff time, relevant data sets, and so forth.

A critical aspect would be coordination of research efforts, which could be facilitated by formulation of an advisory committee consisting of interested agencies working jointly to find applicable programmatic means for bringing resources to bear. Thus, it is envisioned that research needs would be addressed through a wide variety of individual projects that would be funded through numerous programmatic avenues appropriate to specific research projects.

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Advisory Committee on Hydroclimatic Information Needs for the Missouri River Basin

This planning document is a result of discussions among numerous scientists, planners, and water-resource managers. Following is a list of agencies and organizations that have formally participated in efforts leading to the development of this document and who are part of an advisory committee involved with developing and coordinating hydroclimatic research efforts for the Missouri River Basin.

Bureau of Indian Affairs (Great Plains Regional Office in Aberdeen, South Dakota)

Bureau of Reclamation (Seismotectonics and Geophysics Group, Denver, Colorado)

Missouri River Association of States and Tribes

National Oceanic and Atmospheric Administration (including National Climatic Data Center; Missouri River Basin Forecast Center, and National Weather Service, Bismarck Office)

North Central Climate Science Center

Plains and Prairie Potholes Landscape Conservation Cooperative

State of Montana (Department of Natural Resources and Conservation)

State of North Dakota (including Governors Office and Departments of Game and Fish; Health; and State Water Commission)

State of South Dakota (including Departments of Environment and Natural Resources and Game, Fish, and Parks; State Climate Office; and South Dakota State University Extension

State of Wyoming (State Engineers Office and Water Resources Data Systems at University of Wyoming)

U.S. Geological Survey (including Fort Collins and Northern Rocky Mountain Science Centers and Water Science Centers in Montana, North Dakota, and South Dakota)

U.S. Army Corps of Engineers (Missouri River Basin Water Management Division office and Omaha District Hydrologic Engineering Branch)

U.S. Forest Service (Dakota Prairie Grasslands Unit, Bismarck and Northern Region Renewable Resource Management Unit, Missoula)

U.S. Department of Agriculture, Natural Resources Conservation Service (Office of Missouri River Basin Coordination)

Western Governors Association