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Missouri River Climate

Understanding runoff in the Missouri River Basin using NASA and NOAA satellite observations for improved river system management and decision support

 **Technical Report**

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# I. Abstract

[Placeholder - do not put anything here until the final draft submission. The abstract in the project summary is where the working draft of the abstract should “live”]

**Keywords**

Missouri River Basin, Water Management, Plains Snowpack, Soil moisture, Snow Water Equivalent, Microwave Remote Sensing, Seasonality

# II. Introduction

The Missouri River Basin contains the largest reservoir system (by storage) in the United States and covers 529,300 mi2 [“The Missouri River Story”, 2010]. The Missouri River Mainstem Reservoir System is comprised of six dams and reservoirs. The system is operated by the U.S. Army Corps of Engineers (USACE) under the guidance of the USACE’s Missouri River Basin Water Management (MRBWM) office in Omaha, Nebraska. The three uppermost reservoirs, Fort Peck, Garrison, and Oahe, are located in the Upper Missouri River Basin and contain nearly 90 percent of the system’s 71.4 million acre-feet (MAF) of storage [*get citation from JRPS*]. This study focuses on the upper Missouri River Basin since the three reservoirs mentioned above are crucial to the Mainstem Reservoir System and USACE. The upper basin has a low population density and stretches from western Montana to Sioux City, Iowa and covers a majority of Montana, North Dakota, South Dakota, and Wyoming. The Missouri River’s headwaters and many crucial tributaries, such as the Yellowstone River, start in the Rocky Mountains starting at an elevation of approximately 6,000 ft [“Great Plains” 2012]. The river runs through the Northern Plains region – a data poor area – and slowly decreases in elevation to approximately 1,093 ft in Sioux City, IA ["Temperature - Precipitation - Sunshine - Snowfall." 2015]. The more densely-populated lower basin continues from Sioux City to St. Louis, Missouri through the Southern Plains region and then joins the Mississippi River. All the region’s residents and environment depend on a sustained flow of water through the system. The MRBWMD conducts controlled releases from the reservoirs in the Basin. Releases must anticipate future hydrological conditions to maintain consistent water levels in the river system [USGAO, 2014].

MRBWMD currently uses a monthly runoff forecast to anticipate Basin conditions. At the beginning of each calendar year, USACE forecasts expected monthly runoff and each month, they revise the forecast and produce a 3-week forecast. The three-week forecast predicts water supply across the region and determines such decisions as reservoir inflows, releases, storage levels, and hydropower generation. The forecast incorporates present basin conditions, such as soil moisture and snowpack, as well as historical trends and long-range weather and climate expectations using grounddata from meteorological stations and volunteer data collection [USACE, 2006]. However, the Upper Missouri River Basin is a data poor region; there are few stations to detect terrestrial water conditions and few volunteers to collect *in situ* data. For example, although mountain snowpack runoff is well-measured, there is little available information of surface water storage and snow water equivalents in the plains region [Grode, 2015].

The influence of such environmental variables as frost depth, soil moisture, snowpack, and precipitation on the river system is poorly quantified. In particular, coverage of the Northern Plains Region by on-the-ground monitoring sites is sparse, resulting in incomplete understanding of the historical trends, seasonality, and current conditions of the many hydrological inputs to a highly variable river system [Grode, 2015]. They have no protocols for using remotely sensed data for their forecasting. Our study aims to improve the knowledge base of these data-sparse areas. Improved detection of these variables through integrated NASA Earth Observation and NOAA Climate Data Records will be used to improve their decision-making processes concerning basin flood control, fish and wildlife, irrigation, hydropower, recreation, navigation, and threatened and endangered species.

**Project Objectives**

This project will use NASA Earth Observations, NOAA Climate Data Records (CDRs), and *in situ* data to improve the understanding of water supply and runoff in the Missouri River Basin. With a focus on the Northern Plains region of the basin, it will 1) assess the feasibility of detecting historic and present winter severity, soil moisture, and snow water equivalent through a combination of NASA Earth Observations, NOAA CDR, and *in situ* data, 2) create climatologies of these variables that document the normals and end-member states for the Northern Plains region, 3) perform exploratory analysis of the association between these driver variables and stream discharge with a focus on seasonality and anomalous events.

**Study Period**

Our study period starts January of 1980 and ends with November 2015. However, there are differences with data availability throughout the study period. For more information on what data is available for what time periods refer to Tables 1 and 2.

**NASA Application Areas**

The project addresses NASA’s Applied Science Application Areas of Climate, Water Resources, and Agriculture. Although we are not directly looking at climate in our project, soil moisture, snowpack, and winter severity are proxy variables of climate and are very interrelated to each other. This project addresses the storage of water and how that affects the variables being studied and vice versa, which will help USACE understand how to effectively distribute all of the water throughout the basin, especially in years of extreme drought or flood. Likewise, the applications for agriculture depend on the water resources of the reservoir system because without knowledge of the best time to release water from the reservoirs, it could lead to not enough water for the growing season and that could drastically reduce the crop growth and end product for that year.

**Project Partners**

We seek to achieve a product that is both relevant and informational for end-users by working with Kevin Grode, P.E., of the USACE MRBWMD, Dennis Todey, PhD, a State Climatologist and Associate Professor at South Dakota State University, and Doug Kluck, the NOAA Regional Climate Services Director for the Central Region. Kevin Grode directs the Reservoir Regulation Team, a team of hydraulic engineers and computer specialists who conduct studies and produce short- and long-term forecasts pertaining to the regulation of the Missouri River Mainstem Reservoir System.  Of the predictive variables used by the Reservoir Regulation Team to update forecasts, soil moisture, frost depth, and snow water equivalent remain largely unquantified, especially in the Northern Plains region [Grode, 2015]. The MRBWMD will use trends in these variables and their correlation with stream runoff to improve decision-making processes concerning basin flood control, fish and wildlife, irrigation, hydropower, recreation, navigation, and threatened and endangered species.

The work of Dennis Todey and Doug Kluck helps to disseminate information. Dr. Todey is an expert on current climate conditions and outlooks across the Northern Plains and Midwest  and Mr.Kluck works closely with the Regional Climate Centers, state climatologists, and federal and state governments, among others, to develop climate data stewardship, build climate change capacity, and assess climate services needs by sector.  To this end, Mr. Kluck and Dr. Todey are interested in a product that can assist with forecasting runoff in the Missouri River Basin, especially long-term forecasts in light of trends associated with climate change. An improved understanding of trends in these variables and their effect on runoff will aid in their communications with Basin organizations and residents.

# III. Methodology

We achieve the stated objectives through acquisition, processing, and analysis methodologies customized to each variable and the relevant available datasets. All datasets are both left in their original temporal resolution, after they have been verified as serially complete, and aggregated to monthly summary statistics for standardized comparisons with other datasets.

In addition to the data described below, we use shapefiles of watershed boundaries to limit the scope of analysis and to restrict correlations between spatially contiguous independent variables and finite dependent variable of streamflow to the hydrologic regions. DEMs of the Basin region and shapefiles of the river network also provided context reference and were obtained from USGS.

Table 1. Remotely sensed data.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | Data product | Platform | Product level | Resolution | Observation frequency | Time period | Source |
| Precipitation | CMORPH  |  | NCEI CDR | 4km | 30 min | 1991-present | NOAA NCEP CPC |
| Snow water equivalent | GlobSnow SWE | SMMR, SSM/I, ground-based | Daily Snow Water Equivalent (L3A) | 25km | daily, weekly, monthly | 1979-2013 | ESA GlobSnow consortium |
| Soil moisture | NLDAS | GOES |  | 1 degree | monthly | 1979-present | NASA GES-DISC |

Table 2. Ground data.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Variable | Data product | Platform | Distribution of stations | Observation frequency | Time period | Source |
| Discharge | USGS water | stream gauge stations | - | daily (average) | 1979-present | USGS |
| Soil moisture | SCAN | ground stations | ~ 4 sites in study area | daily |  | NOAA NRCS |
| Precipitation | GHCN | array of ground stations | - | daily |  | NOAA |
| Streamflow | HCDN | USGS Streamflow Data Set |  |  | 1974-1988 | USGS |

**Snow Water Equivalent**

The GlobSnow consortium derives an estimate of snow water equivalent (SWE) from satellite observations and ground station data. It incorporates measurements from NASA Earth Observations from the AMSR-E, SSM/I, and SMMR sensors and from the ECMWF weather stations. The GlobSnow data product includes both daily and weekly estimates at 25km grid spacing beginning in 1979 publicly accessible at <http://www.globsnow.info/swe/> [Luojus et al., 2010]. It improves upon SWE calculations derived from SSM/I, which are especially accurate over medium-elevation flat plains with seasonal snowcover [Vuyovich et al., 2014]. The data is available in daily measurements, but is more susceptible to missing data because of lagging pass times of the satellites. Instead, we use the weekly SWE calculations, which are constructed from the SWE on the given day and the previous 6 days so that a daily value summarizes a week-long period.

1. We download the complete series of weekly data in the HDF-4 format (they are also available as netCDF) and convert them to geoTIFF using R. We isolate our analysis to those pixels contained within the Missouri River Basin and extract time series for each pixel.
2. We use R to calculate the summary statistics of the following: onset of winter (or first SWE recordings), onset of spring (50% of streamflow?), total accumulation of SWE in a year, max SWE in a year.
3. Next, we analyze trends in the SWE time series using “R” statistical packages.

**Soil moisture**

We employ two datasets to analyze soil moisture: Soil Climate Analysis Network (SCAN) *in situ* measurements and the NLDAS-2 modeled soil moisture product. SCAN *in situ* stations from the National Resource Conservation Service (NRCS) produce near real-time daily measurements of soil moisture and are available in CSV. Data records from some sites begin in the 1990s and others in the 2000s, depending on the date of installation.

The North American Land Data Assimilation System (NLDAS) provides near real-time data on a ⅛-degree grid over central North America.  It is produced using NASA Geostationary Operational Environmental Satellites (GOES) and ground station data [Xia, 2012]. The model of NLDAS that is being used is Noah. The format of the data was in gridded binary so it had to be read by the system GDAL.

1. After the data was read, it was plotted in Excel for exploratory analysis of it.
2. We put the data into R so that we could take a look at the trends from a visual perspective with graphs.
3. We then look at the seasonality of each of the individual sub-basins that are in our study area.
4. After an individual analysis on the sub-basins in the area, we use the NLDAS data to show the utility of the SCAN sites. We take all the measurements from the NLDAS data for comparison with the area surrounding the SCAN sites to see how closely the SCAN sites can measure the soil moisture for the subbasin that they are a part of.
5. We also use the SCAN sites data to validate the findings of NLDAS.

**Winter severity**

Surface temperature data will be used to find winter severity. Daily temperature observations from 1981-2010 are downloaded from NOAA NCEI’s website for public data. Serially complete, daily temperature maximums and minimums are stored by NCEI. The original temperature measurements came from a Global Historical Climatology Network stations and is processed by NCEI [Bilotta et al., 2015]. This data is specifically used for finding supplemental normals.

1. We download temperature minimums and maximums from 1981 - 2010 in Fahrenheit degrees from NOAA NCEI’s FTP for supplemental normals data and import the dataset into R studio.
2. We use the protocol employed by Bilotta et al. [2015] to calculate the air-freezing index (AFI). We first calculate the Freezing-degree days (FDD) of each season for every station and then calculate the Air-freezing index (AFI) with the found FDD.
3. We download the GHCN station index and imported it into Excel where we format the dataset for import to ArcGIS. In ArcGIS, we import the XY values as a layer and save it as a shapefile with the locations of the GHCN stations. A previously downloaded shapefile of the Missouri River Basin was used to identify GHCN stations within our study region.
4. In R studio we isolate the FDD and AFI of only the GHCN stations within our study region.
5. We calculate the start date, end date, and length of each winter from the FDD and AFI graphs.
6. We perform linear regression analysis in RStudio to identify changing trends in the start date, end date, and length of each winter.

**Streamflow**

We obtain *in situ* measurements of stream discharge for trend analysis and correlation with the driver variables studied here. The USGS provides discharge from 1979 from a well-populated network of stream gauge stations. HCDN-2009 is a more selective dataset of streamflow from 1970-2009 that only includes waterways without major anthropogenic disturbance.

1. We download measurements of daily mean discharge in cubic feet/second (cfs) from 1979 - 2015 in the Missouri River Basin as a CSV from USGS Surface-Water Daily Data. We download the list of HCDN stations and daily discharge data as an Excel file from the USGS HCDN site.
2. We import both datasets into “R” and remove days with missing measurements.
3. We find the stations that are common to both the HCDN-2009 dataset and the USGS Surface-Water network using merge or match in “R”. This produces a dataset from 1979-2015 of streamflow gauges within the MRB that “reflect prevailing meteorological conditions” (no human impacts).
4. We analyze daily discharge in relation to the previously-described independent hydrologic variables: SWE, frost depth, and soil moisture. We use a temporal correlation analysis.

**Precipitation**

PERSIANN-CDR is an estimate of precipitation at 0.25° resolution produced by NOAA NCEI. It was downloaded and clipped to the study area using wget, Dnnpy, and R.

1. We calculate the monthly average precipitation for the 35 years of study in R software. This provides the baseline from which to identify anomalous patterns.
2. We isolate the analysis to sub-basin areas and select only the pixels within the given hydrologic region.
3. Using the time series of precipitation, we correlate the precipitation measurements to time series of streamflow. We perform a multivariate stepwise regression analysis to determine the relative influence of each variable on the streamflow. We iteratively run lagged correlation analyses on both the relevant daily data and data aggregated to monthly time steps. We analyze the lagged correlation from 1-4 days lag and from 1 to 2 months lagged.

# IV. Results & Discussion

[Placeholder for the Rough Draft. We do not yet have any results to describe or discuss, but we expect them to include the following:

SWE:

* Annual time series of SWE at a heterogeneous selection of at least three sites.
* Interannual time series of average annual SWE at the same selection of sites.
* Trends in snowpack for the entire upper basin calculated from statistical analysis.
* Results of seasonal timing of melt onset correlated with streamflow data.
* Spatial and temporal results plotted on an interactive map

Soil moisture:

* Graphics plotting soil moisture change over time for both SCAN and NLDAS
* Maps showing the individual soil moisture mean over time for each year that NLDAS has been operating
* A comparison between the SCAN sites’ data and the NLDAS data showing the utility of the *in situ* data

Winter severity:

* Graphs plotting changes in FDD and AFI for each station
* A map of the region showing changing trends by area.

Discussion will include (from template):

* Analysis of Results: What can you tell from your graphs, images, etc? What does this mean for your project?
* Errors & Uncertainty: What factors could you not account for, what things didn’t work out like you expected they would, etc.
* Future Work: If this project was to be selected for another term, what would be the focus? What other areas would be of interest?

End of placeholder.]

# V. Conclusions

[Placeholder for final conclusions. Word count: 200-600 (~a page).]

# VI. Acknowledgments

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# VII. References

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# VIII. Content Innovation

**Interactive Map Viewer**

We will provide KMZs of our results - summarized trends of SWE, AFI, and soil moisture - that can be viewed and downloaded from Google Earth

**Interactive Plot Viewer**

We will provide those same trends for viewing in interactive plots that include data points, trend lines, and seasonality analyses.

**Audio Slides**

We will provide an abridged presentation with audio to explain the project.

# IV. Appendices

Insert here