Water Supply Forecasting of the Cannonball River Watershed

Category B applicants: Dr. Taufique Mahmood[1], Mr. Tyson Jeannotte[1] and Ms. Alexis Archambault[1]

1. Harold Hamm School of Geology and Geological Engineering, University of North Dakota, Grand Forks, ND -58201.

Category A applicants: Mr. Doug Crow Ghost[2]

2. Department of Water Resources, The Standing Rock Sioux Tribe, Fort Yate, ND.

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Table of Contents

Contents

Executive Summary

Date: Oct 17, 2023.

Applicant Name: Dr. Taufique Mahmood, University of North Dakota, City: Grand Forks, County: Grand Forks, State: North Dakota.

In the Standing Rock Sioux Tribe (SRST), there is an increasing concern about the municipal water supply (from the Missouri River) in the context of climate change, particularly during drought conditions. There is also a growing awareness about the future water security regarding the municipal water supply. To address this issue, in this proposal, we propose to forecast water supply using a field-tested hydrologic model in the Cannonball River Watershed (CRW) which is a major tributary sub-basin draining to the Missouri River. The University of North Dakota (UND), with the support of the Standing Rock Sioux Tribe Department of Water Resources, will use field-based hydrologic and climatic data and cold region hydrologic modeling output to create seasonal forecasts (with proven statistical methods) of streamflow and predict future hydrology for the CRW. We will conduct a series of snow surveys (measuring SWE at distributed locations), install soil moisture sensors and rainfall gauges across the CRW and deploy a streamflow gauge at the CRW outlet. We will use these hydrologic observations to evaluate a physically-based cold region hydrologic model (CRHM) for CRW. Although the model will be calibrated and verified against only two years of field data we collected, we will run the model during 2000-2026 to understand the intermediate processing leading to streamflow generation in recent years. Using the field-verified CRHM model, we will predict/forecast future hydrology of CRW using global climate change (GCM) data for multiple CO_2 emission scenarios. We will forecast the water supply of the upcoming spring by forward running the CRHM model using a mean of an ensemble of climate model simulations as well as historically driest and wettest conditions. The duration of the proposed project is two years (August 16, 2024-August 15, 2026). The proposed budget will be used for equipment installation, data collection, staff salaries (scientists and engineers from UND and SRST) and hydrologic modeling to achieve the project goals.

Applicant Category

The proposed study is a collaborative proposal between Category A applicant and Category B applicant.

Category A applicant: Mr. Doug Crow Ghost is the Director of the Department of Water Resources (DWR), The Standing Rock Sioux Tribe (SRST), Fort Yate, ND. The DWR is committed to a healthy and sustainable SRST. They are implementing policies to protect land, water, and wildlife in and around SRST region. As a director of DWR, Mr. Crow Ghost forms and implements policies and regulations to protect natural resources. In past, he had many grants and successfully managed them.

Category B applicant: Dr. Taufique Mahmood (Project manager and Associate Professor of University of North Dakota), Mr. Tyson Jeannotte (University of North Dakota) and Ms. Alexis Archambault (University of North Dakota).

Dr. Taufique Mahmood (Project Manager, PM): The University of North Dakota (UND) is one of the most prestigious higher education institutions contributing substantially to state's agriculture, water resources, and energy industries via cutting-edge research work. Every year, UND also educates and trains many undergraduate and graduate students and professionals in agricultural hydrology, groundwater science, and environmental geoscience. The UND awards Bachelor, Master and Doctorate degrees in various areas, including science and engineering. Dr. Mahmood is an associate professor (Harold Hamm Geology and Geological Engineering) and founding director of ND Center for Water Research (NDCWR). Since 2015, Dr. Mahmood and his research group, has been investigating the impacts of recent wetting and land management practices on hydrology and water quality in the agricultural and grassland basins of the North Dakota particularly in tribal areas (Standing Rock Sioux Trial land, Turtle Mountain Band of Chippewa Indians area and Three tribe area). Dr. Mahmood collaborates with Native American communities across North Dakota and has extensive experience supervising Native American graduate students and tribal college students (NATURE summer camps) at UND. In particular, the collaboration with Ms. Alexis Archambault and Mr. Doug Crow Ghost from the Standing Rock Sioux Tribe and Mr. Tyson Jeannotte from the Turtle Mountain Band of Chippewa Indians through NSF CAREER grants is noteworthy to mention. He recently received the NSF CAREER award (Hydrologic Science) and other grants from USGS and ND Department of Water Resources. Through these federal awards, Dr. Mahmood has created new hydrologic and climatic data (snow water equivalent via snow survey, all-season precipitation data by installing new precipitation gauges and measuring streamflow by installing stream gauges in respective areas of a watershed), made them accessible to public and used them for hydrologic modeling and forecasting purposes. He also conducted cold region hydrology workshop for the high school students of the White Shield School of the Fort Berthold Indian Reservation to inspire them in water resources science and make awareness on water security and quality issues. In the past, Dr. Mahmood worked on and managed grants from ND EPSCoR, NSF MRI and NDWRRI. In addition, Dr. Mahmood teaches Groundwater Monitoring and Remediation, Hydrogeology, Cold Region Hydrologic Modeling, Introduction to Geology, Water Sampling and Analyses and Conservation and Environmental Hydrology courses in the UND.

Mr. Tyson Jeannotte is an enrolled member of the Turtle Mountain Band of Chippewa Indians is a Senior Research Engineer at the UND's NDCRW. Mr. Jeannotte has vast experience in water science, applying in-field applications to simple and complexed water quality modeling of nutrients and sediment loads particularly in agricultural regions. In addition, Mr. Jeannotte has extensive experience in hydrological modeling at large and small-scale watersheds to in-stream modeling. In the past, Mr. Jeannotte has worked with many tribes installing watershed monitoring equipment (stream gauges, rain gauges, etc) modeling water resources infrastructures (surface and groundwater resources) and promoting outreach in STEM education and research while providing technical assistance in water resources.

Ms. Alexis Archambault is an enrolled member of the Standing Rock Sioux Tribe and will work as a post-doctoral researcher in this project. She is currently a PhD candidate (PhD in Geological Engineering with expertise in Water Resources at UND) under Dr. Mahmood and is expected to graduate by Spring, 2024. She is also one of very few indigenous female STEM graduate students pursuing the highest degree in North Dakota. Ms. Archambault will set the cold region hydrologic model (CRHM) for the Cannonball River Watershed (CRW) and compile the CRW model using the CRHM platform.

Collaboration between the University of North Dakota (UND) and the Standing Rock Sioux Tribe (SRST):

<u>Current and previous work in SRST</u>

The collaboration between UND and the SRST started back in 2017 when Ms. Archambault moved to UND from SRST and started her MS in Geological Engineering and conducted MS thesis under the supervision of Dr. Mahmood. She graduated with her MS degree in 2019 (Archambault et al., 2023) and stayed at UND to pursue PhD in Geological Engineering under Dr. Mahmood. Over the last seven years, Ms. Archambault and Dr. Mahmood collaboratively worked on projects on hydrology and ecology in the context of recent climate and land use changes in the SRST. They also supervise tribal college students from the Sitting Bull Community College (SRST's community college) under the AIHEC (American Indian Higher Education Consortium) program and built baseline environmental remote sensing data in SRST for future climate change studies. Most studies are remotely sensed surface water area (lakes, ponds and wetland from Global Surface Water Dataset by Pekel et al., 2016) analyses over the last three decades, vegetation health change (using remotely sensed vegetation indices) in a family ranch in the Cannonball River Watershed to recent climatic variability over last three decades, Missouri River (near Mobridge, Standing Rock Sioux Tribal area) width and level responses to extreme climatic events and Baseline water quality data development (surface and groundwater) in the Standing Rock Sioux Tribe for the future climate change studies.

Through these academic collaborations, we developed baseline data and improved access to hydrologic, climatic and ecologic data. Surface water area increased in response to climatic wetting and cooling (temp dropped by 5^{o} F) during the 2006-2009 period (Figure 1). After 2009, the increased water area was sustained due to continued high precipitation. Due to the 2019 flood, another sharp increase in the surface water area was observed (Figure 1). The NDVI of the family ranch exhibits a decreasing trend in response to the prairie drought during 2000-2006 period while an increasing NDVI trend is observed during deluge conditions in 2007-2013 period (Figure 2). Finally, a recent decreasing NDVI trend is observed during 2014-2020 period. An increasing trend indicates healthy and growing vegetation while a decreasing trend indicates stressed vegetation. Our findings have a great implication in the family ranch as cattle grazing depends on the growth and health of the prairie grasses. In the wet years like 2019, the Missouri River flooded both banks whereas during an extreme dry year like 2021, the low Missouri River level significantly threatened the municipal water supply to the SRST.

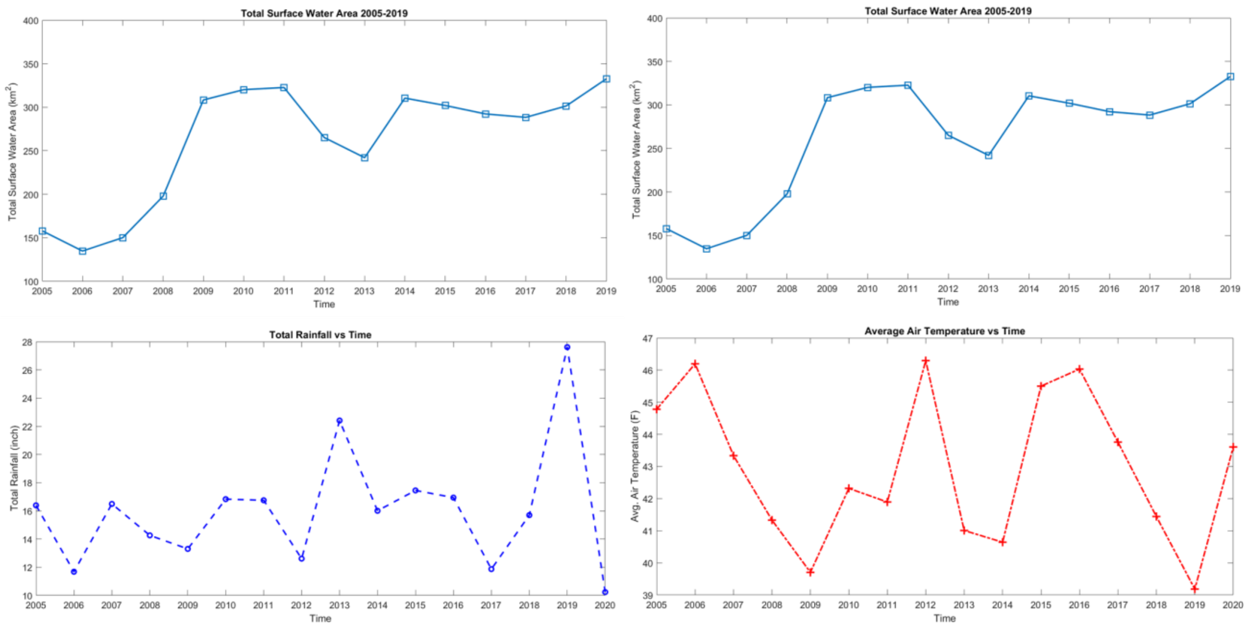

Figure 1: Surface water area changes during 2005-2019 period. Rainfall and air temperature are from nearby NDAWN station (Fort Yates, ND).

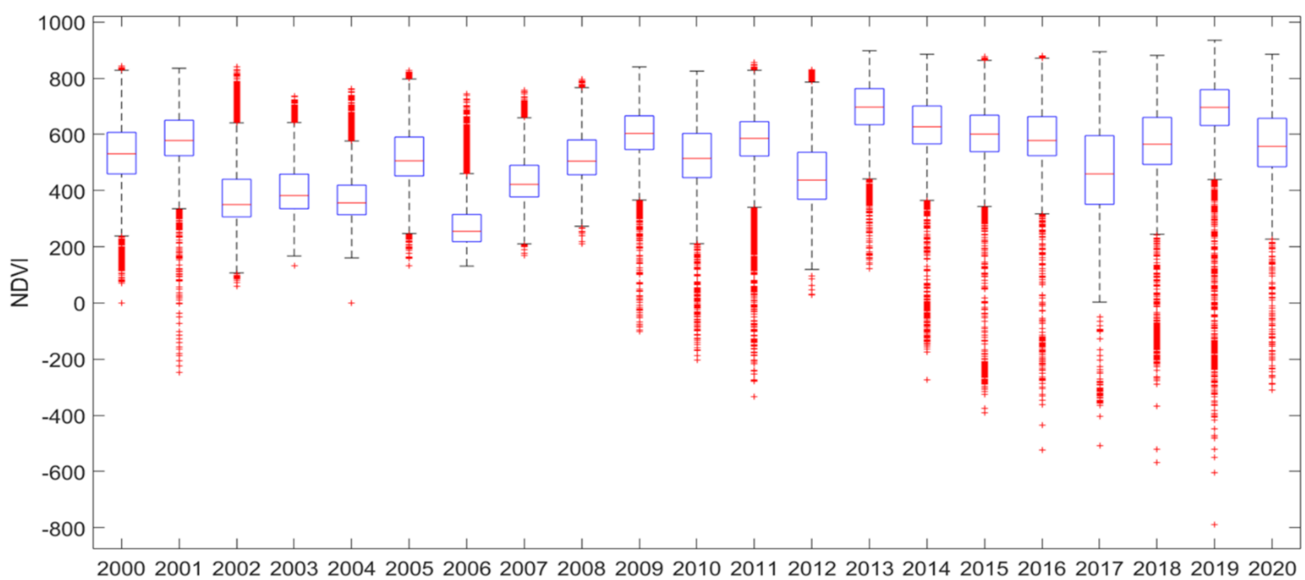

Figure 2. Normalized Vegetation Index (NDVI) changes during 2020-2021 in a family ranch of southern Cannonball River Watershed. All pixels in the family ranch for each were considered in each box-plot.

Recently, Archambault et al (2024) is using the recently developed and novel approach involving Best Available Pixel (BAP built using Python by White et al, 2014) and building different remotely sensed indices to detect vegetation health changes since 1984.

Proposed project development

Mr. Doug Crow Ghost reviewed above mentioned UND's ongoing and previous work in the SRST and was impressed with the scientific rigor and quality of UND's work. Mr. Crow Ghost (Director of SRST DWR) decided to develop a partnership UND's Dr. Mahmood, Mr. Jeannotte and Ms. Archambault over six months ago and asked UND to work on developing a science-based solution on the water quality and contaminant transport issue in an aquifer of the SRST. During our conversation, uncertainty and concerns were raised regarding the water security of the SRST's municipal water supply from the Missouri River Basin (MRB). The most notable concern came from a low water supply in 2021 due very dry winter and summer. After a detailed discussion with SRST DWR, we reviewed the SRST surface water sources and decided to propose a project forecasting water supply in the Cannonball River Watershed (CRW). The CRW is one of the major contributors to the Missouri River and a very large (11,184 km^2) tributary basin (sub-basin) draining to the Missouri River from which SRST receives the municipal water supply. The CRW drains through both tribal and non-tribal areas of southern North Dakota (Figure 3A). It also passes through the SRST city of Cannon Ball. The farmers and ranchers in tribal and non-tribal areas depend on the Cannonball River for irrigation and domestic water supply. To date, the current knowledge of the hydrologic and water supply forecasting knowledge in the CRW is based on remote sensing data and few groundwater wells lacking state-of-the-art surface water monitoring observatories and cutting-edge cold region hydrologic modeling in the SRST. The goal of SRST DWR's partnership with UND is to bring these state-of-the-art surface water monitoring observatories and cutting-edge cold region hydrologic modeling technology and build a robust predictive framework of water supply forecasting for the CRW. The proposed project is step 1 of achieving this goal.

Since, the SRST is located in the cold prairie region of seasonal freezing conditions, the area is vulnerable to recent climate change via fluctuations of precipitation and temperature regime. The SRST and other communities in the area continue to thrive and experience agricultural and economic growth set against the context of warming and wetting climate, changing land management practices and other environmental challenges. In particular, the impacts of short and long-term climate change exert strong control on the water supply in the CRW. The CRW region experienced a series of wetting-cooling, wetting-warming, and cooling-drying climatic phases over last three decades resulting in uncertainty on the streamflow of the CRW. Thus, a series of hydrologic observations (snow water equivalent, soil moisture, outlet streamflow) is needed to understand CRW hydrology. In addition, a modeling framework is also needed to understand the mechanism of hydrologic change to climate fluctuations and predict streamflow accurately. Finally, a water supply forecasting framework is needed using the hydrologic model to predict future water supply for the SRST.

In this proposal, we propose to forecast water supply using a field-tested hydrologic model in the CRW. We will conduct a series of snow surveys (measuring SWE at distributed locations), install soil moisture sensors and rainfall gauges across the CRW and deploy a streamflow gauge at the CRW outlet. We will use these hydrologic observations to evaluate a physically-based cold region hydrologic model (CRHM) for CRW. Although the model will be calibrated and verified against only two years of field data we collected, we will run the model during 2000-2026 to understand the intermediate processing leading to streamflow generation in recent years. Using the field-verified CRHM model, we will predict/forecast future hydrology of CRW using global climate change (GCM) data for multiple CO_2 emission scenarios. We will forecast the water supply of the upcoming spring by forward running the CRHM model using an ensemble of climate model simulations as well as historically driest and wettest conditions.

Detailed Project Description

Study area

The study site is the Cannonball River Watershed (CRW) (11,184 km^2), which is a cold region, high-latitude, semiarid, agricultural, and low-relief watershed. Note that the CRW itself is also a sub-basin of the Missouri River. The CRW (11,184 km^2, 90% is the effective contributing area) is located in southern ND covering both tribal and non-trial areas (Figure 3A). The highest point in the CRW is 911 m on the western edge of the CRW while the lowest point is 485 m near the outlet of the CRW (Figure 3A). Note that city of Cannon Ball is also located very close to CRW outlet and can serve as a backup drinking water supply if anything were to happen to Missouri River. In general, the terrain slopes from west to east with a relief of ~426 m and an average elevation of ~735 m (Figure 3B). The CRW is located within the Missouri Plateau ecoregion covering parts in the west of the Missouri River where the landscape opens up to become “wide open spaces” (U.S. Environmental Protection Agency et al., 1998). The topography of the Missouri Plateau was barely affected by glaciation and retains its native soils and embedded stream drainage pattern. Major land cover types are agricultural land (western part of CRW) and herbaceous grassland/wetland (eastern part). A mix of spring wheat, alfafa and other crops covers the crop land while grazing land covers with shortgrass prairie dominate herbaceous areas. Herds of bison, elk and cows graze in the grassland area.

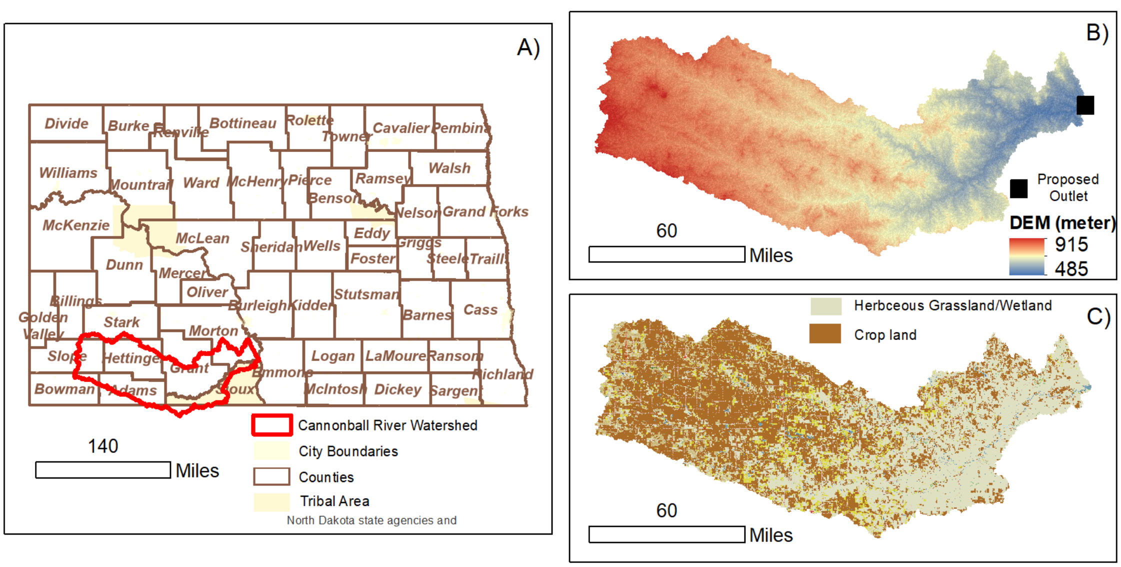

Figure 3. Study site: 3A. Location of the Cannonball River Watershed (CRW) in North Dakota; 3B. SRTM Digital Elevation Model (DEM, 30 m resolution) with a proposed outlet location of the streamflow gauge and 3C. NLCD 2021 land cover map for the CRW.

Methods

Data collections

Snow survey: Snow observations for the winters during 2024-2025 per will be collected using a Metric Prairie Snow Sampler (MPSS) in the CRW. The MPSS is designed after the Environment Canada ESC 30 to estimate snow depth and measure SWE using a calibrated SWE scale (Geo Scientific Ltd.). The PM's group has already conducted snow survey using the MPSSs near Devils Lake, Oakes and Harvey, ND during the 2016-2023 winter seasons, estimating snow depth, density, and snow water equivalent (SWE) (Van Hoy et al., 2020). The snow data collections in the MCB were conducted with collaboration from the local community. The proposed timing for snow survey will be during peak snow accumulation (~late Feb – early April depending on winter season) and just before the onset of snowmelt (~ late Mar –early April depending on winter season). We plan to conduct 2-4 snow surveys in a winter season. Snow cores will be collected and measured to obtain the weights for calculations of snow density and snow water equivalent. We will record whether a basal ice layer exists or not, as basal ice significantly affects snowmelt runoff during the spring period. Spatiotemporal snow observations will be utilized to understand snow accumulations, temporal evolution of SWE, snowmelt streamflow-generation mechanisms, and evaluate the snow simulations. Since there are currently few snow observations available in the Missouri Plateau area, the snow survey portion of this project will add useful knowledge to the sparse snow observation records in the greater Missouri Plateau area. Note that PM's group is one few group collecting snow data in the Northern Great Plain (NGP).

Climatic Data Collection: The climatic data such as rainfall, air temperature, solar radiation, wind speed, and relative humidity will be obtained from the North Dakota Agricultural Weather Network (NDAWN) station at Fort Yate, ND (SRST site operated by NDAWN)) which is 10 miles way from the CRW. In addition, we will install three rainfall gauges and soil moisture sensor to supplement the NDAWN's and SRTS's current capability.

Streamflow gauge installation and data Collection: We will deploy a streamflow gauge at the outlet of the CRW. The outlet location is shown in Figure 3B. Mr. Jeannotte has vast experience in deploying streamflow gauges (pressure transducers) while developing rating curves through in-stream modeling (HEC-RAS) in various watersheds in North Dakota.

Cold Region Hydrologic Model: Physically-based models can be utilized to extrapolate limited field observations over broader spatiotemporal scales to investigate the hydrological controls. In this proposal, I propose to use an object-oriented, multi-physics, modular modeling system (Cold Region Hydrologic Model (CRHM)) that allows set up of hydrological models that represent key cold regions hydrological processes (Pomeroy et al., 2007). CRHM has a flexible modular design and is spatially-distributed based on hydrologic response units (HRUs) allowing for fine-scale resolution and parameterization. A HRU is a model element (smallest possible unit) that has unique land cover, soil, topographic description and geographic location. HRUs are derived from land cover maps in which we consider each agricultural field as a HRU. Here, I propose to use modules representing governing cold region hydrological processes such as frozen, partially frozen and unfrozen soil infiltration, blowing snow transport, energy balance in the snowpack governing melt processes, evapotranspiration, fill and spill hydrology in wetland and wetland processes in depression areas (Figure 2). The PM received training on CRHM during postdoctoral work under Prof. John Pomeroy, published a paper (Mahmood et al., 2017) with him and the PM's group also published preliminary results in Van Hoy et al., (2020). The following is a description of the major modules are proposed and how they will represent physical processes:

Canopy Module: model the snow and rain that is intercepted by vegetation. It also deals with the unloading, sublimation, and melting of intercepted snow, and the evaporation and drip of collected rain (Ellis et al., 2007, 2010; Pomeroy et al., 2009).

Energy-Balance Snowmelt Module: utilizes incoming and outing shortwave and longwave radiation to estimate the radiative, advective, convective, and internal thermal snowpack energy that is available to melt snow. As runoff, streamflow, and to a lesser extent infiltration in spring are controlled not only by the snowmelt amount but also the rate of snowmelt it is vital to have a module that handles this process (Pomeroy et al., 2007). This module is based on algorithms that have been created from the algorithm that were derived from years of observations for heat transfer (Gray & Landline, 1988; Granger & Male, 1978), net radiation (Brunt, 1932; Brutsaert, 1982; Garnier & Ohmura, 1970), and albedo (Gray & Landline, 1987; Pomeroy et al., 2007). This module has been successfully used in recent studies (Mahmood et al., 2017; Cordeiro et al., 2017; Fang et al., 2010; Van Hoy et al., 2020) all of which were done in the NGP. It is more advanced than other models as it is designed to account for differences in energy caused by slope, aspect, and varying snow albedo over time (Pomeroy et al., 2007). Snow can change albedo due to wind ablation, redistribution, compaction, and mixing with soil.

Infiltration Module: In non-winter months this module accounts for unfrozen soil infiltration for rainfall based on soil properties i.e. soil thickness, soil texture, and agricultural practices, such as tillage and tile drainage (Ayers, 1959). However, during winter months there are three different types of soil infiltration into frozen soil: restricted, limited, and unlimited. Restricted: impermeable layers due to fully frozen soil and basal ice layer (i.e. ice lenses somewhere on or near the surface) have minimal infiltration resulting in meltwater going to runoff and ET (Pomeroy et al., 2007). Limited: infiltration is controlled by snow-cover water equivalent and amount of frozen water in the first 30.0 cm of soil (Gray, Pomeroy, & Granger, 1986; Pomeroy et al., 2007). Unlimited: Soil is heavily fractured or has large pores so that all melt after a major snowmelt event goes to unlimited infiltration (Pomeroy et al., 2007). Unlimited conditions end when melt ends (Pomeroy et al., 2007).

Evaporation Module: utilizes the Penman-Monteith (Monteith, 1965) combination method along with surface resistance (Jarvis, 1976) and available energy to simulate ET for most HRUs. Other HRUs having open water uses the Priestley-Taylor method to calculate evaporation (Priestly-Taylor, 1972). This module is required because evaporation has an effect on soil moisture, which in turns affects how much water will infiltrate and how much water will become overland flow during snowmelt or rain events.

Soil Module: simulates moisture balance, slough storage, overland flow, and subsurface flow (Pomeroy et al., 2007; Dornes et al., 2008; Fang et al., 2010, 2013). It uses a three-layer approach wherein the top layer collects water from sloughs/depression, snowmelt, and rainfall and outputs it to crops via transpiration. The second layer receives its water from the top layer of soil and also outputs water through transpiration or allows it to percolate to the third layer. The third layer is the groundwater reservoir that contributes to base flow. The module makes sure that ET does not exceed interception, slough storage, and "soil water withdrawal characteristics" (Mahmood et al., 2017). In this module, the proposed model set up considers fill and spill hydrology from wetlands in a simple way using depressional storage. The discretization of each sub-basin includes multiple wetland HRUs with parameters: area (A), depressional storage (Sd) and maximum depressional storage (Sd_max). The Sd receives water from snowmelt, rainfall and routed water from neighboring HRUs. When Sd equals to Sd_max, water is spilled to neighboring HRU based on the spatial organization of HRUs for routing.

Fill-spill hydrology in soil module: To address fill and spill hydrology, the proposed model setup represents wetlands in a simple way using depressional storage in soil module. The discretization of each sub-basin includes multiple wetland HRUs with parameters: area (A), depressional storage (Sd) and maximum depressional storage (Sd_max). The Sd receives water from snowmelt, rainfall, and routed water from neighboring HRUs. When Sd equals Sd_max, any additional stored water is spilled to the neighboring downslope HRU based on the spatial organization of HRUs for routing. The Sd also decreases when the water is consumed by open water evaporation from a depression during spring and summer (no evaporation occurs when the water is frozen inside a depression). Thus, the channels in these sub-basins are not able to generate streamflow until Sd is equal to Sd_max in a wetland/herbaceous area HRU. For example, when the Sd equals Sd_max for a wetland/herbaceous HRU, the HRUs routing into this wetland/herbaceous HRU start contributing to streamflow and subsequently increase the contributing area. In our recent work (Van Hoy et al., 2020), based on USGS channel network [Moore and Dewald, 2016] across the MCB, we assume that all the HRUs are contributing to outlet stream when Sd equals Sd_max for all the wetland and herbaceous areas. The amount of contributing area depends on the status of the depressional storage (Sd) of the wetland/herbaceous areas located near channels.

The estimation of the maximum depressional storage (Sd_max) for each HRU is challenging as there is no field-based observation available and the storage delineation from high-resolution DEM still needs improvement [Huang et al., 2011] . To determine the volume of maximum storage, I propose to utilize the LiDAR-derived bare-earth DEM (available via ND SWC) and quantified the sink area and sink-depth of pixels in each depression or sink. The sink-depth (Δh) of each pixel was estimated by subtracting the LiDAR DEM from the filled DEM [Wu and Lane, 2017]. I propose to use an arc wetland hydrology toolbox developed by Wu and Lane [2017]. Then, I can estimate total maximum storage volume for each HRU by integrating maximum storage volume (sink depth × sink area) of all pixels within a HRU. For example, our results suggest that only 57 km2 out of 129 km2 of wetlands contributed to streamflow in a headwater basin of Devils Lake (Van Hoy et al., 2020). The estimated volume of maximum storage contributing to streamflow generation (57 km^2 wetlands) in the MCB is 5.7×10^7 m^3.

Prairie Blowing Snow Module (PBSM): models sublimation and blowing snow transport across HRUs using wind speed, air temperature, and relative humidity from the observation module. Snow is redistributed from areas of low vegetation height (i.e. low stubble) to high vegetation to taller vegetation (i.e. higher stubble, grass, and trees) and higher altitude to lower altitude areas (valleys and depressions). Windy conditions are common on almost a daily basis in the NGP, due to partly the fact that there are no natural windbreaks as there are in mountainous regions, such as the Rockies, Alps or Andes. Therefore, blowing snow, especially in high accumulation years, is a noticeable component of the hydrological mass balance that needs to be incorporated into any model. Blowing snow results in two modes of transportation saltation and suspension. When the snow particles are suspended they have maximum exposure to air, and can easily sublimate accounting for as much as 15.0 to 41.0% of snowfall (Pomeroy et al., 2007; Pomeroy & Gray, 1995). Blowing snow creates larger differences in SWE in areas of varying land cover (Pomeroy et al., 2007; Gray et al., 1979).

Routing: It routes water from HRUs to downgradient HRUs or to the sub-basin outlets and then from the sub-basin outlets to the basin outlet at the lowest elevation using the Muskingum routing method in the model (Mahmood et al., 2017). In the proposed study, the flow will be routed from an HRU to the nearest stream HRU. All streams will be used to route water to the mainstream.

Model evaluation(Calibration and Validation period): The model will be evaluated against distributed SWE (snow water equivalent), soil moisture and outlet streamflow observations. Since our study period is limited to two years and there is no existing hydrologic data available, the selection of calibration and validation period will be little challenging. The calibration period will be 2024-2025 water year and the validation period is 2025-2026 water year. In case of SWE simulation, the parameters from PBSM, EBSM and canopy modules will be varied and calibrated. The parameters from routing, infiltration and soil module will be calibrated for streamflow simulation. For calibration of depression storage, parameters from evaporation modules can be calibrated. I think the conventional calibration approach still remains a compelling and rare feature for its application in this region. In the case of a substantial mismatch between model and observations, the researcher needs to investigate the model physics and refine it. For calibration purposes, the Dr. Mahmood already coupled (automated) a Monte-Carlo analysis toolbox (Wagener et al, 2001) with the CRHM model via Matlab platform. The PM worked on this coupling and received training during his tenure as a postdoctoral fellow under Professor Howard Wheater. Our calibration will not accept unrealistic parameter values or combinations of parameters. We will use root mean square error (RMSE), Nash-Sutcliffe efficiency (NSE) and relative bias (Rbias) to assess the model performance (Van Hoy et al. 2020). Model performance will be considered adequate if the model will be able to reproduce inter-annual and intra-annual variability of observations (estimated volume using remotely sensed surface water area) with reasonable NSE (> 0.5), RMSE, and Rbias (± 15%).

Future Hydrology Prediction: We will predict future hydrology by running CRHM (compiled for CRW) using future climatic parameters (e.g., temperature and precipitation) from General Circulation Climate models (GCM). The mean of ensembles (downscaled GCM products) for each Representative Concentration Pathway (RCP) scenario will be used (RCP 2.6, 4.5, 6.0 and 8.5 scenarios) to assess a range of future scenarios. We will conduct future simulations from 2027-2075, as the SRST is expected to experience a depletion of terrestrial water storage in mid-century and slight gains late-century from GCM results under RCP 6.0 scenario (Pokhrel et al. 2021).

Spring water supply forecasting:

Approach I (Numerical Modeling): We will run the CRHM model (compiled for CRW) as a forward time model so that the model will predict spring and summer streamflow using late winter (Feb) CRHM state as the initial condition and assumed multiple climatic scenarios of the upcoming spring and summer season. In the case of climatic scenarios of the upcoming spring and summer season, we will use the mean of an ensemble of climatic scenarios from last three decades as well as the extreme dry (e.g. 2002, Mahmood et al., 2017) and wet (e.g. 2005, Mahmood et al., 2017) spring and summer condition. Our assumption will also include a condition having a wet spring followed by dry summer and vice versa. The model simulations under multiple climatic wetness will help the SRST Department of Water Resources (DWR) detect the water supply vulnerability for the upcoming spring and summer season..

<u>Approach II (Empirical Equations):</u>

Considering the highly uncertain nature of the climate in the NGP and Missouri Plateau, it is challenging to forecast seasonal (particularly spring hydrology) streamflow. In addition, large-scale climatic oscillations such as El Nino and La Nina indirectly exert control on the winter precipitation in this region. Here, we will use precipitation, simulated streamflow and intermediate fluxes and state variable from 2000-2026 model run to forecast spring streamflow (snowmelt streamflow) using proven statistical techniques such as logistic regression. He et al., (2021) developed a statistical forecasting model for streamflow and precipitation using a small of number of samples. Here we can forecast spring streamflow at the beginning of the water year by using precipitation and hydrologic simulations over the last three decades. The computer with expert knowledge from us will analyze the input hydrologic data of the 2000-2026 period and reveal the best model.

Goals

Below is the project goals, strategies and outcomes in Table 1.

Table 1: Project objectives, strategies and outcomes

Project Objectives	Strategies	Outcomes
Objective 1. Increase current knowledge on the CRW hydrology by field measurements of SWE, soil moisture and outlet streamflow during 2024-2026 period.	**UND Project PM** (PD), Senior Research Engineer (SRE), graduate students and SRST Water Resources Director and his staff will SWE, soil moisture and streamflow data. UND SRE (with assistance from two graduate students) will install streamflow gauge at CRW outlet, three soil moisture sensors and rainfall gauges at distributed locations of the CRW in second month of the project. **(Year 1)**	This dataset will be the first baseline data in the Standing Rock Sioux Tribe for the current and future climate change and water resources studies. **One publication** from the data mentioned above.
Objective 2. Increase knowledge of CRW hydrology by compiling a process-based and distributed cold region hydrological model (CRHM). Then the run the model for 2000-2026 period. It provides insights into the intermediate processes leading to snow accumulation and streamflow generation.	**Use the** observation data (SWE, soil moisture and streamflow) to evaluate the model for 2024-2026 period. **Use the** intermediate processes (e.g. snowmelt-soil interaction, frozen and unfrozen soil infiltration, sublimation and blowing snow transport) and state variables (SWE and soil moisture) from CRHM to understand the mechanism of hydrologic changes under changing climate during 2020-2026. **UND post-doctoral researchers (Year 1)**, graduate students (Year 2) and PM (Year 2) will be responsible for this task.	Field-tested CRHM model will provide the SRST Water Resources Director a tool to assess the current water supply from CRW. **One publication** from modeled data.
Objective 3. Predict future hydrology using the compiled model (Objective 2) and future climate scenario from GCM model.	**Run** the compiled CRHM model for CRW using climatic projections from the General Circulation Model (GCM). The mean of ensembles (downscaled GCM products) for each Representative Concentration Pathway (RCP) scenario will be used (RCP 2.6, 4.5, 6.0 and 8.5 scenarios) to assess a range of future scenarios. We will conduct future simulations from 2027-2075. **UND PM and SRE** are responsible for this task.	**The outcome** will inform us about the future hydrology of the SRST. One publication from future hydrology modeling data.
Objective 4. Forecast spring streamflow using numerical modeling (Approach I) and proven statistical techniques (Approach II).	UND PM will lead this task with the help of the SRE, postdoc researcher and graduate students.	A very powerful seasonal forecasting technique for SRST Water Resources Director.

Ecological Significance

The proposed project has specific ecological significance. Simulated open water evaporation and snowmelt streamflow generation across the CRW will explain the surface water area variation in the SRST and CRW. The surface water area and connectivity between water bodies are important for fish habitat and migration. The preliminary results from the Archambault et al., (2024) indicate the substantial variation of NDVI from the various ecosystems in SRST and CWR. Precipitation, simulated evapotranspiration from grassland and net primary productivity, simulated soil moisture, simulated snowmelt infiltration, simulated vertical flux (ET, sublimation) and later flux (streamflow) will help to explain the such variation in different ecosystems in the SRST and CWR. For example, The NDVI of the family ranch (Figure 2) exhibits a decreasing trend in response to the prairie drought during 2000-2006 period while an increasing NDVI trend is observed during deluge conditions in 2007-2013 period. Our preliminary hydrologic simulation indicates that the prairie drought (2000-2006) is dominated by high V/P (V is vertical outgoing fluxes: ET and sublimation and P is precipitation) while the deluge period in 2007-2013 is dominated by high Q/P (Q is streamflow and P is precipitation).

Data Management Plan

We plan to store this data long-term the University of North Dakota (UND's) data repository (https://commons.und.edu/) and SRST tribal website. The PM's group stored hydrologic data from past projects in the UND's repository. It also practices the FAIR principles and specializes in the data for our scientific domain. An example is Van Hoy et al, (2020) in https://commons.und.edu/data/14/

Van Hoy, D.F., Mahmood, T.H., Todhunter, P.E. and Jeannotte, T.L., 2020. Mauvais Coulee Basin Hydrologic Data (Observation and Simulation).

Other requirements

The project does not need any permits/approvals and environmental/cultural compliances. Mr. Crow Ghost is fully supportive of the proposed project. If needed, UND will work with the Standing Rock Sioux Tribe Department of Water Resources to obtain permits and other necessary compliances.

Water Management Challenge

There is serious uncertainty and concern regarding the water security of the SRST's municipal water supply from the Missouri River Basin (MRB). The most notable concern came from a low water supply in 2021 due very dry winter and summer. After a detailed discussion with SRST DWR, we reviewed the SRST surface water sources and decided to propose a project forecasting water supply in the Cannonball River Watershed (CRW). The CRW is one of the major contributors to the Missouri River and a very large (11,184 km^2) tributary basin (sub-basin) draining to the Missouri River from which SRST receives the municipal water supply. The CRW drains through both tribal and non-tribal areas of southern North Dakota (Figure 3A). It also passes through the SRST city of Cannon Ball. The farmers and ranchers in tribal and non-tribal areas depend on the Cannonball River for irrigation and domestic water supply. To date, the current knowledge of the hydrologic and water supply forecasting knowledge in the CRW is based on remote sensing data and few groundwater wells lacking state-of-the-art surface water monitoring observatories and cutting-edge cold region hydrologic modeling in the SRST. The goal of SRST DWR's partnership with UND is to bring these state-of-the-art surface water monitoring observatories and cutting-edge cold region hydrologic modeling technology and build a robust predictive framework of water supply forecasting for the CRW. The proposed project is step 1 of achieving this goal.

Since, the SRST is located in the cold prairie region of seasonal freezing conditions, the area is vulnerable to recent climate change via fluctuations of precipitation and temperature regime. The SRST and other communities in the area continue to thrive and experience agricultural and economic growth set against the context of warming and wetting climate, changing land management practices and other environmental challenges. In particular, the impacts of short and long-term climate change exert strong control on the water supply in the CRW. The CRW region experienced a series of wetting-cooling, wetting-warming, and cooling-drying climatic phases over last three decades resulting in uncertainty on the streamflow of the CRW. Thus, a series of hydrologic observations (snow water equivalent, soil moisture, outlet streamflow) is needed to understand CRW hydrology. In addition, a modeling framework is also needed to understand the mechanism of hydrologic change to climate fluctuations and predict streamflow accurately. Finally, a water supply forecasting framework is needed using the hydrologic model to predict future water supply for the SRST.

Project Benefits

The following benefits will emerge for the water resource director/manager of the Standing Rock Sioux Tribe from the proposed project:

1. Baseline hydrologic and climatic data for the current and future water supply study under a warming climate.
2. A compiled and tested hydrologic model (CRHM) can be used for any water supply studies in CRW under any climatic and land use change scenario.
3. A tool that can forecast of seasonal water supply for CRW.
4. Future hydrologic prediction) using the CRHM model (compiled for CRW) for the SRST CRW.
5. The proposed methodology can be used in any other watersheds of the Missouri Plateau area and SRST area.
6. Ecological benefits and hydrologic connection

Project Implementation:

The proposed methodology (field-based observations, hydrologic modeling, future hydrology prediction and forecasting spring streamflow for CRW) is described under the Method section and the time line is reported in Table 1.

Dissemination of Results:

Observation data (SWE, soil moisture, rainfall and streamflow) will be stored in the Excel file and instantly available for SRST via Excel file or UND's data repository. We plan to store this data long-term the University of North Dakota (UND's) data repository (https://commons.und.edu/) and SRST tribal website. The CRHM model has a Windows-Based Graphical User Interface that makes operation much easier. At the end of the project we will provide SRST DWR a compiled and tested CRHM model for CRW and forecasting tool so that they can use for future purposes. If needed, we will arrange CRHM workshop for the tribal DWR staffs. The scientific findings from this project will be disseminated through scientific publications and conference presentations.

Presidential and DOI priorities:

The proposed project is in line with Presidential and DOI (Department of Interior) priorities as it has addressed racial equity (water supply and recreational water resources of the tribal area), tribal benefits (described under Project Benefits), and climate crisis. The Standing Rock Sioux Tribe is one of the underrepresented communities lacking state-of-the-art observation and modeling technologies for managing their surface water resources. The proposed project will be a great start for the Standing Rock Sioux Tribe Department of Water Resources to manage and predict surface water supply from CRW using state-of-the-art observation and modeling technology.

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Standing Rock Sioux Tribe
DEPARTMENT of
WATER RESOURCES

1 North Standing Rock Avenue
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(701) 854-7214
Fax (701) 854-3077

Date: 10/10/2023

To: Department of Interior; Bureau of Reclamation Water Resources and Planning Office

Subject: Letter of Support – WaterSMART: Applied Science Grant

The Standing Rock Sioux Tribe strongly supports the application submitted by Dr. Taufique Mahmood titled, "Water Supply Forecasting of the Cannonball River Watershed" and intends to partner/commit resources as detailed in the Project Narrative if this proposal is selected for funding through the DOI BOR-NOFO No. R23AS00446.

The Standing Rock Sioux Tribe is actively working to ensure water quality and quantity to its tribal membership throughout our tribal boundaries to members living in a more rural setting and for those living within city limits and/or border towns while being considerate to our and the environment's aquatic and ecological values. The Cannonball River Watershed is one of the major sub-basins (draining through part of the Standing Rock Tribal area) of the Missouri River from which we receive our municipal water supply.

This project would support ongoing efforts performed by the Standing Rock Sioux Tribe to dial in an available water budget for our region. This project would allow us to make informed water resource decisions based on a robust physically based Cold Region Hydrologic Model of the Cannonball River Watershed.

In closing, I would like to reiterate our support and commitment to partner with Dr. Taufique Mahmood on this project.

Sincerely,

Doug Crow Ghost, Jr.
Water Administrator/Director of Water Resources
(701)854-8534

Budget Narrative

Personnel

	Name: University of North Dakota		
	Budget Year 1	Budget Year 2	Institution Total
SALARIES AND WAGES			
Principal Investigator(s)	12,153.75	12,761.44	**24,915.19**
Senior Research Engineer	16,986.32	17,665.77	**34,652.09**
Post-doctoral researcher(s)	52,000.00		**52,000.00**
Graduate student(s)	27,000.00	27,000.00	**54,000.00**
TOTAL Salaries and Wages	**108,140.07**	**57,427.21**	**165,567.28**

Principal Investigator
Dr. Taufique Mahmood, an Associate Professor in the University of North Dakota, Harold Hamm School of Geology and Geological Engineering, will commit 11% effort in each project year based on a 9-month institutional contract. The salary in the above table is based on his current salary with 5% escalation per year. Dr. Mahmood is also the founding director of North Dakota Center for Water Research. Dr. Mahmood is the project manager and will lead the overall management of the project, installation of equipment (streamflow gauge, soil moisture sensors and rainfall gauges) and cold region hydrological modeling. Dr. Mahmood will also supervise a post-doctoral researcher and graduate student. Dr. Mahmood will also commit 2 months of his time (22%) each year as a part of cost-share.

Senior Research Engineer
Mr. Tyson is a Senior Research Engineer (SRE) in the ND Center for Water Research (NDCWR) will commit two months (33% effort) of his time each year with 4% escalation per year. Mr. Jeannotte is one of the few indigenous environmental engineers in North Dakota and also an enrolled member of Turtle Mountain of Band of Chippewa Indian tribe. Mr. Jeannotte will design and conduct instrumentation (streamflow gauge, rain gauge and soil moisture sensors), data collection and instrument management. He will also be in charge of field data management and input data collection for model setup. In addition, Mr. Jeannotte will communicate with the Standing Rock Sioux tribe for different purposes.

Post-doctoral Researcher
Ms. Alexis Archambault will work as a post-doctoral researcher in this project. She is an enrolled member of the Standing Rock Sioux Tribe. She is currently a PhD candidate (PhD in

Geological Engineering with expertise in Water Resources) under Dr. Mahmood and is expected to graduate by Spring, 2024. She is also one of very few indigenous female STEM graduate students pursuing the highest degree in North Dakota. Ms. Archambault will set up the cold region hydrologic model (CRHM) for the Cannonball River Watershed (CRW) and compile the CRW model using the CRHM platform. Since the CRHM is a distributed and physically based model, it needs input parameters characterizing watershed properties such as vegetation, soil and topography. Ms. Archambault will be in charge of setting up the model and parameterizing the model at a very high spatial resolution. The post-doctoral researcher will be paid at the College of Engineering and Mines standard rate of $52,000/per year for the first project year.

Graduate Student

One graduate student will assist in instrumentation and cold region hydrological modeling. The student will develop his/her dissertation using watershed-scale data from the Cannonball River Watershed. The student will be paid at the College of Engineering and Mines standard ½ time rate of $2250 a month for 12 months each project year.

Fringe Benefits

FRINGE BENEFITS	Budget Year 1	Budget Year 2	Institution Total
Principal Investigator(s)	2,916.90	3,062.75	**5,979.65**
Senior Research Engineer	7,304.12	7,596.28	**14,900.40**
Post-doctoral researcher(s)	23,400.00		**23,400.00**
Graduate student(s)	135.00	135.00	**270.00**
TOTAL Fringe Benefits	**33,756.02**	**10,794.03**	**44,550.04**

The fringe benefit rates are 24% for Dr. Mahmood, 43% for Mr. Jeannotte, 45% for Ms. Archambault, and 0.5% for the graduate student. Amounts shown for fringe benefits are estimates determined by historical data and are provided for proposal evaluation purposes only. Actual fringe benefit costs will be charged to the grant according to each employee's actual benefits. UND's fringe benefits cover Federally mandated payroll costs including Social Security, Medicaid, and Workers Compensation. In addition, UND's fringe benefits cover health insurance and other items such as dental and vision insurance.

Travel

Travel (Year 1 & 2, FY 2024 and 2025)				
Item	Unit	$ Unit Price	Per Person	Per Trip
Lodging	3 nights	107	321	642
Mileage	700 miles	$0.655/per mile	458	458
Per diem	4 days	50	200	400
Total per trip				1500

Two members of the project team will take 2 trips a year from Grand Forks, ND to Fort Yates, ND for fieldwork, estimated at 4 days per trip. Mileage include travel to and from Fort Yates and an additional 64 miles per day for travel to field sites. Travel costs are estimated based on GSA guidelines and UND Travel policy.

Supplies

Two of the major tasks of this proposed project is to collect field observations on snow accumulations, soil moisture measurements and perform water sampling for solute measurements in Cannonball River Watershed. A breakdown of other project supplies is provided below:

Materials and supplies (Year 1, FY 2024)			
Supplies	Unit	$ Unit Price	$ Subtotal
Stream flow gauge (Pressure Transducer)	1	5,000	5,000
Rain gauge and soil moisture sensors	3	2,000	6,000
DATALOGER	1	1,000	1,000
Total			12,000

Contractual

Contracting with the Standing Rock Sioux Tribe (SRS) scientist and engineers, for assisting in field work arrangement, installation of rainfall, soil moisture sensors and streamflow gauge and collection of data. **($200/day for 35 days each year).**

Other

Tuition Remission is requested for the student working on the project. Tuition is based on the UND tuition calculator international rate of $1,090.30 per credit escalated 3% per year, assuming 18 credits per year, prorated to the student’s effort on the project. This has further been divided in half, equaling $9,960 in requested tuition remission with the College of Engineering and Mines providing a tuition waiver in the same amount as cost share.

Indirect Costs

The indirect cost rate included in this proposal is the federally approved rate for the University of North Dakota. Indirect costs are calculated based on the Modified Total Direct Costs (MTDC), defined as the Total Direct Costs of the project less individual items of equipment $5,000 or greater, tuition, and subcontracts in excess of the first $25,000 for each award. Applying the approved rate of 41% to the MTDC of $242,117, indirect costs equal $99,268.

Cost Match

Personnel

Principal Investigator
Dr. Mahmood will also commit 2 months of his time (22%) each year as cost-share. With 5% escalation in Year 2, this totals $49,828 in salary.

Graduate Student
One graduate student will work on a ¼ time basis at the College of Engineering and Mines standard rate of $1,250 per month for 12 months in Year 1.

Fringe Benefits

Fringe benefits are estimated at 24% for Dr. Mahmood and 0.5% for the graduate student. Amounts shown for fringe benefits are estimates determined by historical data and are provided for proposal evaluation purposes only. Actual fringe benefit costs will be charged according to each employee's actual benefits.

Other

Tuition Waiver
The College of Engineering and Mines will provide tuition waivers for the graduate student working on the project. Tuition is based on the UND tuition calculator international rate of $1,090.30 per credit escalated 3% per year, assuming 18 credits per year, prorated to the student's effort on the project. This has further been divided in half, equaling $9,960 in tuition waivers.

Indirect Costs

The indirect cost rate included in this proposal is the federally approved rate for the University of North Dakota. Indirect costs are calculated based on the Modified Total Direct Costs (MTDC), defined as the Total Direct Costs of the project less individual items of equipment $5,000 or greater, tuition, and subcontracts in excess of the first $25,000 for each award. Applying the approved rate of 41% to the MTDC of $76,862, indirect costs on cost match equal $31,514.

Funding Source	**Amount**
Federal Funding	$351,345
UND Cost Match (25%)	$118,336
Project Total	**$469,681**