Collecting groundwater flux and geophysical data to improve operational integrated modeling in the Socorro reach of the Middle Rio Grande

Proposal for *USBOR NOFO R23AS00446: WaterSMART Applied Science 2023*

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1. Executive Summary. 16 October 2023, Alex Rinehart, Socorro, Socorro County, New Mexico

New Mexico Tech in partnership with the New Mexico Interstate Stream Commission and the Middle Rio Grande Conservation District will conduct a series of drainage surveys to measure the flux of groundwater entering the surface water system, environmental tracer sampling surveys to partition the groundwater discharge into its different sources (return flows from irrigation, regional groundwater flow, and deep axial flows), and regional gravity surveys with geophysical inversions in the San Acacia reach of the middle Rio Grande to provide aquifer flux boundary conditions and aquifer geometry constraints for the NMISC integrated hydrological model that is being used for water management decisions. Currently, the model is largely unconstrained in discharge boundary conditions or aquifer geometry; this project fills that gap. It is critical in the face of climate-change induced changing streamflows along the Rio Grande to have correct parameterizations of the model, especially in the San Acacia reach which is the final reach of the middle Rio Grande before streamflow is delivered to Texas to meet the terms of the Rio Grande Compact. Accurate modeling using this study's data will lead to better management of water deliveries and also better management of natural flows and habitat restoration for the endangered Rio Grande silvery minnow.
Project duration of two years, beginning August 1 2024 and ending August 1 2026
Project is not located on a Federal facility.

2. Technical Project Description

2.1 Applicant Category: *Category B (University).* New Mexico Tech is proposing this work in collaboration with the New Mexico Interstate Stream Commission (NMISC) and the Middle Rio Grande Conservation District (MRGCD). *New Mexico Tech is an academic research and teaching university focused on science, engineering and technology.* Within New Mexico Tech are academic departments and programs, such as the Hydrology Program within the Earth and Environmental Science Department, and research entities like the Hantush-Deju National Center for Hydrologic Innovation, and the New Mexico Bureau of Geology and Mineral Resources.. *The NMISC has broad powers to investigate, protect, conserve, and develop New Mexico's water* including interstate and intrastate stream systems. The State Engineer is the secretary of the Commission. The NMISC is actively engaged in development and funding of projects and scientific studies to assist the management of New Mexico's river systems, including conjunctive groundwater/surface water administration. The NMISC negotiates with other states to settle interstate stream controversies, ensure basin compliance and to investigate and develop state water supplies. *The MRGCD is the only irrigation district from Cochiti Reservoir to San Antonio in central New Mexico,* where it operates, maintains and manages irrigation and drainage systems, as well as flood control.

2.2. Detailed Project Description. We propose to perform (a) integrated drain surveys with both volumetric flux measurements and environmental tracers to "fingerprint" the sources of groundwater inputs from the river, regional aquifers, and basin-scale aquifers into the Low Flow Conveyance Channel (LFCC), which is the lowest topographic drain in the region and thus serves as the inner boundary condition of the MIKESHE model, and (b) regional gravity surveys to constrain basin geometry to define the bottom and lateral bedrock boundaries of the MIKESHE model.

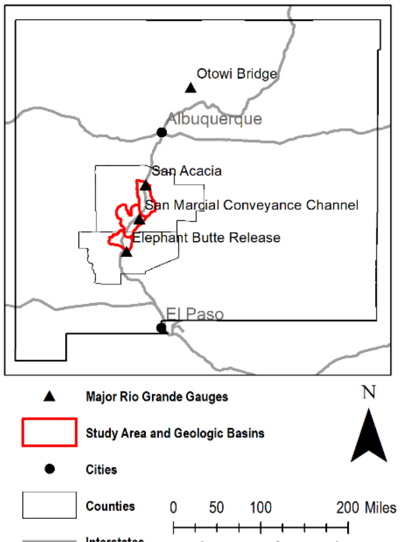

Figure 1. Overview of study area and basins within New Mexico, including key cities, Socorro (northern) and Sierra (southern) counties, and USGS Rio Grande stream gauge locations.

2.2.1. Integrated drainage and tracers survey of Rio Grande and LFCC. The LFCC forms the regional low in the basin, creating an internal boundary condition to the MIKESHE model that draws water from the river, from shallow return flow from irrigated agriculture, from lateral aquifers sourced in the higher elevation regions surrounding the floodplain, and, at the bottom of the geologic basins (Socorro, San Marcial and Engle; Fig. 2), from the deeper axial flows forced to the surface. However, despite this central role, the river rather than the LFCC is used for water deliveries. This opens the management questions of how much and when does water transfer from the river to the LFCC, what is the volume of water from other sources, and what volume is effectively returned to the Rio Grande at the LFCC outfall. The quantitative answers to these questions are the water balance and boundary conditions currently not constrained in the MIKESHE integrated hydrological model used for management.

To address these challenges, we propose to perform a series of drainage surveys of the river, the LFCC and the internal drains within the floodplain across the 2025 irrigation season (Feb. 2025 to Dec/Jan. 2025). We will use a combination of differential gauging and radon concentration measurements to quantify where and how much discharge is coming into the LFCC and other drains. To quantify the source of the water, we will sample for a suite of environmental tracers and water quality at locations collocated with the drainage surveys, as well at representative well and spring locations to develop end-member models. This work is modelled on similar work done by the team in (Williams, 2022)

Differential gauging will be used to quantify the net inflow of a gaining drain segment (or the net outflow of a losing river reach). Manual flow measurements taken across a channel cross-section using a velocimeter mounted to a handheld wading rod have proven to be effective at collecting useful discharge data in a similar study of the Albuquerque Basin (Williams, 2022). Aquatic vegetation complicates this method of stream gauging, but it is observed to be seasonal and spatially discontinuous in the study reach. By differencing the channel flow measurements at the inlet and outlet of a study reach, a precise measure of net gain/loss is obtained. In order to obtain differences that are larger than the measurement uncertainty, reaches should be hundreds of meters to several kilometers long. Campaigns to collect flow data from a series of sequential reaches during a period of steady flow, known as seepage runs, enable quantification of the spatial variability of groundwater inflows. Due to the greater effort involved in a full seepage run, we expect to only conduct one run and to focus rather on discrete reaches, at transects where water chemistry samples will be collected, during most field efforts.

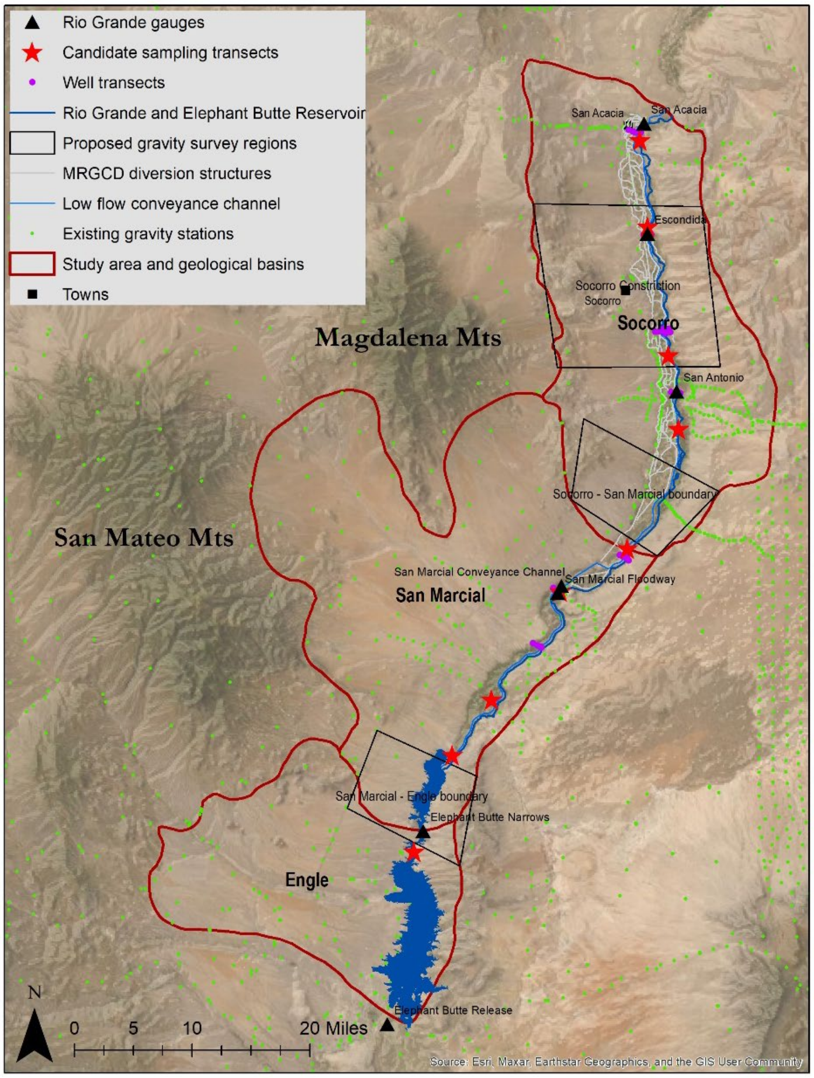

Figure 2. Proposed study area showing geologic basin (red), Rio Grande (dark blue line), LFCC (light blue line), MRGCD structures (grey line), stream gauges (black triangles), proposed sampling locations (purple stars), current gravity points (green dots), proposed gravity survey areas (black lined boxes).

Radioactive radon (Rn-222) gas is produced in the subsurface from the decay of radium-226 as part of the uranium-238 decay chain (Clark, 2015), a relatively common elements in sediments sourced from igneous terrains such as the volcanic rocks and granitoids that bound the study area (New Mexico Bureau of Geology and Mineral Resources, 2003). Rn-222 gas is then dissolved into the groundwater and swept along with it. Rn-222 has a short (3.8 day) half-life, so as it is swept along it decays, even as additional gas is produced by the surrounding sediments and dissolved (McCallum et al., 2012; Quindos Poncela et al., 2013), with the dissolved gas concentration eventually reaching secular equilibrium (Clark, 2015). In surface water where groundwater is discharging, the radon concentration reflects a balance of groundwater discharge at secular equilibrium, upstream inheritance, and exsolution of the radon gas into the atmosphere, These processes can be modeled based on site-specific data or calibrated at controlled sites to provide a more robust estimate discharge rates (McCallum et al., 2012).

We will estimate radon concentrations by sampling 250 mL of water in a zero-head space bottle from each of the sites, noting the time, and then using a Durridge RAD AQUA degassing apparatus with the RAD7 detector in the laboratory, applying WAT250 protocol (Durridge RAD7 User Manual); measurements will begin at the end of every field sampling day.

Geochemical and isotopic tools can be used in several different ways for water source apportionment studies. Species that can reasonably be expected to behave conservatively (i.e. persist without chemical or biological modification) in a given setting may be used as tracers of water sources, so long as their concentrations are distinct in contributing endmembers (Vengosh, 2003). In this study, we will use chloride (Cl-), bromide (Br-), stable isotopes of water (δ18O, δ2H), and 87Sr/86Sr isotopes to build our quantitative mixing model of the different sources of groundwater fluxes into the LFCC and internal drains (Williams, 2022). These tracers are commonly used because of their more conservative behavior under many conditions (Négrel et al., 1997; Shin et al., 2020; Vengosh, 2003; Zhang et al., 2021), and the use of multiple tracers, as well as supporting geochemical evidence from general water chemistry can help identify non-conservative behavior in potential tracers and better constrain mixing models.

To account for possible seasonal changes related to irrigation practices and monsoon rainfall, samples will be collected during pre-, early, mid, and late irrigation times, as well as mid-monsoon. At every sampling location, water quality field parameters (temperature, pH, ORP, specific conductivity, and chloride) will be measured at the gauging and sampling locations using a YSI EXO1 multiparameter sonde. Samples for general water chemistry, stable isotopes of water, and trace element analysis will be collected using the standard methods of the United States Geological Survey (Chapter A6. Field Measurements, 2008), and analyzed in the Analytical Chemistry Laboratory of the New Mexico Geological Survey. Samples for strontium isotopes will be filtered through 0.45 micron filter paper, collected in HDPE sample bottles, and sent to the University of Texas El Paso for 87Sr/86Sr analysis.

Once analyzed, tracer data will be used to create a quantitative mixing model of waters contributing to flow in the LFCC using MixSIAR- a framework for creating Bayesian mixing models in R (Stock et al., 2020). Bayesian models have several advantages over the traditional strict mass balance approaches, including the ability to better incorporate variability in source and mixture composition and relief from the tracer/end-member ratio constraints (Stock et al., 2018). The MixSIAR framework is robust and flexible enough to handle a variety of inputs and research questions in a variety of hydrologic applications (Birkel et al., 2021; Kay et al., 2021; Li et al., 2022).

Sampling and gauging locations will be finalized in consultation with the ISC and MRGCD staff. Preliminarily, we will plan on performing gauging and sampling at up to nine (9) transects (Fig. 2). These will consist of measurements at the northern and southern ends of each hydrogeological basin, along internal sampling in each basin. Locations will also be chosen to enable use of secondary long-term information (e.g., well transects, gauging stations, …) that can generalize our results from a single irrigation season for longer periods.

2.2.2. Gravity survey to characterize basin geometry. As detailed below, the bottom boundary of groundwater models impact persistent, volumetrically significant fluxes and flow directions of water into and out surface water bodies. It is not logistically possible measure the thickness of aquifer material in deep, extensional basins via direct drilling; geophysical methods are employed. These range from passive and active seismic (Finlay et al., 2020; Grauch and Connell, 2013; May et al., 1994; Russell and Snelson, 1994), aeromagnetic surveys (Grauch et al., 2009; Grauch and Connell, 2013; Grauch and Hudson, 2007), different varieties of terrestrial and airborne transient electromagnetic surveys (Grauch et al., 2009) , and gravity surveys (Grauch et al., 2009; Grauch and Connell, 2013). Gravity surveys are commonly used due to their low-cost and their direct reflection of variations in basin-fill thickness with some standard inverse modeling (Blakely, 1995; Grauch and Connell, 2013; Hinze et al., 2013).

Regional gravity surveys have been used since the 1950s to map subtle variations in the gravitational acceleration (Hinze et al., 2013). Because the gravitational acceleration at a point is a direct function of the density of material around it, spatially distributed measurements of the acceleration of gravity can be used to develop three-dimensional maps of density contrasts, such as between unconsolidated sediment and basement rocks, or between different densities of sedimentary rocks, for example (Blakely, 1995; Grauch and Connell, 2013; Hiebing et al., 2018; Shah and Boyd, 2018).

In our application, we will be estimating the contact between unconsolidated to poorly consolidated sediments of the Santa Fe Group aquifer (including alluvial fan, ancestral Rio Grande, and playa deposits), and the underlying Oligocene-aged volcanic rocks (New Mexico Bureau of Geology and Mineral Resources, 2003). The volcanic rocks overlie a series of Mesozoic and Paleozoic-aged sedimentary rocks (~5000 ft thick) that lay on top of Precambrian granites and metasedimentary basement rocks (Gallant et al., 2022; Jochems, 2015; Koning et al., 2020b). This target is similar to Grauch and Connell (2013)'s work in the Albuquerque basin estimating the thickness of basin-fill using gravity data.

To constrain gravity surveys, the geology must be understood. Throughout the San Acacia reach, geological mapping has been completed (Cikoski et al., 2017; Jochems, 2015; Koning et al., 2020b, 2020a) and is currently being compiled in the Socorro basin (D. Koning, in preparation). This mapping has been limited to mostly surface interpretations due to the lack of subsurface and geophysical data. In previous work, senior personnel on this proposal have undertaken regional gravity surveys in the San Acacia area (A. Rinehart and R. Chamberlin, personal communication) and near the abandoned town of San Marcial (Gallant et al., 2022). In addition to these recent surveys, there has been reasonable historical coverage of gravity surveys throughout the region (Fig. 2). This data is publicly available on request from UTEP.

To understand the underlying geological structure, it is necessary to focus on gravity variations from subsurface structure. To do this, it is common to examine the data in the so-called complete, or terrain-corrected Bouguer anomaly, which applies standard corrections for latitude, tides, elevation, standard density of the underlying crust and the impact of surrounding terrain (Hinze et al., 2013). The remaining gravity anomaly 'images' the deviations from these known effects (Hinze et al., 2013). Additional processing to remove the regional bedrock signals from the Bouguer anomaly to focus on basin-fill thickness can be performed (Barbosa and Silva, 2011; Blakely, 1995; Gallant et al., 2022; Grauch and Connell, 2013).

When examining the recent and historical gravity data coverage, three gaps appear in the data at (1) the Socorro accommodation zone, (2) the boundary between the Socorro and San Marcial basins, and (3) the boundary between the San Marcial and Engle basins (Fig. 2). This requires ~50 new gravity measurements to achieve a ~1 km to ~1.5 km spacing to image these transitional zones; these measurements will generally be performed along roads for simplicity. We will follow the methods and use the same equipment as described in (Gallant et al., 2022), where relative gravity measurements are tied into an absolute gravity base station network established by the National Geospatial Intelligence Agency.

Once the data has been collected and reduced to the relevant anomaly, approximate thicknesses can be determined either from comparison to similar geological locales, such as (Grauch and Connell, 2013) or by geophysical modeling of the cross-sections or the three-dimensional structures imaged by the gravity, using density models based on the regional geology and local geological mapping. We will use the internationally developed, open-source Harmonica software (Fatiando a Terra Project et al., 2023). By inverting the anomaly that is focused on basin-fill thickness, we then will be able to construct quantitative maps of the depth-to-bedrock.

3. Water Management Challenge

3.1. Overview. The Rio Grande is a highly managed river that feeds a large agricultural area and the largest population center in New Mexico (Fig. 1). It is experiencing increased duration and severity of drought (low-flows) – due to climate change causing decreased snow-packs in its headwaters and increased evapotranspiration throughout – coupled with interstate river compact delivery and Endangered Species Act compliance requirements. To meet this challenge, the NMISC developed an integrated hydrological model within the Middle Rio Grande (from Cochiti Lake Reservoir 40 miles north of Albuquerque to Elephant Butte Reservoir; Fig. 1) on the MIKESHE platform. This model, which is licensed to NMISC by DHI Water & Environment, Inc, (Colorado, USA) adapts insights and boundary conditions from previous surface water (https://www.spa.usace.army.mil/Missions/Civil-Works/URGWOM/) and USGS-constructed MODFLOW groundwater models (Bexfield et al., n.d.). Within the Middle Rio Grande, the San Acacia reach (San Acacia to Elephant Butte) is vital for deliveries to Texas (Fig. 1). It contains the Low Flow Conveyance Channel (LFCC; Fig. 2), a deep drain next to the Rio

Grande that was constructed to provide more efficient conveyance of water from New Mexico to Texas (Phillips et al., 2015). Because there have been no diversions into the LFCC since 1985 (Phillips et al., 2015), it acts as the sink of groundwater from adjoining aquifers and the Rio Grande. There are three separate geologic basins that complicate groundwater flow paths, particularly those of the alluvial aquifer and deeper flow paths (Fig. 2). The deeper flow paths include both axial flow and transverse flow sourced from surrounding highlands (Fichera et al., 2023).

The San Acacia reach has many unique features that the MIKESHE model should incorporate to provide more accurate results. These features include the USFWS Bosque del Apache Wildlife Refuge (BAWF), a region of geothermal upwelling warm waters near the BAWF and just south of the study area (Barroll and Reiter, 1995; Mailloux et al., 1999; Pepin et al., 2016; Reiter, 1999), and a reach of the Rio Grande that has ongoing sedimentation and drying concerns from the BAWF through the 'Narrows' in Elephant Butte (G. Haggerty, personal communication). These factors are of critical concern for MRGCD water management and the NMISC effort to ensure sufficient water flow to Elephant Butte Reservoir. The lack of knowledge in how these features interact with geology and groundwater make managing surface water a challenge in the San Acacia reach, which is one of the reasons the MIKESHE model has been developed here.

An additional management challenge is balancing human-use-driven and interstate water deliveries with the protection of the Rio Grande silvery minnow, an endemic endangered species. In the early 1990s, the Endangered Species Act was used to control flows in the Rio Grande in order to provide habitat for the species (Phillips et al., 2015). Since then, a series of infrastructure and habitat restoration projects have taken place to protect the species (Cowley, 2006). Nonetheless, low river flows from ongoing drought threaten these efforts (Archdeacon et al., 2020), creating a need for accurate water management simulations throughout the middle Rio Grande and especially in the San Acacia reach.

Despite both the need for efficient water deliveries and the increasing complexities throughout the San Acacia Reach, *very little data is available to constrain and calibrate the MIKESHE model*. Current subsurface aquifer structure is constrained in the northern half of the reach by (Anderholm, 1987). Other than sparse gravity data and a more detailed gravity study that did not model specific depths to bedrock (Gallant et al., 2022), geophysically based constraints on aquifer structure is poor south of BAWF, despite crossing through two more geological basins (Fig. 2). Additionally, only a handful of gauges and well transects exist in the reach for calibration (see Fig. 2).

The MIKESHE model is becoming one of the NMISC's primary tools to planning and managing water distribution and deliveries throughout the Middle Rio Grande, for planning and managing responses to drought, and for understanding how hydraulic changes to the system will change delivery efficiency. Additionally, it will be the primary tool for quantifying conjunctive management of surface water and groundwater resources. In the San Acacia reach, the lack of constraint of different water fluxes (riparian, agricultural return flows, lateral midlevel groundwater, and deep, salt-rich groundwater) into the main ditch delivering water means that the model will not be robust under different conditions, particularly as climate change alters the flows in the river (Dunbar et al., 2022). Similarly, subsurface aquifer structure represented in the model is key to rigorously representing groundwater inputs into the surface water system (Anderson et al., 2015). The model cannot represent a physical system when its input data, such as geologic structure and deeper groundwater flow paths, is limited and poorly defined.

3.2. Water use, distribution and management under changing climate. The snowmelt-fed Rio Grande flows entirely in arid and semi-arid valleys from southern Colorado through New Mexico into Texas and Mexico, eventually emptying into the Gulf of Mexico. Within the middle Rio Grande, extending from Cochiti Reservoir to Elephant Butte Reservoir in central New Mexico (Fig. 1), it is the primary source of freshwater, providing water for a broad range of uses including agricultural, municipal, domestic, and industrial uses. However, ~80% of its water is used for agriculture within this reach via surface water irrigation as distributed by the MRGCD (Magnuson et al., 2019). South of Elephant Butte, the Rio Grande and conjoined aquifers are the source of water for one of the nation's largest pecan producing regions, in addition to a variety of other crops that include the iconic Hatch green chile.

Because the Rio Grande crosses state and national boundaries, it is governed by an interstate compact, the Rio Grande Compact, which requires deliveries from upstream states to downstream states. Written in the 1930s and still the subject of litigation, the Rio Grande Compact has a long and complicated history. New Mexico is legally obligated to deliver ~43% of the flows gauged at Otowi gauge to Texas (Phillips et al., 2015; https://sourcenm.com/2023/07/11/judge-oks-states-plan-to-end-rio-grande-dispute/), as gauged at the inlet to Elephant Butte Reservoir, despite Elephant Butte Reservoir being in New Mexico (Fig. 1). Additionally, federal courts require the protection of the endangered and endemic silvery minnow in the Middle Rio Grande. Within the New Mexico Office of the State Engineer, the New Mexico Interstate Stream Commission is responsible for maintaining flows for the silvery minnow and delivery of compact waters to Texas.

In the San Acacia reach, irrigation is the primary consumptive use of surface water and groundwater (87,000 acre-feet surface water, 27,000 acre-feet groundwater) followed by reservoir evaporation (7,570 acre-feet) and municipal and domestic supply (60 acre feet surface water, 2,700 acre-feet groundwater) (Magnuson et al., 2019). *However, the entire volume of water delivered to the Lower Rio Grande and Texas passes through this reach.* This creates a conundrum: how to ensure water delivery for interstate compact requirements while also delivering water to local rights holders. Challenges facing delivery include maintaining river flows to comply with the endangered species act, sedimentation of the river raising the riverbed and accelerating groundwater flow from the river to the LFCC and adjoining groundwaters, and river bed drying – even as the LFCC and often irrigation canals continue to flow. In the

Albuquerque basin to the north, previous work has found that a small, but significant and persistent amount of groundwater is discharged into the riverside drains and then into the river. Extensive evidence exists of similar sources of water in the San Acacia reach (Hogan et al., 2007; Phillips et al., 2003) along with geothermal waters (Barroll and Reiter, 1995), but *no data exists quantifying proportions and partitioning of different sources of groundwater, which is needed for the operational MIKESHE model to be calibrated and used.*

The Rio Grande basin in general has been in an extended period of drought since 2000 (Williams et al., 2020). This has led to a series of extreme low flow events along the Rio Grande (Dunbar et al., 2022). Normal allocations along the Middle Rio Grande are ~3.5 acre-feet/acre of irrigated lands (A. Marken, MRGCD, personal comm.). However, since 2010 it has become common to have reduced allocations, two years have experienced allocations of < 0.5 acre-feet/acre of feet (A. Marken, MRGCD, personal comm.). During such reduced diversions, irrigators move to irrigating with groundwater (A. Marken, MRGCD, personal comm.), dropping the water table and likely increasing the flow of water from the river into the adjoining aquifers – and making deliveries even harder. This would similarly decrease the contribution of groundwater to the LFCC and thus the water delivery to Texas. *A lack of drainage surveys and of constraint on the mixed sources of discharge (return flows and river water vs. regional aquifers vs. deep basinal brines) makes management of water during drought challenging and highly uncertain.*

There is no relief in sight for the drought. With climate change, the Rio Grande basin has been *experiencing increasing temperatures and diminishing headwater snowpack – streamflow will likely decrease or, at best, become more intermittent* (Dunbar et al., 2022) *as climate changes.* Diminishing surface water supplies will increase reliance on groundwater – with the complications described above – and additional legal pressure on New Mexico from local water rights owners and from the Rio Grande Compact members. This emphasizes the need for robust, physically based integrated models that can capture the connection between the river, different engineered drains and canals, agriculture and other water uses, and regional and deep groundwater flow. And such models need *accurate, unequivocal data on the amount and source of groundwater flowing into surface for calibration.*

3.3. Regional hydrology and data gaps. The San Acacia reach is formed by a perennial to intermittent trunk river (i.e., the Rio Grande) within a narrow valley flanked by ephemeral tributaries. The region has semi-arid to arid climate with relatively dry winters and a short rainy season from July to mid-September. All irrigation is provided from surface water diversions or groundwater sources; precipitation provides relatively insignificant volumes of water directly.

The size of aquifers underlying and adjoining the surface water infrastructure and river is controlled by the regional geology. The Rio Grande valley is comprised of a series of extensional tectonic basins that are each 40-100 km long and 10-60 km wide. In the San Acacia reach, there are three basins: Socorro basin, San Marcial basin and Engle basin. These basins are filled by large thicknesses of sands, gravels and muds which form the Santa Fe Group aquifer (Bexfield and Anderholm, 2000; Johnson et al., 2013; Spiegel and Baldwin, 1963). The aquifers thin gradually to abruptly towards their respective boundaries. At inter-basin boundaries, existing gravity data suggests bedrock is relatively high, consistent with exposed geology at the basin margins near these boundaries that focuses all groundwater flow to the surface water (Hogan et al., 2007; Phillips et al., 2003; Williams, 2022).

The basins are fault-bounded and have one or two up-thrown side(s) forming a series of bounding mountain chains (New Mexico Bureau of Geology and Mineral Resources, 2003). For the San Acacia reach, these include the Socorro-Lemitar mountains (5700-7000 ft amsl; not labeled), the Chupadera (5700-6300 ft amsl; not labeled) and Magdalena Mountains (8,000-10,000 ft amsl; Fig. 2), and the San Mateo Mountains (8,000-10,000 ft amsl; Fig. 2). These regions provide a source of deep (1000s ft) and midlevel (100s ft depth) groundwater that is generally flowing towards (transverse), oblique, or subparallel to the north-south axis of the central valley (Bexfield and Anderholm, 2000; Fichera et al., 2022; Rawling, 2023). While the mountains have proven to drive groundwater flow in neighboring basins and geochemical evidence in the Socorro basin indicates that it is likely occurring there (Fichera et al., 2022), *lack of data results in this being unproven in the San Marcial and Engle basins*.

The location and geometry of the basins is poorly constrained. The thickness and basin boundaries of the Socorro basin in the MIKESHE model are based on historical gravity surveys that were incorporated into the only systematic study of the Socorro basin hydrogeology (Anderholm, 1987); this has not been updated with modern measurements. The MIKESHE model in the San Marcial and Engle basins is a rough approximation based on engineering judgment – not data. That is because 1:24,000 geologic mapping (see above) and detailed geophysical surveys (Gallant et al., 2022) have only recently been conducted in these basins.

There are also a handful of studies of groundwater/surface water interactions (McLain, 2022) leveraging a series of shallow well networks installed in the late 2000s in transects from San Acacia to Fort Craig from the river out across the LFCC and into the floodplain. Ultimately, these studies have shown that there is a strong connection between the river, the LFCC and the shallow alluvial aquifer, but have not disaggregated other fluxes or been put in a larger hydrogeological context – *because of the lack of tracer and geophysical data*.

Hogan et al. (2007) document a series of longitudinal studies from the headwaters of the Rio Grande to the Ft. Quitman, TX, where the river goes dry. In these studies, the river, LFCC and some tributaries were sampled for stable and radiogenic isotopes, and the salt content and chloride concentrations were measured. Within the San Acacia reach, the primary observation was that the chloride concentration increased at the southern (down-gradient) ends of the hydrogeological basins, though Engle basin remained enigmatic given that Elephant Butte Reservoir filled into the basin during the survey, masking groundwater inputs (Hogan et al., 2007; Phillips et al., 2003; Szynkiewicz et al., 2011). These studies formed the basis for similar studies focused on endogenous sources of groundwater near San Acacia (Williams et al., 2013;

Wolaver et al., 2013), and quantifying sources of groundwater discharge into the river and riverside drains in the Albuquerque basin (Williams, 2022). However, the original studies do not have the needed spatial or temporal resolution, nor the necessary suite of tracers to quantify sources of groundwater discharge within the San Acacia reach.

3.4. Current MIKESHE model representation, data sources and data gaps. The current implementation of the MIKESHE model in the Middle Rio Grande captures detailed physical representations of diversions, irrigation, canal and drains, river dynamics, and groundwater flow, along with a simplified representation of unsaturated zone processes. However, the 3D model domain is based on previous, geophysically-based maps of basin-fill thickness and geology, and the model parameterization is based on calibrations of other models based on existing data such as water levels, water chemistry and tracers, pump tests, and others.

As shown above, this data is largely non-existent in the San Acacia reach, particularly south of the Bosque del Apache. *This was acknowledged by the modeling team contracted with the NMISC during a series of meetings in September 2023 and this data gap is the primary reason for this application*. The model lacks controls on subsurface geometries, and lacks constraints on groundwater/surface water fluxes through the system. By coupling gravity surveys with drainage and environmental tracer surveys, this proposed work will provide a first, critical set of data on the model domain and its boundary conditions *explicitly needed by the model but currently missing*.

4. Project Benefits

On 9 August 2023, the New Mexico Bureau of Geology and Mineral Resources hosted a workshop with interested university researchers, NMISC staff, MRGCD staff, and the consultants who are developing the MIKESHE model of the middle Rio Grande. During the workshop, several major gaps in data were identified. Following the meeting, we participated in a series of coordination meetings throughout September with MRGCD and NMISC staff to identify which projects they would support with cost-match to fill the major gaps of data and knowledge in the MIKESHE model in the San Acacia reach that limit its usefulness for water management, conjunctive management of surface water and groundwater resources, and drought management. Again, if the model is not calibrated to different sources of water to the LFCC and river, and does not realistically represent the adjoined aquifers, it cannot be expected to realistically represent the system under normal operational conditions, much less drought and changing climate conditions.

During the coordination meetings, we proposed a series of gravity surveys in critical gaps of historical data, and a series of drainage surveys through an irrigation season of the LFCC and interior drains that include differential gauging and radon dissolved gas concentration sampling to estimate groundwater discharge, and a suite of co-located environmental tracer (stable isotopes of water, Sr-isotopes, trace and general chemistry) samples would be collected. The geophysical survey will constrain subsurface bedrock topography. The drainage survey will quantify volumetric fluxes and proportional sources of groundwater into the drains. The drain survey would be implemented beginning in January 2025, between irrigation seasons, and completed the following year (January 2026). The gravity surveys will be conducted in Summer 2025, followed by reduction and analysis of the data into a useable format.

This data will be synthesized and provided to the NMISC, MRGCD and their contractors at the end of the project. The data will then be used, with support from the investigators, to constrain the geometry of the groundwater model of MIKESHE, and to calibrate the model. The addition of this data will increase the fidelity and robustness of the MIKESHE model as it is used to predict and understand how to deliver water to irrigators in the San Acacia reach and how to make the legally required surface water deliveries to Elephant Butte Reservoir from New Mexico to Texas.

Because of the increasing shortage of water and the ongoing drought in the region (Dunbar et al., 2022), we expect this data to be a critical first step in the calibration of a robust, physically based model representation of the reach that ties the riparian corridor (river to LFCC) to the floodplain (irrigated regions and distal riparian forest and wetlands) and to the regional aquifer systems. Given the NMISCs role in managing the river, the improved representation of the surface water/groundwater system in the model should increase the responsible management of the resource for all of the basin's stakeholders, as well as the state of New Mexico; this study, however, is of primarily regional interest.

5. Project Implementation

In this study, we are proposing to collect data to constrain an integrated hydrological model in MIKESHE platform that is used by NMISC for water management decisions along the San Acacia reach of the middle Rio Grande. The current MIKESHE model is missing constraints on boundary conditions for groundwater discharge into the LFCC and surface water system, and on the subsurface geometry of the aquifer system throughout the San Acacia reach. To provide the boundary conditions and subsurface geometry, we will

1. Conduct differential and radon-based drainage surveys of the LFCC, river and internal drains across the San Acacia reach to estimate groundwater fluxes into and out of the different surface water features.
2. Conduct water quality and environmental tracer sampling coincident with the gauging; these samples will be analyzed for major and trace elements, δ18O, δ2H, and 87Sr/86Sr in order to develop a quantitative mixing model of the different sources of groundwater fluxes into the LFCC and internal drains.
3. Conduct and interpret regional gravity surveys at current gaps in data at the Socorro Constriction, the Socorro-San Marcial basin boundary, and the San Marcial-Engle basin

boundary; estimates of basin-fill thickness and identification of internal structure will be done in the Harmonica software platform.

The results of this study along with the raw data will be provided to the NMISC and MRGCD staff in the form of reports and in presentations to them. In addition, data will be provided in machine readable format with complete metadata through the water data catalog, with the NM Water Data Initiative (https://catalog.newmexicowaterdata.org/). This state supported data catalog is also utilized for other WaterSMART projects, improving findability of water data from regional, state and federal sources relevant to water management and planning.

6. Tasks and Milestones.

There are two separate tasks for this study:

1. Synoptic drain surveys with integrated gauging and environmental tracer sampling.
2. Regional relative gravity survey of San Acacia reach.

The milestones for this study are as follows, assuming the start of the project is August 2024:

- August 2024. Initiation of project with initial virtual kick-off meeting with NMT team and NMISC and MRGCD collaborators.
- October 2024. Identification of the location of absolute gravity base stations, and submission of permit applications to BLM and/or USFWS for establishment of absolute gravity base stations.
- January 2025. Finalization of water quality sampling, gauging and radon sampling plan, including trial field testing with students and staff. Submission of permits for absolute gravity stations to be established. Work with federal collaborators to establish new absolute gravity base stations, pending granting of permits.
- February 2025. Pre-irrigation synoptic sampling event (including differential gauging, water sampling and radon analysis).
- April 2025. Early irrigation season synoptic sampling event. Finalization of gravity survey design.
- May 2025. Initiation of regional relative gravity surveys.
- June/early July 2025. Mid-irrigation season synoptic sampling event.
- Late August/ early September 2025. Monsoon season synoptic sampling event. Completion of regional relative gravity field surveys and absolute gravity measurements.
- Late October/ early November 2025. Late irrigation season synoptic sampling event. Finalize gravity data reduction.
- January 2026. All tracer data analyzed. Initial geophysical model development.
- May 2026. Mixing model and geophysical model completed.

- August 2026. Completion of project with delivery of summary report, data, and a final team meeting to communicate results to NMISC and MRGCD.

7. Products

The results of this study are summarized in Table 1. Data results will be provided to partners and also archived at the New Mexico Water Data Initiative. Synthesis of drain surveys will be in the form of mixing analyses tied to volumetric flux rates for all of the surveys, as well as a report, peer-reviewed publication and at least one conference presentation. Similarly, the gravity survey data will be synthesized in georeferenced maps of gravity anomalies and estimated basin-fill thickness, which will be discussed in a completion report focused on the needs of our partners, a peer-reviewed publication and at least one conference presentation.

Table 1. Summary of products from proposed study.

Description	Type	Use
Differential gauging results	Data	Model calibration
Radon gauging results	Data	Model calibration
Stream chemistry (general chemistry and trace elements)	Data	Model calibration
Stream water isotope content	Data	Model calibration
Mixing model of discharge sources	Analysis	Model calibration
Compilation of existing gravity data	Data	Primary source
New relative gravity survey data	Data	Primary source
New absolute gravity survey data	Data	Primary source
Contour map of gravity anomaly	Analysis	Model geometry
Raster of estimate basin-fill thickness	Analysis	Model geometry
Synthesis report linking gravity, drainage and tracer surveys	Communication	Communication with partner organizations
Peer-reviewed manuscript based on report	Communication	Communication with broader water management
Regular meetings with partner organizations	Communication	Communication with partner organizations
Kick-off and final meeting with partner organziation	Communication	Communication with partner organizations
Presentation at NM Water Conference and one international water conference	Communication	Communication with broader water management

8. Partners

The proposers are partnering with the NMISC (New Mexico Interstate Stream Commission) and the MRGCD (Middle Rio Grande Conservation District). These entities work closely together to manage the water along the Rio Grande and have begun focusing on improving informed management in the San Acacia reach. Both partners will be closely involved in the final planning process of the surveys, helping choose and give access to sites. MRGCD will provide field support, with their teams performing part of the differential gauging and water sampling during the synoptic sampling events, as well as access to their database of operational data to aid in interpretations. In addition to planning, we will be holding quarterly meetings with them and their contractors to better tie our survey results and locations to their management questions. They will also provide access to new water measurement infrastructure (new gauging stations and well water level measurements) they are installing along the San Acacia reach that will better inform our work.

9. Personnel

Dr. Alex Rinehart (PI) is the hydrogeodesy focus lead for the National Center of Hydrological Innovation and an assistant professor of hydrology at New Mexico Tech. He will oversee the overall project, including supervising reporting and field methods, organizing meetings, and be involved with hiring additional students. He is also the task lead for the gravity surveys. Rinehart has nine years of professional experience in hydrology geophysics. Of direct relevance to this project, he has led gravity surveys (Gallant et al., 2022; Robertson et al., 2023), synoptic water sampling surveys (Fichera et al., 2022; Williams, 2022) and basin-scale hydrogeological studies (Koning, Daniel J and Rinehart, 2021; Pepin et al., 2022; Rinehart et al., 2020), geological mapping (Allen et al., 2013; Rinehart et al., 2014), and hazard assessments (Koning et al., 2019; Rawling and Rinehart, 2018; Rinehart et al., 2017) throughout New Mexico, including winning the national AASG John C. Frye award for his part of estimating aquifer lifetimes in the Southern High Plains (Rawling and Rinehart, 2018). He is able to begin work on this project immediately upon award.

Dr. Rachel Coyte is a new Assistant Professor of Hydrology at NMT with expertise in hydrogeochemistry. She will oversee the proposed water sampling and quantitative mixing model development for source water contributions to the LFCC. She has conducted field campaigns for surface and groundwater sampling in North Carolina and India, Ohio, and New York (Coyte et al., 2020, 2018), and worked as collaborator on multiple studies of relevance to this proposal, including using geochemical and isotopic tracer data to infer hydrogeochemical processes(Coyte et al., 2019; Ni et al., 2018) and developing mixing models for source apportionment (Vengosh et al., 2022; Wang et al., 2021). She will be able to begin work immediately on this project upon award.

Dr. Daniel Cadol (Co-PI) is an Associate Professor of Hydrology at NMT, and Director of the Hydrology Program within the Earth and Environmental Science Department, with expertise in surface water hydrology and fluvial geomorphology. He will oversee the proposed differential flow gauging, having likewise supervised this aspect of a similar study in the Albuquerque basin (Williams, 2022). He has supervised two other recent studies focused on shallow groundwater-surface water interaction in the San Acacia reach (McLain, 2022; Roussel, 2022). He is also the lead collaborator on a project with the Bureau of Reclamation S&T program to develop new surrogate methods to monitor sediment delivery to the Rio Grande from ephemeral tributaries. He is able to begin work on this project immediately upon award.

Daniel Koning is a Senior Field Geologist at the New Mexico Bureau of Geology at New Mexico Tech. He has over 25 years of professional experience performing field mapping and geophysical surveys, much of it on the structure, stratigraphy and sedimentology of the rift basins of the Rio Grande (Cikoski et al., 2017; Gallant et al., 2022; Grauch et al., 2009; Koning, Daniel J and Rinehart, 2021; Koning et al., 2020c, 2019). For this study, he will be supporting the geophysical surveys and interpretation of the geophysical data to understand the geological structural controls on groundwater flow and basin geometry. This is consistent with his long-term research, and is reflected in a recent publication on the structure of the San Marcial basin based on gravity data collected with Dr. Rinehart. Koning has been awarded the GSA Florence Bascom Geologic Mapping Award in recognition of his excellence and dedication to field mapping, and the AASG John C. Frye award for his work linking the geology surrounding a community to its long-term water management future.

A graduate student for the drainage and tracer tasks, and up to two undergraduate (on matching funds) for the gravity surveys will be recruited to work on this project. Graduate students with a successful academic record in environmental science or geosciences will be recruited, with preference given to students with a background or interest in aqueous chemsitry. Undergraduates will be recruited from rising juniors from physics or geoscience degrees with a proven record of detailed, conscientious work.

10. Dissemination of Results

Results will be disseminated to the NMISC and MRGCD partners throughout the project during regular planning and update meetings, and in final forms as two reports summarizing the methods, results and conclusions of the synoptic drain survey and the regional gravity survey. Direct communication about the results will be shared with NMISC and MRGCD with an end-of-project remote workshop, where partner staff and contractors will be able to discuss with the academic team how exactly the data can appropriately be incorporated into the MIKESHE model. Water data and quantitative synthesis (i.e., mixing models) will be provided in Excel spreadsheets and in a geodatabase to the NMISC and MRGCD, and will also be archived in the New Mexico Water Data Initiative database. Gravity data and results will be provided directly to the partners as a geodatabase as well as Excel spreadsheets, and will be archived at the New Mexico Bureau of Geology. In addition, we will hold an online workshop with the NMISC and MRGCD staff and their contractors. More broadly, the results of our work will be shared with regional water managers at the New Mexico Water Conference and the New Mexico Water Data Workshop, and to the broader water management community at a national water manager conference such as the AWRA Annual Conference or the annual NGWA Water Week meeting. The results of this study will also be in at least one peer-reviewed publication.

11. Alignment with Presidential and Department of Interior Priorities

The proposed work will directly inform MRGCD operations and will constrain the integrated hydrological model in the San Acacia reach. The majority of flow in the Rio Grande is from annual snowmelt in its headwaters in northern New Mexico and southern Colorado. For the last twenty years, this region has been in chronic drought, thought to be worsened by ongoing climate change. Snowpack in these headwaters shifted from annual to intermittent/ephemeral as early as 2005 (Mote et al., 2005) and snowmelt is predicted to shift earlier in the season, decreasing the effective run-off in the Rio Grande (Dunbar et al., 2022; Musselman et al., 2018, 2017). Future projections in the region reveal a rapidly decreasing streamflow trend in the Rio Grande, which will increase the importance of capturing groundwater inputs into the surface water system (Dunbar et al., 2022).

By providing more realistic constraints to the geometry and flux boundary conditions of the MIKESHE model in the San Acacia reach will allow it to more robustly predict or mimic the effects of more sporadic and diminishing streamflows. The MIKESHE code is a physics-based program, developed to be able to address changing conditions as well as to predict under the current regime. But that ability is dependent on accurately representing the boundary conditions and geometry of the domain correctly – the exact goals of the data collected in this project.

The communities along the middle Rio Grande are majority Hispanic and are underdeveloped economically. The San Acacia reach of the Rio Grande is entirely within Socorro County, a rural, majority Hispanic and agricultural county whose school districts are 100% Title I – effectively every child is eligible for food stamps. By increasing our ability to better manage water along the Rio Grande by having a better constrained integrated hydrological model, these communities will have more reliable, or at least better informed, access to water for their traditional uses.

12. Goals

1. To estimate the basin-fill aquifer thicknesses via the incorporation of new gravity surveys with historical gravity data and corresponding modeling across the San Acacia reach of the Rio Grande, spanning the Socorro, San Marcial and Engle hydrogeological basins.
2. To quantify the spatial and temporal variations in groundwater fluxes via differential discharge gauging and radon concentration synoptic surveys in the LFCC, the river and internal drains over the course of the 2025 irrigation season.
3. To quantify the source (river, irrigation return flows, deep axial groundwater discharge, or lateral groundwater inputs from recharge areas) of groundwater discharges into the

LFCC via mixing analysis using a suite of environmental tracers collected in conjunction with the synoptic drainage survey.

13. Project budget

The overall project budget is summarized in Table 2. A granular budget and budget justification are found attached in the application package.

Table 2. Summary of budget.

FUNDING SOURCES	AMOUNT
Non-Federal Entities	
1. New Mexico Tech	$196,862
Non-Federal Subtotal	$196,862
REQUESTED RECLAMATION FUNDING	$196,862

14. Data Management Practices

All data will be collected, stored and distributed in an ESRI geodatabase, with separate geodatabases for the drainage survey, tracer survey and gravity survey tasks.

15. Overlap and Duplication of Effort Statement

There is no overlap between the proposed project and any other active or anticipated proposals or projects in terms of activities, costs, or commitment of key personnel.

16. Conflict of Interest Disclosure Statement

The PI has no actual or potential conflict of interest in the proposed effort.

17. Uniform Audit Reporting Statement

The NMT audit is available through the Federal Audit Clearinghouse website.

October 9, 2023

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

U.S. Bureau of Reclamation
Water Resources and Planning Division
P.O. Box 25007, MS 84-51000
Denver, CO 80225

RE: Letter of Support for New Mexico Tech WaterSMART Applied Science Grant Partnership

To Whom It May Concern:

This letter is written on behalf of the Middle Rio Grande Conservancy District (MRGCD), a state agency with the role of providing river flood control, drainage, and irrigation water in the Middle Rio Grande Valley.

New Mexico Tech including the Hantush-Deju Center of Hydrological Innovation, the Earth and Environmental Science Department and the New Mexico Bureau of Geology is submitting a proposal for the Bureau of Reclamation WaterSMART-Applied Science Grant for Fiscal Year 2023 (Opportunity No. R23AS00446) for a project relating to developing **improved data access in the Rio Grande Basin, specifically within the San Acacia Reach**. The MRGCD intends to participate as a partner in this project by coordinating data access for multiple modeling efforts underway in the San Acacia Reach of the Rio Grande. New Mexico Tech's project would support and improve upon existing modeling efforts in the area that are intended to help refine and enhance our understanding of the water budget.

With this letter, the MRGCD agrees to participate in the project as a partner, especially by providing input and feedback on usability and access to key data needed by various modeling efforts in the San Acacia Reach. MRGCD hopes to utilize data products developed through this Applied Science grant upon its completion in two years.

Please feel free to contact Casey Ish casey@mrgcd.us if you need any additional information.

Sincerely,

Jason M. Casuga, P.E.
CEO/Chief Engineer

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NEW MEXICO INTERSTATE STREAM COMMISSION

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October 13, 2023

Subject: WaterSmart Applied Science 2023 Proposal entitled, "Collecting groundwater flux and geophysical data to improve operational integrated modeling in the Socorro reach of the Middle Rio Grande"

To Whom It May Concern:

On behalf of the New Mexico Office of the State Engineer (NMOSE)/ Interstate Stream Commission (NMISC), I offer this letter of partnership and support as a Category A partner to New Mexico Tech for the WaterSmart- Applied Science Grant 2023 titled: "Collecting groundwater flux and geophysical data to improve operational integrated modeling in the Socorro reach of the Middle Rio Grande." The principal investigator is Alex Rinehart Ph.D. with the Hantush-Deju National Center for Hydrological Innovation (HD-NCHI) and New Mexico Tech.

The NMISC has broad powers to investigate, protect, conserve, and develop New Mexico's waters including both interstate and intrastate stream systems. The Commission's authority under state law includes negotiating with other states to settle interstate stream controversies. New Mexico is a party to eight interstate stream basins compacts, including the Rio Grande Compact. To ensure basin compliance, Interstate Stream Commission staff analyze, review, and implement projects in New Mexico and analyze streamflow, reservoir, and other data on the stream systems.

The NMOSE/ISC recognize the need to greatly improve our understanding of the geologic controls on the groundwater and surface water system in the Middle Rio Grande, and especially in the Socorro/San Acacia Reach of the basin. In development of a sophisticated integrated hydrologic model (MIKESHE) the NMISC found that without more accurate data on the subsurface environment in the Socorro region that model outputs will not be as reliable as needed for decision making on costly solutions. New Mexico Tech's expertise in providing critical data input to the model through collection of and processing geophysical and geochemical data is essential for the best outcome of numerous efforts in this region. For example, this research will assist in completion of a model that reflects subsurface conditions in this geologically complex area and thus can be used in the design and monitoring of several river realignment projects by the U.S. Bureau of Reclamation, the evaluation of the Low Flow Conveyance Channel, and establishing more effective irrigation practices by the MRGCD.

The NMISC believes that a WaterSmart Applied Science grant is the most appropriate funding mechanism for New Mexico Tech to engage its faculty and students in this exciting study because results from the project will reduce gaps in our knowledge of the subsurface in the Socorro region. New Mexico Tech has the expertise and familiarity to successfully accomplish this research. This study has implications for multiple efforts in this region that will benefit government agencies, environmental organizations, and local communities. Additionally, state and federal interest in obtaining and sharing quality controlled water data continues to expand with the challenges of climate change induced water scarcity. We are interested in partnering with New Mexico Tech, MRGCD, and the federal agencies to develop state-of-the-art tools such as integrated hydrology modeling platforms to fully address the state's water issues, including not the least, preserving and enhancing the Rio Grande's imperiled ecosystem. Cost share funding of approximately $112,000 from the NMISC for modeling support, well monitoring, and NM Tech student assistance is available for this project should it be selected.

If you require further information from the NMISC, please contact me at 505-469-6963, or by email at grace.haggerty@ose.nm.gov.

Sincerely,

Grace M Haggerty

Grace M. Haggerty
Sr Hydrologist/Program Manager
Rio Grande Basin
New Mexico Interstate Stream Commission
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