Proposal Application Form (2022–2023 TWRI Graduate Student Research Programs)

1. **Title**: Mapping tap water distribution using isotope-based metrics to improve water management in the metropolitan region of north-central Texas
2. **Student Information**
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    - **Program/Degree:** PhD in Earth and Environmental Sciences
    - **Starting-Ending:** Fall 2022-Fall 2026
3. **Faculty advisor information**
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    - **Department:** Earth and Environmental Sciences
    - **Appointment:** Associate Professor
4. **Which program(s) are you applying for (only select one option)?**
   X USGS Research Program (any Texas university; categorical funds and/or tuition)
   *Not eligible for the Mills Scholarship Program
5. **Have you received either the Mills Scholarship or USGS Research Program funds before?** No.
6. **Would these funds be initiating new research or supporting ongoing research?** The funds will be used to initiate a new research project on the emerging topic of Urban Tracer Hydrology in north-central Texas. Equipment (triple water isotope analyzer) and facilities use (Tracer Hydrology Group) will be provided from the startup package (Department of Earth and environmental Sciences) and the Rising STARs (Science and Technology Acquisition and Retention) Award granted to Dr. Sánchez-Murillo.
7. **Focus Categories:** Hydrology, Drought, Water Supply
8. **Research Category:** Water Scarcity and Availability
9. **Keywords**: North-Central Texas; Water stable isotopes; Isoscape modeling; Bayesian mixing model; Demographic characteristics; Urban water supply management.
10. **Congressional District:** TX-006

11. **Abstract**: Persistent droughts coupled with increasing water needs are shaping the co-evolution of Texas's socio-economic assemblages, water laws/regulations and future water supply allocation. The main goal of this project is to produce a new urban isotope-informed database within the Tarrant Regional Water District of north-central Texas. Combining high-resolution urban isotope data with key water supply information will provide a basis for a) identification of the spatiotemporal structure of tap water sources across the distribution network through GIS isoscape modeling, b) estimation of mixing ratios using Bayesian calculations, c) evaluation of evaporative losses based on isotope mass balance, d) correlating water sources with population characteristics. By providing a new traceable spatiotemporal tool (from the source to the end user) linked to demographic parameters, water managers and stakeholders will improve urban water management and conservation strategies to aid in implementing the Texas State Water Plan. Emerging patterns (in time and space) will advance the understanding of water use/availability implications on urban systems in the light of inter-annual climate variability, climate change and drought on Texas water resources. This methodology can be transferred to other urban

settings across the state, whether they are influenced by groundwater extraction or a large spectrum of water sources.

12. **Description of your research proposed research**

Statement of critical regional or state water problem: Texas is characterized by sub-humid tropical climate (Peel et al., 2007) with notable annual mean temperature (N-S: 18-25°C) and precipitation (W-E: 250-1,450 mm yr^{-1}) gradients (Nielsen-Gammon, 2011a). A complex interconnection between geographical features (i.e., the North America Cordillera, the Gulf of Mexico, and the central-eastern North American Continent) with oceanic and atmospheric large-scale processes (i.e., El Niño Southern Oscillation, the Bermuda High, and southwest monsoon incursions) make Texas a water deficient-state and extremely susceptible to prolonged/severe droughts (Cavazos, 1999; Banner et al., 2010; Schmidt and Garland, 2012; Okumura et al., 2017; Ray et al., 2018). Persistent drought periods and increasing water needs are shaping the co-evolution of the state's socio-economic assemblages and water laws/regulations and future supply allocation (Nielsen-Gammon, 2011b).

This climatically vulnerable region is home of roughly 30 million people with a near two-fold increase expected by 2070 (US Census Bureau, 2022). The $1.9 trillion Texas GDP economy is the second biggest in the U.S. and it was ranked nineth worldwide in 2021 (Texas Economic Development Corporation, 2021). However, Texas's population and economic growth are posing a large stress on water availability and urban allocation. For example, water needs in 2020 (i.e., municipal, livestock, steam electric power, manufacturing, mining, and irrigation) represented 18.5% (~3.1 acre-feet yr^{-1}) of the existing water supply. Water needs are expected to increase up to 49.6% by 2070 (6.9 acre-feet yr^{-1}) (Texas Water Development Board, 2022). Therefore, there is an urgent need to explore new perspectives and hydrological tools to expand our understanding of water problems and potential water conservation strategies in emerging large urban settings.

Texas is divided into 16 regional water plans. Region C in north-central Texas represent over a quarter of Texas' population and almost one-third of states GDP's economy (Region C Water Plan, 2021). The Dallas-Fort Worth (DFW) metroplex is the most prominent socio-economic area in Region C. Historical large municipal water use records in this region have commonly been associated to La Niña-induced dry weather spells (e.g., 1996, 1998-99, 2000, 2006, 2011) (Ropelewski and Halpert, 1986; Fernando et al., 2016). In 2020, municipal use accounted for 87% of the water demand in north-central Texas, of which 61% was concentrated in the Tarrant and Dallas counties alone (Region C Water Plan, 2021). Due to the continuous decline in water table levels (de Graaf et al., 2019) and vanishing of spring seepages, water managers have resorted to the exploitation of regional surface water resources, large-scale inter-basin transfer, and water reuse from artificial wetlands. These spatial and temporal variations of water are also altering the ecohydrological cycle, where urban environmental flow is a topic of large debate and concern (Wenger et al., 2009; Breyer et al., 2018, Marx et al., 2021; Fillo et al., 2021).

Statement of expected results or benefits: By providing a new traceable spatiotemporal tool linked to demographic parameters in the DFW area, water resource managers will improve urban water management and conservation strategies to aid in implementing the Texas State Water Plan (Texas Water Development Board, 2022). This project will also provide a new evaluating perspective of water transmission and allocation from the source to the end user. Emerging spatiotemporal patterns will advance the understanding of water use and availability implications on natural-urban coupled systems in the light of inter-annual climate variability, climate change and drought on Texas water resources. This methodology can be transferred to other urban settings across the state, whether they are solely influenced by groundwater extraction or a large spectrum of water sources.

Nature, scope, and objectives of the research, including a timeline of activities: Water sources in Region C are mainly composed of surface water reservoirs (78% largely from the Trinity River basin), groundwater (15.4% mainly from the Trinity Aquifer), and reuse water (6.6%). Imported surface water from the Sabine and Sulphur River basins accounts for less than 20% of the total surface water supply (Region C Water

Plan, 2021). One of the major providers in Region C is the Tarrant Regional Water District (TRWD). TRWD supplies only raw water to more than 30 wholesale customers from four major reservoirs (Lake Bridgeport, Eagle Mountain Lake and the Cedar Creek and Richland Chambers Reservoirs), one wetland (Richland Chambers), and three storage reservoirs (Lake Arlington, Lake Benbrook, and Lake Worth). After nearly 100 years of operation, this water distribution system has evolved to more than 150 miles of pipelines, 9 pump stations, and 14 treatment plans across the cities of Fort Worth, Arlington, Mansfield, and Midlothian (Integrated Water Supply Plan, 2013).

Water managers have traditionally used pipe network analysis (Chenoweth and Crawford, 1974) to predict the flow rates and calculate head losses in urban water supply networks (Tipple et al., 2017). Nevertheless, in large metropolitan settings such as DFW, results obtained from these techniques are typically quite difficult to verify and can be susceptible to error due to outdated/incorrect information on the water supply infrastructure (i.e., pipeline and pumping variables, system longevity) (Jameel et al., 2016). The inherent complexity of urban water supply systems invokes the need of traceable hydrological tools to underpin connections (or discontinuities) and spatiotemporal variations within water transmission networks (Ehleringer et al., 2016).

The main goal of this project is to produce a new urban isotope-informed database within the coupled natural-human Tarrant Regional Water District of north-central Texas. The study will combine high-resolution isotope data within the supply system with key water infrastructure information and volumetric data. The specifics are to a) identify the spatiotemporal structure of tap water sources and overall functioning of the pipeline network through GIS isoscape modeling, b) estimate water source mixing ratios using Bayesian calculations, c) evaluate evaporative losses based on isotope mass balance (detectable at the metropolitan scale), and d) correlate water sources with population characteristics (e.g., population estimates, housing, income, ethnicity), in the context of rapid urban growth and inter-annual climate variability in Texas. This project will be conducted during one hydrological year (2023). In total 2 large sampling campaigns will be performed to capture major isotope seasonality (temperature dependent; winter-summer) and high urban consumption periods (summer) within the Tarrant Regional Water District (February and July 2023). Sampling logistics and water isotopes analysis will require 2-months of preparation and posterior analytical work, respectively. One seminar (2023) will be offered to the Tarrant Regional Water District. Preliminary results will be also presented during the DISCOVER College of Science Research Symposium at the University of Texas, Arlington (2023), and AGU annual meeting. One manuscript draft for peer-review publication will be prepared by the end of summer 2023.

Methods, procedures, and facilities

Sample collection: The sampling campaigns will be designed to target a high-water consumption period as well as to capture seasonal variations during one hydrological year (2023). Most samples will be collected from taps in businesses, public facilities with a small subset coming from private homes supplied by students, faculty, and community members as part of a crowdsourcing and citizen science driven effort. Samples for each survey will be collected on 1-2 days. At each location, samples will be obtained by running the tap water for 15 s before filling, capping, and sealing (with Parafilm) a clean 30 mL HDPE bottle. Daily precipitation samples will be collected throughout the study period using a passive collector (Palmex Ltd., Croatia; Gröning et al., 2012) installed on the roof of the Geoscience building, University of Texas at Arlington. Main reservoirs (Lake Bridgeport, Eagle Mountain Lake, Cedar Creek, Richland Chambers Reservoirs, Lake Arlington, Lake Benbrook, and Lake Worth) will be sampled biweekly, while samples from Rush Creek (urban stream draining in S-N direction) will be grabbed weekly, in clean 30 mL HDPE bottle sealed with Parafilm. All samples will be stored at 4°C until analysis.

Stable isotopes analysis: Stable isotope analysis will be conducted at the Tracer Hydrology Group facilities of the Department of Earth and Environmental Sciences, University of Texas, Arlington using a water isotope analyzer GLA431-TLWIA (LGR Inc., USA). Two in-house secondary standards will be used to normalize the results to the VSMOW-SLAP scale, while a third standard will be used for quality and drift control. Stable isotope compositions will be presented in delta notation δ (‰, per mil), relating the ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ (Vienna Standard Mean Ocean Water; V-SMOW) as follows $\delta=[(R_{sample}/R_{std})-1]\cdot 1000$, where R represents the $^{2}H/^{1}H$ or $^{18}O/^{16}O$ abundance ratio, and R_{sample} and R_{std} are the ratios in the sample and standard, respectively.

Isoscape modeling: The spatiotemporal analysis of the tracer data will follow the methods described by Jameel et al. (2016) and Tipple et al. (2017). First, normality of distributions will be tested with the Shapiro-Wilk test (Shapiro and Wilk, 1965). Moran's I statistic (Moran, 1948) will be used to determine the spatial autocorrelation of the isotopic values of tap water. This spatial analysis determines the relationship between the density of similar isotope values and the distance between sampling sites. Spatial autocorrelation analysis and mapping will be conducted using ArcGIS 10.8.1. Principal Component Analysis (PCA) of the tracer data will utilized to decompose the information into orthogonal variables. Clustering will be focused on $\delta^{18}O$, *d*-excess, and *lc*-excess values from all sampling campaigns. Groups will be recognized from the PCA output using *k*-means analysis with the Hartigan-Wong algorithm, splitting the dataset into *k* groups by maximizing between-group variation relative to within-group variation. PCA and cluster analysis will be performed in R (R Core Team, 2021).

Stable isotope Bayesian mixing model: The stable isotope mixing model from the R package Simmr (Parnell and Inger, 2016) will be used to partition relative endmember (reservoirs, wells, rainfall, wetlands, treatment plants) water contributions for each sampling campaign using a Bayesian statistical framework based on a Gaussian likelihood as described by Sánchez-Murillo et al. (2020). The main advantage of Bayesian mixing models over simple linear models relies on the ability to input isotope data from multiple sources (Ma et al., 2016, Gokool et al., 2018, Correa et al., 2019). The model requires three sets of input data as a minimum to determine the proportions of water used within the supply system: i) $\delta^{2}H$ and $\delta^{18}O$ of tap water (known as the mixture), ii) mean $\delta^{2}H$ and $\delta^{18}O$ for the endmembers, and iii) standard deviations of $\delta^{2}H$ and $\delta^{18}O$ for the endmembers. Source water contributions to the mixture will be determined using a Markov Chain Monte Carlo (MCMC) function (Brooks, 1998) to repeatedly estimate the proportions of the various sources in the mixture and determine the values which best fit the mixture data (Parnell and Inger, 2016) (100,000 iterations). Gelman-Rubin (1992) diagnostic test will be performed to test model convergence using $\delta^{2}H$ and $\delta^{18}O$ values. The test evaluates MCMC convergence (Gelman-Rubin value equal 1) by analyzing the difference between multiple Markov chains. Median values of source water contributions from the posterior parameter distribution will be used for practical comparisons of the water supply operation.

Evaporative loss: To understand the impacts of ambient temperature and relative humidity seasonality, the total evaporative loss from water sources and the distribution system employed by water district will be estimated using the modified Craig-Gordon model (Craig and Gordon, 1965) using the algorithm developed by Skrzypek et al. (2015), which provides robust estimations of evaporation based on the isotopic composition of water. The evaporation to inflow (E/I) ratios will be calculated using the following equation (Gibson and Reid, 2014; Gibson et al., 2016; Esquivel-Hernandez et al., 2017):

$$\frac{E}{I}=\left(\frac{1-h}{h}\right)\left(\frac{\delta_s-\delta_{rain}}{\delta^{*}-\delta_s}\right)$$

where h is the average local relative humidity fraction, δ_{rain} is the average isotopic composition of precipitation, δ_s is the average isotopic composition of lake water or tap water, and δ^{*} is the limiting isotope composition enrichment; δ^{*} will be estimated as:

$$\delta^{*}=\frac{h\cdot\delta_{vapor}+\ \varepsilon}{h-\frac{\varepsilon}{1000}}$$

where ε is the total isotope fractionation and δ_{vapor} is the isotopic composition of water vapor. The total isotope fractionation is defined as:

$$\varepsilon = \frac{\varepsilon^{+}}{\alpha^{+} + \varepsilon_{k}}$$

where ε^{+} is the equilibrium isotope fractionation factor, ε_k is the kinetic isotope fractionation factor, and α^{+} is the equilibrium isotope fractionation factor. ε^{+} values are temperature dependent, with $\varepsilon^{+} = (\alpha^{+}-1)\cdot 1000$ (Horita and Wesolowski, 1994). The ε_k values will be approximated using the following equation:

$$\varepsilon_{k} = (1 - h) \cdot C_{k}$$

where C_k is the kinetic fractionation constant, 12.5‰ for δ^{2}H and 14.2‰ for δ^{18}O (Gonfiantini, 1986). The δ_{vapor} will be estimated using local records of precipitation and their stable isotope composition (δ_{rain}) during the sampling periods, as follows:

$$\delta_{vapor} = \frac{\delta_{rain} - X \cdot \varepsilon^{+}}{1 + X \cdot \varepsilon^{+} x 10^{-3}}$$

The *X* term is a correction factor to minimize the difference between the calculated slope of the local evaporation line and the observed slope (Skrzypek et al., 2015). In addition, two second-order variables will be calculated to estimate evaporation spatial trends due to secondary kinetic fractionation. Deuterium excess will be calculated as *d*-excess=δ^{2}H-8·δ^{18}O (Dansgaard, 1964), while the line-conditioned excess will be estimated as *lc*-excess= δ^{2}H-a·δ^{18}O-b, where a and b correspond to the slope and intercept of the local meteoric water line (Landwehr and Coplen, 2006).

Tracer and demographic correlation analysis: Potential correlations between tracer and demographic data will be explore using demographic information from the United States Census Bureau (https://www.census.gov/quickfacts/TX), including population estimates, ethnicity, median household income, and persons per household. These variables will be aggregated for each municipal district within the Tarrant County.

13. **Related research**: Water isotopes studies have been heavily concentrated across natural and agricultural landscapes (Kendall and McDonnell, 2012), while research initiatives in water supply systems are limited. Nevertheless, there is an increasing worldwide demand to understand water supplies and dynamics in urban settings (Ehleringer et al., 2016; IAEA, 2018). Tracer applications of water stable isotopes have proven to enhance the understanding of contrasting urban transmission systems within coastal and semi-arid regions of western US (Jameel et al., 2016; Tipple et al., 2017; Fillo et al., 2021), humid tropical and sub-tropical cities (Sánchez-Murillo et al., 2020; de Wet et al., 2020) and continental settings (Wang et al., 2018). This project will combine existing methodologies to study one of the fast-growing metropolitan areas in Texas. In contrast to previous studies, the TRWD is affected by prolonged droughts and mainly relies in surface water sources (~80%), which are highly susceptible to isotopic variations due to changes in ambient temperature and relative humidity. The spatiotemporal analysis will allow to capture such variations across the supply system.

14. **Training potential**. At least 2 graduate students from the PhD program in Earth and Environmental Sciences and 3 undergraduate students in the are expected to receive training in the project.

15. **Intended career path**: I am a highly motivated and self-driven woman geoscientist from Botswana. One of the main challenges that we face in my village and Botswana in general is water shortage. For a very long time our water supply was disconnected due to problems with the borehole that supplies the whole village with water. I completed a BS program in Geology at the University of Botswana (2010), and a M.Sc. program in isotope geochemistry at the Botswana International University of Science and Technology (2020). My career goal is to end up in the groundwater exploration and surface water purification industry. This PhD program will help me take a step towards to a better understanding of hydrological processes in water-deficient regions. I plan to also go back to my village to work on water quality and quantity issues.