Integrated field, model, and theoretical advances inform a predictive understanding of transport and transformation in the critical zone

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Joel Singley, Roger Williams University (jsingley@rwu.edu)

Martin Briggs, Observing Systems Division, Hydrologic Remote Sensing Branch, USGS (mbriggs@usgs.gov)

Beth Hoagland, S.S. Papadopulos & Associates (bhoagland@sspa.com)

Rachel Lauer, University of Calgary (rachel.lauer@ucalgary.ca)

Jessie Meeks, Colorado School of Mines (jmeeks@mines.edu)

Aaron B Regberg, NASA Johnson Space Center (aaron.b.regberg@nasa.gov)

David M. Rey, Observing Systems Division, Hydrologic Remote Sensing Branch, USGS (drey@usgs.gov)

Kenny Swift Bird, Colorado School of Mines (kswiftbird@mines.edu)

Adam S. Ward, Oregon State University (adam.ward@oregonstate.edu)

Corresponding author:

Adam S. Ward
Dept. of Biological & Ecological Engineering

Oregon State University
124 SW 26th St
Corvallis, OR 97331

Email: adam.ward@oregonstate.edu
Phone: 541-737-2041

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Abstract

Dr. Kamini Singha's work has been transformative in advancing our predictive understanding of transport and transformation in Earth's critical zone. She integrates empirical, numerical, and theoretical advances at scales spanning individual pores to regional aquifers, and works seamlessly across disciplines to connect otherwise disparate fields. Her work has both applied and basic research dimensions, ensuring advances inform best practices across the industry. That she has achieved prominence in research while maintaining a successful portfolio of teaching, mentoring, and service to the profession is particularly impressive. Indeed, Singha has fostered the burgeoning discipline of hydrogeophysics and ensured that this discipline, and its role in critical zone science, is an open, accessible, and welcoming field. Here, we summarize Singha's impact on hydrologic science as a researcher, educator, mentor, and agent of change in the field.

1. Introduction

The work of Dr. Kamini Singha in her career to-date has already shaped the field of hydrologic science. Her body of work pioneers novel geophysical techniques and applications, pressing the bounds of our observational abilities and the associated theoretical underpinnings to inform transport and transformation in aquifers and coupled surface- and groundwater systems. She intentionally addresses both basic and applied research domains, making meaningful strides in both domains. Perhaps most importantly, Singha's work links disciplines, producing the connective studies that enable modern critical zone science, linking empirical observations, mathematical models, and theoretical underpinnings to advance our predictive understanding of hydrologic science, specifically contributing to our ability to understand the critical zone. The breadth and impact of her research has transformed the field of hydrologic science, and the community of scientists practicing in private industry, agency science, and academia.

Dr. Singha began her research career following completion of a Bachelor's of Science in Geophysics at the University of Connecticut in 1999 where she worked with the USGS Branch of Geophysics. She then went on to receive a Ph.D. in Hydrogeology from Stanford University in 2005. Immediately following completion of her Ph.D., she started as an Assistant Professor in the Geosciences Department at Pennsylvania State University, where over a period of 8 years she rapidly built a robust research program and broad network of students and colleagues. In 2012, she continued her career at the Department of Geology and Geological Engineering at Colorado School of Mines, where she is currently a University Distinguished Professor. During her time at Colorado School of Mines she has served in various service roles, including as the Associate Director of the Hydrologic Science and Engineering Program, the Associate Department Head of the Department of Geology and Geological Engineering, and the Associate Dean of the Earth and Society Program. Over the course of her career to date, she has received 9 university-level fellowships and more than 20 awards and honors in the fields of hydrogeology and geophysics. Select honors received by Dr. Singha include a Fulbright Scholarship, the National Groundwater Association Darcy Lectureship position, a National Science Foundation CAREER Award, the Reginald Fessenden Award from the Society of Exploration Geophysicists, and the 2022 American Geophysical Union's Witherspoon Lecture.

Dr. Singha's impact on hydrology and adjacent fields is evidenced by a prolific publication record. A search for Singha's work on Scopus identifies 118 publications across 49 unique journals for the period 2005-2022 (Fig. 1A; Scopus, 2023). Of these, 49% are in 15 unique hydrologic sciences journals (identified as those with 'water' and/or 'hydro' in the journal name), with the remaining 51 spanning 34 journals in related disciplines (Fig. 1A, 1B). The 2,760 citations of her work during the same period are even more diverse in their impact, including 22% in 24 unique hydrologic sciences journals, with the remaining 78% spanning 578 other journals (Figs. 1C, 1D). Ultimately, this analysis documents both a distinct impact on and relevance to not only hydrologic sciences, but also to host of interdisciplinary applications.

Here, we summarize Singha's impact on the hydrologic sciences to-date. First, we summarize her impact in four key areas of research: non-Fickian transport and pore-scale dynamics (section 2.1), working across scales to constrain emergent transport behavior (section 2.2), hydrogeophsyical characterization of the critical zone (section 2.3), and the study of coupled surface- and groundwater systems on redox dynamics and contaminant transport (section 2.4). Taken together, these topics represent a step-change to our understanding of contaminant transport and transformation in Earth's critical zone. While presented as distinct topics, these research advances integrated by common themes of an openness and excitement to work across disciplines, a focus on systems that display multiscale spatial behaviors and the time-domain analog, problems with apparent non-Fickian transport dynamics leading to 'heavy-tailed' behaviors, and thoughtful application of geophysical tools to hydrological and critical zone science. Next, we summarize her role above-and-beyond research, in which she has fostered a diverse and thriving hydrogeophsyics community. Finally, we reflect on the underlying traits that have enabled her impact thus far and summarize her achievements and recognitions. Taken together, Singha's body of work has had an outsized impact on hydrologic science that is worthy of synthesis.

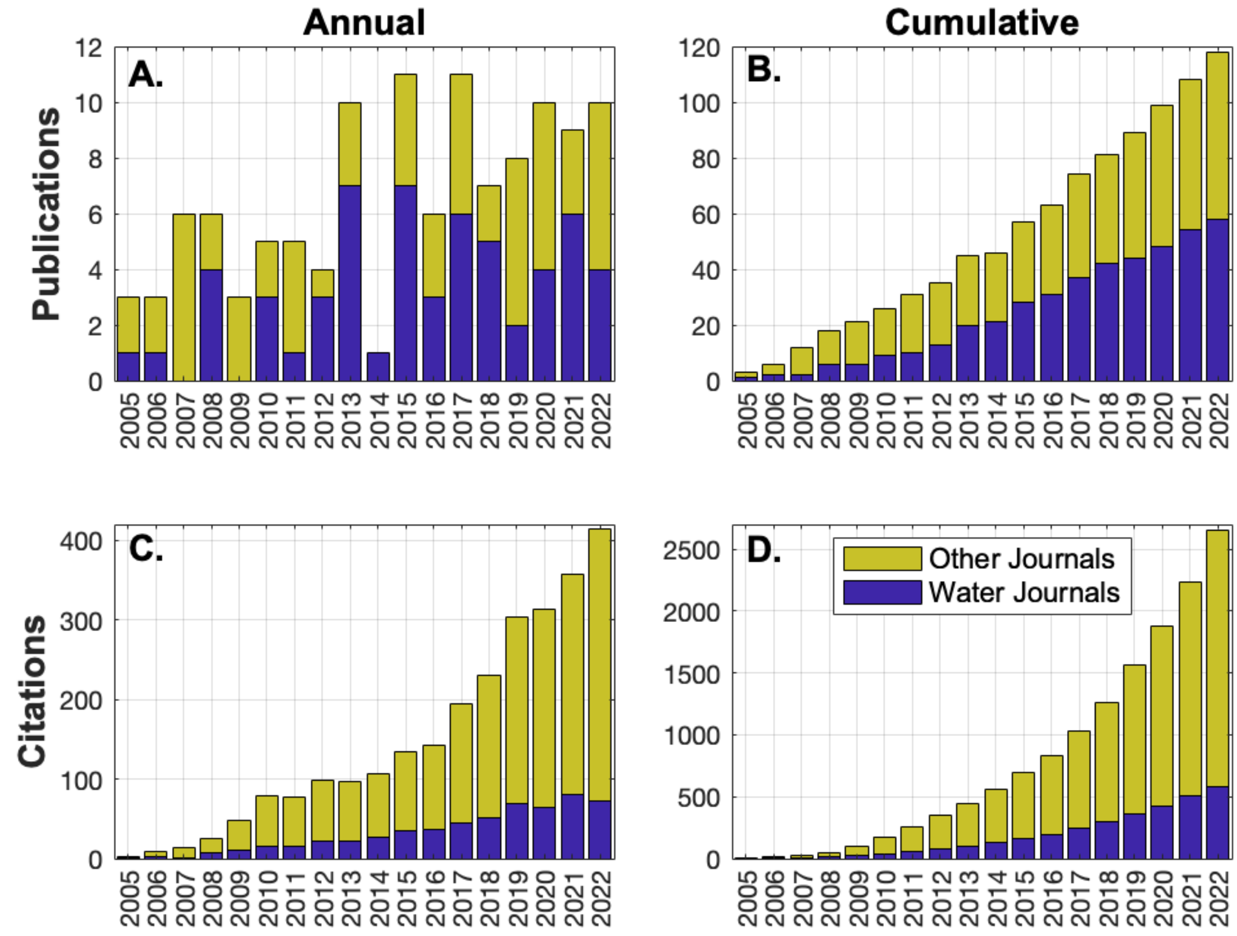

Figure 1. Summary of annual (left column) and cumulative (right column) publications (top row) and citations (bottom row) authored by Dr. Kamini Singha during the period 2005-2022 (data from Scopus, 2023).

2. Research Advances & Contributions

2.1 Dr. Singha has advanced the theory that underpins non-Fickian transport and pore-scale dynamics

Dr. Singha's fundamental research related to non-Fickian solute transport highlights her unique ability to develop geophysical theory and methodology in novel ways to inform elusive physical critical zone processes, and interpret their biological implications. Over previous decades, there have been numerous observations of extended 'tailing' of conservative solutes at late time relative to initial concentration breakthrough, along with pronounced solute concentration rebounds after groundwater pump and treat systems are shut down. This type of behavior is not predicted by advection-dispersion transport mechanics alone and has been often conceptually attributed to exchange with pore spaces of reduced connectivity compared to the more 'mobile', connected matrix pores. Similar to transient storage models of stream solute transport, non-Fickian transport dynamics in porous media are typically represented by at least one immobile (or less-mobile) domain that exchanges (via diffusion and/or slow advection) with better connected mobile porosity where advection and dispersion processes dominate. Although 'mass transfer' dynamics between pores of varied connectivity have been theorized for decades (e.g., Haggerty and Gorelick, 1995), field-scale observations were almost entirely based on mobile porosity solute breakthrough curve data alone, rendering any observations of less-mobile-mobile solute exchange indirect in nature. This is due to a simple experimental constraint of pumped water samples, as the mobile domain is preferentially sampled when fluid is extracted, even at flow rates similar to ambient advection. The major methodological advance that Dr. Singha and her co-authors developed was to pair fluid sampling with co-located measurements of electrical resistivity collected at comparable scales, such that solute exchange with less-mobile porosity could more directly be observed and quantified.

Several early publications by Dr. Singha and colleagues presented ‘anomalous’ field data coupled with novel analysis and model development (Culkin et al., 2008; Day-Lewis and Singha, 2008; Singha et al., 2007). The ‘anomalous’ data were discovered during an experimental evaluation of aquifer storage and recovery potential within a fractured limestone aquifer (Culkin et al., 2008; Singha et al., 2007). The authors plotted co-located fluid electrical conductivity and bulk electrical resistivity (the inverse of conductivity) data in concentration space and found unexpected, pronounced hysteresis between the data types. For example, as fresh water was pumped into the saline aquifer and then extracted, fluid electrical conductivity changed and reached equilibrium points substantially faster than the co-located electrical resistivity data. This hysteresis defies the simplified concepts presented by Archie (1942), where changes in bulk resistivity over time reflect a scaled version of fluid conductivity changes, when grain surface conductivity is neglected and the geologic matrix remains constant. Dr. Singha and her co-authors realized that they could explain the observed fluid-bulk electrical hysteresis by developing a bicontinuum version of Archie’s law that included rate limited mass transfer. Their hypothesis was that changes in less-mobile porosity solute concentration would lag behind concentration shifts in the mobile domain as governed by the relative sizes of the two domains and the mass-transfer rate between them (i.e. ‘rate limited’). Simple manipulation of the governing bicontinuum model parameters showed that the shape of the fluid-bulk electrical hysteresis loop was highly sensitive to these parameters, indicating that their estimation via inverse methods was possible (Singha et al., 2007).

Further numerical model experimentation by Day-Lewis and Singha (2008) supported the rate limited mass transfer explanation. Dr. Singha summarized this rapid advance in understanding of rate limited mass transfer for a general hydrologic audience in Singha et al. (2008). A few years later, Dr. Singha’s research group conducted more complex numerical flow and transport modeling through heterogeneous porous media using COMSOL Multiphysics. Where rate-limited mass transfer was not assumed, these modeling exercises indicated that observed electrical hysteresis patterns could still be accounted for by a simplified bicontinuum model, which included both slow advection and diffusion-dominated exchanges with pore water (Wheaton and Singha, 2010).

While fundamental advances in aquifer fate and transport related to non-Fickian process are no doubt important, throughout her research career Dr. Singha also recognized biological implications of physical hydrologic processed, particularly at the groundwater-surface water interface. Following the concept that less-mobile porosity by nature enhances localized water and solute residence times, Dr. Singha and others theorized that such enhanced reactive contact time within less-mobile pores might explain other type of ‘anomalous’ field observations, such as biogeochemical signatures of anoxic redox reactions measured in apparently oxic pore waters of the hyporheic zone (Briggs et al., 2015). Dr. Singha and colleagues further explored these apparently anoxic zones nested in oxic hyporheic sediments by pairing controlled chamber hyporheic injections of conservative and reactive solutes with cm-scale geoelectrical monitoring (Briggs et al., 2018). Dr. Singha and others found direct evidence of less-mobile porosity dynamics in lake and streambed sandy interface sediments along with potential signatures of anoxic ‘microsites’ embedded in bulk-oxic, more mobile flow (Briggs et al., 2018; Hampton et al., 2019). Further, they found that both the exchange timescales of less-mobile porosity and co-located reactive processes such as nitrous oxide production were sensitive to flow rates (Hampton et al., 2020; MahmoodPoor Dehkordy et al., 2019). As with earlier ideas regarding rate-limited mass-transfer, such flow sensitivity had been previously theorized but rarely directly measured.

Taken together, these theoretical and applied methodological advances form a basis for understanding the origin and impact of non-Fickian transport with applications to basic and applied problems in environmental transport and fate of solutes.

2.2 Dr. Singha has worked across scales to advance characterization of heterogeneous processes in the context of emergent dynamics

Dr. Singha's research has focused on identifying pore-scale processes that affect or control macro-scale measurements or properties. As discussed above, non-Fickian transport is a mechanism invoked to explain the non-ideal behavior of chemical tracers and contaminants from pore to system scales. At the aquifer-scale, tracers and/or contaminants exhibit decreases in concentration through time with strong late-time tailing that cannot be accurately modeled by only considering advection and dispersion. This presents a practical problem when these models are used to develop remediation strategies for contaminated aquifers. If a standard advective-dispersive model systematically underpredicts contaminant concentration at later times, then remediation efforts could be concluded too quickly. To improve models that inform reach-scale or aquifer-scale processes, Swanson et al. (2012) used fluid and bulk measurements of electrical conductivity in columns packed with zeolite or quartz sand to evaluate the pore-scale processes that influence tracer transport. This experimental modeling by Dr. Singha and colleagues found that the volume and arrangement of pores space, rather than grain size, can mediate transport properties and measured geophysical parameters (Swanson et al., 2015, 2012).

Extending a deep understanding of non-Fickian transport to other problems and domains is a hallmark of Singha's career. For example, she readily extended theory and conceptual models explaining non-Fickian transport in porous media to the hyporheic zone, coupling pore-scale behavior with emergent reach-scale applications. The same anomalous tailing that is found in aquifers due to non-Fickian transport also manifests in transport within the river corridor, where transient storage is broadly understood to yield long tailing. A host of applications focus on solute transport, including developing tools for planning tracer injections (González-Pinzón et al., 2022), flume- and tank-scale studies (Foster et al., 2021; Wilhelmsen et al., 2021), interpretation of tracer data (González-Pinzón et al., 2015; Ward et al., 2014, 2013), modeling efforts (Ward et al., 2010b), and emerging integration of hydrogeophysical data with solute tracers to understand process dynamics (Pidlisecky et al., 2011; Singley et al., 2022). Dr. Singha's work across scales is further evident in her contributions to critical zone science, discussed in the next section.

Taken together these efforts link studies of anomalous tailing across multiple scales and approaches, with scales spanning landforms and scales including pores, flowpaths, hillslopes, stream reaches, and aquifers.

2.3 Dr. Singha has brought hydrogeophysical tools to bear on critical zone structure and function

Dr. Singha's affinity for working across scales and disciplines found a natural fit in critical zone (CZ) science. Work within the CZ is interdisciplinary by nature as the CZ contains complex interactions between water, rock, soil, the atmosphere, and living organisms (Richter and Mobley, 2009). As a consistent pioneer of new tools and applications that bridge disciplines, Dr. Singha leveraged her existing expertise in subsurface hydrology, surface water-groundwater interactions, and near-surface geophysical methods to explore dynamic processes within the CZ. Dr. Singha and her collaborators played an important role in applying geophysical methods to investigate hyporheic exchange (Doughty et al., 2020; Hagarty et al., 2010; Singha et al., 2008; Ward et al., 2010a, 2010b), saturated pore-scale exchange (MahmoodPoor Dehkordy et al., 2019; Singha et al., 2008), plant water uptake (Harmon et al., 2021; Mares et al., 2016;

Voytek et al., 2019), and the role of CZ structure in hydrologic storage and routing (e.g., Kuntz et al., 2011; Voytek et al., 2016).

Dr. Singha and others continued to demonstrate the value of near-surface geophysical observations to new hydrologic problems by applying time-lapse electrical resistivity surveys to the study of hyporheic exchange processes. Traditionally, characterization of stream hyporheic zones relied on parameterizing numerical models to replicate tracer breakthrough curves measured within the stream (e.g., Bencala and Walters, 1983; Stream Solute Workshop, 1990). These measurements and models represent the aggregate response of the stream between the point of tracer injection and the measured breakthrough curve, making the identification of spatial variations in hyporheic exchange challenging to identify (Choi et al., 2000; Kelleher et al., 2019, 2013; Ward et al., 2016). By conducting time-lapse electrical resistivity surveys during conductive tracer injections, Dr. Singha and others were able to begin characterizing spatially variable processes within the hyporheic zone, and start identifying areas of slower distributed exchange (Ward et al., 2012, 2010a). In addition to novel applications of near-surface geophysical methods to the hyporheic zone, Dr. Singha and her collaborators continued to advance associated theory (Singha et al., 2011), while simultaneously synthesizing their advances for a broader hydrologic audience (Singha et al., 2015).

A consistent theme in Dr. Singha's career is her work across disciplines, and her contributions to CZ science are not an exception. Dr. Singha and her collaborators have played an important role in applying near-surface geophysical methods to help characterize ecological controls on subsurface storage and routing of water within the CZ (Sullivan et al., 2022) or controls of those flowpaths on ecology (Rey et al., 2021, 2019). Dr. Singha mentored several students who utilized time-lapse electrical resistivity surveys, both of the surrounding soil and the tree itself, to look at coupled tree-soil systems (Harmon et al., 2021; Luo et al., 2020; Mares et al., 2016).

Mares et al., (2016) compared temporal patterns of tree sap-flux and soil-moisture with results from time-lapse electrical resistivity surveys of the tree trunk and surrounding soils. This study demonstrated the promise for the application of electrical methods to track spatially variable changes in soil-moisture as a function of tree-water uptake and potentially even hydrologic redistribution. Expanding on work from Mares et al., (2016), Harmon et al., (2021) used similar resistivity methods and wavelet analysis to examine the physical relationships between tree water storage and atmospheric and pedologic variables.

Taken together, Singha has cemented the role of hydrogeophysical tools as an essential part of the critical zone toolkit.

2.4 Dr. Singha has worked across disciplines to constrain the influence of GW-SW interactions on redox dynamics and contaminant transformations

Dr. Singha's research frequently relies upon interdisciplinary teams that integrate techniques from geophysics, hydrology, and (bio)geochemistry. Her interdisciplinary work has resulted in significant contributions to the scientific community's understanding of how groundwater-surface water exchanges mediate solute fate and transport. Research by Dr. Singha and colleagues that is focused on this topic has utilized a combination of field and lab methods, including continuous salt-injection tracer tests, electrical resistivity tomography, fine-scale geoelectrical monitoring, water, sediment, and porewater sampling and analysis, as well as numerical modeling. Dr. Singha and colleagues have applied these techniques to explore metal redox chemistry in mine-impacted hyporheic zones (Hoagland et al., 2020; Johnston et al., 2017; Larson et al., 2013; Rickel et al., 2021), nitrogen cycling in urban streams (Hampton et al., 2020) and kettle lakes (Briggs et al., 2018; Hampton et al., 2019), arsenic and uranium fate and transport in groundwater on the Pine Ridge Reservation (Swift Bird et al., 2020)), and resazurin (a reactive tracer) oxidation in an engineered streambed (Herzog et al., 2018).

Several key findings have emerged from the novel coupling and repeated application of diverse hydrogeophysical and (bio)geochemical techniques by Dr. Singha and her colleagues. First, several studies have revealed that fluid exchange rates, hydraulic conductivity, and bio-clogging in the hyporheic zone often mediate the distribution of biogeochemical microzones and may result in strong feedbacks on nutrient transport (i.e. advection- vs diffusion-dominated). In a series of iron oxide reduction experiments, biofilms were found to form electrically conductive pathways, occlude pore space, and increase bulk electrical conductivity (Regberg et al., 2011). Later research that paired geoelectrical monitoring with porewater sampling revealed that anaerobic processes occurred in less-mobile pore spaces in shallow sediments even though porewater sampling had indicated bulk-oxic conditions (Briggs et al., 2018). The concept of co-located anoxic and oxic microzones in bulk porous media was explored further using computational models that evaluated different stream and sediment conditions such as variable hydraulic fluxes and nutrient concentrations, as well as scenarios with and without biomass (Roy Chowdhury et al., 2020). From this modeling, the Chowdhury et al. hypothesized that microbes were a key control on nutrient transformation in hyporheic sediment, but their associated biomass growth can clog hyporheic pore spaces, reduce hydraulic fluxes, and lead to the formation of anoxic microzones. These concepts have important implications for nutrient transformations. For example, intermediate residence times in hyporheic sediments were found to favor incomplete denitrification compared to shorter or longer residence times, resulting in the release of the greenhouse gas N_2O (Hampton et al., 2020).

Dr. Singha’s research characterizing redox conditions in response to dynamic mixing in the hyporheic zone has had important implications for our understanding of metal geochemistry in streams receiving acid mine drainage (Bethune et al., 2015; Hoagland et al., 2020; Johnston et al., 2017; Larson et al., 2013; Rickel et al., 2021). A second key finding from her body of work is that groundwater-stream exchanges and metal-oxide precipitation in the hyporheic zone influence the attenuation or export of metals from acid mine drainage streams. For example, Larson et al. (2013) found that the rate of mass transfer between the stream and hyporheic zone controlled the location and depth of Fe(II)-oxidizing niches, where niches characterized by slower exchange rates promoted biotic Fe(II)-oxidation and enhanced the precipitation of terraced iron formations and the sequestration of iron. Later work by Dr. Singha and colleagues further established the link between iron oxide precipitation and hyporheic exchange, where Fe(II)-oxidation resulted in a physical barrier separating an acid mine drainage stream from underlying, shallow groundwater (Rickel et al., 2021). This physical disconnect resulted in a small hyporheic zone with steep hydrogeochemical gradients, high concentrations of toxic metals, and low microbial diversity dominated by Fe(II)-oxidizing bacteria (Hoagland et al., 2020).

Dr. Singha's multi-disciplinary research also works to address environmental contamination and environmental justice issues in marginalized communities both domestically and internationally (Hagarty et al., 2015; Swift Bird et al., 2020; Tschakert and Singha, 2007). For example, Dr. Singha and colleagues worked collaboratively with the Oglala Sioux Tribe to delineate hydrogeologic and biogeochemical controls of arsenic and uranium dissolution into the Arikaree aquifer on the Pine Ridge Reservation, where many people rely on domestic wells as their drinking water source. Elevated alkalinity and pH levels were found to be the driving factors of arsenic and uranium mobility in the Arikaree aquifer. Downgradient sections of the aquifer in the northern portions of the Pine Ridge Reservation were most likely to be impacted by metal(loid) contamination due to water - rock reactions that increase pH and alkalinity (i.e., groundwater evolution) and proximity to volcanic ash that acts as a regional metal(loid) source (Swift Bird et al., 2020).

Tschakert and Singha (2007) evaluated environmental and human health impacts of small-scale galamsey (i.e., illegal and unregulated) gold mining in Ghana, through a pilot study working with galamsey miners to understand their perspectives on mining risks, environmental hazards, and research communication. Galamsey miners use manual, rudimentary, and often hazardous techniques to extract and process gold ores, including amalgamation with mercury. The use of mercury causes negative health impacts for miners and can contaminate water sources, crops, and soils near mining sites. Galamsey miners make up the majority of the mining labor force in Ghana, but they are considered outlaws and environmental criminals, and are generally excluded from regulatory and policy considerations on mining. Tschakert and Singha (2007) worked to quantify miner's understanding of mining risks and actively involved galamsey miners in mercury testing using indicator strips. Their approach found synergies between political ecology, environmental justice, and ecohealth, and many galamsey participants advocated for similar outreach and education in other mining communities. The researchers recommended recognition of galamsey miners, and active involvement of mining communities as a first step out of the impasse in the Ghanian mining sector.

Taken together, these research advances are directly transferable to addressing applied problems of contaminant transport and fate, particularly for cases where redox dynamics and/or coupled GW-SW systems are essential to governing the success or failure of remediation.

3. Fostering an open & inclusive hydrogeophysics community

Dr. Singha's contributions to the broader earth science community are not well captured by traditional academic metrics alone. In addition to an active research program, Dr. Singha's contributions include both direct mentorship of individuals outside her immediate research group, impactful courses and lectures for all career stages, as well as continued efforts to build a more inclusive earth science community. Notably, the activities we detail below are above and beyond her already notable service to the community including service on CUAHSI's Board of Directors, an Editorial position at Water Resources Research, her role as PI of the inclusion-focused Critical Zone Research Coordination Network (RCN), regular service organizing panels and sessions at conferences, and many more activities.

During the first 15 years of her career in academia, Dr. Singha has mentored a network of over 40 graduate students, postdoctoral scholars, and research technicians (as of August 2022). Dr. Singha is a responsive, engaged mentor, eager to contribute to field work, writing, and providing her students with opportunities to collaborate with other scientists. Dr. Singha is known to support her students and postdocs regardless of their career goals, and she encourages students to be "broadly brilliant" and excel in all aspects of their lives, not just academic pursuits. These mentorship traits are aptly reflected in the diversity of positions currently held by her former mentees, which span multiple fields in academia, environmental consulting, national laboratories, federal agencies (e.g., USGS, NOAA), or the private sector. The successes of her advisees across a breath of applications, disciplines, and industries is a testament to the consistently strong mentoring she provides. Dr. Singha's support is not limited to her current students and postdocs, as she eagerly provides support to her mentees across all stages of their career, from the undergraduate-level to graduate-level to early career faculty members.

In a recent interview with the Colorado School of Mines newspaper, Dr. Singha noted that "the students, hands down, are my favorite part of my job. I've always loved teaching, and I also love working with new researchers to help them channel their talents to explore real-world problems"

(Mines Staff, 2020). Dr. Singha's passion for teaching and desire to provide students a supportive environment and curriculum in which they can grow is apparent in the fun and energetic nature of her courses. Dr. Singha's passion for teaching comes across in her determination to provide meaningful lectures that reach all students within the class. This is personified in how Dr. Singha solicits feedback on her courses, not just from mid- or end of the year reviews, but from students directly and often. Dr. Singha may ask students to write down the main point of the lecture and / or three questions that they had afterwards, providing her immediate feedback on whether key concepts were effectively being communicated, and allowing her to continually refine course material. As a result, her lectures provide students an experience that is undeniably engaging, and has led to multiple teaching accolades from each of the institutions where she has been a professor. At Penn State University, Dr. Singha was awarded both the college-wide Wilson Award for Excellence in Teaching, as well as the university-wide George W. Atherton award for teaching excellence. Subsequently in 2017, Dr. Singha received the Dean's Faculty Excellence Award from the Colorado School of Mines, given for significant and meritorious achievement in teaching and scholarship. These peer nominated awards demonstrate a high regard amongst fellow faculty members for the quality of instruction that Dr. Singha brings to her courses. In addition to providing a high-energy and engaging atmosphere during her lectures, she also goes above and beyond the course syllabus, teaching skills valuable to budding scientists that are not specific to the course material. For example, Singha has created educational resources to support various hand-on demonstrations and modeling applications for undergraduate education (Singha, 2008; Singha and Loheide, 2011). Additionally, she has authored an open access textbook to introduce hydrogeophysical techniques to budding hydrogeologists (Singha et al., 2021).

Dr. Singha consistently strives to be a positive force for change within the Earth Science community. For Dr. Singha, this is manifested in her continued work to provide support and resources for early-career faculty, as well as foster an inclusive culture that encourages historically underrepresented students to consider STEM as a career path. While at Mines, Dr. Singha created an early career development program called “Launching your Academic Career” aimed at providing early career faculty with the knowledge and tools they needed to succeed in their new academic environment. For this program, Dr. Singha was awarded the Mines W.M. Keck Mentorship award. In addition to mentoring early career faculty, Dr. Singha has routinely recognized the need to improve inclusion and access for historically underrepresented groups in the Earth Science’s (Singha et al., 2020). While she was a professor at Penn State University, Dr. Singha helped develop and run the Penn State Hydrogeophysics Field Experience. This program provided undergraduate students from Penn State and three Historically Black Colleges and Universities (HBCUs), with a field experience that spanned the entire data collection and field experimental design, through data analysis, modeling, and interpretation while under the guise of academic, federal, and private industry experts. In addition to data collection and interpretation, students learned to work in a team, and effectively communicate their findings.

Dr. Singha has previously alluded to time spent in the field collecting data as a key driver to her pursuit of hydrology and near-surface geophysics, now she continues to provide students with similar opportunities to discover their love and curiosity for Earth Science. Graduate students within her group often have a significant field component to their research. Further, Dr. Singha’s research group often hosts summer interns from a host of institutions, including many recruited via the m. This program supports field-intensive summer internships for students from traditionally underrepresented groups in STEM. From 2014-2022, Dr. Singha’s research group collaborated with 8 individual students through the UNAVCO program (as of August 2022). Many of these students have gone on to pursue graduate studies both in Dr. Singha’s research group at Mines and at other universities. Along with other colleagues in the Critical Zone RCN, Dr. Singha developed programming to integrate new researchers and expand diversity and inclusion in the field of critical zone science. The initiative has included offering travel grants to conferences or meetings focused on diversity, inclusion, and access in STEM, hosting a critical zone meeting specifically for early-career critical zone scientists, and organizing virtual symposiums for “Critical Conversations” on critical zone science topics. Additionally, Singha’s effort in the Mining for Talent Program, which, in collaboration with the Society for Hispanic Professional Engineers, brings in students from Alameda International Junior/Senior high school, a Latinx-serving high school in Lakewood, CO. To-date about 40 students and 5 teachers have visited Mines for a tour that highlighted four cutting-edge research labs at the school, including hands-on activity in these state-of-the-science facilities.

4. Reflections

Singha’s impact on the discipline is extraordinary, as evidenced by her widespread success in grantspersonship, publication, education, mentoring, and community building. She has accumulated a host of awards and recognitions - including the American Geophysical Union’s Witherspoon Lecturer (2022), being named a Geological Society of America Fellow (2018), serving as the National Ground Water Association’s Darcy Lecturer (2017), and the Florence Bascom Lecturer at CUAHSI’s 2023 Biennial. These notable examples are only a few selected from her litany of accolades, while additional recognitions for mentorship, teaching, and outstanding performance grace her vitae. While these awards are visible and certainly well-deserved, we have taken the opportunity of this special issue to document the substance that underlies these metrics of success.

While we provide a review of Dr. Singha’s specific contributions to basic research (Section 2) and her role in fostering a hydrogeophysics community (Section 3), we reflect here on the traits that underpin her successes, forming the foundation upon which a successful and impactful career research, teaching, and mentoring is built:

(1) Dr. Singha is both a pioneer of new tools and applications. Critically, she also ‘closes the loop’ to demonstrate how these technical innovations may advance our theoretical or conceptual models. Taken together, Dr. Singha is an inventor of approaches and the requisite theoretical underpinning to deploy them in novel applications, ultimately pushing the limits of what is possible.

(2) Dr. Singha’s work is not esoteric, but intentionally spans disciplines and both basic and applied research niches. Her advances in theory, observation, and modeling each contribute to societally relevant problems, and the outcomes of her scientific advances are ‘moving the needle’ in society’s greatest challenges, particularly in relation to groundwater.

(3) Dr. Singha has a comfort and competence working across disciplines. We have regularly heard her modestly remark “I’m a hydrologist at geophysics meetings, and a geophysicist amongst hydrologists”. She has not shied away from expertise spanning disciplines and embodies the ideal of calls for increased interdisciplinary science and has an innate sense of good timing for developing diverse collaborations (Brantley et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2020; Singha and Navarre-Sitchler, 2022).

(4) Dr. Singha mentors individuals to achieve their own goals, putting her advisees first. In a field where indices of productivity and individual accolades could motivate self-interest, Dr. Singha instead chooses to invest in building the skills and success of her team, yielding a network of motivated professionals who get the support they need to ‘level up’ their subsequent

careers. She is fair in both praise and criticism of student research, helping train productive and resilient natural scientists.

(5) Dr. Singha values and proactively fosters a diverse community of scholars. Her advances include forward-looking commentaries shaping the future of the field (e.g., Robinson et al., 2008; Singha and Navarre-Sitchler, 2022), engaging with the next generation of scientists (e.g., her field school in partnership with HBCUs), and proactively opening doors for diverse scholars and welcoming them into new areas of research (e.g., Singha et al., 2020).

While each of these traits is admirable on its own, we contend that the combination of these in one researcher - particularly coupled with overwhelmingly positive energy and boundless enthusiasm - positioned Dr. Singha to have a disproportionately large impact on the field of hydrologic sciences thus far, and will undoubtedly continue to serve her well moving forward.

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