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Letter from the Editors

We are pleased to introduce a new feature of the *Journal of Contemporary Water Research and Education*: Perspective Pieces. We invited experts in the water arena to give us their perspectives on a water issue near and dear to them. In this issue, Dr. Len Shabman, Senior Fellow at Resources for the Future, shares his thoughts on the federal role in river management and the need to reframe the discussion. Dr. Don Siegel, Emeritus Professor of Earth Sciences at Syracuse University, offers us some thought provoking insights on the current state of public discourse on environmental issues. Perspective pieces were a hallmark of our journal since its inception as *Water Resources Update* in 1964 and our editorial team wanted to reemphasize this feature in 2019 after a long absence. So, please enjoy Dr. Shabman's and Dr. Siegel's pieces and we invite you to consider sharing your perspectives on an important water issue with our readership. We look forward to hearing from you.

Sincerely,

Karl W.J. Williard
Jackie F. Crim

Karl W.J. Williard and Jackie F. Crim
Co-Editors, *Journal of Contemporary Water Research and Education*

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Perspective Piece

Reflections on the Federal Role in River Management*

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**Adapted from remarks made upon acceptance of the Warren Hall Medal, UCOWR/NIWR Annual Water Resources Conference, June 2018*

Federal government agencies' responsibilities for national water resources management grew rapidly in the 20th century, along with the budget to execute those responsibilities. In most places today, river flows are the result of rainfall and runoff, as well as the presence of the water development projects of these agencies. Meanwhile in the nation's watersheds, demands on water resources are changing along with changes in rainfall and runoff volume and patterns, suggesting the possible need for new investments and different management of the investments currently in place. However, by historical standards, there has been a radical reduction in the Federal roles and budgetary commitment to river management. This diminished Federal role has resulted from competing water management visions that I will refer to as "old water conservation," "new water conservation," and "watershed restoration." Old water conservation is where I begin.

Throughout the nation's first 200 years, engineering works (i.e., infrastructure) were supposed to remove the tails from the hydrograph – that is remove natural variation in river flows – promoting material prosperity and general social well-being. In 1934, the National Resources Planning Board declared[1],

> "In the interests of national welfare there must be national control of all the running waters of the United States, from the desert trickle that may make an acre or two productive to the rushing flood waters of the Mississippi."

> In the words of the 1936 Flood Control Act "… the Federal Government should *improve* or participate in the *improvement* of navigable waters …. if the benefits to whomsoever they may accrue are in excess of the estimated costs, and if the lives and social security of people are otherwise adversely affected." (emphasis added)

In 1963, when dedicating the Whiskeytown Dam on the Trinity River in California, President Kennedy concluded his remarks by endorsing the old water conservation vision, as follows:

> {by these works water will not run} " … unused to the sea" when it could "… irrigate crops on the fertile plains of the Sacramento Valley and supply water also for municipal and industrial use to the cities to the south. And while running {its} course, … generate millions of kilowatts of energy and help expand the economy of the fastest growing State in the Nation. In these ways … <u>man can improve on nature</u>, and make it possible for this State to continue to grow." (emphasis added)

A drawing of an ideally managed *large* river basin in the 1950 Truman administration's report on water resources has an illustration of the old

[1] Citations for extended historical quotes and other material can be found in Shabman, L. 2008. Water Resources Management and the Challenge of Sustainability. In: *Perspectives on Sustainable Resources in America,* R. Sedjo (Ed.). Resources for the Future Press, Washington, D.C., 45pps.

water conservation. In the upper reaches of the smaller watersheds, cover crops and reforestation on eroded soils slow runoff and control erosion. Downstream, small dams are combined with diversion channels and other conveyance facilities to move water to irrigated farm fields and small communities. Previously wet areas are drained by small ditches leading to larger canals, with the drained land dedicated to cities and farms. On the larger rivers, dams create reservoirs to store water, while levees along the river edges and deepened river channels limit flooding of fertile soils. Cities are located adjacent to flood-protected rivers, and their manufacturing and other commercial facilities along the river edge are served by ports and barge terminals. The water stored in reservoirs irrigates agricultural fields, generates electric power, and provides for other water uses in dry times.

This grand vision of the ideally managed river basin was to be executed by Federal construction of levees, channels, dams, and reservoirs paid for by the Federal taxpayer. The Federal efforts were accompanied by state and local governments building water supply reservoirs, pipes, and open canals and transferring that stored water over long distances. This national investment in advancing the old water conservation vision transformed a natural water supply that varied unpredictably across watersheds (with the season and between years) into a reliable water source for all users in all regions of the nation. The high- and low-flow extremes of the natural hydrograph rarely interfered with normal uses of water or with the use of land adjacent to rivers and streams.

By the 1970s this old conservation vision had run its course, and was to be replaced by the new water conservation to then be supplanted by a management vision of watershed restoration. The 1960s nascent environmental movement grew to its current prominence around events such as the oil soaked beaches in Santa Barbara, California, when offshore wells blew out. However, perhaps most galvanizing for building a constituency for a new water conservation were proposals to build dams at Tocks Island in the Delaware Water Gap, in Hells Canyon in the Pacific Northeast and in the Grand Canyon National Park. In his classic book *Encounters with the Archdruid: Narratives About a Conservationist and Three of His Natural Enemies*, John McPhee in 1977 wrote the following:

> "In the view of conservationists, there is something special about dams, something – as conservation problems go – that is disproportionately and metaphysically sinister. The outermost circle of the Devil's world seems to be a moat filled mainly with DDT. Next to it is a moat of burning gasoline. Within that is a ring of pinheads each covered with a million people – and so on past phalanxed bulldozers and bicuspid chain saws into the absolute epicenter of hell on earth, where stands a dam. The implications of the dam exceed its true level in the scale of environmental catastrophes. Conservationists who can hold themselves in reasonable check before new oil spills and fresh megalopolises mysteriously go insane at even the thought of a dam. The conservation movement is a mystical and religious force, and possibly the reactions to dams is so violent because rivers are the ultimate metaphors of existence and dams destroy rivers. Humiliating nature, a dam is evil …"

Note that McPhee claims to be a conservationist, but as an expression of a new and different vision for river management. This new water conservation would stand in opposition to any further engineering works that altered the hydrology of the nation's rivers and the associated wetlands and riparian areas.

Other critiques of the old water conservation vision also were ascendant in the 1970s and these were given prominence in the 1972 report to Congress by the National Water Commission. First, no longer were water projects accepted as stimulants to economic growth. Water projects were judged on an economic efficiency logic that was given voice by academics such as Otto Eckstein at the Harvard water program and John Krutilla at Resources for the Future. For example, new investments in our waterway system were expected to serve documented transportation demand and are not expected to stimulate such demand.

There was more to the economic efficiency idea as well. The nation needed to make the best of the already built water infrastructure, before spending added dollars on projects that would change a watershed's hydrologic regime. And, economic efficiency demanded that beneficiaries paid for project services to the extent they could be identified and made to pay. And, non-Federal levels of government would pay more toward the costs of such projects. By 1986, user fees, trust funds, and cost sharing by project beneficiaries were in place.

The new water conservation would replace the old and then 25 years later create the foundation for watershed restoration as a new principle for water resources management. Whether in the humid east or the arid west, the new water conservation meant stopping any and all changes to the existing flow regimes, wetlands, and riparian areas. Watershed restoration would call for putting back some of the variability in the hydrograph to support species that have life cycles dependent on the pre-water control hydrologic regime. Watershed restoration would mean reestablishing and rehabilitating wetlands and riparian areas that were altered by previous human activity. The value premise of the new water conservation and the link to watershed restoration was that humans should make do with less in dry years, retreat to high ground in wet years, cease efforts to control river flows, and actively reengineer rivers to replicate past variability.

These twin challenges to the old water conservation took hold and over the past 40 years have brought fundamental change to Federal roles in water resources management. Three Federal water development agencies were relied upon to deliver the old water conservation. Beginning in the early 1900s the Bureau of Reclamation had water programs in the 17 western states. In the 1950s the Department of Agriculture had a robust water development program for "small watersheds." The Corps of Engineers operated across the nation with a history dating to 1824, but its program grew dramatically beginning in the 1920s. Just prior to World War II and then into the early 1950s these three programs constituted as much as 3-5% of all Federal spending. Today the figure is probably far less than 0.05%.

Now the United State Department of Agriculture (USDA) program is all but gone and the Bureau is limited to taking care of what it built many years ago. The Corps carries on, but has to be motivated more by agency survival than with the old water conservation vision of multipurpose planning and management, as described in the vision of the Truman era report of 1950. To survive it has organized its program and is budgeting around single purpose mission areas that can assure some public support – flood hazard reduction (risk management) and support for waterway and harbor navigation.

In 1999, the Corps did add a free standing aquatic ecosystem restoration mission, that was to "…(restore) significant ecosystem function, structure, and dynamic processes that have been degraded to partially or fully reestablish the attributes of a naturalistic, functioning, and self-regulating system." Eight years later Congress acted to affirm this new free standing aquatic ecosystem restoration mission. This mission has its own planning and decision-making criteria and its own budget justification criteria, and is in competition for funds with the flood and navigation missions.

How has that worked out for redirecting the focus of this remaining Federal water management agency? One answer to the question is found in the total Corps budget which is about $7 billion each year, if we ignore post disaster emergency supplemental funding, which is targeted to areas that suffered significant flood or hurricane damage and the use of funds is limited to those areas.

First, the Corps' annually appropriated budget in inflation adjusted terms has been essentially flat for decades, and today as much as 30% of its funding comes from the users of ports and waterways and must be spent on that old water conservation mission area. This means that the dollars available from the general taxpayer to the Corps for flood protection and restoration are around $3-4 billion to be spread over the 50 states, the tribal areas, and the territories. In this budget setting, funds have increasingly shifted to operating, maintaining, and rehabilitating what was built in the heyday of the old water conservation, leaving few dollars for new investments in ports, waterway locks and dams, flood risk management, or for ecosystem restoration.

Today, when the Corps is in the news it is mostly about criticism and rarely about praise – and the reason can be traced to these severe budget constraints. Consider a few high profile – in the news – illustrations, but there are dozens of other examples across the nation. Addicks and Barker dams above Houston had to be operated during Hurricane Harvey in ways that flooded thousands of homes, because there had been no investments in increasing storage capacity – there was no money. The hurricane protection system for New Orleans was compromised by Katrina and the replacement has, by the Corps recent reporting, an "unacceptable" rating – there was limited money to provide protection before Katrina and there were limited dollars afterward.[2]

The poster child for restoration – the Florida Everglades system – is a massive engineering project of historic portion. This most significant restoration will mean more engineering and more concrete and more bull dozers – and significant amounts of money. However, the failure to move aggressively forward on Everglades restoration after decades of study and analysis, is related in part to the difficulty in justifying the allocation of scarce Corps budget funds to that effort.

In retrospect, the advocates for the new conservation and restoration visions have beaten back all three of the Federal programs that delivered the old water conservation. However, while old water conservation is on the ropes, advocates for restoration have not secured a significant Federal financial commitment to that cause. Both old water conservation – now limited to the flood risk reduction and navigation missions – and restoration are starved for Federal funds, and advocates for all these missions are frustrated. The Congressional frustration is curious, and perhaps disingenuous, because Congress has been reluctant to provide robust Federal funding for decades.

Another dimension of Congressional expressions of frustration with the Corps is the 25 years (and counting) of decision gridlock over how to manage the water flows that are now controlled by dams on the Missouri, Columbia, and Snake Rivers, or how to operate reservoir outflows from places such as Lake Lanier. The fact is that the old water conservation capital stock created real and de facto property rights to certain flow regimes that were locked in place in operating manuals and project operations. Current beneficiaries of a project need not accept changes in project operations to serve changing demands (water supply at the expense of flood control) or watershed restoration – even when such restoration is to comply with the Endangered Species Act. The Corps is blamed for being inflexible, but the inflexibility lies in the ridged operating rules and political opposition of those who benefit from current project operations. Offering financial or other forms of compensation to those who would lose current benefits might ease the way for making changes in project operations, but compensation schemes would cost money that Congress has not provided.

The Corps cannot build new projects to serve the old water conservation vision due to opposition or lack of funds. It cannot move aggressively on the restoration mission – again for lack of funds. And it has barely enough funding to keep what it has built and is now being asked to make operational changes to meet new demands in the face of significant opposition. Perhaps this might satisfy some interests. However, there are changing demands on our water resources. There are foreseeable changes in the patterns of rainfall and runoff. And there is a tradition of Federal water project infrastructure that we rely on to align demands and new supply realities. I am not sure how much more money will be needed, but I am sure it is more than Congress is now providing.

However, new funds only will follow if opinion leaders can agree on a different way to frame the river management discussion and the Federal role in that management. Here is an opportunity for what is old to become new. What do I mean? The trendy concept of ecosystem services might be usefully relabeled "watershed services." The relabeling as watershed services might make space in water management discussions to consider both the services that motivated advocates for the old water conservation and the services that now motivate watershed restoration. The relabeling as watershed services is a recognition that in most places humans will and must continue to bend and manage nature – even as nature itself is changing. The relabeling as watershed services would acknowledge that water resources planning and decision-making is about intentionally manipulating the existing hydrograph and geomorphic conditions to secure

[2] Woolley, D. and L. Shabman. 2008. Decision Making Chronology for the Lake Pontchartrain & Vicinity Hurricane Protection Project. Final Report for the Headquarters, U.S. Army Corps of Engineers. Available at: https://biotech.law.lsu.edu/katrina/hpdc/hpdc.htm.

socially preferred vectors of watershed services.[3] The relabeling as watershed services leaves behind the limited focus of the old water conservation, the new water conservation, and watershed restoration, which have become competing visions of how we should manage rivers.

These ideas are not new. Gilbert White in the 1960s called for full consideration of all water management measures – what today we call gray and green – to serve "multiple purposes" – what I would call multiple watershed services. The water research programs of decades past wrote about analytical procedures to help decision makers recognize and then honestly and openly debate the pros and cons of the tradeoffs among means, multiple services, and multiple social objectives as rivers were being managed. Today there is a strong interest in analysis to support "shared" or "collaborative" decision-making for watersheds.[4] If these old ideas become new then Federal water management programs might again grow in ways that make a contribution to national river management.

Author Bio and Contact Information

Leonard Shabman, Senior Fellow at Resources for the Future, joined RFF in 2002 after 30 years on faculty at Virginia Tech, where he also served (10 years) as the Director of the Virginia Water Resources Research Center. He received his Ph.D. from Cornell University. He also has served as Staff Economist at the United States Water Resources Council; Scientific Advisor to the Assistant Secretary of Army, Civil Works; Visiting Scholar at the National Academy of Sciences; and Arthur Maass-Gilbert White Scholar at the Corps of Engineers Institute for Water Resources. Dr. Shabman's work balances research with advisory activities in order to have a bearing on the design and execution of water and related land resources policy. His publications include over 300 book chapters, journal papers, technical reports, and outreach papers on decision-making for water resources and water quality management. He has held leadership positions on governmental advisory committees in areas as diverse as the Great Lakes, the Missouri River Basin, Chesapeake Bay, South Florida, and Coastal Louisiana. Shabman has served on or chaired 18 National Academy of Sciences Committees focused on water and related resources management and in 2004 was recognized as an Associate member of the National Academy of Sciences. He may be contacted at Shabman@rff.org.

[3] This proposed framing for decisions on river management is consistent with the logic of novel ecosystems management. Available at: https://www.ecologyandsociety.org/vol19/iss2/art12/.

[4] For example, see: https://onlinelibrary.wiley.com/doi/full/10.1111/jawr.12067.

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Perspective Piece

Fallacies, Fake Facts, Alternative Facts, and Feel Good Facts; What to do About Them?

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Both sides of the political spectrum now use deception and misinformation to argue their philosophical positions on environmental harm, present and future. And both use common logical fallacies to enhance their views: *cherrypicking* (selecting data fitting their preconceived outcome); *hasty generalization* (suggesting conclusions from a small set of data implies the same conclusion elsewhere); and *ad hominem* (personal attacks on the ethics, funding, or perceived associations of those having different views).

Beyond these long-known logical fallacies, the public debate of science includes outright lies, "fake and alternative facts," and "feel good facts" information or ideas that *feel* like they should be true but are not. Real facts consist of information that can be reproduced by anyone with the same skills. How many people showed up at President Obama and President Trump's inaugurations? This information can be found in the public record through photographs made by the U.S. Park Service and those made independently by others.

How do scientists change the conversation to allow for measured civil discourse to solving the large environmental challenges of the future? The fakery in public debate usually starts with the *cherrypicking* and then moves to never setting a bar for collective agreement. If these approaches fail to win the day, the *ad hominem* attacks begin and invocation of conspiracy theories which *appeal to public ignorance* (another fallacy). I became subject to these tactics in debate over hydraulic fracturing ("fracking") used to obtain oil and natural gas out of solid rock. I even wrote a paper on what happened to me when the dust settled (Siegel 2015).

Briefly, I challenged the premise of a published paper that concluded groundwater quality in northeastern Pennsylvania could be broadly contaminated by fracking. The paper used flawed statistics and a non-random small data set. I gained access to chemical analyses of groundwater from more than ten thousand water wells in the same area and showed that no broad environmental harm had in fact occurred. Indeed, groundwater quality in that part of Pennsylvania has actually improved since fracking, although this improvement did not relate to fracking (Wen et al. 2019).

Some of those who philosophically felt fracking *should* cause harm to groundwater (for them, a "feel good fact"), could not dispute the science since I effectively used the entire population of water wells. So, they attacked me *ad hominen* and suggested I participated in a conspiracy with the hydrocarbon industry. I ultimately testified at a Congressional hearing over the matter. You can find all the references and pertinent URLS to my unpleasant experience in Siegel (2015).

I see similar discourse happening to scientists across disciplines in almost every part of the environmental sphere. Social scientists know the reasons for the current change in discourse, and their work has been well summarized in more accessible fashion by Kobert (2017) and Beck (2017). Best-selling books have even been written on the topic (e.g., Gladwell 2007; Kahneman 2013; Wieland 2017).

Basically, people make decisions three ways: they use their head, heart, or "gut." The head part consists of logical mulling over of real facts to arrive at conclusions or opinions. This takes time and effort. Using one's heart appeals to good intentions, what feels "right to do," and takes less time. Using the gut refers to quick intuitive decisions, often without much thought or data to buttress them. Sometimes the heart and gut work well and sometimes they do not. In the public arena, research shows that heart and gut decisions usually win over the head in at least the short term. Social circles - those people with whom you most connect - profoundly affect your heart and gut decisions. Nobody wants to be isolated from their close personal friends, family, and professional contacts because of philosophical differences. The influence of these social circles, based on social media, religion, political party affiliation, or regional cultural differences (e.g., Woodard 2011) cannot be underestimated.

For example, during my involvement in the national debate on fracking, I had the opportunity to discuss water pollution with the chief operating officer of a major national environmental organization. After I explained why fracking would not seriously contaminate groundwater, he agreed that his organization "oversold" water pollution as a talking point, but that he could not retract what it said because his membership would not tolerate it.

In turn, I gave a presentation to leaders in the gas and oil industry, and told them they were very smart people, and so they had to know burning their product affected global climate. They could not admit that for fear of losing economic purchase and the respect of their peers who felt otherwise. In private, the oil and gas leaders agreed with me. The social pressure to conform may be as powerful a driver for human behavior as sex!

So, what can scientists do to move public debate out of this swamp of discourse? I use Randy Olson (2009, 2013) as a guide. Olson suggests that scientists should not be "such scientists" when they explain their work to the public. They need to be "storytellers" - avoid jargon, and certainly not use just their heads (e.g., "the data say this…"). Scientists need to also use their hearts and guts, tell personal anecdotes, and incorporate humor. I can say from personal experience that this mode of discourse can be difficult.

Most of all, scientists have to *publicly* acknowledge the fears and concerns of those who disagree with them. Acknowledgment does not mean that we agree with the positions. It means we respect that others can *have* another opinion, even if we think they may be wrong.

I also no longer tell people they "are wrong." Instead, I ask questions: "What led you to think this? That's interesting. Can you tell me more? What is your goal with your position?" I try to show that I want to understand the position from where they come.

I began to use Olson's approach toward the end of the fracking debate in my home state of New York and found that many who publicly called me "the frackademic" suddenly began to interact positively with me. We found agreement on many issues related to fracking, including the fact that groundwater would not be seriously contaminated.

How did I do that? I took Olson's advice to try to tell my "story" in only one word, and then in one grammatically correct compound sentence.

My one word on fracking? "Unscathed (with respect to water quality)."

My compound sentence? "I agree with you that fracking hundreds of thousands of gas wells has caused a few instances of methane contamination to well water and also locally spilled chemicals to streams that temporarily killed fish; but given the tiny number of incidents, can we instead focus on the larger problems: enhanced climate disruption, economic disparity, and stresses on local public services, air quality, and community development?"

This sentence showed that I respected those frightened of fracking by misinformation campaigns and scare tactics. My public respect for their concerns opened the door to communication - along with using more analogies and far less data driven graphs.

Try it. It works.

Author Bio and Contact Information

Donald I. Siegel earned his BS in Geology from the University of Rhode Island, a MS in Geosciences

at Penn State and his Ph.D. in Hydrogeology at the University of Minnesota. He subsequently worked for the U.S. Geological Survey as a hydrologist/geochemist, and then joined Syracuse University in 1982 and taught and did research there on topics related to hydrogeology and water chemistry for 35 years. His research interests ranged from topics tied to the hydrogeology of deep basins and hydrocarbon-bearing rocks, methanogenesis in wetlands, organic and inorganic groundwater contamination, and drought-induced recharge in arid wetlands. Professor Siegel served as Chairman of the National Water Science and Technology Board of the National Research Council (NRC) and participated on many NRC panels related to water resources. He served as associate editor for most water topic journals and as book editor for the Geological Society of America. Geological Society of America's Hydrogeology Division awarded Professor Siegel its *Distinguished Service Award, O.E. Meinzer Award* and *Birdsall-Dreiss Lectureship,* and he is a Fellow of the American Association for the Advancement of Science, the Geological Society of America, and the American Geophysical Union for his contributions to water science. Not retired now but rewired, Siegel now serves as a partner at *Independent Environmental Sciences,* a consulting group specializing in forensic hydrogeology and geochemistry. He recently competed on the *Food Network* in 2016 and is developing a secondary career playing solo jazz guitar at coffeehouses, wineries, and various receptions in upstate New York. He may be contacted at disiegel@syr.edu.

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Reduced and Earlier Snowmelt Runoff Impacts Traditional Irrigation Systems

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Abstract: Seasonal runoff from montane uplands is crucial for plant growth in agricultural communities of northern New Mexico. These communities typically employ traditional irrigation systems, called acequias, which rely mainly upon spring snowmelt runoff for irrigation. The trend of the past few decades is an increase in temperature, reduced snow pack, and earlier runoff from snowmelt across much of the western United States. In order to predict the potential impacts of changes in future climate a system dynamics model was constructed to simulate the surface water supplies in a montane upland watershed of a small irrigated community in northern New Mexico through the rest of the 21st century. End-term simulations of representative concentration pathways (RCP) 4.5 and 8.5 suggest that runoff during the months of April to August could be reduced by 22% and 56%, respectively. End-term simulations also displayed a shift in the beginning and peak of snowmelt runoff by up to one month earlier than current conditions. Results suggest that rising temperatures will drive reduced runoff in irrigation season and earlier snowmelt runoff in the dry season towards the end of the 21st century. Modeled results suggest that climate change leads to runoff scheme shift and increased frequency of drought; due to the uncontemporaneous of irrigation season and runoff scheme, water shortage will increase. Potential impacts of climate change scenarios and mitigation strategies should be further investigated to ensure the resilience of traditional agricultural communities in New Mexico and similar regions.

Keywords: *climate change, acequia, water resource management, system dynamics, irrigation valley*

Traditional agricultural communities have existed in New Mexico for hundreds of years (Hutchins 1928). These communities rely upon irrigation ditches called acequias, which divert available surface water from nearby streams, to maintain their pastoral lifestyle (Clark 1987). A majority of the water used for agricultural purposes in these communities has typically come from spring and early summer runoff produced by melting snowpack upstream of the irrigation community (Mote et al. 2005; LaMalfa and Ryle 2008; Rango et al. 2013). In recent years, data have shown that runoff produced by snowmelt has decreased, leading to less available water for the acequias in northern New Mexico (Rango et al. 2013; Harley and Maxwell 2018). The likelihood of future diminished snowpack in the southwest United States is supported by several studies (Thomas 1963; Mote et al. 2005; Rango et al. 2013; Mote et al. 2018).

Snowpack is the main source of surface water in New Mexico (Rango et al. 2013). Mountain snowpack accumulates during winter months and melts, producing runoff during spring and early summer. With increasing temperatures, the proportion of precipitation realized as snowfall is reduced, which impacts the timing and magnitude of the resulting runoff (Xiao et al. 2018).

Historically, drought impacts in NM were notable in 1900–1910, 1932–1937, 1945–1956, 1974–1977, 2002–2004, and 2011–2013 (Meyer 2018). Drought in New Mexico places stress on the agriculture. Drought is different from other natural hazards, since it occurs slowly and persistently (Thomas 1963). Meyer (2018) discussed that the current drought occurring in the Southwest is lurching into mega drought, which is prolonged for decades. Drought is caused by many factors (e.g., rising temperature, decreasing precipitation, diminished snowpack), which in turn increase the likelihood of severe wildfire. Drought adversely impacts the ecosystem and societal activities (such as agriculture) that are supported by the water system (Weiss et al. 2009). The duration and intensity of drought can be quantified with the Palmer Drought Severity Index (PDSI) (Weber and Nkemdirim 1998). PDSI is a popular meteorological drought index, which uses a water balance approach based on precipitation, temperature, and the local available water content (AWC) to quantify drought (Zargar et al. 2011). In ungauged areas where real-time runoff data are lacking, PDSI is able to improve drought monitoring and early warning due to its strong correlation with runoff (Tijdeman et al. 2018). Combining PDSI and stream flow simulation can be especially informative for agricultural practices during the irrigation season.

Hydrologic Modeling

Hydrologic models have been used to address variations in climate and soil properties and are useful for water resource management (Clarke 1973). Because limited infrastructure and available instrumentation exist in unpopulated mountainous areas, the modeling of watershed response to climate change is necessary to evaluate potential impacts on available water resources for downstream agriculture.

In order to make full use of hydrologic models, it may be useful to construct them in a fashion that allows future integration of the human dimension to the system. For this purpose, a hydrologic model alone is not sufficient. A system dynamics platform is helpful for integrating hydrologic models with future social dynamics (Gastelum et al. 2018; Tidwell et al. 2004, 2018). System Dynamics (SD) modeling is an integrated tool applied extensively in a broad range of natural resource management scenarios. SD involves the use of interconnected pathways representing changes of quantities over time (Gastelum et al. 2018). The underlying principle of SD is incorporation of feedback mechanisms. The method was developed as one way to conceptualize the physical world with interacting variables. It consists of stocks and flows to display a quantity footprint. Water can be influenced by factors such as population change, irrigation decision-making, and economic influences, which are typically not included in a hydrologic model (Scott 2018). The SD approach provides a solution to incorporate these factors into overall system simulations.

Research Objectives

The issues of climate change have been studied in many cases with large-scale watersheds. For example, the severity of flooding and drought both tend to increase over time, as indicated by climate change simulations in 12 major river basins in India with the Soil & Water Assessment Tool (SWAT) (Gosain et al. 2006), while a highly uncertain future was demonstrated by a model with 18 climate change scenarios in Iran (Farsani et al. 2018). Similarly, there is a need to understand the impact of climate change in small-scale watersheds, which are defined as smallest hydrologic units by the United States Geological Survey (USGS). Small irrigation communities, which rely on small-scale, upland watersheds are particularly vulnerable to the changes induced by climate changes due to limited water volumes and storage infrastructure in those regions. Shifting hydrological regimes caused by climate change can adversely affect the regional economy, human society, and ecosystem in traditional communities.

As described by Cruz et al. (2018), irrigation in traditionally managed communities in northern New Mexico is directly related to acequia flow, which originates from the upland watershed. The available irrigation and irrigation duration affect a community's decision regarding its farming and grazing schedule. Downstream community diverts water from runoff in the irrigation season; they also use forested uplands for grazing during the non-irrigation season. Precipitation and temperature shifts will affect upland pasture production and crop growth in irrigated land. Climate change could significantly impact the timing and length of the year available for farming and grazing practices.

This study examines potential impacts of climate change on runoff of an upland watershed and subsequent implications for irrigation management in the receiving downstream community. It is hypothesized that climate change will cause drier conditions after the mid-21st century. The SD model is expected to contribute a solid model base describing hydrologic processes to alternative management practices involving essential social and economic elements by simulating flow rate and schedule of runoff.

Materials and Methods

Study Area

The upland watershed feeding the El Rito, NM irrigation community is located in the Carson National Forest in northern New Mexico. This watershed forms a tributary to the Rio Chama, which flows to the Rio Grande. The area of the watershed is 188 km^2. The elevation ranges from 2113 to 3180 meters above sea level (Figure 1). The headwater sub-watershed is defined as the region that drains to USGS gauge 08288000 at El Rito, NM.

The irrigation community and irrigated lands of El Rito, NM are shown in Figure 2. It has been shown that there is a relationship between river runoff from upland watersheds and the water supply diverted into an acequia. The Census of Agriculture 2017 reports that the top crop in Rio Arriba County, where El Rito is located, is forage, and the top value in agricultural sales is cows and calves; irrigated pasture lasts from the end of April to October, when irrigation is indispensable (USDA 2019). Forage is not only an important source of sale income for local farmers, but also important for food storage for their livestock in the non-irrigation season (López et al. 2018).

El Rito receives more than 40% of its annual precipitation from July to October (Western Regional Climate Center 2009). Annual runoff sources vary throughout the year. Runoff from February to May is primarily from snowmelt, and runoff from June to September is primarily from monsoon rains. The average minimum and maximum historical monthly temperatures are 1.4 °C and 17.3 °C, respectively (Western Regional Climate Center 2009); the highest maximum temperatures are generally observed in August (34.33 °C) while the lowest minimum temperatures are observed in December (-16.95 °C).

Land cover is an important factor affecting interception, transpiration, and infiltration. Land use data were obtained from the Web Soil Survey (USDA NRCS 2017). The watershed was categorized into four classes: forest (mix/deciduous) (74.83%), evergreen forest (8.14%),

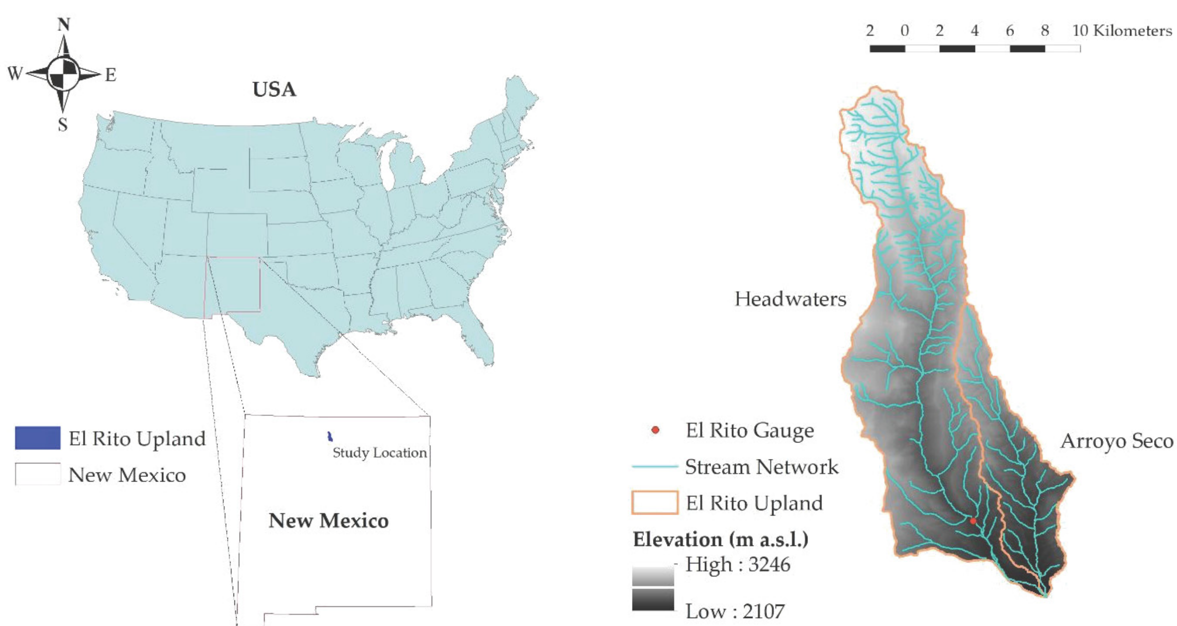

Figure 1. Upland watershed in El Rito consists of two sub-watersheds: the headwaters and the Arroyo Seco.

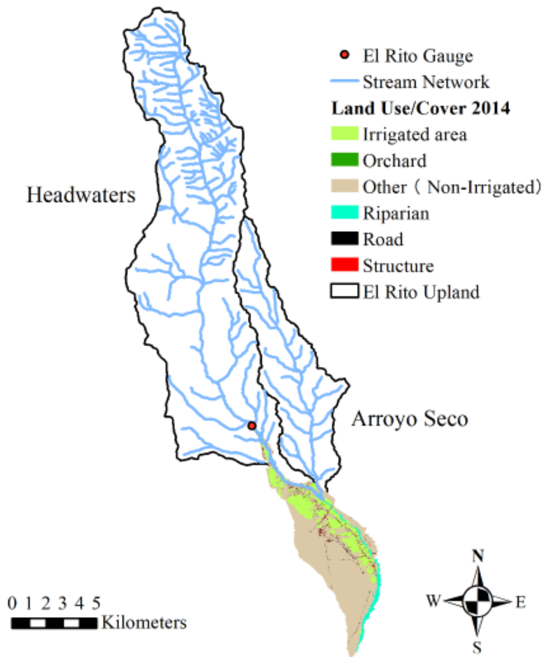

Figure 2. The land use of the irrigation community located downstream of the gauge: the upland watershed river feeds the downstream community (Sabie et al. 2018).

shrub land (6.18%), and grasslands/herbaceous (10.84%) (Figure 3). The soil types are clay (61.3%), loam (27.6%), and unweathered bedrock (11.1%). The entire watershed consists of two sub-watersheds, with the headwater watershed being defined by the USGS gauge placement. Runoff measurements at the gauge were made from 1930 to 1950 (U.S. Geological Survey 2019) and from 2010 to 2015 (Cruz et al. 2018). The measurements for river discharge (2010 to 2015) were collected directly adjacent to USGS gauge 08288000, above El Rito, NM.

Cruz et al. (2018) studied the relationship between upland river runoff and community ditches in northern New Mexico and concluded that every unit increase in river flow (cubic meter per second, m^3/s) leads to an increase in ditch flow. The relationship found between river-ditch flow by Cruz et al. (2018) ranged from 0.0561 to 0.1397. The ratio of 0.1397 was used to convert the simulated runoff from uplands into available irrigation supply (equation 2). The highest relationship ratio (0.1397) found by Cruz et al. (2018) was used to acquire a conservative estimate of the possibility of an irrigation water deficit in future scenarios.

Irrigation demand (equation 1) was calculated with community consumptive irrigation requirements (CIR) (cm/month) (Table 1) and the current agricultural land in the community (10.2 km^2). The monthly average irrigation demand during the irrigation season (April to October) was 1.2 m^3/s, used to compare with irrigation supply.

$$\text{Irrigation demand} = \text{Irrigated area} * \sum CIR \qquad (1)$$

Coefficient "α", was defined as a supply coefficient, which consists of irrigation supply and irrigation demand during the irrigation season to assess the supply level.

$$\alpha(t) = \frac{\sum_{\text{April}}^{\text{October}} \text{irrigation supply}}{\text{irrigation demand}} \qquad (2)$$

Data Collection

Climate and Hydrological Data. River discharge data were obtained for the years 2010 to 2015 (Cruz et al. 2018). Monthly climate datasets compiled for the SD model included precipitation and temperature data obtained from an area weather station and maintained by National Centers for Environmental Information (NCEI) (located at 36.3466°N, -106.1877°W), as well as climate projections from RCP scenarios 4.5 and 8.5 from HadGEM2-ES of the Coupled Model Intercomparison Phase 5 (CMIP5) model (Taylor et al. 2011). CMIP5 uses a weighted average method with a statistical downscaling approach applied to the General Circulation Model (GCM) (Taylor et al. 2011). RCP 4.5 and RCP 8.5 were chosen as they represent different concentration assumptions: the global emission peak is around 2040 in RCP 4.5, and the global emission continues to rise until the end of the 21st century in RCP 8.5. These two RCP's were selected to bracket future climate impacts. RCP 8.5 follows a business as usual case whereas RCP 4.5 addresses the case of concerted worldwide effort to reduce emissions. The whole simulation period was classified into three periods to capture the historical (1950–2000), current-term (2001–2049), and end-term (2050–2099).

Watershed Characteristics. A 30 m digital elevation model (DEM) was obtained from the USGS (U.S. Geological Survey 2016). Soils data

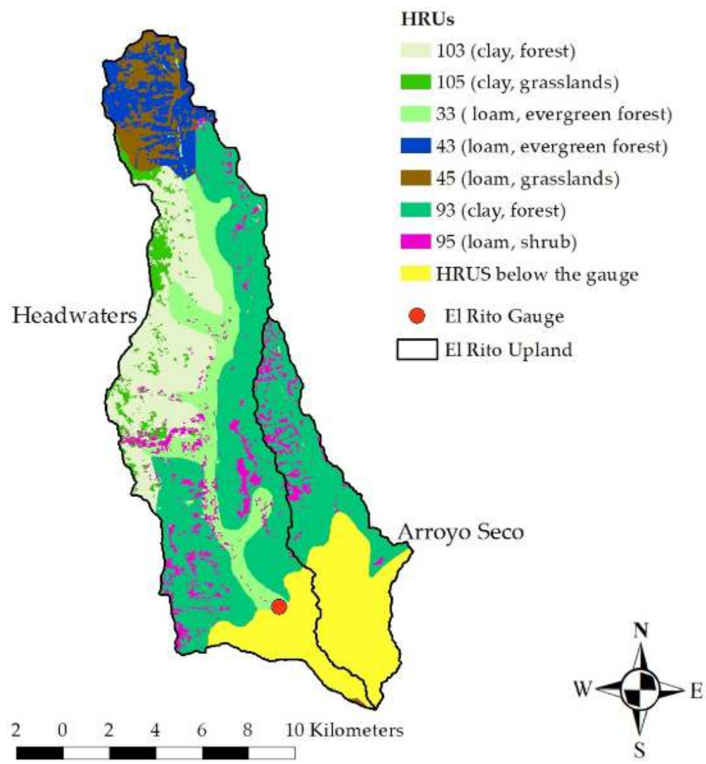

Figure 3. Hydrological response units in the El Rito study area. The eight HRUs represent the different soil texture and land cover combinations present in the region.

Table 1. Agricultural consumptive irrigation requirement (CIR) (cm/month) used in irrigation demand. Only months April through October are shown as the irrigation season.

April	May	June	July	August	September	October	Total
5.6	5.6	5.6	5.6	5.6	5.6	5.6	39.2

were provided by the Web Soil Survey (USDA NRCS 2017) (Table 2). The land use and land cover data were used to delineate hydrological response units (HRUs) (Table 3). The eight HRUs delineated distinct soil properties and vegetation combinations present in the El Rito watershed (Figure 3). The unique characteristics of soil and vegetation of each HRU determine interception, evapotranspiration, and infiltration rates in the hydrologic model components.

Hydrological Modeling

Description of SD Model. The simplified hydrology model was built on the platform of SD with the purpose of simulating hydrological flows (e.g., base flow and saturated excess flow) with the potential for adding future components such as human interactions (Winz et al. 2009). The hydrologic component of the SD model includes canopy capture, soil recharge, moisture storage, evapotranspiration, base flow, excess saturation runoff, and deep recharge. The hydrologic component is a continuous time model with a monthly time step. The model was physical-based (using climate and soil information) and suited to spatially and temporally large applications. The conceptualized diagram of the model based on interacting physical relationships is displayed in Figure 4.

The construction of the model was motivated by parsimony to capture the main hydrological processes. All governing equations are provided to explain the mass movement in the hydrologic cycle; this model was previously used to evaluate runoff in a similar watershed near Taos, NM (Gunda et al. 2018). Climate data from projections were provided in one eighth degree resolution and averaged by HRU for incorporation in the model. The SD model runs from 1950 to 2099, with the period from 2010 to 2015 (when runoff data were available) used for model calibration and validation. Calibration was conducted manually using the Powersim (Powersim Software AS, Bergen, Norway) (Powersim 2017) optimization tool to identify optimal soil coefficient parameters for each of the HRUs (Table 2).

Climate Change Projections

Projected Temperature. Climate projections indicate an increase in T_{mean} by about 2.67 °C and 3.77 °C in RCP 4.5 and RCP 8.5, respectively. Temperature increases are indicated across all

Table 2. Soil coefficient parameters used in calibrated model.

HRU	Porosity	Residual Water Content	Field Capacity	Wilting point	Conductivity
3	0.3	0.03	0.25	0.11	9
33	0.45	0.03	0.29	0.14	1.3
43	0.45	0.03	0.29	0.11	1.3
45	0.45	0.03	0.28	0.1	1.3
93	0.3	0.03	0.26	0.12	0.6
95	0.3	0.03	0.26	0.11	0.6
103	0.4	0.03	0.26	0.1	0.6
105	0.4	0.03	0.25	0.1	0.6

Note: HRU = hydrologic response unit.

Table 3. Eight hydrologic response units (HRU) representing soil and land cover information.

HRU	Area (%)	Soil Texture	Land Cover
3	9.2	Unweathered bedrock	Forest
33	15.8	Loam	Forest
43	8.1	Loam	Evergreen forest
45	6.4	Loam	Grassland
93	36.5	Sandy clay	Forest
95	6.1	Clay	Shrubland
103	19.7	Silt clay	Forest
105	3.5	Silt clay	Grassland

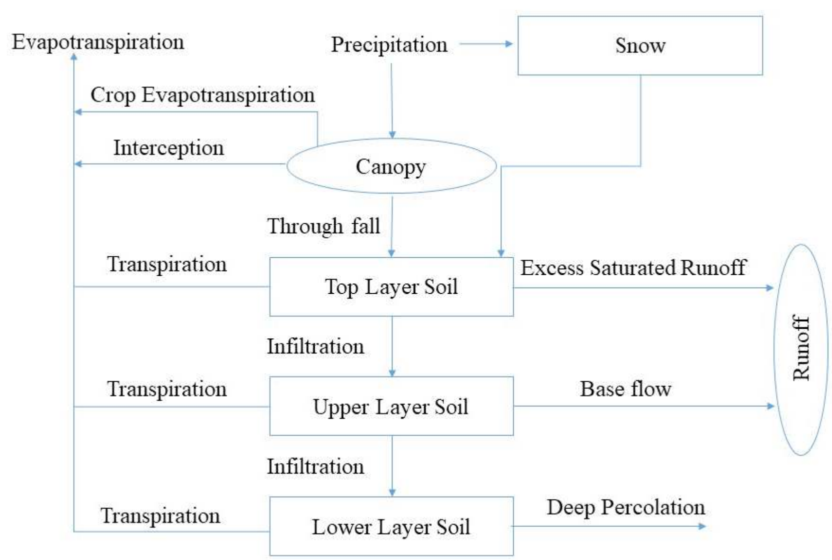

Figure 4. Primary dynamics included in the System Dynamics (SD) model. The SD model includes precipitation as rain or snow, interception, evapotranspiration, infiltration, deep percolation, excess saturation runoff, and base flow. Runoff generation includes both excess saturated runoff and base flow.

months in both scenarios (Figure 5), and monthly differences between maximum and minimum temperature enlarge from 17.6 °C historically (T_{max} 13.5 °C, T_{min} -4.1 °C) to 18.3 °C (T_{max} 17.4 °C, T_{min} -0.9 °C) and 18.5 °C (T_{max} 19.4 °C, T_{min} 0.9 °C) at the end of the simulation period under RCP 4.5 and RCP 8.5, respectively. The end-term projections of both scenarios show increased temperatures. Increased temperatures, particularly during winter and spring months, have implications on the amount and timing of snowfall and snowmelt runoff.

Projected Precipitation. Intra-annually, the El Rito upland watershed is characterized by three periods: dry season (October to February), snowmelt season (March to May), and monsoon season (June to September). RCP projections indicate a decrease in precipitation during the snow melting season for both terms relative to current conditions, which are more similar to historical conditions (Figure 6). During the monsoon and dry seasons, however, climate projections indicate increased precipitation for all terms of both scenarios compared with current and historical conditions. The seasonal precipitation shows the varied trends in three seasons. In both scenarios, the seasonal precipitation of the end-term has the largest standard error, which indicates the variability of precipitation in the future.

In RCP 4.5, the seasonal precipitation pattern throughout the year remains similar with historical records but has an increased magnitude. In the dry

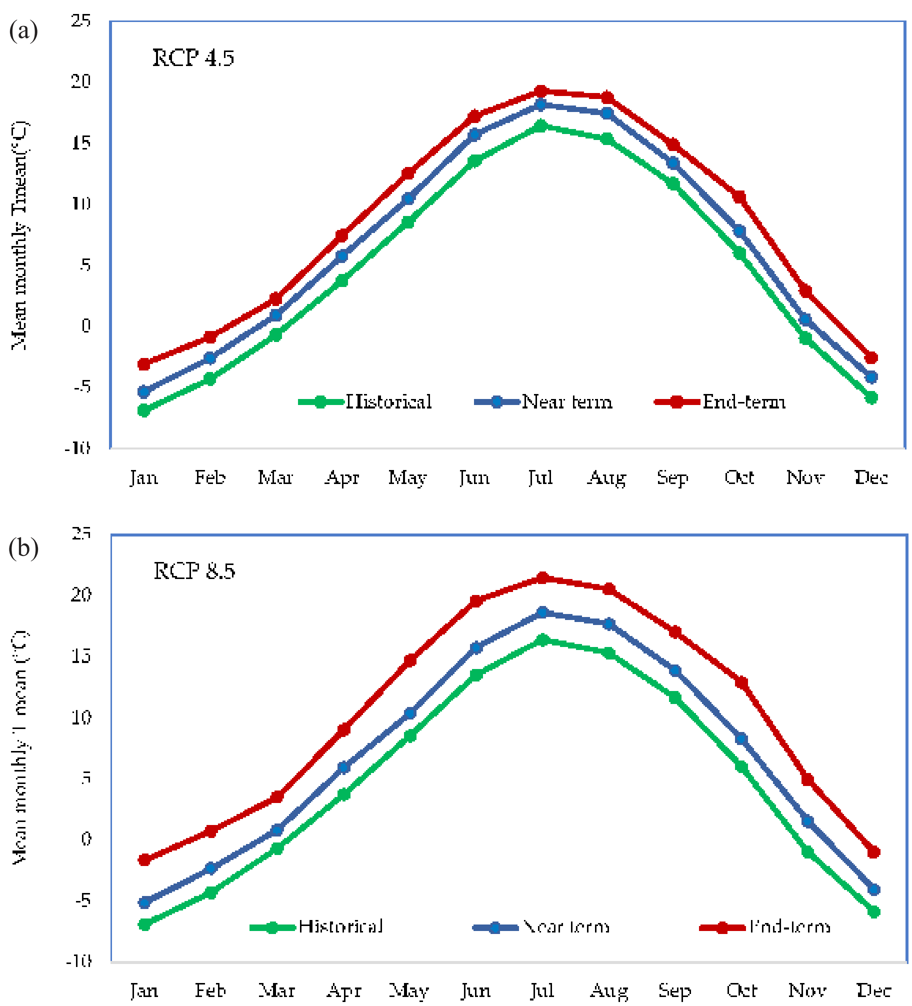

Figure 5. Projected mean temperature for the future in (a) representative concentration pathways (RCP) 4.5 and (b) RCP 8.5. Relative to the historical period, temperatures are consistently higher across the months in the future. Values represent historical (1950-2000) and projected, current term (2001-2049) and end-term (2050-2099) conditions.

season, precipitation is projected to increase by over 35% in the current-term and by over 20% in the end-term compared with historical conditions.

A notable difference of RCP 8.5 projections compared with RCP 4.5 is a smaller increase of precipitation during the dry and monsoon seasons of the current-term. Precipitation during the snow melting seasons is greater than historical conditions by over 30% in the current- and end-terms. Snow melting season precipitation in the end-term is predicted to be reduced from current conditions and be closer to historical conditions.

PDSI. PDSI was used to assess the severity and duration of drought. The Self-calibrating Palmer Drought Severity Index (sc-PDSI) DOS command line can be downloaded from the website (National Climatic Data Center 2003) and populated with parameters representing local conditions (AWC = 254 mm, station latitude = 36.5°N). The value of the PDSI is calculated to reflect how soil moisture compares to normal conditions.

Based on the drought classification, moderate drought and extreme drought will occur once the PDSI is lower than -2 and -4, respectively (United States Drought Monitor 2019). Long-term drought is defined as a duration of drought over six months and short-term drought has a duration of drought under six months (Northeast Regional Climate Center 2016). The drought percentage is calculated using the counts of drought occurrence and 12 months in a year. There is an increasing frequency of both short- and long-term, moderate and extreme drought in the future (Figure 7). Short-term moderate/extreme droughts could be

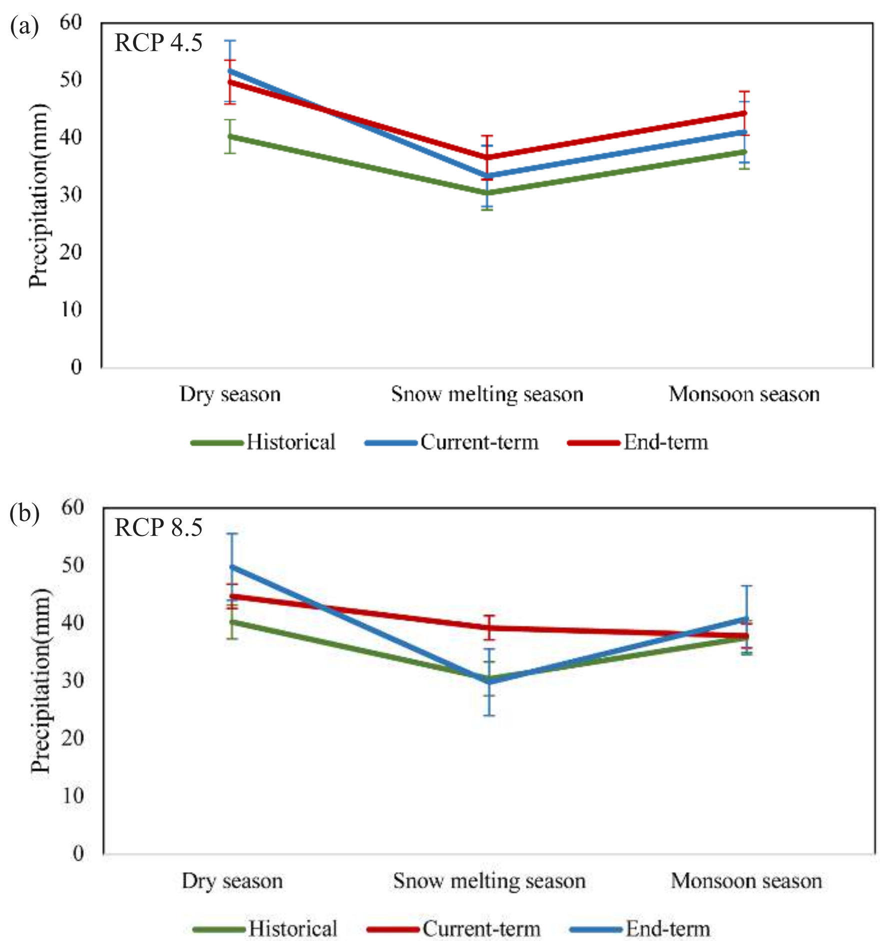

Figure 6. Seasonal precipitation trends in (a) representative concentration pathways (RCP) 4.5 and (b) RCP 8.5. Values represent historical (1950-2000) and projected, current term (2001-2049) and end-term (2050-2099) conditions.

a considerable risk in the current- and end-terms with a predicted frequency of over 40% in both scenarios. The total frequency over two duration categories and two drought categories are over 100, which means it will be likely to have not only short- or long-term drought with moderate or extreme levels simultaneously through one year but a combination of drought types and durations. In the end-term, under both scenarios, the extreme drought frequency reaches the highest frequency with RCP 4.5 and 8.5 reaching 47% and 63%, respectively. Overall, these scenarios show that drought will occur more often.

Results

Model Calibration and Validation

Model simulations of runoff indicate a pronounced spring peak (Figure 8), which ranges from 0.5 to 3.0 m^3/s, followed by summer peaks corresponding to large monsoonal precipitation events. Runoff generation that lags after rainfall events is less than two months. The coefficient of correlation between measured runoff and the simulated model runoff is 0.83 during the calibration period (2010–2011). The coefficient of correlation during the validation period (2012–2015) is 0.55.

Simulated Annual Runoff

In RCP 4.5, runoff increases are not as large as the projected precipitation increases (Table 4). With increases in precipitation, the runoff response ranges from 0.5% to 8.6% increase. In RCP 8.5, annual precipitation is again projected to increase for all terms, but simulated annual runoff shows increases in the current-term and a 24.7% decrease in the end-term. The changes in runoff are driven by higher temperatures, which drive increases in evapotranspiration (ET) rates over time.

Simulated Monthly Runoff

Simulation results indicate significant changes from the historical runoff regime at a monthly scale (Figure 9). Simulations from RCP 4.5 and

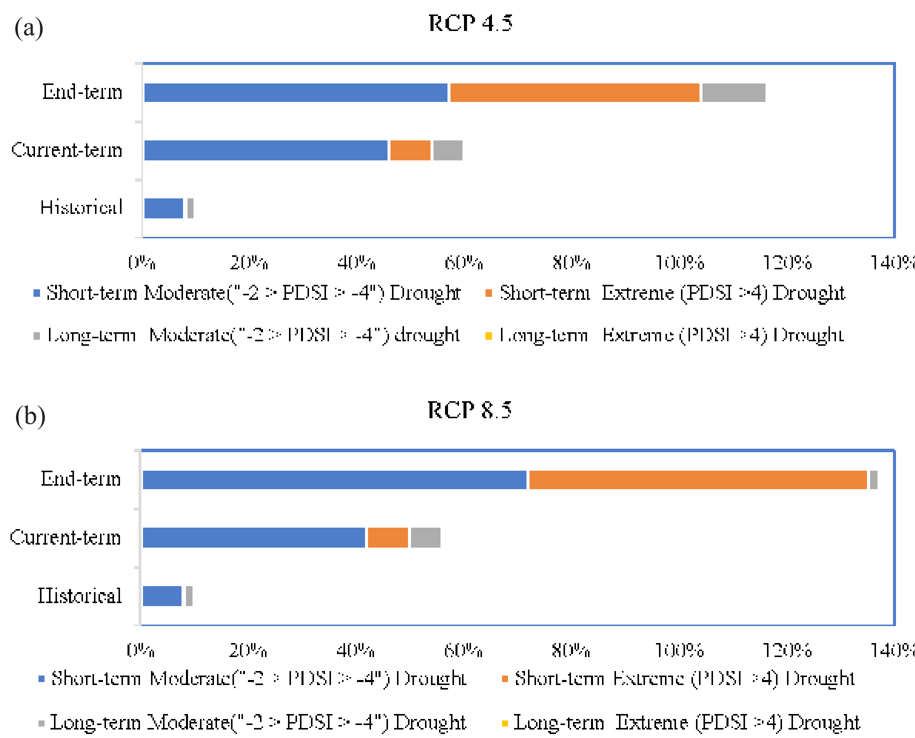

Figure 7. Short-term and long-term drought frequency (%) in (a) representative concentration pathways (RCP) 4.5 and (b) RCP 8.5. The y-axis represents the time from historical to the end-term. The drought frequency is analyzed in terms of duration and degree through one year. In the perspective of extreme and moderate drought, the frequency equals to 100%. Short-term drought could occur more than once through one year.

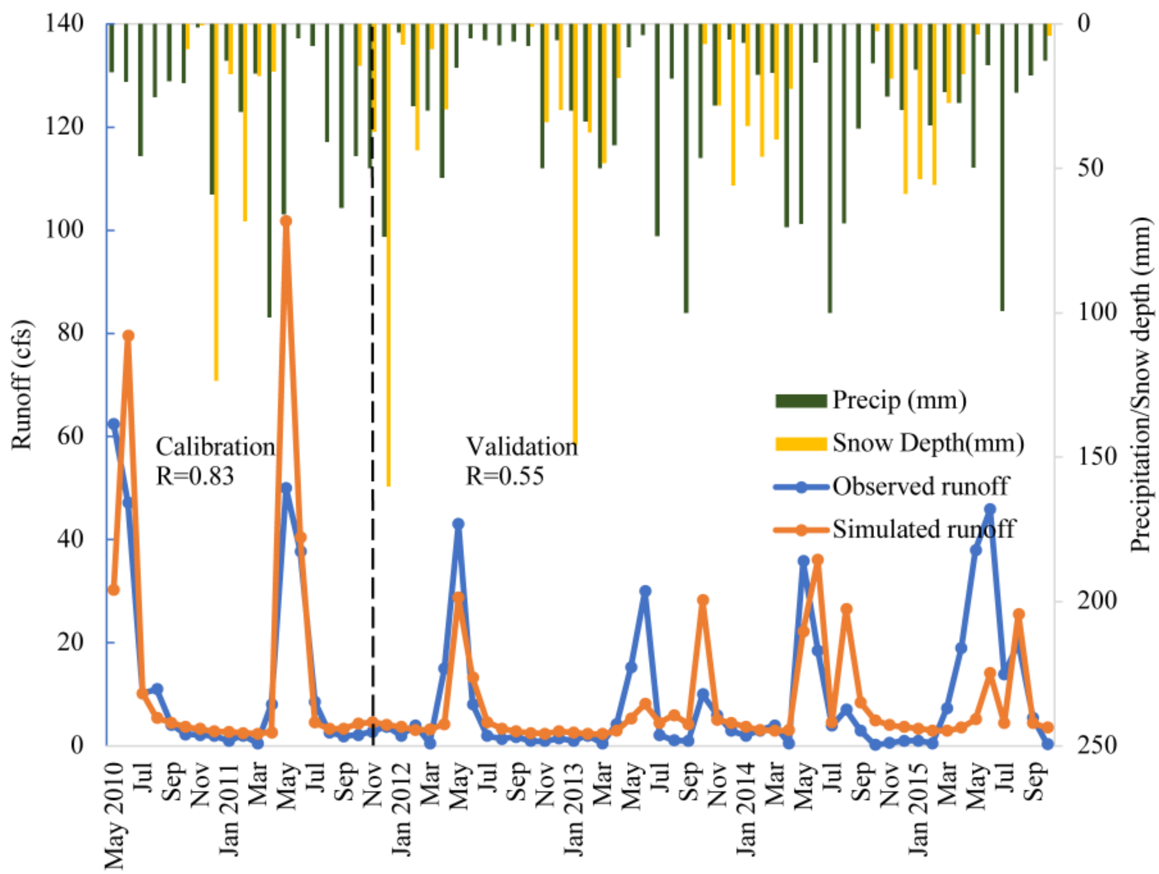

Figure 8. Model calibration and validation. The blue curve is observation and the orange curve is simulation with historical climate input. The green histogram represents the observed monthly precipitation depth and the yellow represents the simulated monthly cumulative snow water equivalent.

Table 4. Simulated runoff in the representative concentration pathways (RCP) 4.5 and RCP 8.5 scenario of HadGEM2-ES.

Value		----------- RCP 4.5 -----------		----------- RCP 8.5 -----------	
	Historical	**Current-term**	**End-term**	**Current-term**	**End-term**
Mean annual precipitation (mm)	439	523	535	493	501
ΔP (%)		18.8	21.8	12.1	14.0
Mean annual runoff (m^3/s)	5.5	6.0	5.5	5.8	4.1
ΔR (%)		8.6	0.5	5.1	-24.7
Mean annual evapotranspiration (ET) (mm)	266	315	337	306	331
ΔET (%)		27.0	18.4	24.4	14.9

8.5 show some disagreement in terms of volume and timing of runoff in the current-term. In RCP 4.5 it appears that conditions could stay similar to historical conditions in the current-term and show an increase in runoff during the snowmelt season in the end-term. Simulations of RCP 8.5 suggest an increase in runoff during the early two months of the snowmelt season in the current-term and a decrease in the end-term. Standard error shows that the runoff during March to June with RCP 4.5 and RCP 8.5 in the current-term has large variation when compared with other months.

Toward the end of the 21st century, simulations of both RCPs show several similar trends (Figure 9). End-term simulations of both projections show reduced runoff between the months of April and August, when agricultural activities are occurring. Historically, the runoff ranges from 0.3 to1.5 m^3/s from April to August. RCP 4.5 produces a runoff ranging from 0.3 to 1.0 m^3/s in the end-term; RCP 8.5 produces a runoff ranging from 0.4 to 0.6 m^3/s. Similarly, modeled results show snowmelt-induced runoff peaks shifting to earlier times of the year by up to one month and their magnitudes declining in the end-term. The largest decrease in modeled peak flow of the study area can be seen in the end-term of RCP 8.5 when the magnitude in peak flow is reduced by 55%.

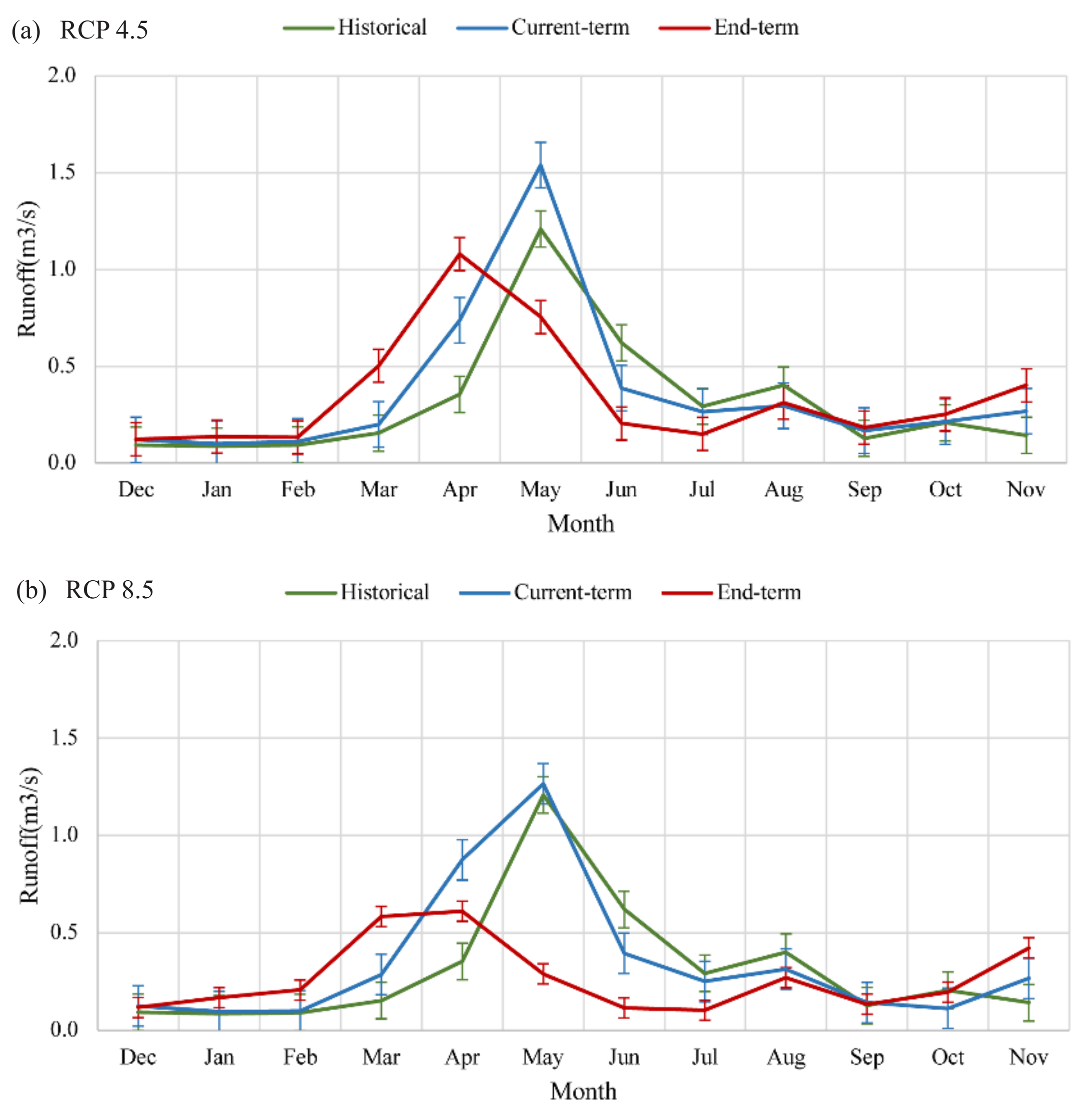

Figure 9. Monthly runoff: simulation projections and historical for (a) representative concentration pathways (RCP) 4.5 scenario and (b) RCP 8.5 scenario. The trends of runoff in the end-term of both scenarios are earlier and reduced.

Simulations of both projections show not only reductions in peak flow in the end-term, but decreases in total runoff from April to August (Figure 9). End-term simulations of RCP 4.5 suggest the total runoff from April to August decreases by 23%. End-term simulations of RCP 8.5 suggest that the runoff during these months decreases by 59%.

Another simulation result that is consistent between the two projections for all terms is increased runoff during the non-irrigation season, Marth to April (Figure 9). This is in part due to increased precipitation projections during these months. Warmer temperatures also lead to a higher percentage of precipitation during these months falling as rain and increased snowmelt. Though future dry season runoff is expected to be much greater than current conditions, the difference is small in relation to reductions in May to August runoff.

Water Balance Changes

The ratio of ET (including Evaporation (E) and Transpiration (T)), which increases by at least 14.9% in simulations, indicates an increase in the ratio of ET to precipitation in the current- to end-term simulations (Table 4). The increase in ET is expected due to projected increases in temperatures. Increases in winter and spring ET in the current- to end-term are in part responsible for predicted reductions in spring runoff. Another cause of reduced spring runoff appears to be an increase in the ratio of deep recharge to precipitation on an annual basis. Diminishing snowpack due to warmer temperatures is also evident (Table 5) as the ratio of snowpack reduces from 1.1% to 0.1%. The ratio of the snowpack is below 0.1% in the end-term of RCP 8.5. Both scenarios indicate a higher percentage of saturation excess runoff in some of the periods. The ratio of saturation excess runoff in all terms increases from historically 9.2% to at least 10.6% (Table 5), indicating more frequent short-interval, high-intensity rainfall events. Soil moisture levels are as low as 0.4% in all future periods compared to 4.9% historically (Table 5).

Irrigation Impacts

The number of frost-free dates in a given year is an indicator of the irrigation season length (Easterling 2002). Historically, El Rito had an average of 4.3 frost-free months per year (Table 6). The number of frost-free days increases with temperature in the RCPs over time. In the end-term of both scenarios, the frost-free duration is over one month longer than historically.

The graph of the water supply coefficient displays the trend of reoccurring stress on water availability through all periods (Figure 10). The current agricultural practices require a constant water supply through the irrigation season due to high ET crops (e.g., pasture and orchard) being grown in this arid area and region. In the end-term, water stress will continue to increase due to high ET rates and uncertainty in precipitation. A low water supply coefficient (<0.2) occurs frequently after 2040, in simulations.

Discussion

Trends in Future Hydrologic Regimes

A variety of hydrologic regime characteristics within the El Rito upland watershed could exhibit changes due to future climate conditions. Reduced runoff trends produced by the two considered climate scenarios were consistent with each other and concur with previous research of others (Rango et al. 2013; Buttle 2017; Coppola et al. 2018). Analysis of model drivers suggests that though precipitation and temperature are both expected to increase, the effect of the increase in precipitation could outweigh the negative effects of temperature on snowmelt runoff in the current-term.

An accordant trend between scenarios was that runoff will have altered timing, with the beginning and peak of spring runoff occurring much earlier in the year (Foulon et al. 2018; Hwang et al. 2018). Historically, peak runoff had been characterized by a single peak produced primarily from snowmelt in May. The difference between low flow in winter and high flow in spring was dependent upon winter and spring snowfall depth. Although climate projections showed a general trend of increasing annual precipitation, a shift in the timing of precipitation and a shift from snow to rain was predicted, which is in agreement with similar research (Fix et al. 2018).

A recent study by Chavarria and Gutzler (2018) in the Upper Rio Grande basin concluded that

Table 5. Water balance table of simulation (% of total precipitation).

		RCP 4.5		RCP 8.5	
	Historical	Current-term	End-term	Current-term	End-term
Snowpack	1.1	0.1	0.1	0.1	0.0
Rain evaporation	14.4	15.5	15.8	15.4	15.7
Snow evaporation	4.6	4.8	4.4	4.8	4.4
Soil evapotranspiration	58.7	60.1	60.4	60.0	61.1
Saturation excess runoff	9.2	11.2	11.2	11.5	10.6
Baseflow	6.1	6.0	5.8	6.0	5.9
Soil moisture	4.9	0.7	0.4	0.7	0.4
Deep recharge	1.1	1.5	1.9	1.5	1.9

Note: RCP = representative concentration pathway.

Table 6. Average frost-free months per year, when minimum temperature is above 0 °C.

	Historical	Current-term	End-term
RCP 4.5	4.3	4.8	5.8
RCP 8.5	4.3	4.8	6.2

Note: RCP = representative concentration pathway.

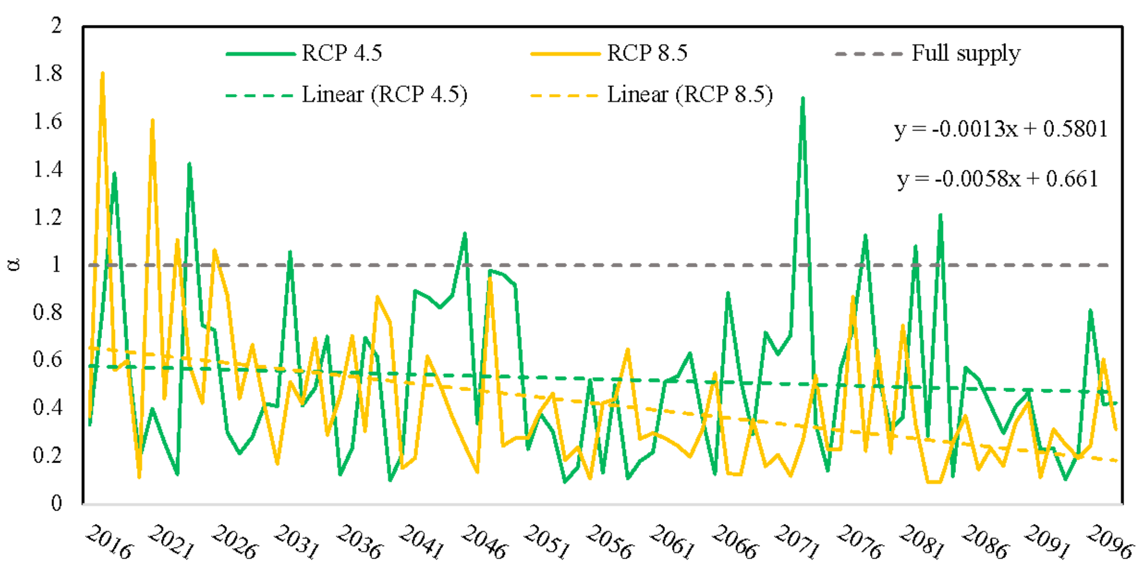

Figure 10. The water supply coefficient ranges from 0 to positive larger number. A coefficient closer to 0 means the water supply experiences significant stress; a coefficient over 1 means the water supply is sufficient. The slopes of two lines show that the water supply coefficient declines over time.

there has already been an observed reduction in April to July runoff attributable to increased winter and spring temperatures, decreased snow water equivalency, and a decreased relationship of runoff to precipitation since 1958. In the future, precipitation increases may moderate the runoff decline from diminished snowpack, but to date there is no evidence in actual observations (Udall and Overpeck 2017). Temperature strongly induces the runoff curtailment (Vano et al. 2014). The trend of snow pack diminution can be seen from climbing temperatures under both scenarios (Table 5). It would appear from simulations that a decreasing spring runoff trend is to be expected for the El Rito watershed in the end-term, and possibly sooner. End-term simulations of both climate scenarios showed reduced and earlier runoff in spring months, even though annual runoff was expected to increase for nearly all periods of both simulations.

Snowpack and soil moisture ratios decrease to less than 0.2% and 0.7% in both scenarios; the recharge ratio increases to 1.9% in the end-term of both scenarios (Table 5). Towards the end-term, the drought frequency in moderate and extreme level all exceed 40% (Figure 7). Even the precipitation in the end-term of RCP 8.5 is 14.0% more than historical, and the runoff decreases by 24.7% (Table 4). These analyses imply that the upland watershed is facing uncertainty in the timing and quantity of spring and early summer runoff due to unpredictable precipitation patterns and water distribution in hydrologic processes. Seasonal drought caused by climate change, such as diminished snowpack, higher temperatures, increased ET, and decreased soil moisture has been observed in other upland watersheds. Mao et al. (2015) used modeling and statistical approaches to analyze historical records of the snowpack, runoff, and other hydrological variables; they confirmed the correlation between warmer temperature and decreasing spring snowpack and runoff. It is widely recognized that ET will increase in scenarios that include a longer growing season and greater atmospheric demand in response to higher temperatures (Weiss et al. 2009; Serrat-Capdevila et al. 2011). Both scenarios produced increased ET (Table 4) and prolonged frost-free months (Table 6). Jung et al. (2010) discussed that a decrease in ET could be driven primarily by moisture limitation. The relation between soil moisture and ET corresponds with the trends in soil moisture and ET in Table 4 and Table 5. The increase in ET in the end-term of RCP 8.5 is 14.9%, which is less than the current-term (24.4%), but the precipitation in the end-term is slightly higher (Table 4). Soil moisture in the end-term of RCP 8.5 (0.4%) (Table 5) reflects the limitation of moisture on ET. Simulations in the context of this paper suggest that large increases in ET may cause uncertainty in runoff in the El Rito watershed, particularly toward the end-term. Though increased precipitation could offset effects of increased temperatures during some years, with increasing temperatures drought will be an inescapable reality. The phenomenon referred to as mega drought (Ault et al. 2016; Meyer 2018) is likely to occur in the current-term, even during years with average levels of precipitation, due to warmer temperatures, increased ET, and decreased soil moisture.

Management Implications

Model simulations support the conclusions of previous research (Rouhani and Leconte 2018) that there is potential for earlier and reduced runoff in spring and early summer. Results suggest a shift in the timing of spring runoff by over a month earlier than historically observed. Rather than focusing upon the timing of peak runoff, measures should be taken to cooperate with the trade-off between elements of practice, culture, and economy, and water availability to negate the effects of climate uncertainty (Hou et al. 2018).

New Mexico is experiencing water shortages for agricultural, ecological, and even domestic uses (Scarborough et al. 2018; Theimer et al. 2018). Shifts in runoff patterns that are suggested here could potentially lead to agricultural water shortages under current practices (Ahn et al. 2018). According to Cruz et. al. (2018), there are direct hydrologic connections between upstream rivers and downstream acequias in the irrigated communities of northern New Mexico. Residents who live in downstream areas might have to take adaptive actions to keep their agropastoral practices sustainable with limited water resources (López et al. 2018). Also, longer duration and increased drought from not only decreased precipitation, but also increases in temperature, or hot drought, could compound difficulties in agricultural practices. Investment in agricultural infrastructure, although not typical in the area, may be needed in the future to store and release water from intense precipitation events and runoff experienced during the winter.

The workforce for farming and grazing in the irrigation community is increasingly transitioning out of acequias to urban areas for better work and lifestyle opportunities (Benson et al. 2018). The enlarging gap between water demand and irrigation supply may intensify the trend of the workforce immigrating out of acequias, which reduces the sustainability of acequia communities in turn. In the end-term of both scenarios, water supply tends to be lower than 50% (Figure 10). The 50% water supply gap could indicate that the assumption of future water demand for farming and grazing may be substantially different from the past. With warmer climates, farmers might plant earlier in the season, which would change the timing of water demand. Similarly, recent modeling efforts have shown that the timing of water demand may not coincide with surface water deliveries (Cody 2018).

Prolonged periods of drought throughout a single year, and the increasing frequency of drought implies farmers may need to shift to crops which are tolerant to deficient irrigation practices and suitable for growing in winter months. Prolonged drought will likely have effects on the upland watershed in the long-term as well. This would have effects on the water supply to El Rito farmers. Prolonged drought could increase the rate of tree mortality and forest fires in forested areas (Daly et al. 2000; Hou et al. 2018). There could also be a long-term transition from larger species such as Ponderosa Pine (Pinus) to smaller trees such as Pinon Pine (Pinus) or Juniper (Juniperus) in areas that receive snowfall. This could potentially lead to small increases in summer and fall runoff from rain due to decreased interception. More importantly, reduced tree cover would lead to increased runoff after precipitation events and exacerbate the trend of reduced and shifted runoff (Wine and Cadol 2016).

Water supply coefficients, "α", is generally less than 1. "α", which in a few years is over one, indicates sufficient supply. The variation among years and seasons adds to the risk in water supply (Figure 10). In the future, the agricultural area will change as will the agriculture market. This requires adaptive agricultural practices such as modified crops and water-saving irrigation in order to cope with future potential drought while responding to social and market changes.

The unpredictable drought and prolonged frost-free periods will also change the water runoff supply to landscape and its timing, affecting the mechanism of farming and grazing in the watershed. Unpredictable drought not only affects the biomass production in publicly grazed forest, but also the hay production from farming for livestock. Thus, residential collaboration in traditional communities might become more necessary to maintain the sustainability of their grazing, farming, and rotational activities. Wehn et al. (2018) pointed out that engagement with the stakeholder in water management ensures social learning conditions, which foster the adaptive capabilities in decision-making. Richart et al. (2019) stated that with a multifunctional irrigation system, stakeholders could engage together to achieve good water governance by reducing tension, redirecting strategy, highlighting water scarcity, undertaking responsibilities, and sharing values among stakeholders. Konar et al. (2019) summarized the development of socio-hydrology; they pointed out that engagement with broader water management communities is a key opportunity for socio-hydrology to play a functional role in policy-making and scientific practice. Collaborative activities among stakeholders, communities, and institutes bring insight into science communication. They form the force crossing disciplines and scale to be more prepared to risk climate change brings.

Conclusion

Results suggest a general future trend of increasing annual runoff due to projected increases in annual precipitation. The most significant implications include shifts in runoff and precipitation regimes by the end of the 21st century. The two scenarios suggest hydrologic regimes that will deliver the majority of runoff from snowmelt up to one month earlier than historically observed. Simulations towards the end of the 21st century also suggest reduced snowmelt season runoff, during the time when irrigation activities are being performed. This could lead to operational water shortages later in the irrigation season.

Snowmelt dominated watersheds in northern New Mexico and southern Colorado have already shown earlier and reduced runoff during some recent years, suggesting climate change impacts are occurring. Though projections of precipitation show uncertainty as to annual and seasonal variability, projections of increased temperatures throughout the year appear likely. Regionally focused modeling, which couples hydrologic and social systems, could improve the resilience of local communities. Predictions of future potential risks caused by hydrologic regime changes could help communities develop management strategies before negative impacts are realized. Modeling efforts could also provide the ability to develop adaptive response strategies to avoid potential conflicts from competing demands for water. For those traditional agricultural communities without available advanced irrigation technologies and capital for large infrastructure, community-based and integrated management could be more flexible and practical for adapting to environmental changes, including future drought.

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Simple Approaches to Examine Economic Impacts of Water Reallocations from Agriculture

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Abstract: Facing an anticipated shortage declaration on the Colorado River and reductions in surface water for agricultural use, rural stakeholder groups are concerned about how water cutbacks will affect their local economies. Local farm groups and county governments often lack the analytical tools to measure such impacts. While one can learn much from large-scale hydro-economic models, data, cost, and time limitations have been barriers to such model development. This article introduces three basic modeling approaches, using relatively low-cost and accessible data, to examine local economic impacts of water reallocations from agriculture. An empirical application estimates the effect of agricultural water reductions to Pinal County, Arizona, the county that would be most affected by a Colorado River Shortage Declaration. Water cutbacks to agriculture are modeled using two variants of a "rationing" model, which assumes that farmers will fallow their acres that generate the lowest gross returns (Rationing Model I) or the lowest net returns (Rationing Model II) per acre-foot of water. Rationing models have modest data requirements given that crop and region specific data are available. Building off these simpler rationing models, an input-output (I-O) model provides more detailed information about the impacts on different rural stakeholder groups as well as the impacts to non-agricultural sectors and the local tax base. Given imminent water cutbacks, access to low-cost data and information that are easy to interpret is essential for effective community dialogue.

Keywords: *Pinal County, Arizona; Colorado River; shortage; agricultural water use*

The states of the Colorado River Basin (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) face growing challenges of balancing increasing water demands with limited and possibly declining supplies. The region's population is projected to grow by 12 million people (about 19%) over the next 20 years (University of Virginia 2018), increasing demands for municipal and industrial (M&I) water uses. On the supply side, the region faces a number of challenges. First, water supplies are over-allocated. The 1922 Colorado River Compact allocated (i.e., gave the legal rights to) 16.5 million acre-feet (maf) of water per year between the Basin States and Mexico, based on annual runoff estimates at the time of the Compact. Longer-term streamflow records, however, suggest average runoff of only 15 maf/year (Garrick et al. 2008). Tree ring reconstructions place the figure even lower, between 13.5 and 14.7 maf/year (Stockton and Jacoby 1976; Woodhouse et al. 2006; Meko et al. 2007). Second, few potential sites for dam projects for large-scale water storage remain in the West, while projects face greater scrutiny over their environmental impacts. Although there is renewed interest in "auxiliary projects" to increase storage capacity at existing dam sites (Perry and Praskievicz 2017), these are at best a partial solution. In addition, climate change is projected to further reduce Colorado River runoff (Overpeck and Udall 2010) and increase agricultural demands for water (USBOR 2012).

With limited (and possibly shrinking) water supplies and growing water demands, water planners expect large reductions in agricultural use will occur to balance Basin water supplies and demands. The Bureau of Reclamation's (BOR) *Colorado River Basin Water Supply and Demand Study* (USBOR 2012) projects Colorado River agricultural water use to fall by 0.3 to 0.6 maf/year, depending on the scenario, with the bulk of these reductions occurring in Arizona. Agricultural water use from all sources in the Basin is projected to fall between 0.7 and 3 maf/year (depending on scenario). The BOR scenarios assume, "[t]he overall decrease is almost entirely due to a reduction in irrigated acreage, as per-acre delivery shows slight increases across all scenarios" (p. C-29). A survey of state and regional modeling studies of western state adjustments to water shortages (Frisvold et al. 2013) found that "agriculture would be the sector that alters its water use the most, to adapt to regional water shortages and protect municipal and industrial (M&I) uses" (p. 231). In December 2017, the BOR Commissioner Brenda Burman called on the seven Basin States to develop Drought Contingency Plans (DCPs) in response to persistent drought and declining regional water supplies stored in Lake Powell and Lake Mead. Although states have yet to precisely allocate cutbacks across sectors, their tentative plans require agriculture to account for the bulk of water use cutbacks.

Rural stakeholder groups are concerned about how agricultural water cutbacks will affect their local economies in terms of lost agricultural production, farm income, and jobs, as well as broader economy-wide impacts on non-farm sectors and the local tax base. Yet, local farm groups and county governments often lack the analytical tools to measure such impacts. While one can learn much from large-scale state and regional hydro-economic models, these suffer from several drawbacks. They have significant data requirements, which can make them expensive and time-consuming to develop. Furthermore, state- or water basin-level models based on broader averages across larger geographies may not fit specific, local farming conditions well. California has invested considerable resources to develop modeling capacity at multiple geographical scales (see Sunding et al. 1994, 2002; Harou et al. 2009; Howitt et al. 2014; Medellin-Azuara et al. 2015). Yet, other states have followed suit to only a limited extent, perhaps because of the large budget and expertise required. This article introduces more basic modeling techniques to examine local economic impacts of water reallocations from agriculture. It begins with simple "back of the envelope" methods that have low data requirements, providing results that are easy to interpret by non-economists. It then builds up to a more complex input-output (I-O) model. I-O models are an extension of simpler methods and can be the basis of more sophisticated models, such as computable general equilibrium (CGE) models (Berck et al. 1991; Seung et al. 1997, 1999; Goodman 2000). In contrast to CGE models, local planners often employ (or are familiar with) I-O modeling methods.

The empirical application for this article estimates economic impacts of agricultural water reductions to Pinal County, Arizona. Previous BOR analysis identified Pinal as the county that would be most affected by surface water cutbacks to Central Arizona agriculture triggered by a Colorado River Shortage Declaration (USBOR 2007). Pinal County agriculture has also been at the center of debate and negotiations over the Arizona DCP.

The article proceeds as follows. Section 2 provides basic information about the role of agriculture in the Pinal County economy. Section 3 discusses the structure, assumptions, and data requirements of three modeling approaches. These include two variants of a "rationing" model of water cutbacks. Rationing models have the benefit of easy interpretation and very modest data requirements. The third modeling approach is an I-O model whose assumptions about agricultural production technology, cropping patterns, and short-run economic responses build off those of the simpler rationing models. The I-O model provides more detailed information about the impacts on different rural stakeholder groups (e.g., farmers, farm workers). It also provides information about how contractions in agricultural production affect non-agricultural sectors. Section 4 introduces a water supply shock – a 300,000 acre-foot (AF) reduction – in surface water supplies to Pinal County agriculture. This hypothetical shock is comparable to water reductions under earlier BOR shortage scenarios and reductions envisioned under the Arizona DCP. Section 5 discusses the importance of modeling assumptions and the final section closes by discussing limitations of the three modeling approaches and identifying areas of future research to better assess impacts of water cutbacks.

Pinal County Study Area

Pinal County in Central Arizona is bordered to the north and south by urban counties, Maricopa (metropolitan Phoenix) and Pima (metropolitan Tucson) (Figure 1). Archeological evidence suggests that irrigated agriculture in Central Arizona started as early as 600 AD when the native population, the Hohokam, began construction of a network of large canals near the Salt and Gila Rivers to irrigate their crops (Howard no date; Lahmers and Eden 2018). Today, important agricultural goods in Pinal County include cotton, milk, cattle, alfalfa, and other livestock feed and forage. With about two-thirds to three-quarters of Pinal County's annual agricultural sales derived from livestock and their products (USDOC BEA multiple years), the county is a leading producer of cattle and calves and milk from cows. According to the 2017 Census of Agriculture, Pinal County accounted for 44% and 31% of Arizona's cattle and milk sales, respectively, ranking it in the top 2% and top 1% of U.S. counties with cattle and milk sales (USDA NASS 2019).

Pinal County is an especially important source of milk for the large urban centers of Phoenix (Maricopa County) and Tucson (Pima County). In 2017, the county accounted for just 6% of the state's total population (AOEO 2019) but 31% of the state's milk sales. Dairy product manufacturing accounts for 18% of county manufacturing jobs (USDOL BLS 2017). Annual wages per employee are $13,754 per year higher in the dairy manufacturing sector ($66,830 per employee per year) compared to the county average for all manufacturing jobs ($53,076) (USDOL BLS 2017). About 96% of the cattle and calves sold in the county originated from 25 farms, which each have more than 500 head. This reflects the presence of a number of large feedlots in the county (AZDA 2018).

The importance of livestock and dairy production is reflected in Pinal County crop production, where the county ranks in the top 2%, top 3%, and top 6% of counties nationwide for hay and haylage, corn silage, and barley acreage, respectively. The

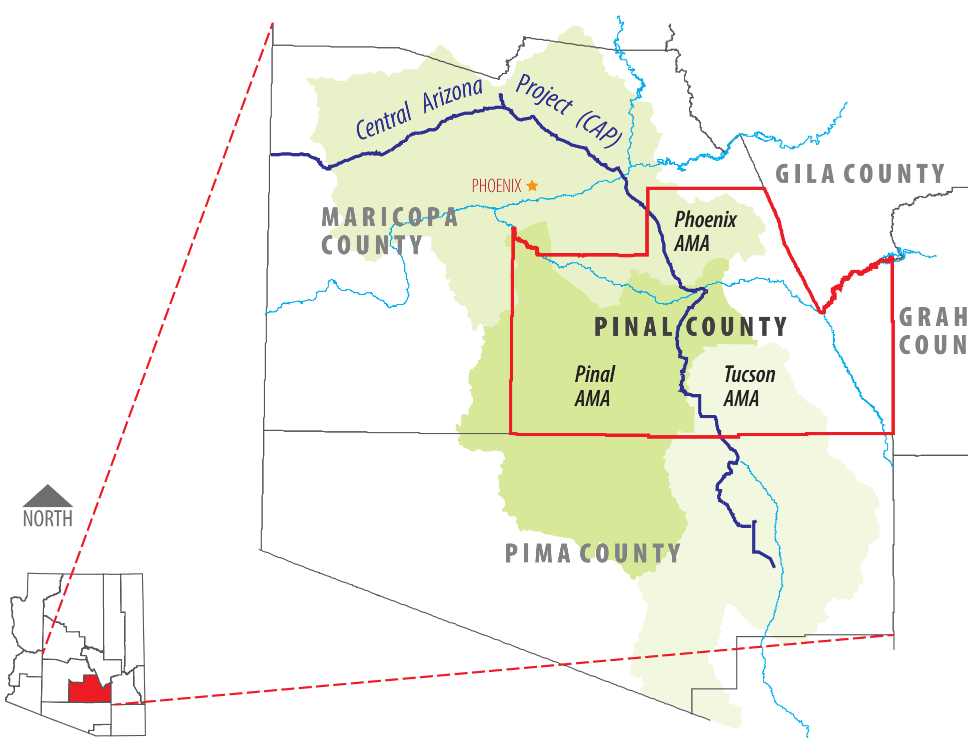


Figure 1. Map of Pinal County.

county also ranks in the top 1% of U.S. counties for "other crops and hay" sales, where alfalfa sales dominate (USDA NASS 2019). Meanwhile, in 2017, cotton and cottonseed were the county's top crop in terms of sales, ranking Pinal County in the top 2% of all U.S. counties in cotton and cottonseed sales. Wheat production in the county is primarily durum wheat, a market class of wheat utilized around the world for pasta making (Duval et al. 2016).

With average annual precipitation in Pinal County ranging from only 8 to 10 inches per year, the availability of irrigation water is of utmost importance to crop production (ADWR 2010, 220). Groundwater and surface water from the Colorado River, transported by the Central Arizona Project (CAP) canal, are the primary sources of water for irrigation in Pinal County. Most of Pinal County falls within an Active Management Area (AMA), an area designated by the state through the 1980 Groundwater Management Act to manage, preserve, and protect groundwater supplies. In fact, Pinal County falls within three of the five AMAs in the state, with approximately 42% of county land within the Pinal AMA, 15% within the Phoenix AMA, and 13% within the Tucson AMA. The remaining 29% of land in Pinal County does not fall within an AMA (Figure 1).

Pinal County agriculture is a large water user. Based on data from 2001 to 2005, approximately 96% of the average annual water demand in the Pinal AMA (the largest proportion of Pinal County land) was for agricultural use. In the same period, average annual demand for agricultural irrigation water in the Pinal AMA was supplied through groundwater (439,600 AF or 45%) and from non-groundwater supplies, including surface water, CAP, effluent, spill water, or tailings water (534,900 AF or 55%) (ADWR 2010).

In Pinal County, CAP water plays an important role. CAP water is divided into priority pools, with high priority pools allocated to M&I and Indian water users, and lower priority pools for non-Indian agricultural (NIA) users and the "Ag Pool." The Ag Pool (Agricultural Settlement Pool), created in 2004, offered a pool of excess CAP water (subject to availability) to agricultural water users in Central Arizona at energy-only rates through 2030 (CAP 2016). The Ag Pool supplies a large portion of irrigated agriculture in Central Arizona, most of which is used by non-Indian agriculture and would be the first to be cut in the event of a shortage on the Colorado River (CAP 2016; Lahmers and Eden 2018).

Persistent drought conditions and warming temperatures have increased the likelihood of a shortage on the Colorado River. In 2007, the Lower Basin States (Arizona, California, and Nevada) enacted a shortage sharing agreement, which determined how they would allocate water in the event of a shortage on the Colorado River. They established a tiered system where mandatory cutbacks would occur if Lake Mead dropped to pre-determined elevations. A Tier 1 shortage would be declared on the river if Lake Mead falls to 1,075 feet. The BOR projects that a Tier 1 shortage could occur in 2020, where the state of Arizona, with a low priority water entitlement, would lose 320,000 AF (ADWR and CAP 2018; USBOR 2018) (Figure 2). A Tier 2 shortage would be triggered when Lake Mead reaches 1,050 feet and a Tier 3 shortage would be triggered when Lake Mead reaches 1,025 feet. The BOR projected that a Tier 3 shortage could occur as early as 2023 and would result in a reduction of 480,000 AF for the state of Arizona (ADWR and CAP 2018; USBOR 2018; Western Resource Advocates 2019) (Figure 2).

With Arizona having a low priority water entitlement among other Basin States and many Pinal County and other Central Arizona farmers relying on the Ag Pool and NIA water allocations, farmers in Pinal County would be the first to be affected by a shortage declaration on the Colorado River.

Modeling Economic Impacts of Water Cutbacks

We begin by presenting two versions of a "rationing model," then illustrate how an I-O model is an extension of the rationing model approach.

Rationing Models

Rationing models are based on the "putty-clay" production function approach to modeling production relationships (Houthakker 1955; Johanson 1972; Hochman and Zilberman 1978; Moffitt et al. 1978). In economics, a production

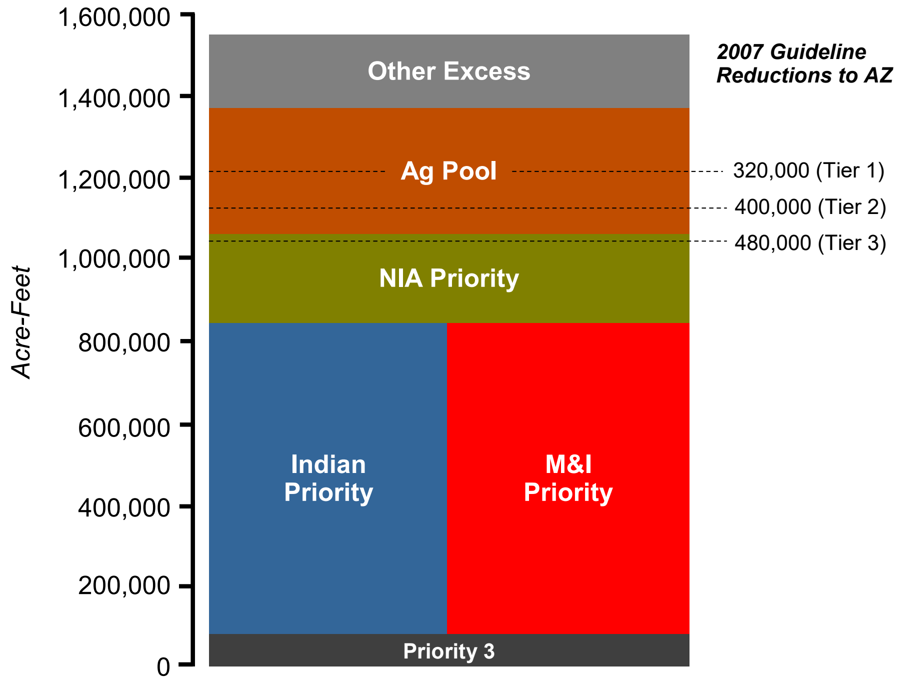


Figure 2. Projected impacts to Arizona CAP water allocations due to Colorado River Tier 1, 2, and 3 shortages. Source: Adapted from ADWR and CAP 2018.

function is just a mathematical representation of how much output can be produced as a function of the mix and levels of inputs used. Prior to making investments in new capital equipment and technology or entering into marketing contracts, producers have a certain degree of flexibility in which production processes and practices they can employ. This is the "putty" (flexible) aspect of production relationships. Once producers commit, however, to fixed capital investments in often highly specialized equipment, or to plant particular crops of particular seed varieties, or to enter into marketing agreements with particular buyers, etc., their production decisions are highly limited by these prior choices. This is the hardened "clay" (inflexible) aspect of the production process. So while in the longer-term, producers can choose technologies that use different mixes of inputs, in the short-run they may not be able to substitute between inputs and their ratio of output to inputs will be fixed (Moffitt et al. 1978). Dale and Dixon (1998) argue that the types of responses farmers make to water cutbacks depend on the time frame one considers. Some changes, such as fallowing crops, can be made rapidly. Others, such as shifting cropping (and marketing) patterns or investing in new irrigation technology may be more gradual.

Several studies have applied the putty-clay approach to examine reallocations of water from agricultural production. Based on this approach, Sunding et al. (2002) argue, "[a]t each location, farmers have invested substantial resources in production infrastructure, including equipment for harvesting, packing, and irrigation. As a result, crop mix choices are largely predetermined in the short-run and appropriate for an individual location" (p. 218). Regarding Pinal County, alfalfa production supports large feedlot and dairy industries that in turn supply the Phoenix and Tucson metropolitan areas with a combined population of 5.7 million. In many cases, dairies are also engaged in feed and forage production, much of which cannot be imported economically from outside the region, so their scope to switch away from these crops is limited. For other major Pinal County crops, such as cotton and wheat, producers harvest them using expensive, specialized equipment, so substitution between crops would require large capital investments.

Sunding et al. (2002) appeal to other research on water productivity (Letey et al. 1985; Letey and Dinar 1986) to further argue, "[a]gronomic evidence suggests … a crop should either be irrigated with a certain amount of water, the 'water requirement,' or not irrigated at all[.] […] [W]ater supply reductions […] are likely to be met in the short-run with the only response available to growers: reducing the amount of land cultivated while retaining the existing production technology on the land remaining in production" (p. 219).

Thus, a number of studies have assumed that farmers will respond to water shortages in the short-run by fallowing their crops (Sunding et al. 1994, 2002; Dale and Dixon 1998; USBOR 2007; Frisvold and Konyar 2012). The empirical analysis for Pinal County corresponds to a situation where farmers do not have much time to adjust and therefore represents short-run response to a water cutback. Which crop acreage is fallowed though? Here is where the rationing model gets its name. In an area facing water cutbacks, crops are ranked by gross revenue per AF of water (Rationing Model I) or by net income (profit) per AF of water (Rationing Model II). To adjust to the water shortfall, farmers will fallow acres of the crop that generate the least gross or net returns per AF of water first. If fallowing the acreage of the least valuable crop (per AF of water) is not sufficient to meet the water constraint, farmers move on to the crop with the next lowest returns per AF of water. Farmers continue to fallow crops with higher and higher returns per AF until their water use adjusts to their new, lower supplies.

Rationing Model I assumes growers will respond to water cutbacks by fallowing acreage of crops with the lowest gross revenues per AF of water first, then move on to fallowing crops of increasingly larger revenues per AF, until the water cutback is met. Economic losses are measured in terms of lost gross revenues. This approach has the advantages of having quite modest data requirements, being easy to calculate by non-economists, and providing an impact measure (reduced sales revenues) that is readily understandable by decision-makers. Gross revenues and acreage for major crops are usually available from the USDA, state agricultural departments, or irrigation districts. If one knows water use per acre for crops, it is then straightforward to calculate gross revenues per AF: Revenues per AF of water = [Gross Revenues/Acres] / [Water Use/Acres]. Sunding et al. (1994) argue that a rationing model based on gross revenues rather than profits may be preferable because gross revenues include net revenues plus production costs, especially labor. They note that many field workers in California agriculture may have limited opportunities for alternative employment in other industries so that the lost production "expense" of wages represents lost income to the agricultural labor force in areas facing water cutbacks. Many production expenses, however, are non-labor variable inputs, such as fuel, fertilizer, and pesticides. Fallowing land reduces farm expenditures on these items, so one might question whether reducing such costs constitutes a loss.

Rationing Model II ranks crops by profits per AF of water, fallowing the least profitable crop per AF of water first (Dale and Dixon 1998; USBOR 2007; Frisvold and Konyar 2012). This approach requires data on costs of production in addition to the basic data needed for Rationing Model I. Production costs are often available at the county or state level from crop enterprise budgets published by state Cooperative Extension Service. These budgets are generally crop and region specific, but may not be updated regularly. Production expense data are also available from USDA, Economic Research Service Commodity Cost and Returns data and from the USDA *Census of Agriculture* that is published every five years. USDA budgets are updated more regularly, but may not reflect local production costs for specific crops. These data report labor expenses separately from non-labor expenses. Rationing Model II accounts for the fact that fallowing reduces both gross revenues and expenses. It also measures on-farm income losses from fallowed acreage. Therefore, it provides measures of short-term income losses to two stakeholder groups: farmers and farm workers. Given that data are available, up-to-date, and representative of the production practices in the region, data requirements are still modest and results are easy to calculate and interpret.

Again, Rationing Model II considers short-term responses to surface water shortages. In the longer term, growers could make capital investments, such as developing groundwater resources. In the short-run, however, the existing technology infrastructure may be viewed as a sunk cost that does not affect immediate choices. Because the rationing models implicitly assume individual crops have a constant profitability per acre of land and per AF of water, one obtains the extreme, "corner solutions" common in linear programming. If marginal profitability varies for crops, one may have some crops with lower average profitability continue to be produced. The rationing approach, however, can provide a useful indication of which crops will face relatively larger contractions. For example, Frisvold and Konyar (2012) applied both a water rationing model and a quadratic programming model to examine large-scale water reductions across the Southwestern U.S. The rationing model suggested all cotton, barley, and apple acreage would be taken out of production to meet the water cutback constraint. Meanwhile, the quadratic programming model estimated that cuts to these crops would be less severe (and that production of other crops would also decline). Nonetheless, the three crops identified in the rationing model also had the largest percentage change reductions in production in the programming model. In a study of California grower response to drought, Dale and Dixon (1998) estimated that under a rationing model 100% of the acreage fallowed would be field crops. Using a more sophisticated programming model, field crops accounted for 98% of the acreage reduction, while vegetables accounted for 2%.

Input-Output Models

Wassily Leontief was awarded the Nobel Prize in economics for developing I-O models as a means of examining how different sectors in the economy are linked and how changes in demand in one sector affect demands in other sectors (Leontief 1936). The underlying assumptions about technology in I-O models match those of the rationing models. Inputs are used in fixed proportions in production processes, reflecting no input substitution in the short-run. There are fixed ratios of inputs to outputs and prices are fixed in the models. The fixed-price assumption may be reasonable if one is considering smaller regional scales where producers and consumers can be viewed as price-takers. Across small regions, prices may be determined primarily by international or national markets. The fixed price assumption may be less tenable for larger geographical scales (where price-endogenous mathematical programming or CGE models may be more appropriate).

While I-O models share assumptions about technology and prices with rationing models, they consider linkages between different economic sectors in detail. A key feature of I-O models is their capacity to capture indirect and induced multiplier effects. When producers within a local economy buy inputs, they generate additional rounds of spending in that local economy. Input suppliers themselves require inputs, and so on. Initial spending on inputs generates subsequent rounds of input purchases. The effects of these backward linkages in the economy are called indirect multiplier effects. Induced multiplier effects occur when business owners spend their profits and workers spend their salaries on consumer goods and services in the local economy. This demand for goods creates subsequent additional demands for goods and services in the local economy. While some inputs are produced locally, others are "imported" from outside the local area. Spending on goods from outside the area – called "leakage" – represents money leaving the local economy. With each round of local spending, more money leaks out of the local economy, such that the indirect and induced multiplier effects on demand diminish with each round and eventually cease.

Constructing I-O models is substantially more difficult than applying the rationing model approach. First, I-O models require substantial amounts of data on input use, prices, I-O relationships, and spending patterns across multiple sectors of an economy. Once constructed, economic expertise is needed to avoid large errors in model application and interpretation (Coughlin and Mandelbaum 1991; Beattie and Leones 1993; Loomis and Helfand 2001). Today, there are a number of combined database-modeling platforms available to conduct regional economic analyses. Among the most popular are the IMPLAN model (originally produced by the USDA/Forest Service but now supported by a private firm) (IMPLAN 2017), the REMI model supported by Regional Economic Models, and the U.S. Department of Commerce's RIMS II model (Rickman and Schwer 1995). The present study relies on the IMPLAN modeling platform and data for Pinal County.

IMPLAN reports several effects not accounted for in the rationing models. It measures impacts on the number of jobs in each sector. It measures not only direct impacts on the sectors experiencing change – in our case the Pinal County farms fallowing land – but also effects on other sectors of the Pinal County economy via indirect and induced multiplier effects. IMPLAN also reports effects on value added, which is the local equivalent of Gross Domestic Product (GDP) at the national level. Value added measures the value created by an industry over and above the costs of inputs. At the county level, value added combines net farm income, profits in other industries, employee compensation, and tax revenues. It is thus a summation of economic effects on various stakeholders (farmers, other business owners, farm labor, other labor, and county and state agencies concerned about effects on tax revenues). An understanding of these effects can inform compensation programs that can be used as a strategy to mitigate the economic impacts of fallowing. In California, payments have been made to farmers to fallow land and transfer water to higher-value uses (Akhbari and Smith 2016). Colby et al. (2007) note compensation can not only help avoid conflict, but also offset third party impacts within the local economy. They state that often "[t]he parties most affected by proposed transfers generally are not those who have water to sell, but rather are suppliers of inputs and labor (farm workers) to growers and post-harvest processing enterprises (such as cotton gins)" (p. 10).

Rationing model and I-O approaches complement each other. While direct effects on farming sectors of a water cutback should be similar across models, the I-O model provides more information on jobs, sectors linked to agriculture, and effects on the local tax base. One may use data from Rationing Model II to better calibrate the base IMPLAN model to local production conditions. IMPLAN's I-O coefficients rely on embedded assumptions about input cost shares based on national averages. For agricultural production especially, local production coefficients can be quite different from national averages. Using localized data from Cooperative Extension Service crop enterprise budgets, USDA county-level data, or both, one can more accurately characterize local production technology.

Hypothetical Agricultural Water Reductions in Pinal County, Arizona

To evaluate economic impacts of agricultural reductions from a Colorado River Shortage Declaration, the BOR followed a rationing model approach to select crops to model water supply shocks in their I-O analysis (USBOR 2007). Crops were ranked from lowest to highest in terms of profits per AF of water and crop acreage with the lowest profits per AF would be fallowed. These acreage reductions were then entered as output reductions in IMPLAN. For Pinal County, the study estimated that the first crop that would drop out of production would be wheat, followed by cotton, then alfalfa hay. One scenario the study considered was the effect of a 400,000 AF cutback to Arizona agriculture in 2017. The BOR did not report how much water would be taken away from each Arizona county, but about two-thirds of the job losses and 70% of the income losses occurred in Pinal County. Recall that under a Tier 1 Colorado River shortage (if Lake Mead's elevation falls below 1,075 feet), Arizona's CAP would lose 320,000 AF of surface water, primarily used by Central Arizona agriculture. Under a Tier 2 shortage (Lake Mead elevation 1,050 feet) the cutback would be 400,000 AF.

The present analysis considers the impact of a hypothetical 300,000 AF reduction in Pinal County's agricultural surface water supplies for the calendar year 2017. Under the recently approved Arizona DCP, Arizona would lose 192,000 AF if Lake Mead falls below 1,090 feet and 592,000 AF if Lake Mead falls below 1,075 feet (McGinnis 2019).

Using readily available, county-level data on acreage and yield and state-level commodity price and water application rate data (USDA NASS 2014, 2017), Rationing Model I identifies wheat as the crop with the lowest gross revenues per AF (Table 1), therefore wheat acreage will be fallowed first. Even if 100% of wheat acreage is fallowed, that does not reduce water use by 300,000 AF, so alfalfa acreage is fallowed next. In 2017 alfalfa gross revenues per AF were slightly lower than for cotton. According to Rationing Model I, 100% of county wheat acreage and 62% of county alfalfa acreage is fallowed (Table 3). Under Rationing

Table 1. Gross revenues per acre-foot of water for major Pinal County crops, 2017.

	Wheat	Alfalfa	Cotton/Cottonseed	
AZ water application rate, gravity (2014)	3.3 acre-feet/acre	5.5 acre-feet/acre	4.6 acre-feet/acre	
Pinal County average yield (2017)	103.9 bushels/acre	8.45 tons/acre	1,434 lbs./acre	1.07 tons/acre
AZ average price (2017)	$7.06/bushel	$172/ton	$0.73/lb.	$183/ton
Gross revenues/AF	$222.28	$264.25	$269.15	

Note: Calculations by authors.
Source: USDA NASS 2014; USDA NASS 2017.

Table 2. Net returns per acre-foot of water for major Pinal County crops, 2017.

	Wheat	Alfalfa	Cotton/Cottonseed
AZ water application rate, gravity (2014)	3.3 acre-feet/acre	5.5 acre-feet/acre	4.6 acre-feet/acre
Gross revenues/Acre	$733.53	$1,453.40	$1,238.10
Cash costs/Acre	$534.35	$941.81	$1,201.66
Net returns/AF	$60.36	$93.02	$7.92

Note: Calculations by authors.
Source: University of Arizona Cooperative Extension 2011; USDA NASS 2014; USDA NASS 2017.

Model II, when costs of production are taken into account, cotton becomes the first crop fallowed as it is the crop with the lowest net returns per AF in 2017 (Table 2). Cotton acreage in Pinal County in 2017 is sufficient to reduce water use by 300,000 AF, and is therefore the only crop fallowed. According to Rationing Model II, approximately 75% of county cotton acreage is fallowed (Table 3). The I-O model builds upon Rationing Model II to examine the impacts of land fallowing on the Pinal County economy. Using estimated reductions in labor and non-labor cotton production expenses from Rationing Model II, the effects of farmers and farm workers earning and spending less of their income on consumer goods and services and farmers purchasing fewer inputs are modeled. These are modeled in IMPLAN through a labor income change and customized cotton industry spending pattern. The cotton industry spending pattern was calibrated using local, inflation-adjusted data from Cooperative Extension crop enterprise budgets and the USDA Prices Paid Index (University of Arizona Cooperative Extension 2011; USDA NASS 2017) to better capture the magnitude and distribution of impacts among Pinal County sectors that supply farm inputs. Of particular importance was the input cost share for irrigation water, where Arizona's production coefficient was calculated higher than national average IMPLAN production coefficients (which are inclusive of dryland agriculture).

Table 3. Effects of 300,000 acre-foot water reductions to Pinal County agriculture, 2017. (Numbers reported are losses. Dollar values are in millions.)

	Rationing Model I	Rationing Model II	Input-Output Model
First Crop Fallowed	Wheat	Cotton	Cotton
Acreage Fallowed	19,300	65,217	65,217
% of Pinal County Acreage in Crop	100%	75%	75%
Second Crop Fallowed	Alfalfa		
Acreage Fallowed	42,965		
% of Pinal County Acreage in Crop	62%		
Direct On-Farm Effects:			
Gross Revenues (Total)	$76.6	$80.7	$80.7
Wheat	$14.2	$0.0	$0.0
Cotton	$0.0	$80.7	$80.7
Alfalfa	$62.4	$0.0	$0.0
Production Expenses (Total)		$78.4	
Labor Expenses		$9.5	
Non-Labor Expenses		$68.8	$68.8
On-Farm Income		$11.9	$11.9
[a] Farmer Income		$2.4	$2.4
Farm Worker Income		$9.5	$9.5
[b] *Farm Jobs*			209
Indirect & Induced Effects:			
Value Added			$18.8
[c] Business-Owner Income			$8.8
Employee Income			$9.0
Net Taxes			$1.1
Jobs			239
Total Effects:			
Value Added			$30.7
Farmer and Business-Owner Income			$11.1
Farm Worker and Non-Farm Employee Income			$18.5
Net Taxes			$1.1
Total Jobs			448

Note: Calculations by authors. Figures may not add due to rounding.
Source: University of Arizona Cooperative Extension 2011; USDA NASS 2014; IMPLAN 2017; USDA NASS 2017.
[a] Farmer Income = Gross Revenues - Production Expenses
[b] Farm Jobs = On-farm hired workers (does not include proprietors)
[c] Business-Owner Income = Proprietors Income + Other Property Type Income

Comparing Model Results

Under Rationing Model I, wheat and alfalfa acreage are fallowed to reduce water use by 300,000 AF. Total gross revenue reductions in 2017 are an estimated $76.6 million, with $14.2 million less in wheat sales and $62.4 million less in alfalfa sales (Table 3).

Rationing Model II builds upon Rationing Model I and incorporates more detailed, regional information about costs of production in Pinal County and selects crops to fallow based on net income per AF instead of gross revenues per AF. Rationing Model II identifies cotton as the crop to be fallowed in 2017 and estimates total gross cotton revenue reductions of $80.7 million. While gross revenue reductions between Rationing Model I and Rationing Model II are similar, Rationing Model II identifies a different crop to be fallowed. It also accounts for the fact that while fallowing reduces gross revenues by $80.7 million, it also reduces total production expenses by $78.4 million (Table 3). Reduced production expenses come in the form of reduced costs for labor ($9.5 million) as well as reduced costs for production inputs and operation ($68.8 million). Accounting for both revenue reductions and reduced costs associated with fallowing, net income losses to farmers are an estimated $2.4 million (Table 3). Rationing Model II improves upon Rationing Model I by providing estimates of the impacts of crop fallowing on farmer and farm worker income. While the farmer realizes reduced labor costs of $9.5 million, farm workers, conversely, realize $9.5 million less in wages and compensation. Under the Rationing Model II approach, short-term income losses are more severe for farm workers than for farmers.

The I-O model builds upon Rationing Model II to examine the impacts of fallowing on the broader Pinal County economy. Given results from Rationing Model II, direct losses to farmers and farm workers are an estimated $11.9 million in income. Using average wage data for cotton farming in Pinal County from the U.S. Department of Labor Bureau of Labor Statistics (2017) and the IMPLAN (2017) conversion rate to income (wages, salaries, and benefits), cotton farm worker income losses of $9.5 million would be equivalent to 209 farm jobs (Table 3). The I-O model also accounts for effects on other sectors of the Pinal County economy that result from farmers purchasing fewer inputs (indirect effects) and farmers and farm workers earning and spending less income on consumer goods and services (induced effects). Impacts to Pinal County due to indirect and induced multiplier effects are an estimated $17.8 million less in income in non-agricultural sectors and $1.1 million less in tax revenues, for a total value added impact of $18.8 million and 239 fewer jobs. Income losses of $17.8 million in non-agricultural sectors are higher than on-farm income losses of $11.9 million.

This distribution of impacts raises questions for compensation programs that aim to mitigate the economic losses of fallowing. While financial compensation paid to farmers will help mitigate farmers' losses, it is unlikely that they would reach farm workers or workers in other sectors, possibly leading to disparate impacts on Pinal County residents. A limitation of the I-O model, however, is that it captures immediate, short-run effects. Over time, job and income losses will diminish as some displaced labor will find work in other sectors in Pinal County, mitigating the impacts. Other workers, however, may move out of Pinal County seeking employment elsewhere.

The total economic impacts (direct, indirect, and induced) of a 300,000 AF water reduction to Pinal County agriculture in 2017 are an estimated $30.7 million in reduced value added and 448 fewer jobs (Table 3). Hired workers, for both agriculture and non-agriculture, have income losses of $18.5 million and business-owners (including farmers) have income losses of $11.1 million. Reduced sales in non-agricultural industries, from fewer inputs purchased and fewer farm workers purchasing household goods and services, also reduce tax revenues. Net tax revenue impacts are an estimated loss of $1.1 million.

Comparing results across the three models (Table 3), consider the gross revenue impacts – the main impacts from Rationing Model I. Losses in gross revenues are not particularly close approximations of reduced farm profits (that would be called producer surplus in standard welfare economics). Nor are losses in revenues close to income losses to business-owners (farm and non-farm) and workers (farm and non-farm). Thus, Rationing Model I greatly overstates losses in terms of economic welfare measures or payoff-to-interest-group measures. Furthermore, direct on-farm income losses are lower than income losses in non-agricultural sectors.

Perhaps a more useful way to present the results above is by presenting the losses per AF of water reduced (Howe and Goemans 2003). Using this metric to describe losses allows for a better understanding of the value of water for all aspects of agricultural production. For example, on a per AF basis, direct reductions to farmer income from fallowing cotton acreage equivalent to a 300,000 AF water reduction amount to about $8 per AF (Table 4). Considering the wider impacts to the Pinal County economy (total including multiplier effects), regional value added losses amount to about $102 per AF.

Estimates of losses per AF can provide important information to water planners, agricultural stakeholder groups, county governments, and the general public about the value that would be required to mitigate the economic losses of fallowing. In other words, if farmers were to be compensated for fallowing cotton acreage of this magnitude, compensation would need to be at least $8 per AF to offset farmer income losses. At the regional level, compensation would need to be at least $102 per AF to offset county valued added losses.

While designing compensation schemes for non-farm losses from fallowing can be daunting, such schemes are not without precedent. A water transfer agreement between the Metropolitan Water District (MWD) in Southern California and the Palo Verde Irrigation and Drainage District established a Mitigation Plan and Community Improvement Board to address job losses resulting from a rotational land fallowing program (Taylor and MacIlroy 2015). MWD provided funds for a $6 million endowment to the Palo Verde Valley Community Improvement Fund. The Fund has loaned $6.25 million to local businesses and provided $1.2 in grants to non-profit organizations (PVVCIF 2019). To qualify for loans, borrowers must demonstrate how loans will be used to maintain existing jobs or create new ones. Grants target workforce development. In another case, as part of a water transfer agreement between Imperial Irrigation District and the San Diego County Water Authority, a Local Entity was established to compensate farm input and service providers losing sales from land fallowing. Since 2003, the Local Entity has distributed $14.5 million to these businesses while a competitive grants program supporting local economic development projects has awarded $2.9 million to Imperial County organizations (IID 2019).

Sensitivity Analysis: Importance of Modeling Assumptions

An important consideration for examining the impacts of fallowing on farmers, farm workers, and the local economy is how price, yield, and acreage assumptions affect model results. Farm-level decisions to plant acreage are, in part, in response to expected prices, costs, and returns. In some instances, fallowing might occur regardless of water supply cutbacks, or the incentives to fallow one crop versus another might shift. Regional economic impacts attributable to shortage depend partially on the net change in acreage resulting from water cutbacks. Whereas in this analysis, based on 2017 data, cotton is assumed to be fallowed, there may be years where fallowing wheat or alfalfa could be more advantageous to producers, with different implications for the regional economy.

With this in mind, this study presents a comparison of the crops fallowed using the Rationing Model I and Rationing Model II approaches based on production data for 2015, 2016, and 2017 (Figure 3). When crops are ranked and fallowed by the lowest gross revenues per AF (Rationing Model I), wheat and alfalfa acreage are fallowed in two of the three years, with wheat acreage fallowed first in 2016 and 2017. In 2015, wheat acreage is not fallowed in part due to relatively high wheat prices. When crops are ranked and fallowed by the lowest net income (profit) per AF (Rationing Model II), cotton acreage is fallowed first in all three years. While cotton acreage accounts for all fallowed agricultural land in 2016 and 2017, in 2015 there was not enough cotton acreage in Pinal County to meet the 300,000 AF water cutback. In that year, both cotton and alfalfa acreage are fallowed. While total revenue losses are relatively consistent under the Rationing Model II approach, on-farm income losses, in particular farmer income losses, vary

Table 4. Effects of 300,000 acre-foot water reductions to Pinal County agriculture, 2017. (Numbers reported are losses per acre-foot of water reduced.)

	Input-Output Model Results
Direct On-Farm Effects:	
Gross Revenues	$269.15
Production Expenses	$261.23
Labor Expenses	$31.77
Non-Labor Expenses	$229.46
On-Farm Income	$39.69
[a] Farmer Income	$7.92
Farm Worker Income	$31.77
Indirect & Induced Effects:	
Value Added	$62.79
[b] Business-Owner Income	$29.18
Employee Income	$30.02
Net Taxes	$3.58
Total Effects:	
Value Added	$102.48
Farmer and Business-Owner Income	$37.10
Farm Worker and Non-Farm Employee Income	$61.79
Net Taxes	$3.58

Note: Calculations by authors. Figures may not add due to rounding.
Source: University of Arizona Cooperative Extension 2011; USDA NASS 2014; IMPLAN 2017; USDA NASS 2017.
[a] Farmer Income = Gross Revenues – Production Expenses
[b] Business-Owner Income = Proprietors Income + Other Property Type Income

significantly from year to year, ranging from $2.4 million to more than $10.0 million (Figure 4). Income losses to farmers per AF of water reduced range from $7.92/AF at 2017 prices, to $20.89/AF at 2016 prices, to $35.82/AF at 2015 prices. Lost income to farm workers range from $31.77/AF at 2017 prices, to $31.19/AF at 2016 prices, to $31.80/AF at 2015 prices. The BOR's analysis of fallowing losses in response to a Colorado River Shortage Declaration (USBOR 2007) did not consider effects of changes in crop prices or yields. Results presented here suggest that the annual costs of fallowing to farmers can fluctuate significantly from year to year.

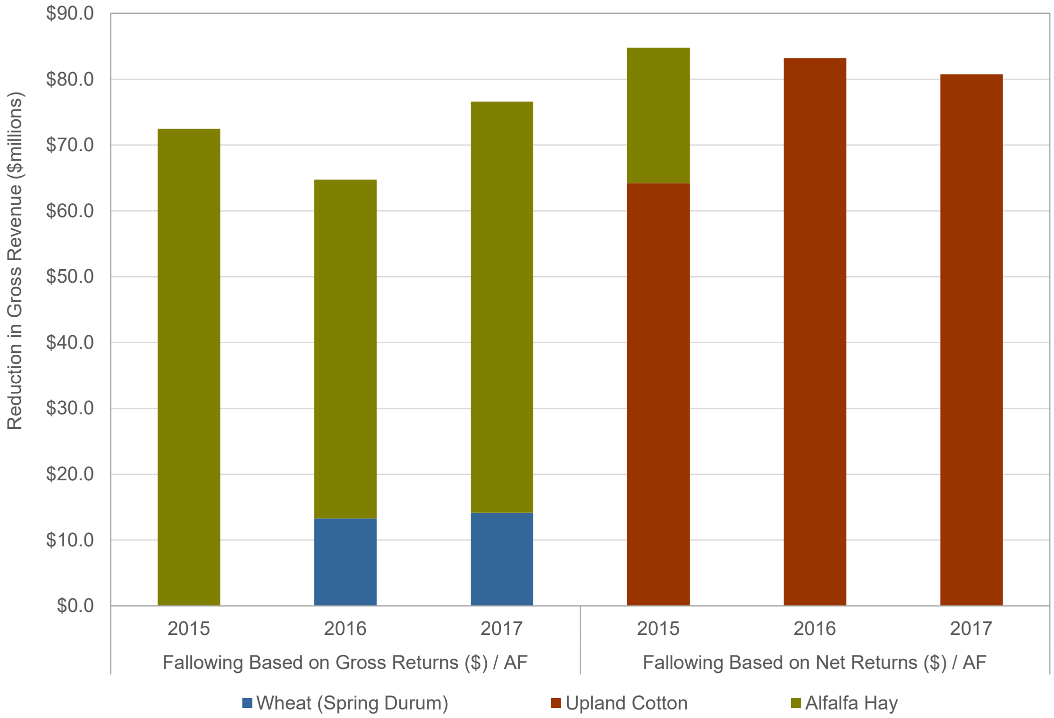
Limitations, Future Research, and Conclusions

One limitation of this analysis is that, although intuitive, fallowing all crop acreage in order of gross revenues per AF or net returns per AF does not account for the realities and complexities of farm-level planting decisions and the resulting incentives to fallow or not fallow crop acreage. Farmers often grow multiple crops and planting decisions are made in light of this multi-crop system, capital investments, and crop commodity payments, among other factors. As mentioned previously, in some instances, fallowing might occur regardless of water supply cutbacks, or the incentives to fallow one crop over another might shift. These shifts in crop production can have different implications for the regional economy.

An extension of this is the potential for impacts on regional livestock feed markets in the case of large-scale alfalfa fallowing. In addition to potential price effects impacting dairy producers, there could be downstream effects to dairy manufacturers, retailers, and consumers of dairy products resulting from any major increases in feed prices. While this model assumes that for small regions, prices are determined primarily by international or national markets, the markets for particular livestock feed crops such as alfalfa or corn silage are typically regional due to high transportation costs. The fixed price assumption may underestimate negative impacts to users of livestock feed crops within the region and those indirectly impacted, as well as any potential positive impacts to alfalfa producers that do not fallow and receive higher prices due to reduced regional supplies.

Farmers can also respond to a water cutback by making planting decisions at the extensive and intensive margins. The simplest case, as modeled here, is to adjust total production by reducing crop acreage. Farmers could also adjust at the extensive margin by shifting some of their acreage to a less-water-intensive crop, thereby using less water and maintaining profits from that acreage. Finally, farmers could adjust at the intensive margin and utilize a practice called deficit irrigation. Deficit irrigation reduces irrigation water use by limiting irrigation to certain times during plant development, meanwhile maintaining a sustainable level of crop water stress and yield reductions. This practice allows farmers to continue growing their customary crops, albeit at lower yields, therefore mitigating full revenue losses resulting from crop fallowing (Colby et al. 2014). Some crops are more amenable to deficit irrigation than others, but if the timing is selected correctly, deficit irrigation is feasible for cotton, wheat, and alfalfa acreage (Kirda 2002; Ottman and Putnam 2017).

Finally, a major assumption of this analysis is that farmers elect to fallow their fields as opposed to shifting to groundwater irrigation. Shifting to groundwater pumping is a viable strategy for many Pinal County producers to offset reductions in surface water deliveries, either in the short- or medium-term. That said, investing in or recommissioning wells and pumps, as well as operating them, changes cost structures for producers, and once again may affect the returns of different crops relative to one another. In the case that producers do shift to groundwater, regional economic impacts could be moderated, and in fact, investment in wells and associated infrastructure could inject money into the local economy, particularly if producers receive outside funds to support well development. In the long term, however, there may be serious implications of this strategy on groundwater supplies, and producers relying on groundwater may be forced to dig deeper wells, incur infrastructure damages due to land subsidence, and future aquifer storage capacity may be impacted. Future research could examine farmers' decisions to fallow or transition to groundwater pumping in the face of irrigation



Sources: Calculations by authors; University of Arizona Cooperative Extension 2011; USDA NASS 2014; USDA NASS 2017.

Figure 3. Individual crop and total gross revenue losses under different rationing rules and year prices.

Sources: Calculations by authors; University of Arizona Cooperative Extension 2011; USDA NASS 2014; USDA NASS 2017.

Figure 4. On-farm income effects under Rationing Model II and different year prices.

water cutbacks in order to assess short-, medium-, and long-term impacts of large-scale irrigation water supply reductions.

Data, cost, and time limitations coupled with the complexities of farmers' responses to changes in agricultural water supplies pose challenges to estimating the local economic impacts of water reallocations from agriculture. More sophisticated models that account for uncertainty, capital investment, and farmers' adjustments to water cutbacks (such as substituting between inputs, shifting crops, practicing deficit irrigation, or investing in groundwater pumping infrastructure) are available and demonstrate that the costs of water reductions can be quite a bit smaller than estimated by rationing or I-O models. However, many county governments and local farm groups do not have the access or expertise to utilize the models. Although there are limitations to the models illustrated in this study, they can provide a useful starting point for community discussion, particularly when farmers have limited time or scope to adjust technologically to water shortages. This study demonstrates how these models can be used to address basic policy questions when faced with water shortages. First, how might growers respond in the short-run to a specific cutback in water supplies? Second, how would reductions in agricultural production affect non-agricultural industries in the local area? We argue that the approaches demonstrated here are useful methods to obtain rapid and low-cost answers to such specific questions.

Though the information we draw on for these models is low-cost and relatively easy to implement, it bears mentioning that access to timely, region-specific, accurate, and publicly available data is of critical importance to this type of analysis. Even basic modeling techniques require quality data and, when that data is not available, the potential for misallocation of resources increases. Continued or increased financial support for the systematic collection of agricultural data will be critical as water resources become scarcer.

Using relatively low-cost, publicly available data, water planners in Arizona and other states within the Colorado River Basin can use the basic modeling techniques presented in this article to derive rough estimates and provide a range of the potential economic impacts of fallowing for their region, including secondary impacts to the local economy. These approaches also allow for consideration of the distributional impacts, including income losses to farm workers and other non-farm business-owners and workers. A greater understanding of these potential disparate impacts can help inform strategies to mitigate and offset direct and indirect economic losses due to fallowing, helping to alleviate resistance at the local level. With limited water supplies, growing water demands, and an anticipated and imminent shortage declaration on the Colorado River, information that is expedient and easy to interpret is essential and provides a useful starting point for community discourse.

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River-Ditch Flow Statistical Relationships in a Traditionally Irrigated Valley Near Taos, New Mexico

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Abstract: Current and predicted drought and population growth challenge the longevity of irrigation systems of northern New Mexico. Irrigation ditches, also known as acequias, draw runoff directly from rivers without use of storage reservoirs, so it is important to understand the effects of changing river flow on irrigation flow. This study sought to examine river-ditch relationships in an agricultural valley of the region. A first order linear model was used to fit the river-ditch flow relationship on which daily river flow was the explanatory variable and daily ditch flow the response variable. A strong positive relationship between river and ditch flow was observed for all but one of the ditches. Using a statistical model approach that addressed serial autocorrelation, heteroscedasticity, as well as outlier observations, statistical evidence at 5% significance level was found in all ditches but one. The ditch without a positive relationship was at a downstream location, subject to upstream flow diversion that may have influenced river-ditch flow relationships. Results from this study can be used to evaluate the potential effects of changing socioeconomic dynamics and climate change projections in the operations of these irrigation systems to better understand and manage their water resources.

Keywords: *acequia, irrigated agriculture, water sharing, community-managed, mixed model, heteroscedasticity, serial autocorrelation*

Water resources may be greatly affected by climate change, with impacts having broad societal impacts (Hurd et al. 2004; Jimenez Cisneros et al. 2014). Agricultural production, particularly in areas where water is already a concern, is more vulnerable to uncertainty of water availability derived from climate change (Alexandrov and Hoogenboom 2000; Nelson et al. 2009; Fedoroff et al. 2010; Iglesias and Garrote 2015). Climate model projections indicate reductions in snowpack and the associated runoff occur earlier in the year (Barnett et al. 2005; Rauscher et al. 2008; Hurd and Coonrod 2012; Elias et al. 2015). This will likely exacerbate water-scarcity issues in some areas of the southwestern United States, such as in northern New Mexico, where irrigation water is drawn directly from streams without the use of storage reservoirs.

The agricultural sector is now confronted with the challenge of developing and implementing adaptive water management practices and strategies to cope with less water in the future (Barnett et al. 2005; Jimenez Cisneros et al. 2014). In New Mexico and the southwestern United States, agriculture uses roughly 80% of the total water withdrawals (MacDonald 2010; Longworth et al. 2013). Approximately 10% of the total surface water withdrawals for agriculture in New Mexico are used by traditional irrigation systems called acequias (Brown and Rivera 2000; Longworth et al. 2013). Acequias are hand-dug ditches constructed by the Spanish settlers of the late sixteenth century (Rivera and Glick 2002). Most of the estimated 700 acequias in New Mexico are in the north-central part of the state, particularly in small to mid-size tributaries of the Rio Grande watershed in the counties of Rio Arriba, Santa Fe, Mora, and Taos (Ackerly 1996).

Acequia systems, hereafter also referred to as irrigation ditches, were built and continue to harness runoff releases from mountain catchments that are mostly snowpack-dominated. They are located in narrow irrigated valleys just downstream of the sub-basins that produce snowmelt runoff (Steele et al. 2014). Driven by gravity, these irrigation ditches were crafted to divert and distribute river runoff through their valley floodplains for irrigating crops during the snowmelt season. At locations where all water diverted is not consumed for irrigation, the surplus water returns to the source river through the irrigation ditch outflow downstream of the irrigated area. With irrigation ditches so highly dependent on streamflow, changed streamflow amount and timing will directly impact acequia irrigation.

Not only are acequias physical conveyance structures, they are also cultural water management organizations (Rivera 1998). The ditches of northern New Mexico are organized into acequia associations. The acequia associations represent irrigation systems that vary in length, irrigated acreage, and the number of members (Guldan et al. 2013). Each acequia association has a commission that oversees the irrigators' legal matters and a superintendent or *mayordomo* who manages the allocation of water in the irrigation system (Rivera 1998). The ditch associations are recognized as political subdivisions of the state (Rivera and Martinez 2009; New Mexico Office of the State Engineer 2016).

Several studies have shown there are strong linkages between the community ditches of northern New Mexico and aspects of the local economy, society, environment, and hydrology (Rivera 1998; Fernald et al. 2012; Turner et al. 2016). Water supply for crop irrigation and livestock production activities has supported local food, forage, and revenue in historically Hispanic communities. Traditional management of land and water, such as water sharing or *repartimiento*, the annual acequia cleaning or *limpia de la acequia*, and water adjudication to priority crops, has resulted in a continuous interaction and a solid engagement between the community and the irrigation systems, and consolidates the identity of the agricultural communities of northern New Mexico (Rivera 1998; Fernald et al. 2012). The use of the ditches for water distribution has promoted important surface water-groundwater interactions. Seepage from ditches themselves and percolation below flood-irrigated fields have been related to shallow groundwater level rises (Fernald and Guldan 2006; Ochoa et al. 2007). Ditch seepage has been shown to dilute groundwater ion concentrations (Helmus et al. 2009). Spring and summer shallow aquifer recharge from ditch and flood irrigation inputs return to the river in fall and winter as groundwater return flow (Fernald et al. 2010; Ochoa et al. 2013; Guldan et al. 2014).

Under currently projected scenarios of water scarcity that threaten the use of irrigation water in the agricultural sector, more studies are needed to understand the connectivity between the ditches and the environment. Knowledge of the benefits resulting from the use of these irrigation systems, as well as the impacts of limited water in their operations, is crucial for their correct management. The objective of this five-year study was to determine statistical relationships between seasonal river flow and each of the eight community-based irrigation ditches (acequias) in the Rio Hondo agricultural valley in northern New Mexico.

Materials and Methods

Study Site

This study was conducted in the agricultural valley along the Rio Hondo, a perennial tributary to the Rio Grande near Taos, NM (Figure 1). Rio Hondo is located in a semiarid region with mild to moderate summers and cold winters. Obtained from the two closest weather stations, mean annual maximum and minimum temperatures, and mean annual precipitation are as follows: 17.6 °C, -0.6 °C, and 314 mm for Taos (16 km S; period of record 1892-2016); and, 15.6 °C, -1.8 °C, and 323 mm for Cerro (24 km N; period of record 1910-2016) (Western Regional Climate Center 2019a;

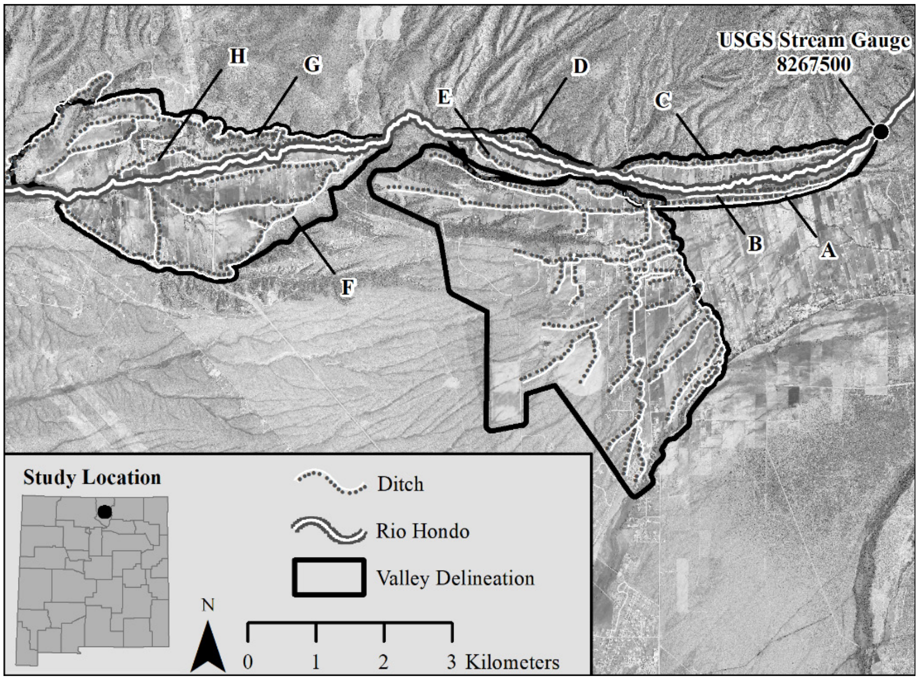

Figure 1. Map of the Rio Hondo Valley (by Robert Sabie Jr., WRRI, NMSU).

2019b). The frost-free period is normally from late May to the end of September and the typical irrigation season is from early April to September.

In the Rio Hondo Valley are the communities of Valdez (3 km^2; elevation 2,265 m), Desmontes (12 km^2; elevation 2,310 m), and Arroyo Hondo (8 km^2; 2,189 m). The area is covered by 70% fallow fields, 22% irrigated pasture (grass and/or alfalfa), 6% roads and structures, 2% riparian vegetation, and only a few scattered orchards (Sabie et al. 2018). Predominant soil textures in the Valdez and Arroyo Hondo communities are clay loam, sandy clay loam, and very gravely sand; soil textures for Desmontes include clay loam, silty clay loam, and silt loam (USDA NRCS 2018).

The Rio Hondo River, 29 km long, rises on the west slope of Wheeler Peak, the highest peak in New Mexico with a summit elevation of 4,012 m. Rio Hondo runs east to west through narrow canyons in the headwaters and merges into the Rio Hondo Valley 14 km downstream. The river then runs through the communities of Valdez and Arroyo Hondo and enters the Rio Grande at John Dunn Bridge (elevation 1,982 m) (New Mexico Office of the State Engineer 1969). Historical (1935-2015) annual flow for the Rio Hondo River is 968 liters per second ($L \cdot s^{-1}$) (United States Geological Survey 2019).

Data Collection and Data Processing

Streamflow and stage data from the Rio Hondo River and the eight main ditches in the valley were collected from March through November, during the years 2011 through 2015. Publicly available streamflow data were obtained from the United States Geologic Survey (USGS), gauging station #8267500, at the Rio Hondo River near Valdez, NM. This USGS station is located 2.5 km east of Valdez, upstream of any irrigation diversions. For the ditches, a gauging station was located downstream of each ditch's head-gate (where water is diverted from the river), before any water diversion to the farms. Each ditch gauging station was equipped with a ramp-type flume (Intermountain Environmental Inc., Logan, UT, USA) and a pressure transducer (Model CS450, Campbell Scientific, Inc., Logan, UT, USA) attached to a datalogger (Model CRX200, Campbell Scientific, Inc., Logan, UT, USA). Manual measurements of streamflow were obtained approximately every two weeks using a portable current meter (Model 2100, Swoffer Instruments, Inc., Seattle, WA, USA).

Manual streamflow measurements and ditch stage data collected by the pressure transducer were used to develop stage-discharge rating curves for each ditch. For ditch B, an additional rating curve was developed for data obtained from August 2013 through 2015. This was necessary because ditch managers had to do some modifications in the ditch that caused backwater to the measuring point. Also, in 2015 equipment at ditch D reported electronic failures from mid-May to mid-June and from the beginning of August to the beginning of September. Electronic failures in ditch E during the same year resulted in missing records from mid-May to the beginning of August. The period of missing records from ditch B in 2013 and those from ditches D and E in 2015 were not included in the analysis for these three ditches.

Mixed Model and Data Analysis

A statistical model-based and descriptive approach was used to analyze and describe the collected information. A first-order linear model was used to fit the river-ditch flow relationship, in which river flow was the explanatory variable and ditch flow the response variable. Scatter and regression plots of the flow information suggested autocorrelation and heteroscedasticity. Linear mixed models incorporate both fixed effects and random effects to effectively model data with non-constant variability and serial autocorrelation (SAS Institute, Inc. 2015). The fixed effects are related to known explanatory variables and the random effects are associated with unknown random variables that are assumed to impact the variability of the data (Li and Jiang 2013; Hao et al. 2015).

A linear mixed model was the basis to model the river-ditch flow relationship. The flow data were analyzed using the MIXED procedure in SAS (Version 9.4, SAS Institute Inc., Cary, NC, USA). Five models were used, corresponding to five different covariance structures. The model with the lowest Akaike's Information Criterion (AIC) value was selected (Akaike 1974; Stroup 2013, p. 191-194). Four of the five models are the same as models that were described in Cruz et al. (2018). All the models fit a common line to all years in the fixed effects. To account for possible correlations among observations within the same year, along with higher variance at higher river flows, random coefficients fitting random lines to years were included in some models. Also, because daily data values were being analyzed, serial autocorrelation among errors was anticipated and some models incorporated the autoregressive-moving-average model (ARMA) (1,1) serial autocorrelation (Dickey 2008; SAS Institute, Inc. 2014) to account for a possible decreasing correlation among errors farther apart in time but within the same year. In addition to fitting the common fixed line to all years, Model 1 estimated a constant variance and assumed independent errors. Model 2 fitted random coefficients (intercept and slope) to years. Model 3 fitted an ARMA (1,1) serial autocorrelation covariance structure. Model 4 fitted both an ARMA (1,1) serial autocorrelation component and the random coefficients to model the covariance structure. Model 5 was similar to Model 4 but dropped the random intercept from the random coefficients and so fitted only a random slope to years. Logarithmic transformation of the flow data was further explored in all the models.

Residual analysis of the five models indicated a more randomized pattern and fewer outlier (residual values ± 3) frequencies in the logarithmically transformed flow data when compared with the raw flow data; thus, logarithmic transformation was applied to the river and ditch flows in all the models. Under this transformation, Model 3 had the lowest AIC values in six of the ditches (A, C, D, E, F, and G) while Model 4 performed better in the rest (B and H). A 0.05 alpha value was defined as the criteria for significance over the resulting t statistic from the t-test. The resulting covariance parameters from those two models were used to analyze how the model captured the variance and the correlation structure of the data. For Model 4, the following expressions were used:

$$VX_{ij} = \alpha + 2 * \tau * Y_{ij} + \beta * (Y_{ij})^2 + R \qquad (1)$$

where, VX_{ij} = variance of a ditch observation (X) on year ($_i$) and day of the year ($_j$); Y_{ij} = logarithmic river flow observation corresponding to the same year ($_i$) and day of the year ($_j$); α = intercept variance from the random coefficients variance component; τ = intercept-slope covariance from the random coefficients variance component; β = slope variance from the random coefficients variance component; and R = residual variance component.

The covariance of two ditch observations (X's) in year ($_i$) and day of the year ($_j$) at ($_n$) number of time periods (days) apart is as follows:

$$Cov(X_{ij}, X_{ij}\text{-}n) = \alpha + (Y_{ij} + Y_{ij-n}) * \tau + Y_{ij} * Y_{ij-n} * \beta + R_n \quad (2)$$

where Y_{ij} and Y_{ij-n} = logarithmic river flow observations corresponding to the time of the ditch observations; and R_n, as described in Cruz et al. (2018), is the value of the residual component implied by the ARMA (1,1) serial covariance structure. As noted in Cruz et al. (2018), for $_n$ = 1, $R_n = R * \gamma$; for $_n$ = 2, $R_n = R * \gamma * \rho$; for $_n$ = 3, $R_n = R * \gamma * \rho^2$; and so on, where γ = moving average coefficient and ρ = autoregressive coefficient. The implied correlation between two observations within the same year is then $AC(X_{ij,} X_{ij-n})$ where:

$$AC(X_{ij}, X_{ij-n}) = Cov(X_ij, X_{ij-n})/\sqrt{VX_{ij} * VX_{ij-n}} \quad (3)$$

Regression and residual plots were used to identify high leverage observations and outliers with the logarithmic flow information (Cook 1977; Schutte and Violette 1991). If found, the chosen linear mixed model was used to fit the flow data with and without the high leverage and/or outlier observations. After removing the outliers, some of the river-ditch flow relationship estimates or standard errors (slope SEs) were impacted sufficiently, particularly those of ditches A and B, to justify additional reporting (Ramsey and Schafer 2002).

In the descriptive approach, basic statistics of flow, weather, and river-ditch flow relationships, as well as agricultural and irrigation practices, were used to characterize the Rio Hondo Valley. Streamflow from the Rio Hondo near Valdez gauge station (1935-2015) was analyzed. Maximum and minimum annual temperatures and precipitation records for the same period were also retrieved from the Taos, NM (Lat., 36.45°N; Long., -105.67°W) and Cerro, NM (Lat., 36.75°N; Long., -105.61°W) weather stations located near the Rio Hondo Valley. Only historical data from the two weather stations (Taos and Cerro) with no more than five months missing (World Meteorological Organization 1989) were used in the analysis. Using the software Sigma Plot (Version 13.0, Systat Software, San Jose, CA, USA), Loess smoothing was applied to historical hydrologic and weather records using an alpha window of 0.40 for all available data. This information was used to generate graphics illustrating long-term average and linear trends for streamflow, precipitation, and temperature in the Rio Hondo Valley. Average flow for the March-November 2011-2015 period and average monthly flow for the same period were estimated using the collected raw flow information (i.e., no logarithmic transformation) during the study period. Information about agricultural practices and irrigation management was obtained from field observations and interactions with farmers and ditch superintendents.

Pearson's correlation coefficients (*r*) between the river and ditches' logarithmically transformed flow were also estimated. The strength of the river-ditch flow relationship was defined according to the resulting *r* values. For values of *r* greater than +0.8 or less than -0.8 a strong relationship was called, if *r* was between -0.5 and +0.5 a weak relationship was defined, otherwise it was defined as a moderate relationship (Devore and Peck 1986).

Results

Descriptive Analysis

Long-Term Streamflow, Temperature, and Precipitation. Long-term streamflow, temperature, and precipitation provided insight into the climatic and hydrologic conditions of the Rio Hondo Valley. Long-term annual streamflow (1935-2015) data showed there were two periods (1952-1978 and 1998-2015) with below average streamflow, and two (1935-1951 and 1979-1997) with above average streamflow (Figure 2a). Below average streamflow years were associated with low precipitation years and above average streamflow years were associated with high precipitation years (Figures 2a and 2b). For temperature, one of the two periods with low temperatures (1935-1957) was associated with one of the periods of high flow (1935-1951) while the other (1997-2015) was associated with one of the periods of low flow (1998-2015); the one period with high temperatures (1972-1996) was associated with the other period of high flow (1979-1997) (Figures 2a and 2c).

Our study period (2011-2015) was developed during the second and most recent period of low flow and precipitation (1998-2015). Average flow for 2011 (524 $L \cdot s^{-1}$), 2012 (691 $L \cdot s^{-1}$), 2013 (493

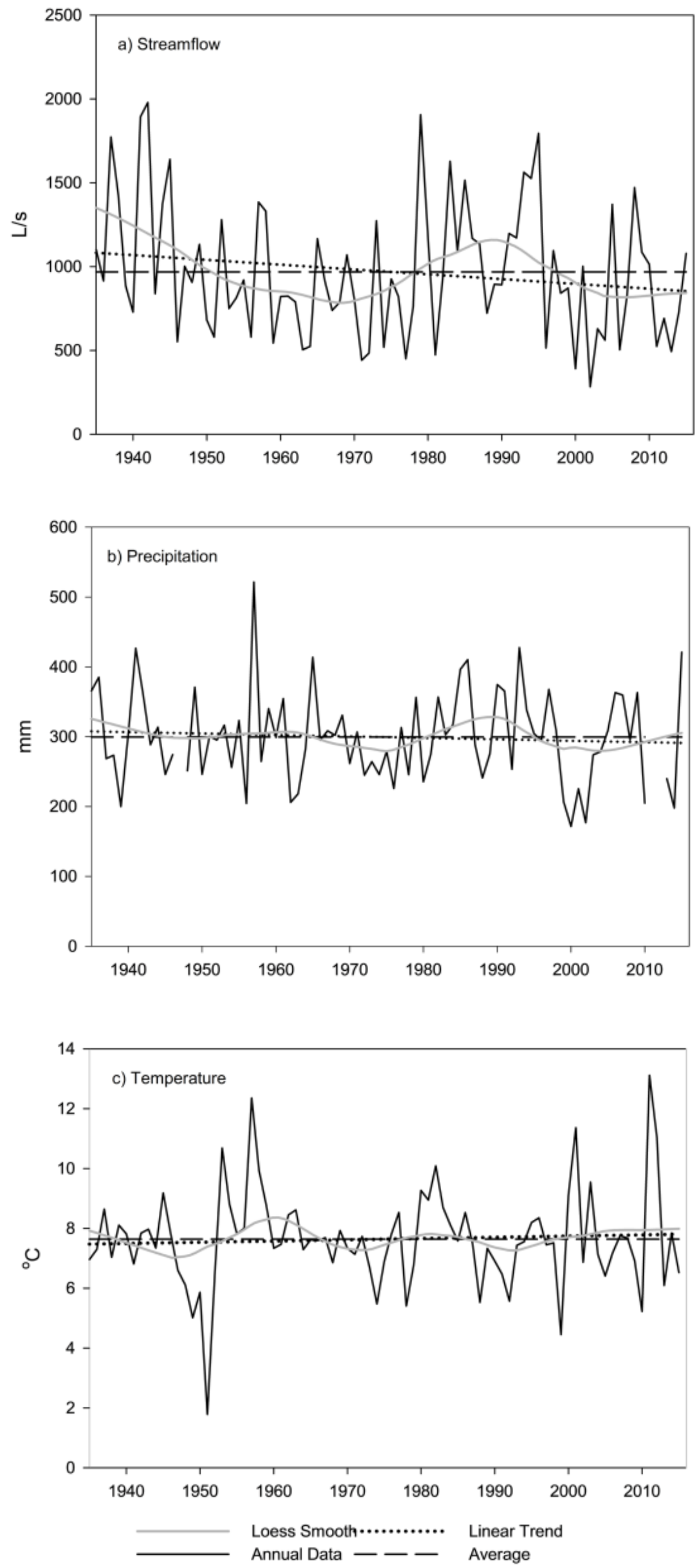

Figure 2. Annual, average, Loess smoothed trend line, and linear trend for (a) Rio Hondo flow from 1935 to 2015; (b) precipitation from Cerro and Taos weather stations from 1935 to 2015 (missing 1947, 2011, and 2012); and (c) temperatures from Cerro, NM and Taos, NM weather stations from 1935-2015.

L·s^{-1}), and 2014 (725 L·s^{-1}) were lower than the long-term average (968 L·s^{-1}); only the flow for 2015 (1,079 L·s^{-1}) was higher than the average (New Mexico Office of the State Engineer 1969).

Irrigation and Agricultural Practices, Flow Seasonality, and Descriptive Statistics. Forages are the most common crop grown on irrigated fields in the Rio Hondo Valley. The irrigation season generally ran from April to October and the number of days between irrigations ranged from 11 to 25. Two to three hay cuts occurred during the irrigation season in every year evaluated. Following the last hay cut, there was at least one additional irrigation, then after that, water was used for livestock watering and small backyard garden irrigations.

It was found that the river and the five ditches with the largest average flow for the period of record (March-November 2011-2015) had the same year with the largest average flow; on the other hand, the river and only one of the ditches had the same year with the lowest average flow (Table 1). The five ditches with the largest average flow values for the period of record were ditches A (424 L·s^{-1}), C (119 L·s^{-1}), E (66 L·s^{-1}), F (170 L·s^{-1}), and G (112 L·s^{-1}). The river and these ditches (A, C, E, F, and G) had the largest average flow in 2015 with values of 1,355, 559, 139, 91, 246, and 155 L·s^{-1}, respectively. The river and ditch E had the lowest average flow in 2011 with values of 626 and 51 L·s^{-1}, respectively. It was noticed that during 2013, the year with the second-lowest average flow in the river (643 L·s^{-1}) and the ditches D (45 L·s^{-1}), G (85 L·s^{-1}), and H (33 L·s^{-1}), the ditches A, B, C, and F had the lowest average flow with values of 338, 37, 89, and 98 L·s^{-1}, respectively.

Seasonal similarities were observed on the river and ditch hydrographs during the study period (March-November 2011-2015) (Figure 3). In 90% of the cases, the river and the ditches had a snowmelt peak within the mid-May to mid-June period. Their flow decreased considerably by the end of July or early August. During mid- to late September 2013, heavy rainfall events from storms characteristic of the monsoon season in the region resulted in substantial rises in river flow (NOAA NCEI 2013). Ditch hydrographs promptly responded to those increases in the river flow in the same way.

For the average monthly flow analysis, it was found that the river and most of the ditches had the largest average flow in either May or June (Table 2). The largest average monthly flow was reported in May for the ditches B (60 L·s^{-1}), D (102 L·s^{-1}), F (355 L·s^{-1}), and H (56 L·s^{-1}) while June was the month with the largest average monthly flow for the river (2,059 L·s^{-1}) and the ditches A (639 L·s^{-1}), C (188 L·s^{-1}), and G (191 L·s^{-1}). In the ditches where May was the month

Table 1. Average flow (L·s^{-1}) for the March-November 2011-2015 period in the Rio Hondo Valley.

Year	River	---------- Ditch ----------							
		A	B	C	D	E	F	G	H
2011	626	433	62	126	55	51	168	105	37
2012	803	411	44	130	82	56	182	83	20
2013	643	338	37	89	45	66	98	85	33
2014	836	416	46	120	50	80	199	137	40
2015	1355	559	41	139	35	91	246	155	35
Average	852	424	45	119	56	66	170	112	33

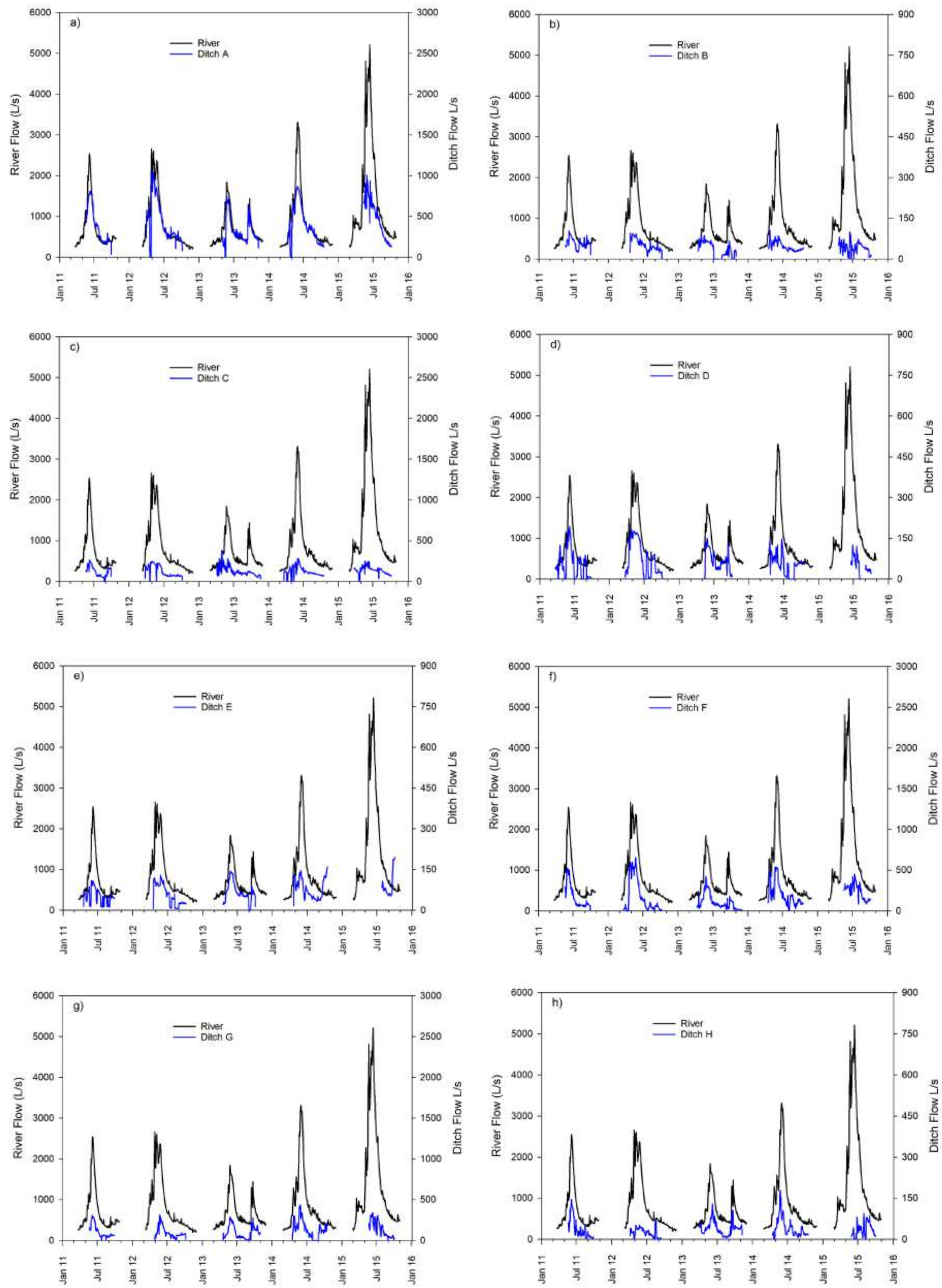

Figure 3. River-ditch flow seasonality for the March-November 2011-2015 period in the Rio Hondo Valley. (a) ditch A, (b) ditch B, (c) ditch C, (d) ditch D, (e) ditch E, (f) ditch F, (g) ditch G, and (h) ditch H.

Table 2. Average monthly flow ($L \cdot s^{-1}$) for the period of record (March-November 2011-2015) in the Rio Hondo Valley.

Location	March	April	May	June	July	August	September	October	November
River	380	738	1721	2059	865	573	525	459	360
A	--	327	599	639	407	325	293	263	239
B	--	57	60	58	39	42	35	21	--
C	148	128	179	188	102	79	85	51	18
D	29	69	102	91	37	37	31	21	5
E	--	73	92	87	50	41	55	117	--
F	24	205	355	294	146	99	73	75	8
G	--	110	168	191	81	47	87	116	--
H	--	22	56	53	26	22	22	23	36

with the largest flow, June was the second and vice versa. Ditch E showed its largest average monthly flow in October (117 $L \cdot s^{-1}$), followed by May (92 $L \cdot s^{-1}$) and June (87 $L \cdot s^{-1}$).

Only positive associations between the logarithmically transformed river and ditch flows were found in the study (Table 3). The positive river-ditch flow associations ranged from 0.22 to 0.65. Moderate associations ($r > 0.50$ to 0.80) were calculated for the ditches E (0.54) and F (0.65) and weak associations ($r \leq 0.50$) for the ditches A (0.36), B (0.22), C (0.45), D (0.43), G (0.50), and H (0.39). A larger r-value was observed in four (C, E, F, and G) out of the five ditches with the largest average flows; ditch A also had the largest average flow although its r-value was 0.36 (Table 1).

Model-Based Analysis

Model Selection. Models 3 and 4 were chosen from the five proposed models to fit the river-ditch flow relationship with logarithmically transformed flow values (Table 3). Logarithmic transformation accounted for some heteroscedasticity observed in the flow information. In Model 1, the simple linear regression, the independence of errors assumption was violated by the time series nature of the flow data. Violation of this assumption led to underestimated SEs resulting in inflated rates of Type I errors invalidating the test based on this model. Models 2, 4, and 5, with the use of random lines, accounted for variations among years from unknown random variables. They also accounted for changing variance at different river flow magnitudes. Models 3, 4, and 5 used an ARMA (1,1) structure to address serial correlation across time. The AIC values dropped substantially on these last three models, indicating a better performance by accounting for the serial autocorrelation. Model 3 had the lowest AIC values in six ditches (A, C, D, E, F, and G) while Model 4 had the lowest AIC values in the remaining two (B and H). Model 3 used the ARMA (1,1) structure and Model 4 combined the ARMA (1,1) structure and the random lines, resulting in a more complex model. Both models approximated well to the variance and led to approximately unbiased SEs as a base for inference.

River-Ditch Flow Relationship Parameters. The resulting linear model parameters (intercept and slope) of the logarithmically transformed flow data from Models 3 and 4 quantified the ditches' overall responses to changes in river flow during the study period (Table 3). While the intercept has no meaningful interpretation, the value of the slope represents the increase in ditch flow ($L \cdot s^{-1}$) to every unit increase in river flow ($L \cdot s^{-1}$). This parameter showed that ditch response to every unit of river flow increase ranged from 0.5320 (H) to 1.1821 (G) and was statistically significant ($p<0.05$) in all the ditches but two (B and H) (Table 3). Like the correlation coefficient or *r*, larger slope values were estimated in four out of five of the ditches with the largest average flow (C, E, F, and G) with the exception of ditch A (Table 1).

Covariance Parameters for the River-Ditch Flow Relationships. The ARMA (1,1) covariance structure in Model 3 and the combined ARMA (1,1) and random coefficients parts in Model 4 modeled the covariance and correlation structure of the logarithmically transformed flow data (Table 4). For Model 3, the ARMA (1,1) covariance structure implied strong correlations among ditch observations at consecutive time points in an exponentially decaying function. For Model 4, the random coefficients portion of the variance (α, τ, and β) modeled a fraction of the estimated variability in the ditch observations that, when combined with the ARMA (1,1) covariance structure, implied a correlation between ditch flow at different time points within a year that decayed over time at a slower rate than that of Model 3 (Equations 2-3). While the model parameters for the river-ditch flow relationship (Table 3) indicate that ditch and river flow are positively related, the covariance parameters indicate that errors from one day to another are highly correlated. Therefore, ditch flow observations at a current point in time are best understood as a function of both recent past ditch flow and current and recent past river flow.

Ditches B and H, for which a positive relationship with river flow was not statistically demonstrated, had large slope SE and large year to year variability (Tables 3 and 4)**.** The SE indicates the amount of variability or error that can be expected in an estimate (slope); slope estimate is more reliable if the SE is small (Harding et al. 2014). Large sample sizes and small variances lead to more reliable estimates of the SE (Harding et al. 2014). The number of observations used for ditches B and H were 811 and 851, respectively. For ditch B, the number of observations (811) was below the average observations used in the ditches (850) but larger than ditch E (752). For ditch H, the number of observations (851) was above the average (850). In both ditches B and H we found large year to year variability (α = 8.3238 in ditch B and α = 23.651 in ditch H) in the random effects portion of the variance. Thus, the large slope SE values found in ditches B and H were not attributed to the sample size but to the greater year to year variability in those ditches (Table 4).

Outlier Effect on the River-Ditch Flow Relationship Parameters. A total of 147 out of 6,798 observations from all the ditches were considered outliers. After their removal, the number of observations in the ditches decreased from 0 (ditch D) to 38 (ditch C); 0.0 to 4.0%, respectively, (Tables 3 and 5). As expected, in all the ditches with outliers removed, the strength of the river-ditch flow association, *r*, increased, and the slope SE decreased (Osborne and Overbay 2004; Cousieau and Chartier 2010). Similarly, lower values of the year to year variability as well as the *R* variance component were obtained (Table 6). Ditch A, the ditch with the largest average flow for the period of record, had the largest increase in *r* (from 0.36 to 0.89) and largest decrease in slope SE (from 0.1228 to 0.0453). While the value of the slope in all the ditches remained within the confidence limits of the raw flow data once the outliers were removed (Tables 3 and 5), the relationship for ditch B changed from being not statistically significant ($p>0.05$) to being statistically significant ($p<0.05$). However, that of ditch H remained not statistically significant ($p>0.05$).

Discussion

In this study, we analyzed the statistical relationships between river flow and community irrigation ditch flows in an agricultural valley in northern New Mexico. River and ditch flow levels during most of the years evaluated (2011-2014) represented below average streamflow conditions. This was in part due to the prolonged drought conditions prevalent in the region (Cayan et al. 2010; Garfin et al. 2013), which resulted in reduced snowpack depths and lower river flow.

Study results show that for every unit increase in river flow ($L \cdot s^{-1}$) there was an increase in ditch flow that ranged from 0.5320 to 1.1821 $L \cdot s^{-1}$ depending on the particular ditch evaluated. Results indicated that ditch flow was related to both current river flow and recent past river and ditch flow conditions. Stronger streamflow associations with the river were observed on the ditches that diverted the largest amount of water. Ditch H, located at the downstream end of the valley, showed a weak streamflow relationship related to the river flow. This was particularly evident toward the end of the ditch flow season. It is possible that the weak relationship observed between river and ditch H flow was in part due to the late-season operations made in upstream ditches.

Social and climate-related changes can negatively influence some of the ditch-river flow relationships observed in these traditional irrigation systems. The population of residents new to the area has increased, and the proportion of local Hispanic families, largely responsible for maintaining community-ditch traditions (such as equal water distribution regardless of river flow), has decreased. It is possible that some of these traditions may be lost if they are not embraced by the newcomers. Another threatening factor is related to the ongoing changes in land use observed in many acequia communities in northern New Mexico. These communities are facing reductions in irrigated land due to residential development (Ortiz et al. 2007; Llewellyn and Vaddey 2013) and increasing demands for water from other sectors (e.g., urban), which may result in reductions of land and water flow for agricultural activities. In previous studies, we documented important hydrological benefits associated with the use of these traditional irrigation systems in northern New Mexico. For instance, during the irrigation season, water diverted from the river is distributed in the irrigated valley moderating streamflow extremes. Ditch seepage and field irrigation deep percolation inputs help recharge the aquifer, which then releases water late in the season when baseflow decreases, resulting in substantially extended hydrographs (Fernald et al. 2010; Ochoa et al. 2013; Gutierrez-Jurado et al. 2017). Under predicted scenarios of water scarcity, climate change adaptation strategies consistently point to reduced surface irrigation (Pamuk-Mengu et al. 2011; McDonald and Girvetz 2013; Xu et al. 2013; Varela-Ortega et al. 2016; Rey et al. 2017). While these measures could in fact reduce water demands, it is possible they may disrupt benefits such as the recharge of local aquifer systems or the delayed return flows and environmental benefits associated with the use of these community-based irrigation ditches.

This research increases knowledge of traditionally managed irrigation ditches and their relationships with society and the environment. In particular, this study contributes important statistical understanding of the seasonality of river and community ditch flow relationships in a natural river flow regime system. Over the centuries, agricultural communities in Rio Hondo and in northern New Mexico at large have adapted to cope with the high and low river flows resulting from winter precipitation and snowmelt runoff conditions. This is different from many other surface-irrigated agriculture regions where river systems are controlled with man-made reservoirs that modulate streamflow deliveries to satisfy irrigation and community water needs.

Some of the statistical relationships observed in this study can be incorporated into simulation frameworks aimed to investigate water resources management at a larger scale. For example, natural river flow and community irrigation relationship metrics derived from this study can be used to parametrize regional water resource models such as the Snowmelt Runoff Model (Rango et al. 2017) and the Acequia System Dynamic Model (Turner et al. 2016), which are being used to evaluate the effects of climate variations and community-based management practices in water availability in the southwestern United States.

Conclusions

Community ditch flows in the Rio Hondo Valley are highly correlated to the natural river flows observed. Climate change-driven projections of reduced snowpack levels and earlier spring flow in the southwestern United States may significantly

Table 3. Model parameters and statistical components for the river-ditch flow relationship with flow values logarithmically transformed.

Ditch	Obs	Model	Intercept	Slope	Slope SE	------ Slope CL ------		*r*
						Lower	Upper	
A	851	3	2.1619	0.5431*	0.1228	0.3020	0.7841	0.36
B	811	4	-0.7247	0.6521	0.2261	-0.0014	1.3056	0.22
C	959	3	-0.6169	0.7622*	0.1081	0.5499	0.9744	0.45
D	872	3	-0.2180	0.5351*	0.1448	0.2509	0.8193	0.43
E	752	3	-1.2391	0.7768*	0.1021	0.5764	0.9773	0.54
F	890	3	-0.7143	0.7793*	0.1396	0.5052	1.0533	0.65
G	812	3	-3.7436	1.1821*	0.1898	0.8095	1.5548	0.50
H	851	4	-0.4348	0.5320	0.3380	-0.4246	1.4886	0.39

Note: Obs = number of observations; Slope SE = slope standard error; Slope CL = slope confidence limits (95%); *r* = Pearson's correlation coefficient; *Significant at the 0.05 probability level.

Table 4. Covariance parameters for the river-ditch flow relationship with flow values logarithmically transformed.

Ditch	Model	α	τ	β	ρ	γ	R
A	3	-----	-----	-----	0.8124	0.8673	0.8007
B	4	8.3238	-1.2087	0.1771	0.8437	0.8465	0.6211
C	3	-----	-----	-----	0.7005	0.8003	0.9213
D	3	-----	-----	-----	0.9356	0.9606	1.4289
E	3	-----	-----	-----	0.9107	0.9504	0.5916
F	3	-----	-----	-----	0.9290	0.9507	1.1136
G	3	-----	-----	-----	0.9348	0.9309	1.5360
H	4	23.651	-3.3284	0.4691	0.8518	0.9015	0.8348

Note: α = intercept variance for the random coefficients' variance component; τ = intercept and slope covariance for the random coefficients' variance component; β = slope variance for the random coefficients' variance component; ρ = autoregressive component of the ARMA (1,1) covariance structure in the residual component; γ = moving average coefficient of the ARMA (1,1) covariance structure in the residual component; R = residual variance component.

Table 5. Model parameters and statistical components for the river-ditch flow relationship with flow values logarithmically transformed and outliers removed.

Ditch	Obs	Model	Intercept	Slope	Slope SE	------ Slope CL ------		*r*
						Lower	Upper	
A	834	3	1.4057	0.6670*	0.0453	0.5782	0.7558	0.89
B	783	4	-2.1153	0.8705*	0.2020	0.3087	1.4324	0.40
C	921	3	-0.0589	0.7015*	0.0584	0.5868	0.8161	0.70
D	872	3	-0.2180	0.5351*	0.1448	0.2509	0.8193	0.43
E	749	3	-1.2072	0.7718*	0.0995	0.5765	0.9672	0.55
F	875	3	-1.1353	0.8485*	0.1208	0.6114	1.0856	0.74
G	783	3	-3.6767	1.1874*	0.1608	0.8716	1.5031	0.58
H	834	4	-0.8149	0.5885	0.3322	-0.3576	1.5346	0.54

Note: Obs = number of observations; Slope SE = slope standard error; Slope CL = slope confidence limits (95%); *r* = Pearson's correlation coefficient; *Significant at the 0.05 probability level.

Table 6. Covariance parameters for the river-ditch flow relationship with flow values logarithmically transformed and outliers removed.

Ditch	Model	α	τ	β	ρ	γ	R
A	3	-----	-----	-----	0.9170	0.9197	0.0880
B	4	6.7577	-1.0232	0.1553	0.9416	0.9349	0.3475
C	3	-----	-----	-----	0.7801	0.8621	0.2177
D	3	-----	-----	-----	0.9356	0.9606	1.4289
E	3	-----	-----	-----	0.9172	0.9537	0.5803
F	3	-----	-----	-----	0.9312	0.9507	0.8152
G	3	-----	-----	-----	0.9081	0.9071	1.0369
H	4	23.535	-3.2764	0.4560	0.8887	0.9162	0.7052

Note: α = intercept variance for the random coefficients' variance component; τ = intercept and slope covariance for the random coefficients' variance component; β = slope variance for the random coefficients' variance component; ρ = autoregressive component of the ARMA (1,1) covariance structure in the residual component; γ = moving average coefficient of the ARMA (1,1) covariance structure in the residual component; R = residual variance component.

impact water resources management in the community-based irrigation systems of northern New Mexico. The river-ditch flow relationships observed were affected by ditch location along the agricultural valley. Also, the volume of water diverted influenced the strength of the river-ditch flow relationship. Future research would benefit from an enhanced understanding of river flow and ditch flow change between wet and dry years, and from improved knowledge of the influence of upstream ditch return-flow to the river.

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A Survey of Perceptions and Attitudes about Water Issues in Oklahoma: A Comparative Study

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Abstract: Understanding people's perceptions of the environment, drinking water issues, and protecting and preserving water resources is of great importance. This study aims to assess and compare the perceptions of the general public (*n* = 414), post-secondary students (*n* = 103), and water professionals (*n* = 104) in Oklahoma on water issues in the state. To address these goals, a 53-item paper questionnaire was first administered to a randomly sampled mailing list of Oklahoma residents. As a follow up to the initial survey, post-secondary students at Oklahoma State University were sampled in addition to Oklahoma water professionals at regional conferences. Respondents ranged from 18 to over 65 years old, with all three demographics agreeing the top water priority to be clean drinking water. The majority were satisfied with their home water supply and felt it was safe to drink, while they were not sure of the quality of ground and/or surface water. Age was a key factor in information delivery and learning preferences as the older participants favored print material versus the younger demographic interest in technology. Data collected via this study provide insight into the perceptions, priorities, and learning preferences of these three populations. Despite our finding that clean water is a priority in Oklahoma, regardless of demographic, results suggest more education and outreach is needed to provide additional information regarding water in Oklahoma.

Keywords: *environmental concerns, learning preferences, water priorities*

Water is one of the most important natural resources (Mahler et al. 2013). Because of this, the United Nations (2015) is working to improve water quality, increase the efficiency of water use, integrate water management programs, and achieve universal and equitable access to safe drinking water for all by 2030. Public support will be critical to achieving these objectives. The theory of planned behavior (TPB) has been used extensively to help explain an individual's behavior based on their attitude, subjective norms, and perceived behavioral control related to their intention to ultimately perform an identified behavior (Ajzen 1991). As a result, numerous studies have evaluated the attitudes and perceptions of underrepresented populations (Kozich et al. 2018) and the general public on water related issues (Mahler et al. 2010; Adams et al. 2013; Boellstorff et al. 2013; Borisova et al. 2013; Mahler et al. 2013; Evans et al. 2015; Gholson et al. 2018). Regardless of the population of interest, perceptions of water issues, environmental impacts, and the protection and preservation of natural resources play a key role in meeting future national and global water supply needs. In particular, failure to allocate equitable water resources among stakeholders may lead to controversies such as that of Lake McClure in California, Canton Lake in Oklahoma, and Lake Granbury in Texas and historic controversies such as at Mono Lake in

California (Loomis 1987; Loomis 1995; Casteel 2013). In Oklahoma, water use in the southeastern part of the state is a long litigated regional issue with conflicting interests of the tribal nations, state of Oklahoma, city of Oklahoma City, and the Tarrant County District in North Texas (Casteel 2013). Further understanding of the public's perceptions can help water managers predict water related behaviors (Jorgenson et al. 2009; Willis et al. 2011) and determine future needs and impacts of water related decisions – e.g., reusing reclaimed water (Parsons 2018) or produced water (Eck et al. 2019) to meet future needs.

The overarching objective of this study is to assess and discuss the perceptions of the general public, post-secondary students, and water professionals on water issues in Oklahoma. For the context of this study, the perceptions and attitudes of participants were considered as potential factors impacting water related decisions as an individual's intentions are assumed to encompass these motivating factors leading to the behavior (Ajzen 1991). Specifically, this study describes participants' perceptions and behaviors related to 1) key water issues and actions, 2) their drinking water sources, 3) protecting surface and groundwater quality, and 4) learning opportunities.

Materials and Methods

The 2018 Water Issues in Oklahoma survey was designed as a follow-up to the 2008 Water Issues in Oklahoma survey, which was part of the National Water Needs Assessment Program (Mahler et al. 2013). The 53-item survey included four sections addressing perceptions regarding the environment, drinking water issues, protecting and preserving water resources, and collecting socio-demographic and learning preference data. Section one assessed 27 items related to the participant's importance of each of the water issues (see Table 1) on a five-point scale of agreement (1 = Not important, 2 = Somewhat important, 3 = No opinion, 4 = Important, 5 = Very important).

Section two included four questions addressing drinking water perceptions, asking participants "where they primarily get their drinking water?", details regarding "their home drinking water system.", "do they feel their tap water is safe to drink?", and "do they have their home drinking water tested?". When addressing the protection and preservation of water resources, ten questions were used, including: 1) "What is the quality of groundwater in your area?"; 2) "What is the quality of surface waters where you live?"; 3) "Do you regard water quantity as a problem?"; 4) "Do you know of or suspect that any of the following pollutants affect either surface or groundwater quality in your area?"; 5) "In your opinion, which of the following are the most responsible for the

Table 1. Identified water issues.

Better management of recreational activities (boating, fishing, ATVs)
Better management of shoreline access to prevent erosion
Building new water storage structures (dams, reservoirs)
Clean drinking water
Clean groundwater
Clean rivers and lakes
Educating municipal officials
Hypoxia (Gulf dead zone)
Improving agricultural practices
Improving home and garden practices
Improving municipal practices
Improving storm water runoff
Improving water quality monitoring to detect pollution
Interstate transfer/sale of water rights
Involving citizens in collecting water quality information
Making water quality and quantity data available to public
Preserving and restoring buffer zones and wetlands
Preserving agricultural land and open space
Residential water conservation
Treating storm water runoff
Water for agriculture
Water for aquatic habitat
Water for commerce/industry/power
Water for household landscapes
Water for municipal use
Water for recreation
Within state transfer/sale of water rights

existing pollution problems in rivers and lakes in Oklahoma?"; 6) "Do you know what a watershed is?"; 7) "How well do you feel each one of these groups is fulfilling their responsibility for protecting water resources?"; 8) "The likelihood of your area suffering from a prolonged drought is:"; 9) "If treatment methods of produced water are successful, would you (check all that apply):"; and 10) "Have you or someone in your household done any of the following as part of an individual or community effort to conserve water or preserve water quality?". Learning preferences were assessed through five questions: 1) "Have you received water resources information from the following sources?"; 2) "If you had the following kinds of learning opportunities to learn more about water issues, which would you be most likely to take advantage of?"; 3) "Have you ever changed your mind about a water issue as a result of:"; 4) "Do you think that the amount of water in your area will change as a result of climate change?"; and 5) "Where do you normally get your news?". The final eight questions were related to socio-demographic data, including, sex, age, education, location, zip code, length of time in Oklahoma, and town population.

Three populations of interest were included in the study - the Oklahoma public, post-secondary students in the College of Agriculture Sciences and Natural Resources (CASNR) at Oklahoma State University (OSU), and Oklahoma water professionals. To collect information regarding the public's perception of water issues in Oklahoma, a random sampling method was implemented through the purchase of a mailing list for 2,000 Oklahoma residents. Following the tailored design method of Dillman et al. (2014), four rounds of communication were utilized. The first survey went out via postal mail to the entire sample and included a personalized cover letter, a 53-item survey questionnaire, and a postage paid, pre-addressed business reply envelope. A reminder postcard was sent to non-respondents two weeks later. The third follow-up included another complete survey packet, which was sent four weeks after the initial survey to all non-respondents, followed again by a final reminder postcard two weeks later. Between each follow-up, individuals who returned the survey or contacted the researchers and indicated they did not want to participate were removed from any additional mailings. Out of the 2,000 initial surveys sent, 192 were returned undeliverable and 414 surveys were completed and returned for an adjusted response rate of 22.9%. Of the 414, only 400 complete surveys were available for data analysis.

Based on the demographics of the completed surveys, we lacked representation of perceptions of a younger demographic. Thus, the second demographic of interest became CASNR students at OSU. The survey for this demographic used the same questionnaire as for the public, with the addition of one question asking participants to "place an X on the line indicating how you see yourself on environmental issues:", and two questions related to learning preferences for water education: "Have you ever participated in any of the following learning activities?" and "Would you like to learn more about any of the following water quality issues?". Although these three questions were added to the survey for student distribution, the results were not included in this paper, as the data was not collected from all groups. A convenience sample of two regularly scheduled classes in the CASNR were utilized for data collection, one class in the fall of 2018 and one class in the spring of 2019. The two classes combined provided a potential of 108 students receiving the survey, of which 103 voluntarily completed it, resulting in a 95.4% response rate.

The third group consisted of 'water professionals' engaged in a water related career in Oklahoma. The water professionals were sampled at two water conferences in Oklahoma, the first in the fall of 2018 and the second in the spring of 2019. Professionals were asked to complete the same survey as the CASNR students at both conferences and a collection box was made available for the completed surveys to be returned. Four hundred surveys were distributed between the two conferences with 104 completed surveys returned, giving a 26% response rate for the water professionals.

This study provides descriptive comparisons between the three samples related to their perceptions of water issues in Oklahoma. IBM SPSS Version 23 (IBM 2015) was utilized for data analysis.

Results

The 2018 Oklahoma water issues survey resulted in a combined respondent age range of 18 to over 65 years of age and an equal split of males and females with 44% each and 12% choosing not to respond to the gender question (Table 2). The majority of respondents (63%) lived inside city limits, and 77% had lived in Oklahoma for more than 10 years. A total of 54% of respondents lived in communities of 25,000 people or more.

Environmental Perceptions

Participants were asked how they feel about the environment by identifying how important each of 27 potential Oklahoma water issues were to them on a five-point Likert-type scale (i.e., not important to very important). Four of the top five priorities were related to clean water/water quality (Table 3) based on mean scores for the public. The water issue receiving the lowest mean score (3.46) was *water for household landscapes*, while the lowest percent agreement (46.6%) was on *interstate transfer/sale of water rights.*

OSU CASNR students had a slightly different perspective on water issues in Oklahoma. Although the most important issue for them was also *clean drinking water*, the leaning towards agriculture indicated by these CASNR students is clearly observed in three of their top five priorities (Table 4) based on mean scores, including, water for agriculture, preserving agricultural land and open space, and improving agricultural practices. Interestingly, on the other end of the spectrum, the issue receiving the lowest mean score (3.23) from CASNR students was *water for recreation*, while the lowest percentage of agreement (46.6%) amongst students was *interstate transfer/sale of water rights*, the same as the public.

Similar to the general public, the water professionals identified clean drinking water, groundwater, and rivers and streams as the top three water issues in Oklahoma (Table 5). However, unlike public respondents, water professionals identified water for aquatic habitat and municipal use as their fourth and fifth priorities. Also similar to the general public, the water professionals identified *water for household landscapes* as the least important item (2.78 mean score), and this topic had the lowest percentage of agreement (38.5%).

All three demographic groups prioritized *clean drinking water* and were all concerned with *clean rivers and lakes* as well. Overall, only one item fell below a mean of 3.0, which was *water for household landscapes* (receiving a 2.78 from the water professionals). All 27 Oklahoma water issues were of at least some importance to our participants. Other issues which were of less concern (although still receiving a mean score above a 3.0) were items related to within state and interstate transfer or sale of water rights, along with water for recreation, and water for household landscapes.

Drinking Water Issues

The majority of respondents across groups utilized public water supplies (i.e., municipal or rural water district) for their home drinking water. Although the majority of participants were satisfied with their home drinking water and felt it was safe to drink, substantially more CASNR students and water professionals shared this view than did the general public (Figure 1).

Further, very few (13.3-22.1%) respondents, regardless of group had tested their drinking water to confirm its quality. Despite the high level of satisfaction and trust in their drinking water, a large percentage of CASNR students and water professionals utilized a home water treatment system, while the general public, with lower percentages satisfied, was less likely to use one.

Protecting and Preserving Water Resources

Ten questions evaluated participants' perceptions related to *protecting and preserving water resources*. Just as the majority of public participants did not know what the groundwater quality was and either did not know or felt surface waters were normal (Table 6), most also did not know what if any pollutants (i.e., pathogens, fertilizer, heavy metals, minerals, pesticides, salinity, pharmaceuticals, petroleum products, algae, sediment, or turbidity) could potentially affect the surface or groundwater quality in their area.

Respondents across groups consistently identified groundwater quality as higher than

Table 2. Demographics of the general public, CASNR students, and water professionals participating in study.

Demographic		**Public 2018** % (n)	**Students** % (n)	**Professionals** % (n)
Gender	Male	46.0 (184)	30.1 (31)	49.0 (51)
	Female	42.5 (170)	54.4 (56)	38.5 (40)
	No response	11.5 (46)	15.5 (16)	12.5 (13)
Years lived in Oklahoma	All my life	40.5 (162)	47.6 (49)	36.5 (38)
	>10 years	44.3 (177)	10.7 (11)	29.8 (31)
	5 - 9 years	3.0 (12)	1.9 (2)	13.5 (14)
	<5 years	1.5 (6)	27.2 (28)	9.6 (10)
	No response	10.7 (43)	12.7 (13)	10.6 (11)
Size of residence community	> 100,000	31.3 (125)	9.7 (10)	35.6 (37)
	25,000 - 100,000	20.3 (81)	38.8 (40)	30.8 (32)
	7,000 - 25,000	14.5 (58)	14.6 (15)	17.3 (18)
	3,500 - 7,000	9.5 (38)	8.7 (9)	3.8 (4)
	< 3,500	17.0 (68)	26.2 (27)	9.6 (10)
	No response	7.4 (30)	1.9 (2)	2.9 (3)
Education	Less than or some high school	3.8 (15)	-	-
	High school graduate	19.0 (76)	13.6 (14)	1.0 (1)
	Some college	34.8 (139)	74.0 (77)	8.7 (9)
	College graduate	24.0 (96)	-	32.7 (34)
	Advanced college degree	16.8 (67)	7.8 (8)	57.7 (60)
	No response	1.8 (7)	3.9 (4)	-
Age	18 - 34	5.0 (20)	87.4 (90)	16.4 (17)
	35 - 49	15.0 (60)	1.0 (1)	34.6 (36)
	50 - 64	29.5 (118)	-	29.8 (31)
	>65	38.8 (155)	-	6.7 (7)
	No response	11.7 (47)	11.6 (12)	12.5 (13)
Residence location	Inside city limits	63.2 (253)	52.4 (54)	73.1 (76)
	Outside city limits, not farming	25.0 (100)	15.5 (16)	14.4 (15)
	Outside city limits, farming	10.3 (41)	32.0 (33)	12.5 (13)
	No response	1.6 (6)	-	-

Note: n = 400 for 2018 public; n = 103 for students; n = 104 for water professionals.

surface water quality. Few (<16%) identified groundwater quality as poor/unacceptable; however, a quarter to a third of respondents identified surface water quality as poor-unacceptable. CASNR student opinions varied regarding the quality of surface and groundwater (Table 6), although most CASNR students surveyed did not know if pollutants were affecting the surface water or groundwater in their area. In contrast, the majority of water professionals felt both surface and groundwater to be normal to good, although over 60% of them identified pathogens, fertilizers, minerals, pesticides, algae, sediment, and turbidity to be a suspected or known problem affecting surface and/or groundwater. When asked about potential sources of pollution in rivers and lakes, there was no clear consensus across the three groups, with the highest percentages of respondents identifying oil/gas production (15.8%) and animal agriculture (11.5%) as potential sources.

A need for greater understanding of water quality, pollution sources, and other aspects of water resources was clearly shown through study results. In addition to the 45% of the public not knowing the quality of groundwater in their area, almost half of the public (47%) and students (44%) surveyed did not know what a watershed was, although 96% of the water professionals did.

When participants were asked if they regarded water quantity as a problem in the area where they lived, the majority of students and public surveyed either did not know or believed it not to be a problem. In contrast, over half of the water professionals surveyed considered water quantity was either probably or definitely an issue (Figure 2).

When participants were asked if they felt the incidence of prolonged drought was increasing or decreasing, 40.9% of respondents felt it was staying the same, while 32.5% identified an increase, 10.1% thought it was decreasing, and 16.5% had no opinion. As a potential solution to help drought-proof some regions of the state, the salty and petroleum contaminated water produced as part of the oil and gas extraction process, known as *produced water,* is being tested as a possible source of water for industry, agriculture, and other uses. Participants were asked if they would consider the use of produced water, assuming

Table 3. Water issue priorities for the general public in Oklahoma in 2018.

Issue	***M***	***SD***	**% Agreement**[a]
Clean drinking water	4.97	0.16	79.7
Clean rivers and lakes	4.75	0.49	78.2
Clean groundwater	4.70	0.59	75.9
Water for agriculture	4.51	0.685	74.6
Improving water quality monitoring to detect pollution	4.47	0.78	72.2

Note: 1 = Not Important; 2 = Somewhat Important; 3 = No Opinion; 4 = Important; 5 = Very Important.
[a] Items marked either a 4 or a 5.

Table 4. Water issue priorities for CASNR students in 2018.

Issue	***M***	***SD***	**% Agreement**[a]
Clean drinking water	4.90	0.30	100.0
Water for agriculture	4.75	0.48	98.1
Preserving agricultural land and open space	4.72	0.53	98.1
Improving agricultural practices	4.63	0.69	95.2
Clean rivers and lakes	4.44	0.79	93.2

Note: 1 = Not Important; 2 = Somewhat Important; 3 = No Opinion; 4 = Important; 5 = Very Important.
[a] Items marked either a 4 or a 5.

Table 5. Water issue priorities for Oklahoma water professionals in 2018.

Issue	***M***	***SD***	**% Agreement**[a]
Clean drinking water	4.94	0.23	100.0
Clean groundwater	4.83	0.41	99.0
Clean rivers and lakes	4.78	0.48	99.0
Water for aquatic habitat	4.58	0.62	95.2
Water for municipal use	4.58	0.50	100.0

Note: 1 = Not Important; 2 = Somewhat Important; 3 = No Opinion; 4 = Important; 5 = Very Important.
[a] Items marked either a 4 or a 5.

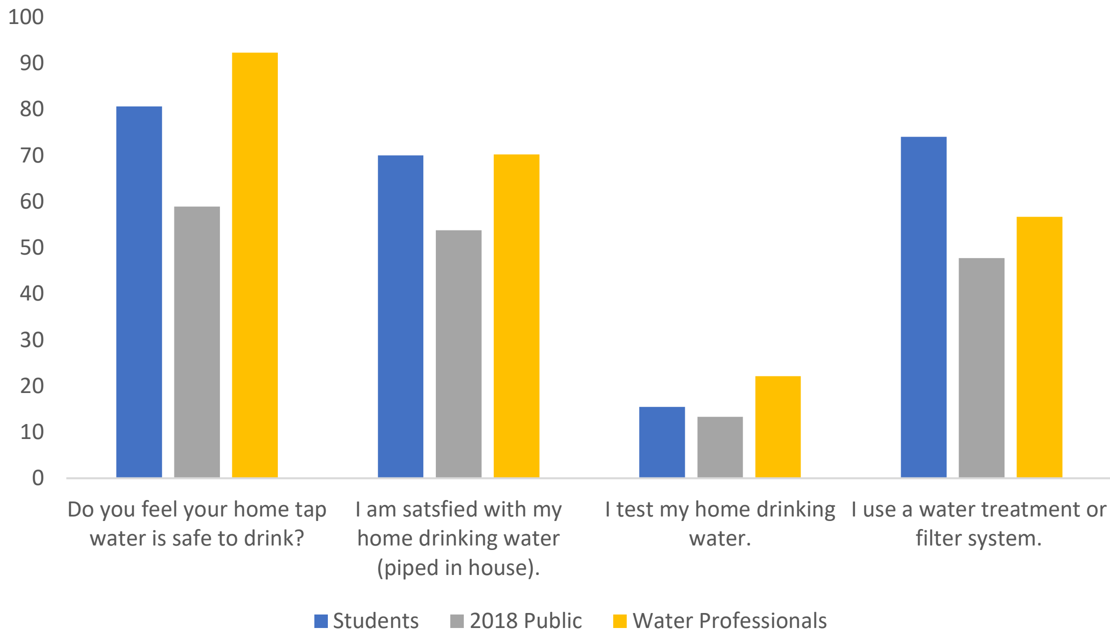

Figure 1. Comparison of perceptions related to drinking water.

Table 6. Perceived groundwater and surface water quality in Oklahoma in 2018.

Population	Condition	Groundwater % (n)	Surface water % (n)
Public	Excellent	4.7 (19)	1.2 (5)
	Good	17.0 (68)	16.0 (64)
	Normal	17.3 (69)	34.7 (139)
	Poor	12.8 (51)	21.3 (85)
	Unacceptable	3.2 (13)	3.8 (15)
	No opinion/don't know	45.0 (180)	23.0 (92)
Students	Excellent	5.8 (6)	1.0 (1)
	Good	29.1 (30)	18.4 (19)
	Normal	27.2 (28)	35.0 (36)
	Poor	9.7 (10)	27.2 (28)
	Unacceptable	1.0 (1)	4.9 (5)
	No opinion/don't know	27.2 (28)	13.6 (14)
Water Professionals	Excellent	9.6 (10)	2.9 (3)
	Good	40.4 (42)	31.7 (33)
	Normal	30.8 (32)	26.0 (27)
	Poor	5.8 (6)	30.8 (32)
	Unacceptable	0.0 (0)	2.9 (3)
	No opinion/don't know	13.5 (14)	5.8 (6)

Note: n = 377 for 2018 public; n = 103 for students; n = 104 for water professionals.

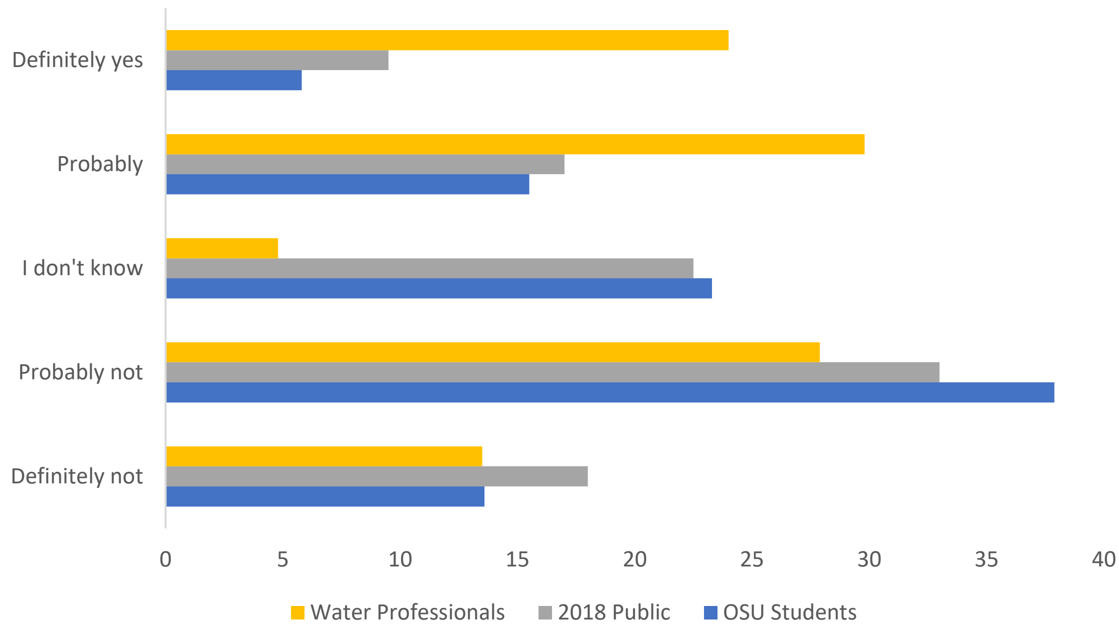

Figure 2. Responses from Oklahoma water professionals, the public, and students regarding whether they considered water quantity as a problem in the area where they lived.

treatment methods are deemed successful, as a potential water source for five uses – drinking water, food production, non-food crop production, environmental flows, and industrial processes (Figure 3). Respondents were generally supportive of reuse of produced water for industrial processes and non-food agricultural production; however, less than 25% of respondents were supportive of using produced water for drinking water.

Finally, participants from all three groups were asked about their efforts to conserve water and preserve its quality. Overall, 30% of respondents have implemented new technologies or changed how often they water their yard, and 20% have changed their use of pesticides, fertilizers, or other chemicals.

Learning Preferences

The overwhelming majority of participants, regardless of demographic group, have received water related resources from one or more sources. The most commonly reported sources of water related information were city/municipal water districts, television, and Universities/Extension across groups. Not only have participants received water related resources information, but 53% of those surveyed have changed their mind on a water issue based on news coverage (i.e., TV, newspaper, internet, etc.), while 48% have made a change based on financial considerations. Speeches by an elected official were much less impactful, resulting in less than 6% of respondents changing their mind on a water issue. Considering participation in learning opportunities about water issues, learning preference varied by population. The public, the majority of which was 50 years old and older, preferred learning via reading printed fact sheets or watching TV coverage. In comparison, students (18-34 year olds) preferred social media or informational videos, while water professionals (35-64 year olds) preferred visiting a website or attending a short course or workshop.

Discussion

Data collected from the Oklahoma public, CASNR students at OSU, and Oklahoma water professionals via this study provide insight into the perceptions, priorities, and learning preferences of these three populations. The vast majority of our public demographic was at least 50 years old, with nearly 40% of the public response coming from those over 65 years of age. This older demographic is of interest as they tend to be concerned with

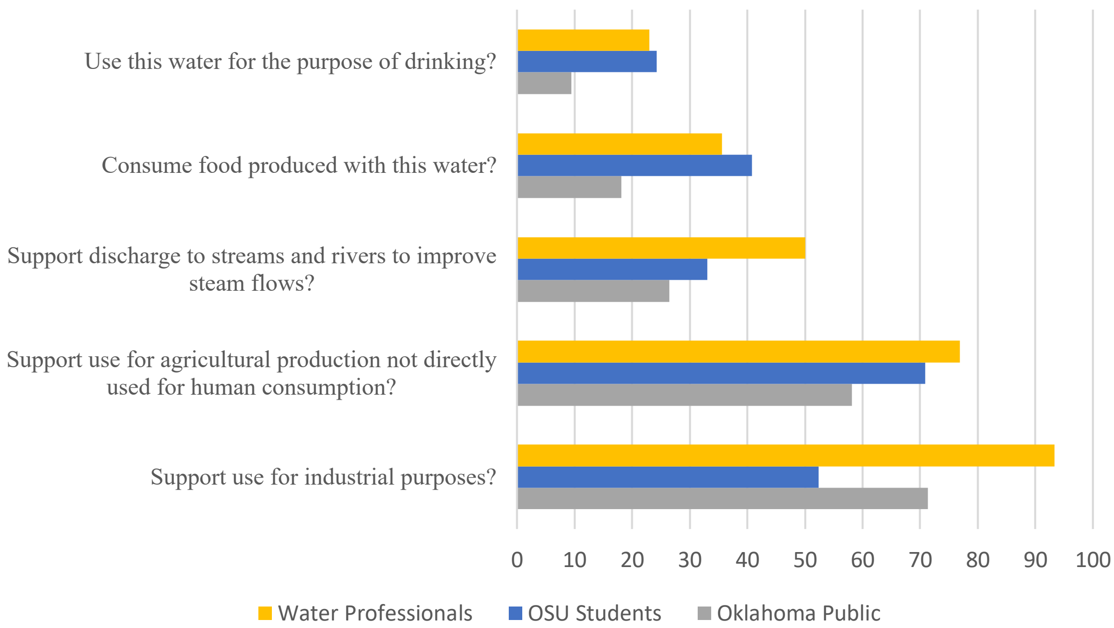

Figure 3. Opinions of treatment and reuse of produced water.

water conservation efforts and aim to conserve water themselves, although they spend more time in the home, leading to greater home water consumption according to Fielding et al. (2012). Likewise, proportionately higher representation of more formally educated, male, and urban residents was similar to that reported by Evans et al. (2015). The public in our study value clean drinking water, clean rivers and lakes, and clean groundwater, and feel their home drinking water is safe to drink. The OSU students surveyed agreed that their home drinking water was safe to drink, although over 70% of them utilized a home water filtration system for their drinking water. The students also agreed with the public on the number one priority being clean drinking water and felt clean rivers and lakes were of importance, although the remaining top five priorities for the OSU students were related to agricultural needs. The student's importance placed on water issues for agriculture is likely related to their being undergraduate students in the college of agriculture at OSU. Water professionals also ranked clean drinking water as the highest priority, followed by clean groundwater, and clean rivers and lakes, aligning with the public's opinion, although the professionals also prioritized water for aquatic habitats and water for municipal use. Outside of this study, clean drinking water has been identified as a key factor related to water perceptions (Mahler et al. 2004; Kopiyawattage and Lamm 2017). Similarly, Adams et al. (2013) found clean drinking water as more important than water for recreation and landscapes in their study of water users from nine southern states.

Ground and surface water quality was largely considered to be normal to excellent, except for the large percentages who did not know what the quality was (Table 6). The large percentages of respondents not knowing the quality of their water, potential pollution sources, or other basic water resources terminology (i.e., watershed definition), provide a strong indication that greater education and outreach regarding water issues is needed in Oklahoma. Not surprisingly, there was no clear consensus on pollution causes and sources possibly because these differ by watershed and region.

Water professionals commonly considered water quantity to be an issue, whereas the students and public considered it to be much less of an issue (Figure 2). This is surprising considering the extent of the drought in Oklahoma in 2011-2012. However, Oklahoma received average rainfall across the state for 2018 (Mesonet n.d.), potentially impacting the views of students and the public as found by previous studies (Evans et al. 2015). Further, regional differences may have impacted results as well. Eastern Oklahoma generally receives adequate rainfall, whereas western Oklahoma is drought prone. Despite this, the state of Oklahoma and its legislature certainly see water quantity as an issue and have performed extensive water planning (OWRB 2012) to ensure sufficient supplies are available in the future, setting a goal of using no additional freshwater in 2060 than it did in 2010 (Oklahoma Water for 2060 Advisory Council 2015). Of the strategies being considered, reuse of various marginal quality waters is a high priority. In our study, all three demographics supported the reuse of produced water for non-food agricultural production and for industrial purposes, although the support for food production use was much lower from the public and students, while the water professionals were split on the issue.

The disparity of public opinion on interstate transfer/sale of water rights is particularly interesting. Recent court battles between Texas and Oklahoma and concerns regarding tribal water rights (O'Brien 2017) have placed this topic at the forefront with some supporting the sale of water to Texas to bolster state coffers, while others wish to protect state and tribal waters for future use and environmental flows. Despite court settlement of these matters, there is no consensus of public opinion.

Finally, demographics play a huge roll in preferred learning methods and information delivery methods as found in this study. Having demographics ranging from 18 to over 65 years of age provided a wide spectrum of preferences related to news outlets and information delivery. Understanding the target demographic is of key importance when developing water related outreach and information, as we found the younger demographic to prefer social media and informational videos, as opposed to the older demographics' preference for printed fact sheets and articles.

Conclusion

Our study clearly showed that clean water is a priority in Oklahoma, regardless of demographic. However, more education and outreach are needed, particularly in the areas of groundwater quality, pollution causes and sources, and water quantity. In order to effectively impact behaviors, education programs should be developed based on TPB and utilizing the survey's findings regarding perceptions, attitudes, and beliefs (Ajzen 1991) related to water resources. Furthermore, in order to effectively conduct these needed education and outreach programs, it will be important to understand target audiences and provide information using the methods preferred by each audience. Based on the findings of this study, accomplishing this goal will require the use of printed materials and television (for those over 50), along with social media and informational videos (for those under 34) to reach the broader public and better inform the attitudes and behaviors (Ajzen 1991) of individuals living in Oklahoma related to water issues in the state.

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Water in India and Kentucky: Developing an Online Curriculum with Field Experiences for High School Classes in Diverse Settings

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Abstract: Maintaining access to sufficient amounts of clean water for human and environmental needs is a global challenge requiring education and community engagement. We developed a curriculum integrating field experiences with online modules focusing on the water cycle, water quality, and human impacts. This year-long curriculum connected nine public high schools in Kentucky with ten private, English-language schools in eastern India. Curriculum design was informed by the Next Generation Science Standards (the new U.S. education standards for science) and utilized freely available, open-access technology. Each instructional module included a narrated slideshow with general information and examples from Kentucky and India, exercises involving online data sets, and guidelines for class projects. Students developed creative products (e.g., posters and dramatic performances) for community outreach on water issues. Class projects involved literature reviews of local water bodies, collection of data using water-quality test kits, and submission of a research proposal, which was evaluated by scientific professionals with a background in hydrology. The highest-rated team from each country traveled to the other country to present their findings at a professional meeting or workshop. Eight of the Indian schools prepared video summaries of their projects, which were reviewed by an undergraduate class at the University of Kentucky. The curriculum and examples of student work are available on a publicly accessible website. Challenges faced during project implementation included difficulty in assessment of student products and, particularly for Kentucky schools, integrating activities into existing curricula. Nonetheless, the proposals, final papers, and other products indicated that students understood hydrologic concepts and were aware of water-quality issues.

Keywords: *international, water quality, surface water, groundwater, environmental education, outreach, assessment*

Solving the world's myriad water challenges requires not only conceptual understanding of hydrologic processes, but also availability or collection of appropriate monitoring data and community-cooperation awareness (UNESCO WWAP 2012). Engagement of youth, particularly at the high school level, is key to these efforts, but access to appropriate educational materials is uneven (e.g., Wagener et al. 2012). High school involves a transition to adult roles and responsibilities, including civic engagement, as well as learning and identity exploration. It is important for high school students, regardless of where they live, to see themselves as participants in their communities, messengers to various groups, and change agents. Young people play a strategic role in motivating society as a whole toward learning and practicing environmental good (e.g., Thunberg 2019).

The U.S. State Department recognized "a knowledge gap in understanding how water systems work, rising pollution levels and their deleterious effects on human health, and what can be done on the local level to address pollution" within the Indian public (U.S. Mission to India 2016). Consequently, the U.S. Consulate in

Kolkata funded the University of Kentucky (UK) to develop an online, modular curriculum focused on water for high school students. Introductory videos and exercises were integrated with local field experiences and communication of water-quality related issues to the public. The project was intended to enable students to partner in research, to compare and contrast each country's problems, and to work mutually on solutions (U.S. Mission to India 2016).

Researchers at UK and three Indian institutions collaborated with a non-governmental organization based in Kolkata (Association for Social & Environmental Development [ASED]) to identify ten schools in eastern India and nine in Kentucky, which participated during the 2017–18 academic year. The fundamental goal of this project was to develop global citizens who have the skills and knowledge to protect the environment, especially water quality, and consider environmental protection a civic responsibility. Teachers at each school were responsible for the selection of students and the integration of project activities into existing curricula. Student teams submitted research proposals that were judged by professionals with experience in environmental education and hydrology. The school with the highest-rated proposal from each country sent a team of students and teachers to the other country to present research results as part of a scientific and cultural exchange.

In this paper, we provide the rationale for the curriculum and the details of its design. We highlight student activities as well as challenges in implementing and assessing the impacts of the project. We make recommendations for addressing these challenges, and we conclude that the curriculum design and the content generated are broadly adaptable for water education in high schools, contingent upon access to the internet and relatively simple water-quality monitoring supplies.

Water Issues in Eastern India and Kentucky

Water quantity and quality problems are increasingly prevalent across India. As reviewed by Mukherjee et al. (2015), the Indian subcontinent hosts ~23% of Earth's population within only ~3% of global land area. Per capita availability of water in India decreased from 4000 m^3/yr in the 1980s to < 1900 m^3/yr by 2008 (Babel and Wahid 2008). Rapid population growth and intensive pumping of groundwater for irrigation are causing water scarcity in much of the country, but water quality is generally a greater issue than water scarcity in eastern India. The region is humid, with annual precipitation ranging from ~100 to 800 cm/yr, and is drained by the Ganges and Brahmaputra Rivers, which are ranked #14 and #5 in the world by discharge, respectively (Dai and Trenberth 2002; Mukherjee et al. 2015). Intense seasonal rainfall and rejected recharge result in frequent flooding in eastern India. The alluvial aquifers of the Ganges-Brahmaputra basin are extensive and highly productive, although other aquifers are less productive and the areas in which they are located are more susceptible to shortfalls in monsoonal rains. Surface waters are commonly polluted by sewage, municipal and industrial wastes, and agricultural activities (Babel and Wahid 2008). Groundwater is impacted by elevated concentrations of naturally occurring arsenic and fluoride, particularly in West Bengal state (Mukherjee et al. 2015). In addition, seawater intrusion is occurring in coastal areas as a consequence of groundwater pumping, and it may be aggravated by sea-level rise (Michael et al. 2013).

Water issues in Kentucky are primarily linked to non-point source pollution and hazards such as flooding rather than water supply. Precipitation averages 100 to 130 cm/yr (Carey 2017). The Ohio River basin drains 97% of the state and surface sources supply about 95% of water used in Kentucky, including about two-thirds of public water systems (KGS 2014; Carey 2017). Approximately 97% of the population receives drinking water from public water systems, but only 52% are on public wastewater-treatment systems (Carey 2017). Primary non-point sources of surface-water pollution include mining (31%), agriculture (29%), land disposal/septic systems (20%), and urban runoff (10%), whereas municipal sewage-treatment plants account for 70% of point sources of surface-water pollution (KGS 2014). Potential sources of groundwater pollution include unplugged oil and gas wells, septic tanks, underground storage tanks, inactive landfills, and dumps (KGS 2014). Approximately 38% of Kentucky is underlain by carbonate rocks whose dissolution has resulted in karst terrain (Currens 2002). This development of integrated surface and subsurface drainage networks, which link sinkholes, conduits, and springs, facilitates rapid movement of non-point source pollutants (Currens 2002).

Project Goal and Objectives

Although the overarching goal of the project was to promote the development of global citizens who have skills and knowledge to protect the environment, especially water quality, and consider environmental protection a civic responsibility, this paper focuses on the accomplishments of three major objectives. These are: 1) the creation of three interactive, inquiry-based, online environmental science modules that engage students in water quality and quantity issues; 2) increasing students' content knowledge of environmental systems, especially hydrologic systems and water quality; and 3) enhancing students' understanding of and attitudes toward water quality and other water issues. Concepts regarding water quality and water-quality awareness (WQA) were interwoven into each of the three integrated online modules. More specifically, Frick et al. (2004) hypothesized that environmental knowledge may lead to pro-environmental behaviors and has three domains, including 1) an understanding of natural processes within ecosystems and the effect of human-nature interactions (system knowledge); 2) an understanding of actions that might be taken to address environmental problems (action-related knowledge); and 3) knowing about options and how effective one may be when choosing from a list (effectiveness knowledge). Therefore, exercises that address the domains of Frick et al. (2004) appeared in each module.

Curriculum Design and Content

Our curriculum design was motivated by the desire to facilitate and encourage interactions between the students in the online/hybrid environment (Wanner and Palmer 2015), a factor that is essential to the success of such instruction (Song et al. 2004). The project presented a series of problems requiring collaboration among students. This form of "inquiry-based learning" has been shown to be very effective in the geosciences (Apedoe et al. 2006).

Next Generation Science Standards (NGSS 2013) informed the design of the curriculum. Through the implementation of these science standards, educators attempt to increase students' ability to conduct scientific practices, including "planning and carrying out investigations" and "asking questions and defining questions." Because some of the participating teachers in Kentucky taught this project in AP Environmental Science classes, the learning outcomes for the overall curriculum were also aligned to the learning outcomes of AP Environmental Science, particularly concerning Earth systems and land and water use (College Board 2018).

In developing the online curriculum, we utilized only freely available, open-access technology to equalize, as much as possible, the technological resources that are available for students in a variety of high schools (e.g., Lane 2009). We also used a free Google service to build the project website. Our initial version was private, but after the project was completed, identifiable student work was removed and a mirror site (https://sites.google.com/view/wiiky-friends/) was published so the curriculum and educational materials could be publicly accessible.

Three modules were developed to increase student knowledge and affect attitudes toward water quality (Table 1). The homepage for each module gave the title, driving questions, and a list of learning objectives. An introductory PowerPoint presentation followed as a narrated video and as an editable PowerPoint file with the narration text available within the slide notes. Modules included case studies from both India and Kentucky, and activities (i.e., exercises) primarily utilizing local- to regional-scale data sets available online. These data sets include rainfall (IMD 2019; UKAWC 2019), groundwater levels in wells in India (India Water Tool 2019), stream levels from the Bangladesh Water Development Board (BWDB 2019), stream flow from the U.S. Geological Survey (USGS 2019), and surface-water quality (USGS

Table 1. Curriculum modules and learning objectives.

Module	Learning Objectives
(1) Water on Our Planet	• Identify water bodies (reservoirs) of the water (hydrologic) cycle. • Identify processes by which water moves from one reservoir to another (fluxes). • Speculate about variability in the movement of water in the water cycle in one's home area. • Describe the availability of water on Earth. • Identify connections between personal water use and flux within local water bodies.
(2) Problems with Water	• Define various chemical and physical measurements of water quality. • Speculate how water quality will vary with changing natural and anthropogenic conditions, both spatially and temporally. • Plan a water-quality research project and collect pilot data.
(3) Humans and Water	• Speculate about the long-term effects of human activities on the water cycle. • Interpret long-term patterns in local and regional fluxes within the water cycle. • Execute a research project to include acquisition of data, analysis of data, and interpretation of results. • Analyze strategies for reducing the human impact on water bodies within their community and select the most appropriate technique(s).

2019; WBPCB 2019). Assignments followed the introduction and folders were included into which students could upload their work. Each assignment addressed a driving question (Table 2).

Each module contained optional formative assessments and a summary project. The formative assessments provided teachers with questions for their students that reinforced concepts in the introductory PowerPoint presentations. The summary projects were designed to scaffold the development of students' final research projects across the three modules. In module 1, students identified an important water body within their community that they wanted to study throughout *all* three modules. In addition, students had the opportunity to explain their water body's cultural and scientific significance and discuss its relevance to their community. In module 2, students studied how to measure water quality. As the summary project for module 2, students were asked to synthesize ideas about water-quality monitoring for their chosen water body and submit a research proposal, which formed the basis of the final project in module 3.

Modules 2 and 3 included simple, local water-quality projects using test kits and multimeters. Each participating school received a waterproof digital wand for measuring temperature, electrical conductivity, and total dissolved solids. Each Indian school received a test kit that used reagents to quantify pH, hardness, chloride, residual chlorine, nitrate, and fluoride, plus a Secchi disk for measurement of turbidity, as well as a kit with reagents for quantitative detection of fecal coliform bacteria (Octopus Inc., Vadodara, India). Each Kentucky school received a LaMotte Earth Force Low-Cost Water Quality Monitoring Kit (Carolina Biological Supply Company, Burlington, NC, USA) with reagents to quantify pH, dissolved oxygen, biochemical oxygen demand, nitrate, phosphate, and total coliform, as well as a liquid crystal thermometer and turbidity measuring scale. As a possible form of project/problem-based learning, field experiences have been shown to be very successful at the secondary school level (Ho and Chan 2015). These exercises helped students make connections between knowledge gained and potential benefit to the local community.

Table 2. Instructional activities and associated driving questions.

Instructional Activity	Driving Questions	Environmental Knowledge Domain
Module 1 Wiki 1	Where is water stored?	System
Module 1 Activity 1	How does water move from place to place?	System
Module 1 Wiki 2	How much water is on our planet and how much is available for our use?	System
Module 1 Summary	Which part of the hydrologic cycle is most visible in your area? Where did the water in it come from? How has this water body shaped your local culture? How does community water use affect the amount of water in this water body?	System
Module 2 Wiki 1	How do you measure water quality?	System
Module 2 Activity 1	How could water quality vary?	System
Module 2 Summary	What is the water quality of your chosen water body? How was or is the water in this body being used? What is your research question? What data need to be collected and what methods will you use? What are your anticipated results?	System, Action
Module 3 Wiki 1	How have humans contaminated water?	System
Module 3 Activity 1	How have fluxes in the hydrologic cycle varied over time?	System
Module 3 Wiki 2	What can humans do to improve water quality?	Action, Effectiveness
Module 3 Summary	What is the water quality of your chosen water body? How was or is the water in this body being used? What is your research question? What methods did you use and what are your findings?	System, Action

Many assignments were open-ended, including the summative assessment for each module and the overall final project for the course, thus promoting creativity and cooperation. Students were encouraged to make connections between water and culture, customize their final projects to their own regions and interests, and use a variety of formats to address their research questions. Students could take a scientific approach through making visualizations of existing data and/or collecting new data, but could also make visual and/or verbal representations of concepts and connections through documentary film-making or other art forms. Some assignments took the form of wikis, encouraging students to build community knowledge by disseminating online videos, posters, podcasts, and brochures (Notari 2006; Parker and Chao 2007). The advantage of a flexible approach is that it accommodates a broad range of learning styles, background knowledge, access to technology, and cultural preferences (e.g., Germain-Rutherford and Kerr 2008; Grünewald et al. 2013). This approach also promotes place-based case studies, which help students to make connections between global-scale issues and their local communities (Semken and Freeman 2008). The combination of multiple formats for presenting work facilitates the integration of all three domains of successful environmental education: system knowledge, action-related knowledge, and effectiveness knowledge (Frick et al. 2004).

Implementation

Participating schools in Kentucky were selected based on previous experiences with the authors, while Indian schools were chosen with help from ASED and other Indian collaborators. Because of the need for effective communication between participants from two countries, only schools that use English as their primary instructional medium were considered for the project. A result of this requirement was that all the Indian schools selected were private. Twelve teachers from nine Kentucky public high schools and 10 teachers from 10 schools across eastern India participated. This group included schools from six Kentucky counties: Fayette, Jefferson, Muhlenberg, Pike, Pulaski, and Woodford. Fayette and Jefferson counties are predominantly urban (Lexington and Louisville, respectively), whereas the others are predominantly rural. Participating Indian schools were located in five cities in three different states: Kolkata, Kharagpur, and Durgapur in West Bengal; Ranchi in Jharkhand; and Guwahati in Assam (Figure 1). University of Kentucky Institutional Review Board (UK IRB) consent and assent forms were obtained from 290 Kentucky students. The principal investigator (Hanley) visited all participating schools in Kentucky to encourage the completion of those forms. However, visiting schools in India was cost-prohibitive, and completion and collection of forms (to meet UK IRB requirements for publicizing assessment results) from afar proved unmanageable.

The Kentucky and Indian students investigated 120 water bodies in total. Almost all were surface-water bodies (Figure 2), ranging from large reservoirs and rivers (e.g., Lake Cumberland and the Kentucky River in Kentucky; the Hooghly [lower Ganges] and Brahmaputra Rivers in India) to local creeks, canals, and ponds (e.g., Beargrass Creek in Louisville; the Chowbaga Canal and Jodhpur Park Lake in Kolkata). One Indian school focused on the East Kolkata wetlands and one Kentucky school chose to study groundwater by testing ten wells.

After completing modules 1 and 2, schools submitted research proposals to UK for judging (seven proposals from Kentucky and eight from India). The Kentucky proposals were scored by a team of four faculty and staff at UK with experience in water-resources research, current water issues, and outreach to K-12 schools. The Indian proposals were scored by a team of three professionals from UK and one from Indian Institute of Technology (IIT) Kharagpur with similar experience.

As part of module 3, students submitted final research papers, which were scored by two members of the project management team using the same rubric as the research proposals (see https://sites.google.com/view/wiiky-friends/modules/module-2 and https://sites.google.com/view/wiiky-friends/modules/module-3). However, grading of individual work was at the discretion of the teachers, even when products were evaluated by outside judges.

The top-rated research proposals were from DAV Model School–Durgapur (studying the Barakar River at Asansol, West Bengal), and from

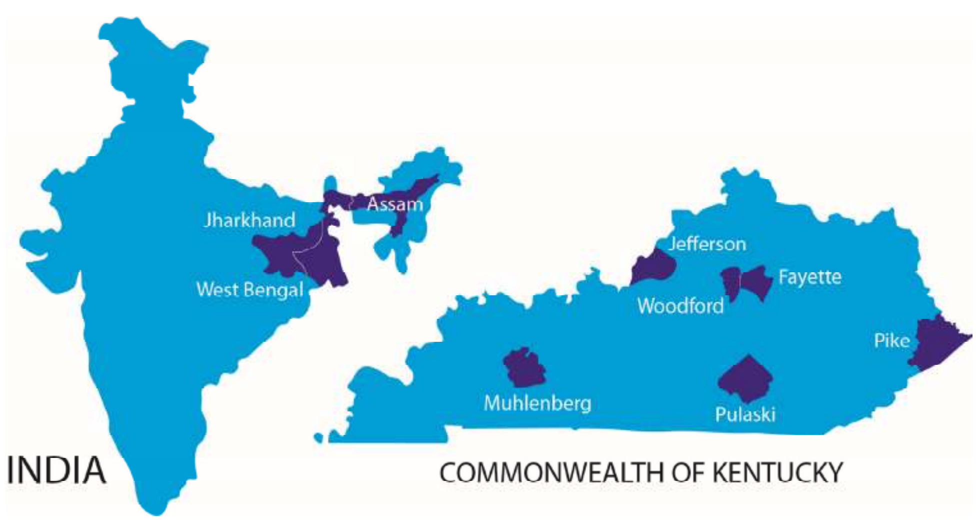

Figure 1. States in India and counties in Kentucky where participating schools are located.

Belfry High School in Pike County, Kentucky (groundwater study) (https://sites.google.com/view/wiiky-friends/modules/module-2). The team from DAV Durgapur traveled to Kentucky and Tennessee April 10-17, 2018 (Figure 3). They attended the Geological Society of America (GSA) Southeastern Section meeting, where a poster on the project was presented. They visited the Great Smoky Mountains National Park and Cumberland Falls State Park in Kentucky, as well as cultural sites, and they met with Kentucky teachers and students. The Belfry team traveled to Kolkata June 19-23, 2018. They presented their final project (https://sites.google.com/view/wiiky-friends/modules/module-3) at a final ceremony at the American Center along with eight of the Indian schools (Figure 4). The Belfry team also visited cultural sites and schools.

Figure 2. Selected water bodies: (a) Dhurwa Dam, Ranchi, India (from Delhi Public School, Ranchi); (b) Chowbaga Canal, Kolkata (from The Heritage School, Kolkata); (c) Hooghly River, Kolkata; (d) Kentucky River; (e) Town Branch, Lexington, Kentucky; and (f) well in Pike County, Kentucky (from Belfry High School).

Figure 3. DAV Durgapur team at (top) 2018 GSA Southeastern Section meeting and (bottom) Cumberland Falls, Kentucky.

Figure 4. Belfry High School and Sri Sri Academy teams along the Hooghly River in Kolkata.

Eight Indian teams submitted final videos for module 3, which were reviewed by 31 undergraduate students at UK in a topical course on World Water Issues (see https://sites.google.com/view/wiiky-friends/modules/module-3 for the video review rubric and examples of videos). Many of the review comments for the videos recognized the success of the high school students in integrating their knowledge of water and environmental systems, actions-related knowledge, and effectiveness knowledge (Frick et al. 2004). The top-rated videos (from DAV Model School–Kharagpur and The Heritage School [Kolkata]) were recognized at the final ceremony at the American Center.

Results

To determine the project's impacts, the UK management team measured students' attitudes toward WQA (project objective 3) and their water-quality content knowledge (project objective 2). The WQA instrument (see link to supplemental appendix), which was adapted from questions developed by Kaiser et al. (1999), Mayer and Frantz (2004), and Brügger et al. (2011), measures connectedness to nature. The instrument included 19 questions regarding the most important uses of water in students' communities, reasons why water quality is declining in those communities, and ways to protect water quality. The instrument used a Likert-type format with five response options: 1) strongly disagree, 2) somewhat disagree, 3) neither agree nor disagree, 4) somewhat agree, and 5) strongly agree. In addition, the WQA instrument included three questions that asked students the top three most important uses of water in their community, reasons for water quality degradation, and ways to protect water quality. There were 11 options for question 1, 10 for question 2, and 10 for question 3. The instrument was pilot-tested with Kentucky high school students using Qualtrics survey software (Qualtrics, Provo, Utah) in June 2017. Results were downloaded into SPSS 24 (IBM, Armonk, New York) and the resultant reliability was $\alpha = 0.839$. The instrument was then administered to participants through Qualtrics as a pretest in September 2017 and responses were downloaded into SPSS 24. After missing data were coded for the Kentucky pretest responses, the reliability for this sample was found to be $\alpha = 0.803$. The readability of the WQA instrument was determined through the Perry Marshall (2018) readability calculator. Average words per sentence were 11.6 and the mean reading level was 8.0, using the Flesch-Kincaid Grade Level Scale. The posttest was also administered through Qualtrics in February and March of 2018, depending on when teachers completed module 3.

The reliability for the posttest with the Kentucky students was α = 0.777.

A paired difference test showed there was no significant difference (α = 0.05) between pre- and posttest means for the Kentucky students' scores on the WQA instrument. For each of the three categories on the instrument, the top two choices remained the same between pre- and posttests (Table 3). Students considered the most important uses of water in their communities (category 1) to be "drinking water" and "fish and wildlife" (which were tied with "domestic uses" on the posttest). The top reasons why water quality was declining (category 2) were "sewage discharge" and "lack of concern", and the top two ways to protect water quality in communities (category 3) were

Table 3. Water-quality awareness responses from Kentucky students.

Name the three most important uses of water in your community	Pre-test (%)	Post-test (%)
Drinking water	93.2	85.1
Fish and wildlife	43.6	34.2
Sanitation	40.7	33.5
Domestic uses	26.1	34.2
Livestock	24.9	18.6
Irrigation	18.4	28.6
Industrial uses	17.5	19.3
Recreation	16.0	28.0
Fishing	11.6	17.4
Transportation	9.5	12.5
Tourism	4.5	11.8
Name three reasons why water quality is declining in your community	**Pre-test (%)**	**Post-test (%)**
Sewage discharge	53.1	50.9
Lack of concern	51.3	44.7
Fertilizer runoff	43.0	41.0
Pesticide runoff	33.8	39.1
Lack of education	30.6	45.3
Lack of regulations	27.3	36.6
Fluids leaking from vehicles	21.4	21.7
Pet waste	19.0	19.3
Exposed soil	11.0	8.1
Runoff from washing cars	9.2	11.2
Name three ways to protect water quality in your community	**Pre-test (%)**	**Post-test (%)**
Improve education	56.4	75.8
Increase regulations	53.1	67.7
Increase government's presence	39.8	50.9
Increase collaboration among concerned groups	33.8	27.3
Protect plants that grow along waterways	30.6	19.3
Increase soil and forest conservation programs	28.8	19.3
Reuse more water	27.3	16.8
Prevent soil from eroding at construction sites	16.3	6.8
Limit growth around water bodies	13.6	10.6
Raise the price of water use	3.3	6.8

"improve education" and "increase regulations". Unfortunately, we are unable to report results for Indian students because of the lack of signed IRB assent and consent forms.

Students' understanding of water-quality content knowledge was measured with an instrument developed by faculty in the UK Department of Earth and Environmental Sciences. However, the results will not be reported because the instrument had low reliability.

Discussion

Through their proposals, final papers, and videos, students demonstrated system knowledge (Frick et al. 2004) of the water cycle and human interactions with that system. Through community outreach activities, students also demonstrated action-related and effectiveness knowledge (Frick et al. 2004) for addressing water-quality problems. Examples of outreach (posters, public theater performances, workshops) are shown in Figure 5 and in Wiki Project 3 of module 3 (https://sites.google.com/view/wiiky-friends/modules/module-3). The activities of several Indian teams and the Belfry (Kentucky) team were also publicized by wire services, regional newspapers, and television, as well as on social media (see https://sites.google.com/view/wiiky-friends/publicity).

One challenge was finding appropriate, valid, and reliable instruments to measure water-quality content knowledge. Each of the three modules was to have a short pre/post water-quality content knowledge assessment. After searching the literature for a suitable validated assessment instrument, the Earth and Environmental Sciences faculty attempted to design one. The three assessments asked students to apply their knowledge in hypothetical situations (ConcepTests), a strategy that has been shown to be successful for encouraging and testing active learning at the college level (Mazur 1997;

Figure 5. Examples of publicity: (a) DAV Durgapur poster (translation from Bengali: "Let's put a halt to bathing of animals in water bodies. Let's make water pollution-free"). (b) DAV Kharagpur poster.

McConnell et al. 2006). We wrote the questions around common misconceptions about water (Munson 1994; Khalid 2001; Feller 2007; Cardak 2009; Francek 2013).

The three assessments were piloted in two college-level online courses, Environmental Science and Oceanography, and one high school science class, involving a total of 85 students. The initial pilot tests showed low reliability; therefore, the best questions from the three assessments were combined into a single, longer assessment that could be used pre/post. Unfortunately, this instrument also had low reliability. Our difficulty in assessing learning gains points to the need for a reliable and valid instrument to assess student learning within the field of hydrology specifically.

Throughout this project, students had multiple opportunities to engage in scientific practices, focusing mainly on asking questions and planning and conducting investigations (including applying statistics, critically reading scientific literature, and communicating scientific and/or technical information), as stated in project objective 3. These opportunities were most likely an introduction to some students, but for others, they may have been a chance to practice previously learned skills. Students improved in some areas, but their improvement was inconsistent. For example, students learned to plan and conduct water-testing investigations, but they still need additional practice in writing research questions and hypotheses.

The time commitment was a major challenge, especially for Kentucky teachers and students, who were required to follow school- and/or district-wide curriculum maps or standards-based curricula. Additionally, when school days were canceled due to inclement weather or other reasons, instructional time was difficult to make up. The schools in India, all of which were private, appeared to have considerably more curricular flexibility. Because of plans to have the winning teams visit each other's countries, those teams needed to be selected by early January. Therefore, schools had to work through the first two modules, including writing their research proposal, during a single semester.

The compressed schedule compounded other logistical challenges, such as the time difference between Kentucky and India (9.5-10.5 hours). Although Kentucky and Indian teachers were paired so they could exchange information about their schools, cooperation did not appear to happen as often as hoped. Another challenge was the Google documents format for uploading assignments, which discouraged students from giving each other feedback. Some schools had problems accessing the Google folders, perhaps because of internet security constraints. Finally, the overall completion of activities declined with time. For example, Kentucky students completed the WQA instrument pretests at a higher rate than the posttests. Even though all schools were encouraged to finish and showcase their projects, two of the Indian schools did not submit either a final paper or a video. Only three of the Kentucky schools submitted final papers and none submitted videos. We attribute this partly to time conflicts and partly to disengagement after the winning teams were selected.

Conclusions

Problems of insufficient water quality and quantity occur in both developed and developing regions and require creative solutions that are greatly enhanced by including youth engagement. Our project suggests that environmental education focused on water issues can improve science literacy. We found that online education can combine well with field-based, data-rich research experiences. Participating teachers and students are now familiar with basic water testing, and the online curriculum is freely available for public use. Challenges included obtaining consent and assent forms from overseas participants; finding reliable and valid instruments; finding a free, user-friendly online platform for course materials; and reconciling a compressed project timeline with existing curricular schedules. Nonetheless, the proposals, final papers, and videos indicated that students understood hydrologic concepts, and the project affected their awareness of water issues. We have maintained contact with students and teachers involved in the project and are publicizing the project website (e.g., Fryar et al. 2018).

Based on feedback from students and teachers and our observations, we make the following recommendations if a similar project is pursued. First, social media could be a rich way to promote cross-cultural environmental education and more interaction between schools (e.g., Dabbagh and Kitsanas 2012). This could serve as at least a partial substitute for travel, which can be expensive. Because of concerns with student privacy, social media groups would need to be private, even though members might post their final products on YouTube as some of the Indian schools did. Second, the student videos (which were encouraged but not required) were especially powerful, and this format might be emphasized over a traditional research paper format. Third, mandated curriculum schedules may make it necessary for teachers to keep only scaffolded assignments leading to the design and implementation of the research project, perhaps integrating them into existing course materials, rather than working through all parts of the three modules. An alternative solution would be to spread the assignments over an entire school year, rather than doing two of three modules during one semester. It might be possible in some schools for teachers to partner with their colleagues to team-teach or co-teach the modules. For example, a biology teacher may partner with a chemistry teacher to enhance student learning of water chemistry. Or, a science teacher might co-teach proposal writing with an English/language arts teacher to improve student technical writing. We recognize the difficulties inherent in these recommendations but put them forth because of the opportunities they afford students.

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A Review of Water Resources Education in Geography Departments in the United States

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Abstract: Geographers have long played an important role in water resources scholarship; however, academic literature has not focused on the teaching contributions of geographers in this area. To address this gap, we cataloged courses taught and faculty interests for geography departments in the United States with a stated focus on water resources. We identified 129 departments with both courses and faculty having water resources expertise. The majority of water-related courses focused on climatology or climate change, suggesting that students are regularly provided opportunities to learn about water topics primarily through the lens of climatology and water resources. We also summarize a panel organized at the 2017 American Association of Geographers Annual Conference that focused on water resources curriculum in geography programs. The panel discussed curriculum and pedagogical approaches, concluding that a water resources course syllabi repository would be beneficial for creating new and refining existing water resources courses. The panel also recommended that faculty consider incorporating water resources topics into their general education classes to concurrently enhance student learning opportunities and positively impact recruitment and interest in geography programs. Additionally, online education represents a substantial change in higher education that presents new challenges and opportunities for geographers. We hope these data and the summary of the panel session stimulate greater discussions of curricular needs across all disciplines that offer water resource focused courses.

Keywords: *water resources, geographic education, curriculum development*

Water resource management is inexorably geographic (Tobin et al. 1989; Platt 1993; Wescoat 2005) because water exhibits spatial and temporal changes in availability, volume, and characteristics. Water is also a necessity, impacting how humans interact with both our natural and built environments (Vogel et al. 2015). Geographers contribute to the field of water resources through their ability to "synthesize the physical and social sciences" (Hedberg II 2017). This can be accomplished through teaching, research, and outreach. Geographers have a long history of engagement in key areas of research on water resources management (Tobin et al. 1989; Platt 1993; Lant 1998; Wescoat 2005; Agnew 2011). Wescoat (2005) provides perhaps the most thorough discussion of subfields in the geographic approaches to water. These include "hydrologic sciences, water management, water quality, law, and hazards" (Wescoat 2005, p. 283). Disaggregated, this discussion includes demand management, community planning, transboundary water allocations, social justice including exposition of indigenous rights, water's role in "gendered responsibilities" (Sultana 2015), climatic effects, water use monitoring via direct and remotely sensed technologies, water quality and study of pollutant dispersal, the water-energy nexus, and geomorphic effects. The fungible nature of water means research within these topical areas is evaluated at local, regional, and international scales.

The subfields of water resource management span the physical and social sciences, demonstrating the necessity of a broad curriculum. Tobin (2009) stated, "we need a comprehensive, inclusive approach." The courses covering these topics should be transdisciplinary. Stentoft (2017) defines transdisciplinary as "the construction of new knowledge synthesized from differing disciplinary epistemologies into a new whole." In the higher education arena, critical reflection on water resources curriculum in geography departments has received scant attention. As a result, identification of opportunities to strengthen water resources curriculum in geography programs is limited.

To address the role geography departments play in educating and training future water resources professionals, we systematically reviewed the 2016-2017 Association of American Geographers (now American Association of Geographers (AAG)) Guide to Geography Programs (AAG GGP) to identify degree options, course offerings, and stated faculty foci. We also report on a water resources panel discussion at the 2017 AAG Annual Meeting to discuss curriculum issues confronting geographers teaching water resources courses. We conclude with a discussion of existing strengths, challenges, and opportunities for geography departments to strengthen contributions to water resources scholarship.

Research Motivation and Origins

This project began as a survey of how many programs, faculty, and courses focus on water resources in geography departments in the United States (Chaney et al. 2015) and was influenced by work on natural hazards education in North American geography programs by Cross (2000). The original survey was based primarily on the 2013-2014 AAG GGP section on departmental specialties which was inspected to identify departments that indicated a focus on water resources. Departmental websites of the identified programs were subsequently reviewed to identify water courses and faculty. The survey and initial website review focused on three fundamental questions: 1) how many geography programs list water resources among their specialties?; 2) how many of their faculty members list water resources among their teaching and research interests?; and 3) how many course offerings focus specifically on water resources management?

The initial survey of geography departments demonstrated a strong focus on water resources; it also revealed the difficulty in documenting geography's influence in this interdisciplinary field (Vincent et al. 2016). It was also clear that the boundaries of water resources and ancillary fields such as climate, fisheries, and geomorphology are difficult to define. As a result, a follow-up call was placed to AAG Water Resources Specialty Group (WRSG) members for comments and input. We discovered some programs were omitted from our review because their interdisciplinary nature meant they were not specifically within the domain of a geography department or the department did not submit information to the AAG Guide (AAG 2014) for the 2013-2014 year. Regardless of the reason, the data gaps were identified, which led to a follow-up investigation.

2016-2017 Survey of Water Resources in U.S. Geography Departments

We inspected the 2016-2017 AAG GGP (AAG 2017) departmental specialties section to identify departments that indicated a focus on water resources (limited to programs in the United States). We also inspected institution membership data for the Universities Council on Water Resources (UCOWR) and the National Institutes of Water Resources (NIWR) which identified eight additional geography departments with water courses and geography faculty indicating a research interest in water. Of the departments with a stated water resources focus, departmental websites were analyzed for additional information such as faculty and course listings.

To address limitations from the preliminary review, we used a broad set of search terms including the critical dimensions of water management in geography identified by Wescoat (2005). The search terms were: water, hydro, river, climat, wetland, watershed, fluvial, marine, and ocean. These terms were used to search department websites to identify faculty with water foci and to search course catalogs. One hundred forty-two of the 192 (74%) U.S. departments identified water resources as a program specialty (Figure 1), with 103 of these departments offering a M.S. degree and 58 offering a Ph.D.

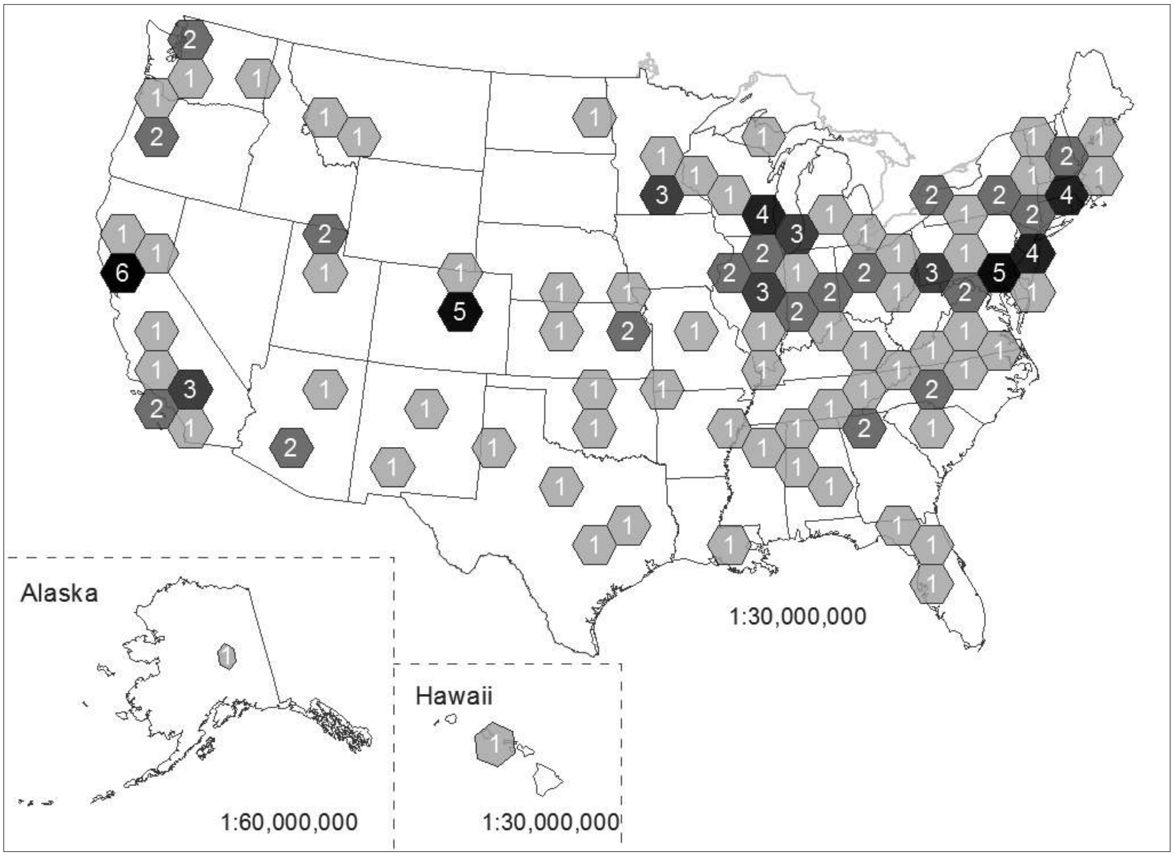

Figure 1. Geographic distribution of geography programs in the United States with a stated water resources foci (Data sources: 2016-2017 AAG GGP, UCOWR, and NIWR member lists). The number indicates the number of schools in that region.

Of the 142 programs with a stated foci on water, 135 programs (95.1%) have faculty who list research interests related to water (Figure 2) (Table 1). Additionally, 129 of these programs (90.8%) have both faculty who list water resources as a research interest and teach water courses with a geography prefix; it should be noted programs that do not appear to offer water courses in geography may offer them under a different prefix. There were 129 programs (90.8%) that offered at least one course that focused on water and 83 departments with three or more course offerings containing these terms (Figure 2). Of departments offering courses with these titles, the mean number of water courses is 4.12.

In total, we identified 532 water-related courses offered through geography programs, of which more than half (n=285) were climatology or climate change focused (Figure 3). To further evaluate the topical focus of identified water courses we excluded climate courses and categorized the remaining water resources courses into the categories of water resources (which broadly includes water resource management and governance), hydrology, fluvial geomorphology, oceans and marine, rivers, wetlands and watersheds, groundwater, and other (Figures 4 and 5). We also observed that water resources courses account for the most common water-specific courses taught in geography programs. These courses include both physical and human elements of water resources, which provide students an overview of the multifaceted nature of water resource issues. These courses may also introduce students to water law, natural resources economics, hydrology, the concept of water as a human right, and ecological aspects of water resources. Other more physical geography focused topics, such as hydrology, fluvial geomorphology, and groundwater are taught with less frequency as standalone courses

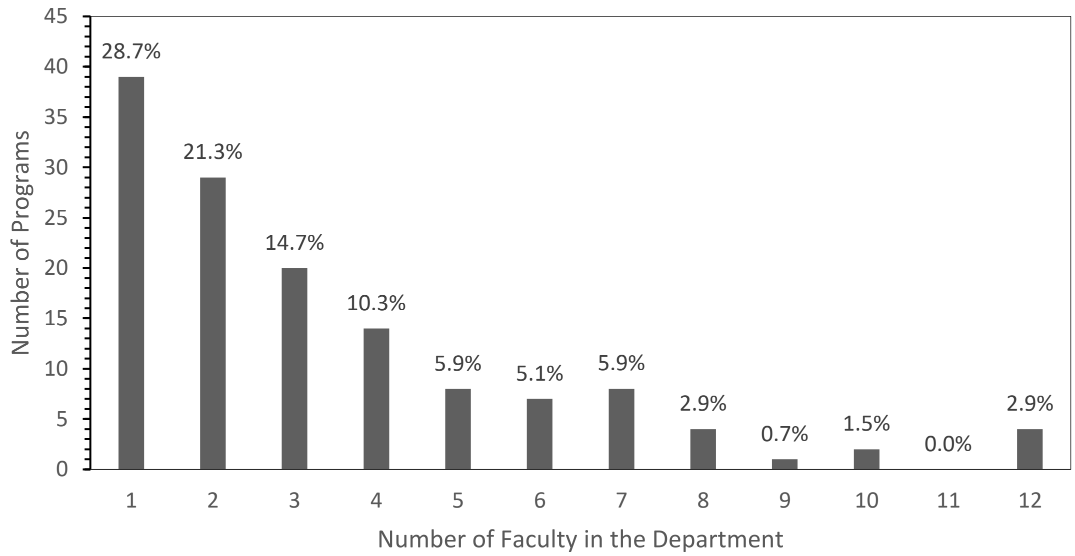

Figure 2. Number of geography departments with a given number of faculty with a focus on water resources (n=135) (Data sources: 2016-2017 AAG GGP, UCOWR, and NIWR member lists).

Table 1. Water resources related fields of interest listed by faculty.

Key Term Category	Faculty (count)
Climate change and impacts	77
Climatology	177
Coastal, marine, and oceans	9
Drought	5
Fluvial geomorphology	43
Groundwater	4
Hydrology and ecohydrology	56
Modeling, remote sensing, and GIS	17
Planning	7
Rivers, stream ecology, and stream restoration	11
Snow and alpine environments	6
Stream and watershed ecology	14
Water quality	5
Water resources and governance	75
Watershed management	7

Note: Each faculty member's first research interest is listed. Many faculty list "water resources" as a somewhat generic term for their research interest which may be the reason some of the subsets seem under-represented in the count (n=513 total faculty).

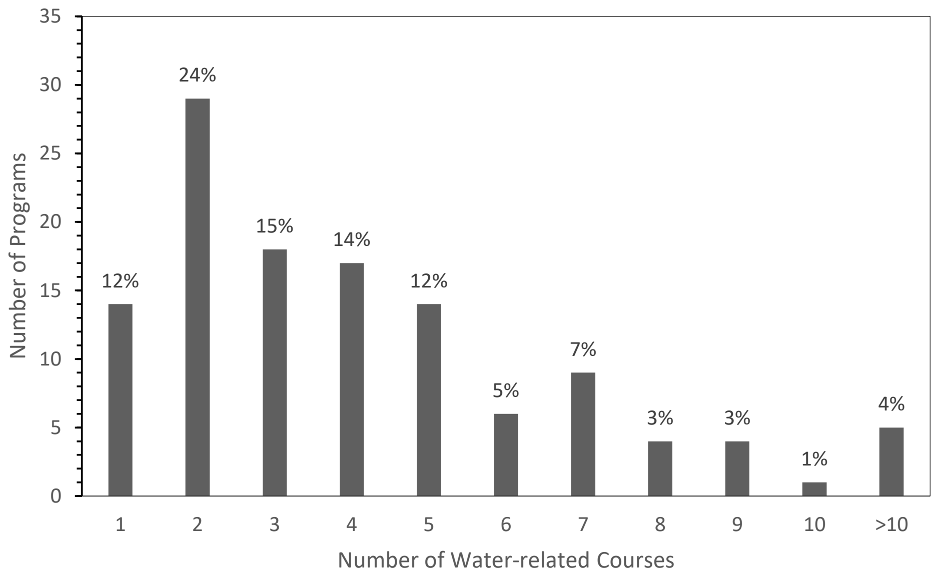

Figure 3. Summary of the number of water focused courses offered per geography department.

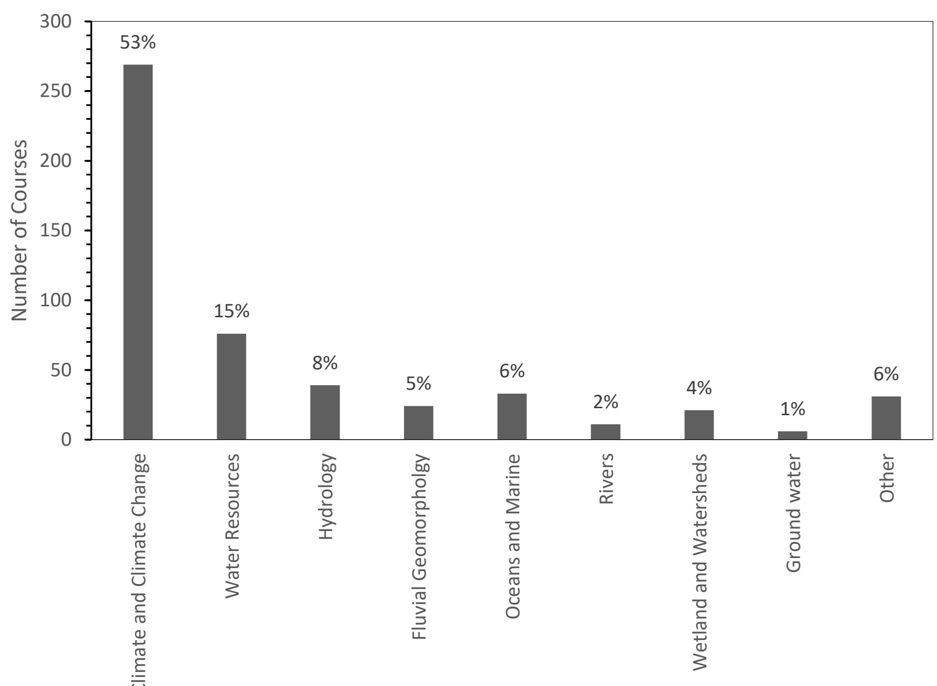

Figure 4. Water focused courses in geography departments.

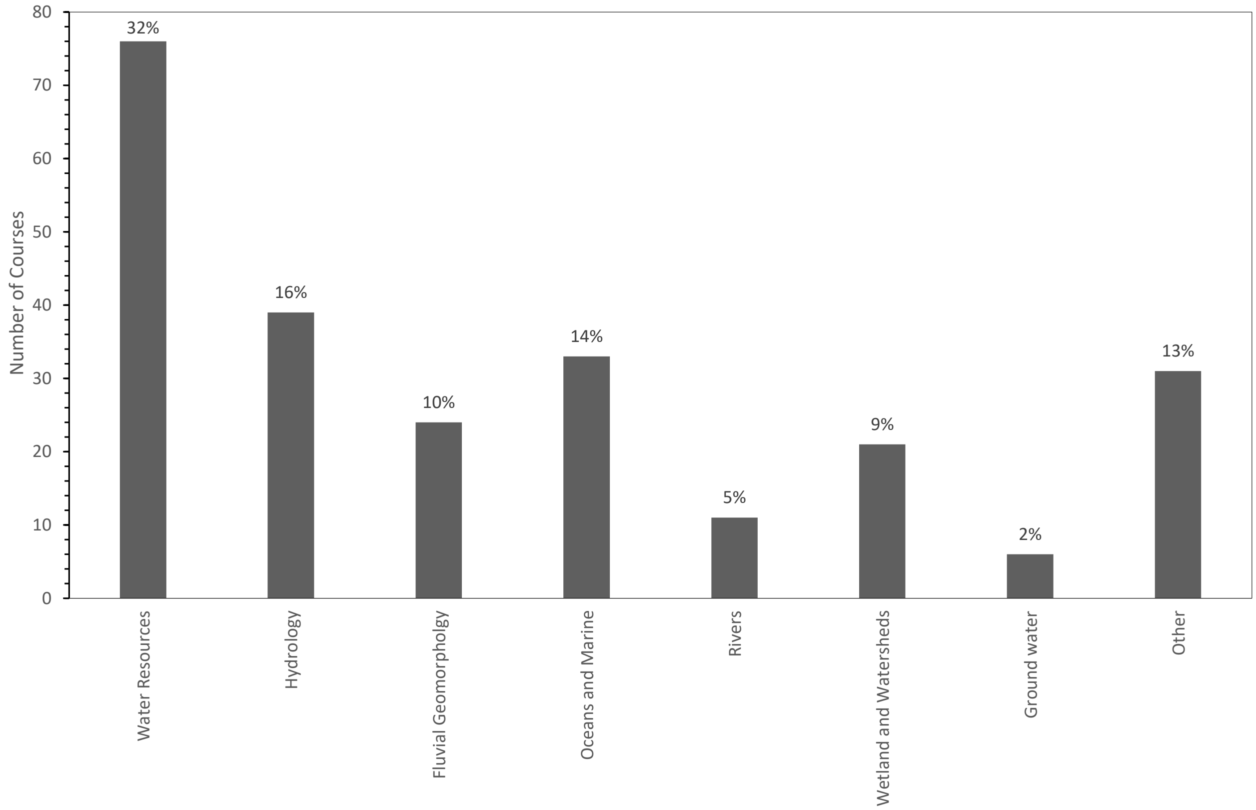

Figure 5. Water courses in geography programs excluding climate courses.

(n=69). Collectively, these results suggest that students are regularly provided opportunities to learn about water topics primarily through the lens of climatology and water resources.

Panel on Water in Geography Programs

To further understand geography's role in water resources scholarship and teaching we organized a panel entitled "Water Resources in Higher Education" at the 2017 AAG Annual Conference in Boston, Massachusetts (Chaney and Pease 2017). The purpose of this panel was to discuss the current structure of geography programs across the United States as it relates to water resources, and to discuss types of technical information and skills that students need at both the undergraduate and graduate levels. The panel consisted of six tenured water resource professors in departments of geography, ranging from research-intensive universities to teaching-focused regional comprehensive universities. For the present paper we focus on the curriculum and course offering comments offered by the panel, as recorded by the notes of the panelists. The curriculum and course offering aspects of the panel discussion were semi-structured, guided by seven pre-scripted questions (Table 2). These questions were crafted based on the results of the analysis of the 2013-2014 AAG Guide to Programs. These questions were designed to solicit conversation about program structure, number of course offerings in water that may be integrated into a geography curriculum, and student recruitment.

Curricular Discussions

The panel discussion initially focused on course syllabi, the importance and process of establishing water courses in general education courses, water resources course sequences, course prerequisites, and course content.

Sample syllabi were shared amongst the panelists and audience members. The need for a discipline-wide repository of syllabi was discussed. This elicited calls for contributions

Table 2. Questions asked in the panel on Water Resources in Higher Education at the 2017 AAG Annual Meeting.

1. What major issues/topics related to water resources should we prepare students to address in the future?
2. What general areas should be covered in a course titled "Water Resources" to provide students a good overview of the field?
3. Should a program promoting itself as having a specialty in water resources actually offer a specific course titled "Water Resources" that provides students an overview of the field?
4. Should a program promoting itself as having a specialty in water resources offer more than one course in the field? If so, how many?
5. Should a program attempt to offer a specific degree (major/minor) or certificate option in water resources? What should it focus on, and what courses should be included?
6. Should geography departments look to partner with other departments to develop "interdisciplinary" degree/certificate options?
7. What major challenges might a department face in attempting to initiate or expand a concentration (degree/certificate) in water resources?

of syllabi and instructional materials using the AAG WRSG Knowledge Community. The WRSG is now collecting contributions of syllabi from all members and is making these available on the WRSG website so members can see what others are covering in their courses. It can also increase collaboration among faculty at different universities teaching similar courses.

The need to represent water resource issues in general education courses was another key topic discussed. Several panelists noted that incoming university freshman are increasingly aware that freshwater issues are important, but lack context and an understanding of the scientific aspects of these issues. The panelists agreed that introducing students to the scientific and engineering aspects of water issues, through a Physical Geography or World Regional Geography course for example, is critical for recruiting students for more advanced water focused classes. Furthermore, several panelists and audience members stated their universities have developed and implemented a general education course focused on water. These general education courses provide students from a variety of programs access to geographic and water resources education and these courses provide recruiting opportunities for water resource and geography programs. It was noted that perhaps this may be the greatest area for growth among geography programs as they relate to water. Increasing general education offerings provides more exposure to issues of water management and sustainability, a fast-growing field (Smith 2009; Cohen 2012; Huggett 2017) in which geography plays a key role (Clark 2009). Increasing general education offerings can be done while also increasing student credit hours for departments, which near universally are being evaluated by this metric (Frazier and Wikle 2017).

Panelists then discussed their experiences establishing logical sequences of water courses. One of the discussion points focused on prerequisites, particularly for hydrology. A modicum of mathematical aptitude is needed for even the most basic hydrology calculations; however, requiring specific math courses can stymie enrollment. Whether such a prerequisite is appropriate is a function of the course level, learning objectives, and specific material covered. Development of analytical thinking and analysis skills was also identified as an important skill for geography students because of job opportunities in state government and industry where a background in hydrology and related subject matter was critical for employment (Rooney et al. 2006; Solem et al. 2008; Solem et al. 2013).

Discussion also addressed the extent to which instructors should integrate law, natural resource economics, social sciences with a focus on social justice and gender equality, and biology into water resources courses. Each of these subject areas merit integration into a complete water curriculum. In particular, social justice issues have been underrepresented in geography water curriculum (Zeitoun et al. 2014), yet are topics within the normal domain of geographic inquiry. However, determining how to integrate these into a broader geography degree is less clear. This ubiquitous 'depth versus breadth' discussion is nonetheless valuable. Most panelists stated a desire to integrate basic environmental law into a water curriculum. It was noted that a basic understanding of civics and administrative processes is part of an undergraduate education. Adding the specificity of the Endangered Species Act, the National Environmental Policy Act, or the Clean Water Act provides needed content to students and helps their professional development. Similarly, providing students with a basic understanding of non-market economics was deemed advantageous.

Pedagogical Approaches

The panel discussion also addressed the challenges and opportunities of using an active-learning based pedagogy in water courses. Utilizing active learning approaches and realistic simulations has received significant attention in pedagogical literature (Smith and Boyer 1996; Halvorson and Wescoat 2002; Fink 2003; Asal and Blake 2006; Baranowski 2006; Pawson et al. 2006; Porter 2012; Schnurr et al. 2014; Lant et al. 2016; Chaney and Doukopoulos 2018; Pease et al. 2018). Active learning simulations and projects can be particularly effective for research issues involving multiple actors (Brown and King 2000; Halvorson and Wescoat 2002; Crossley-Frolick 2010; Kirshner et al. 2011; Schnurr et al. 2014) and highly technical subject matter (Baranowski 2006; Krain and Shadle 2006). Data suggest such simulations and other direct learning structures help students better understand the theories, organizations, and processes involved (Shellman and Turan 2006; Hope 2009).

Panelists indicated water resource management courses seem particularly well suited for the integration of active learning assignments since these courses prioritize competencies over content (Stentoft 2017) and water management requires integration of a variety of issues and stakeholders. Here we define active learning as activities that "engage students in the process of learning through activities and/or discussion in class, as opposed to passively listening to an expert" (Freeman et al. 2014). In their review of interdisciplinary proposals for graduate programs, Borrego and Newswander (2010) recognized "team-based collaboration is the norm in engineering and science." Stentoft (2017) provides a critique of problem based learning for transdisciplinary problems and suggests it can be effective, but crossing disciplines is in itself not pedagogical scaffolding. Mansilla (2010) proposes four interrelated cognitive processes involved in interdisciplinary learning: "establishing purpose; weighing disciplinary insights; building leveraging integrations; and maintaining a critical stance." Each of these are traits that can be appreciated by water managers. No member of the panel indicated they have conducted formal summative assessment of active learning outcomes against direct instruction methods. The lack of rigorous formative assessment of these active-based exercises is an issue acknowledged by several who have conducted research in this area (Borrego and Newswander 2010; Domik and Fischer 2010), and clearly requires further research.

Panel Recommendations

The panel discussion illustrated several key points that warrant additional discussion and investigation. First, the utility of a water resources course syllabi repository was recognized as a tool for creating new and refining existing water resources courses. The WRSG has initiated development of this repository. Second, the panel recommended that faculty consider incorporating water resources topics into their general education classes. Panelists observed that water-related topics frequently resonate well with students and provide opportunity to attract students to the geography discipline. Third, developing course sequences for water resource topics needs to balance math and science pre-requisites with course level and student preparedness. Water resources courses in geography programs are also well suited to incorporate social, legal, and other aspects of water resource issues in an interdisciplinary framework. Water resources courses seem well suited to active learning exercises that may benefit student learning.

While the panelists had limited experience using active learning exercises in their classes, we are aware of others who have applied these techniques. Further investigation is needed to explore barriers and challenges that faculty, at different career stages, face when implementing active learning exercises. We suggest that faculty developing a new water resources course, or refining an existing course, consider some of these recommendations as well as convey successes and challenges to the broader water resources community.

Discussion

The AAG GGP is a valuable source of information about geography programs in the U.S. and abroad. This Guide may serve as a resource for current and future students to learn about programs and to identify departments of interest. Our research presented here, focused on water resources and identified several opportunities for those using and contributing to this Guide. The content of the Guide is updated by individual departments and as a result, information may vary from edition to edition. We identified more departments with a focus on water resources in the 2016-2017 edition than the 2013-2014 edition. We also observed that the AAG Guide encompassed nearly all of the geography departments with UCOWR and NIWR institutional membership.

Analysis of course offerings also provides insight into water-related material taught through geography departments. A majority of the water-related courses we identified were couched in the context of climate and with water resources as the second most common context. Of the 45 programs offering two or less water-related courses, 52 of the 73 courses (71.2%) were climate focused. The emphasis on climate-related courses is mirrored by faculty interest in climate with 254 of 513 identified geography faculty (49.5%) indicating that climate is a research interest. Collectively, this suggests a strong teaching emphasis on climate and climate-related issues, including water resources, which is a timely and critical area of research and education. Topical areas such as groundwater, water quality, and watershed management courses are less frequently taught through geography programs and are examples of future course work that may be of interest to students and important for their career preparation.

These survey results have several limitations that should be acknowledged. Potential sources of error include departments not updating their listing in the AAG Guide, departments not listed in the Guide due to failure to submit their information to AAG, and departments not listed due to some other type of oversight, which likely applies to some 'interdisciplinary' programs. The issue of programs not submitting data to the AAG is a perpetual one. Interestingly, in the 2016-2017 Guide, 46 programs self-identifying a focus on water were not included in the 2013-2014 Guide; this coincides with a concerted effort by the AAG to encourage programs to provide these data for the Guide. It is also possible the increase is the result of some programs adding a focus on water resources with new faculty hires during this time. There is also the possibility water-centric courses were omitted because of our search criteria. For example, courses entitled Arid Lands were excluded but it is possible these courses have water or land use as a central theme. The same could be said for regional courses such as the Geography of the Southwest or the Geography of the Great Lakes Region.

Funding challenges and budget shortfalls may generate a greater need for additional student credit hours to justify funding and staffing (Frasier and Wikle 2017). Anecdotally, competition for student credit hours results in the construction of counterproductive academic "walls" between disciplines (Evans and Randalls 2008; Nation 2008). Some of these struggles over credit hours may directly threaten geography programs because some interdisciplinary programs encroach on the traditional domain of geography (Frazier and Wikle 2017; Hedberg II et al. 2017). Vincent et al. (2016) referred to staffing from geographers as the "glue" holding together interdisciplinary programs. Current funding and accounting models threaten to reduce collaboration, undermining interdisciplinary programs like water resources (Smith 2009). University-level accounting models will determine how individual programs are affected and input from geography faculty may help guide the development and assessment of those models.

This unfortunate reality creates challenges but also opportunities for geography departments. As discussed by the Water Resources in Higher Education panel at the 2017 AAG, general education classes represent an opportunity for recruiting students and focusing these classes towards "hot button" natural resource issues may include topics such as access to freshwater and climate change (Earl et al. 2009). Cross-listing courses and developing general education curricula in which geography classes are required also contributes to student education and may increase enrollment. Despite a more competitive enrollment environment, there remain opportunities for geography departments to integrate with interdisciplinary degree programs, increase student recruitment, and provide greater visibility to students in other programs (Henderson 2014).

Online Education

Online education represents one of the most substantial changes to higher education in the last 50 years (Madge and O'Connor 2004; Kentnor 2015). Here, we are including hybrid courses, those that blend traditional face-to-face and online instruction. Online education opportunities open new possibilities in access, but also carry unique challenges. Debates over the appropriateness and format of courses, i.e., synchronous versus asynchronous formats, are ongoing and should continue (Johnson 2006; Giesbers et al. 2014). Massive Open Online Courses (MOOCs) are a relatively new development in online learning. At the time of this writing, a search of Class Central (2018), a clearinghouse of available MOOCs, indicated 27 courses offered in English with water in the course title and more than 160 courses included water as a course topic. Of these, 37 courses were identified as specifically relating to water management in the range that geographers work (Table 3). We offer no comment on the content of these courses. We include this search of courses because the proliferation of water-focused courses shows its salience and the growing public interest in water resource management issues. Numerous MOOCs are moving to a tiered approach in which the materials are available for free, but a "premium" option is available in which assignments are graded and either university credit or a certificate of completion is available. The impacts of MOOCs on higher education and student learning remain uncertain (Waldrop 2013; Dennis 2017).

Conclusions

Geography provides students and academics opportunities to integrate physical, human, and GIScience research methods to advance understanding of water resource issues from a variety of perspectives. More than half of the geography departments in the United States indicate faculty expertise and program curriculum that nominally support water resources education. Changes to university education and funding models

Table 3. MOOC offerings in February 2018. These data are derived from class-central.com.

Course Type	# of Courses	# Available for Credit/Certificate	Other
Water resource management	15	6	Multiple courses can be taken to earn an additional certificate.
Hydrology or fluvial geomorphology	2	1	
Water-focused climate courses	8	3	
Food and energy nexus	7	5	
Water-focused health and sanitation	8	6	Includes several classes that appear to have recently concluded.

threaten the status-quo, encouraging emphasis on large undergraduate courses that generate higher quantities of student credit hours. Geography departments are well-positioned to provide teaching and research opportunities for students through general education courses, specific water resource management and hydrology courses, and contributions to interdisciplinary programs. That said, geography departments represent one piece of water education, and integration with other disciplines is necessary to ensure students receive education on as many facets of water management as possible. We hope that this article spurs further conversation of geography curriculum and its integration in interdisciplinary programs for students interested in pursuing water resource careers. We recognize the need to develop more formal and rigorous protocols for assessment of curricula. Finally, we see a need to have a broader discussion of online education and its role in water resources.

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Investigating Relationship Between Soil Moisture and Precipitation Globally Using Remote Sensing Observations

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Abstract: The complex relationship between precipitation and soil moisture plays a critical role in land surface hydrology. Traditionally, the analysis of this relationship is restricted by the spatial coverage of both soil moisture and precipitation data that are collected through in-situ observations at limited locations. In this study, we utilized the National Aeronautics and Space Administration (NASA)'s remote sensing products of soil moisture (SMAP: Soil Moisture Active Passive) and precipitation (TRMM: Tropical Rainfall Measuring Mission), which provide near-global coverage, to investigate the co-variation of precipitation and soil moisture regionally, as a function of ecosystem types and climate regimes. We apply information on land cover and climate regimes to provide insight about correlation strength of soil moisture and precipitation. The results indicate that most of the globe has a moderate to strong positive correlation of SMAP soil moisture and TRMM precipitation data during the study period. In relation to land cover, soil moisture and precipitation have the strongest correlations in regions of limited vegetation, whereas forests and densely vegetated regions have weaker correlations. As for climate regimes, they have the strongest correlations in arid or cold regions, and weaker correlations in humid, temperate locations. While remotely sensed soil moisture data are less reliable in dense vegetation, these results confirm that drier, less vegetated climates show a highly linear relationship between soil moisture and rainfall.

Keywords: *TRMM precipitation, SMAP soil moisture, global relationship, satellite observations*

Surface soil moisture accounts for an estimated 0.001% of the volume of Earth's freshwater, and yet, this tiny layer of water plays a powerful role in the hydrologic cycle (McColl et al. 2017). The amount of water in the top soil influences how much heat is exchanged between the land and the atmosphere, along with important hydrologic processes, such as precipitation, river discharge, flood, and drought. Due to its influence, soil moisture is used to forecast weather, predict climate change, estimate agricultural yields, and provide early warning for flood and drought (Entekhabi et al. 2010).

The interplay of precipitation and soil moisture strongly affects the terrestrial water and energy cycles. Some aspects of this relationship are straight-forward, while others are controversial. The spatial and temporal patterns of soil moisture depend on the variability of precipitation, evapotranspiration, and runoff (Famiglietti and Rodell 2013; McCabe and Wolock 2013). However, there are more uncertainties regarding soil moisture's role as a feedback mechanism for precipitation and other hydrologic components than its dependence on above-mentioned hydrologic components (Koster et al. 2004; James and Roulet 2009; Liang et al. 2010).

The interaction between soil moisture and precipitation is complex, varying regionally in correlation direction (i.e., positive/negative) and magnitude (i.e., weak/strong). Previous research has identified some physical mechanisms causing positive correlations between soil moisture and precipitation (Findell and Eltahir 1997; Eltahir 1998; Zheng and Eltahir 1998). These studies support the hypothesis that wetter soil can provide abundant moisture to the atmosphere, increasing humidity and, as a result, enhancing precipitation. From the energy-balance point of view, wetter soil decreases the surface albedo that allows for an increase in net solar and terrestrial radiation, and an increase in moisture convergence, which may ultimately enhance the precipitation. Such a mechanism supports the well-known hypothesis, "wet regions get wetter, dry regions get drier," which theorizes higher risks of floods in wet regions and higher risks of droughts in dry areas.

However, recent studies suggest that in certain localities, soil moisture and precipitation are negatively correlated (Cook et al. 2006; Guillod et al. 2015; Yang et al. 2018). For example, more precipitation is observed in dry soil regions such as Southern Africa because of the strengthened convective system (Cook et al. 2006), which indicates an increase in the risk of floods in dry areas. This opposite phenomenon challenges the well-known "wet regions get wetter, dry regions get drier" trend (Greve et al. 2014; Feng and Zhang 2015) and creates controversy about the soil moisture-precipitation relationship. Moreover, the soil moisture and precipitation interaction is strongly affected by the local climate and environment (Boé 2013; Ford et al. 2015a; Ford et al. 2015b). These bodies of research imply that environmental factors, such as land cover and climate regimes, may play a significant role in how soil moisture interacts with precipitation.

In addition to environmental factors, the study of soil moisture and precipitation is further complicated by the availability and quality of the data. The technology of soil moisture measurements has dramatically advanced in recent years. They are no longer limited to sparse networks of in-situ samplings but have near-global coverage through remote sensing. The Satellite era soil moisture datasets include Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) (Wentz et al. 2014), Soil Moisture and Ocean Salinity (SMOS) (Kerr et al. 2013), and Soil Moisture Active Passive (SMAP) (O'Neill et al. 2016). Although these datasets represent great technological advances in the study of soil moisture, they require validation to ensure data quality.

Launched in 2015, SMAP is the newest satellite soil moisture dataset. Like its predecessor SMOS, SMAP has an L-band radiometer, ideal for detecting soil moisture through layers of vegetation. The initial science objective of the SMAP mission was to provide unprecedented, high-resolution global soil moisture data from the combination of the active and passive sensors. Unfortunately, the power source of SMAP's active radar lost functionality months after its deployment. Thankfully, data from SMAP's passive radiometer were salvaged, albeit at a coarser resolution. As a newer dataset, and in light of the technical challenges that befell the SMAP mission, validation of SMAP data is necessary to understand if the mission was still successful in producing valuable soil moisture data, after losing its most important sensor.

SMAP was considered a better dataset than AMSR2, when compared with in-situ soil moisture samples across the Great Plains (Zhang et al. 2017). SMAP also outranked seven other satellite soil moisture datasets, in comparison to in-situ soil moisture data, over the Little Washita Watershed Network (Cui et al. 2018). Additionally, SMAP products have been validated against one another, including the data produced from the active sensor, from the passive sensor, and from the combination of the active and passive sensor. In a validation study over Northwestern China, SMAP's passive sensor's soil moisture dataset fared better than datasets from the active sensor, and all three datasets were shown to estimate soil moisture better over bare soils than over soils with vegetation (Ma et al. 2017).

The goal of this study is to assess the relationship between soil moisture and precipitation at a global scale using SMAP soil moisture measurements and Tropical Rainfall Measuring Mission (TRMM) precipitation estimates, and to investigate how such a relationship varies with different land cover type and climate regime. It is worth noting that this is the first attempt to relate SMAP soil moisture data to TRMM precipitation data over a global coverage. This study also explores the possibility of using TRMM precipitation data to validate SMAP soil moisture data. TRMM is a well-respected dataset in the satellite precipitation community (Sapiano and Arkin 2009). In theory, the SMAP data will clearly reflect increased soil moisture levels over regions where the TRMM satellite indicates precipitation. Because the expected relationship between precipitation and soil moisture is strong, precipitation would be used to informally validate the accuracy of soil moisture data. Strong correlations between the TRMM precipitation and SMAP soil moisture datasets could be interpreted as indication of SMAP's accurately estimating global soil moisture levels. However, it is also understood that many factors, such as land cover and climate, influence the infiltration of rain water into soil.

Data

Soil moisture data come from the SMAP satellite, available through the National Snow and Ice Data Center (NSIDC) (https://nsidc.org/data/SPL3SMP/versions/4). Despite losing the functionality of its active microwave radar, soil moisture estimates using SMAP's passive microwave radiometer have proven to outperform other satellite soil moisture datasets when compared to in-situ soil moisture data (Ma et al. 2017; Cui et al. 2018). SMAP's microwave radiometer senses the thermal heat radiating from the surface of the earth, and the intensity of heat sensed is proportional to the product of the thermal emissivity and brightness temperature. The soil moisture measurements were estimated using the Tau-Omega model and brightness temperatures (Das et al. 2015). SMAP's sensor measures the near-surface soil moisture (0-5 cm depth) in cm^3/cm^3. The Level 3, Version 4 dataset used in this study comes from SMAP's passive microwave radiometer providing daily coverage from March 31, 2015 (O'Neill et al. 2016). However, near-global coverage is only available every three days (Entekhabi et al. 2014). The data's nominal spatial resolution is 36 km by 36 km, based on the Equal-Area Scalable Earth Grid (EASE-Grid) 2.0 (Brodzik et al. 2012). Global spatial coverage is limited to Latitudes 85.044° to -85.044° and Longitudes -180° to 180°. Additionally, SMAP Level 3 retrievals are bound to vegetation and ice thresholds. SMAP Level 3 data contain vegetation flags for any grid cell with a vegetative water content greater than 5 kg/m^2. SMAP Level 3 data also have a frozen soil flag which assesses the frozen soil area fraction. When the frozen soil area fraction is greater than 0.5, a flag is set and soil moisture is not retrieved (O'Neill et al. 2018). Because of SMAP's vegetation and ice flags, soil moisture data are unavailable in certain regions of the Amazon Rainforest and in some higher latitude locations.

Precipitation data come from the TRMM satellite, available through the NASA Goddard Earth Sciences (GES) Data and Information Center (DISC) (https://disc.gsfc.nasa.gov/datasets/TRMM_3B42_Daily_V7/summary). TRMM collected data through its passive microwave sensor and precipitation radar. This study utilizes the 3B42 Version 7 Research Derived Daily Product dataset (Huffman and Bolvin 2015). The spatial resolution of the data is 0.25° by 0.25° with the near-global coverage of Latitudes 50° to -50° and Longitudes -180° to 180°. This dataset is based on the Version 7 TRMM Multi-Satellite Precipitation Analysis (TMPA) algorithm, which consists of passive microwave derived precipitation estimates and microwave-calibrated infrared precipitation estimates filling in the gaps of microwave imageries, corrected by ground-based gauges (Huffman et al. 2007).

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's Terra and Aqua satellites, provides land cover classifications through the University of Maryland's Global Land Cover Facility. This study uses the MCD12Q1, Version 5.1 dataset, specifically the most recent 2012 classification (Channan et al. 2014). The classification includes 17 land cover types with 0.5° by 0.5° spatial resolution. Latitudinal coverage spans -64° to 84° and longitudinal coverage spans -180° to 180°.

The Köppen-Geiger climate classification (Peel et al. 2007) was obtained through NASA's Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) (https://webmap.ornl.gov/ogc/dataset.jsp?ds_id=10012). This dataset categorizes the globe by climate, considering average temperature and precipitation trends. The classification scheme identifies five main climates, six categories of precipitation, and seven categories of temperature. The spatial resolution is 0.5° by 0.5° with latitudinal coverage spanning -90° to 90° and longitudinal coverage spanning -180° to 180°.

Methodology

In order to assess the relationship of precipitation and soil moisture, the two datasets were preprocessed to have the same spatial coverage and uniform grid resolution. Through examining the SMAP soil moisture estimates, it showed that the 8-day composites of the soil moisture were able to provide optimal global coverage, while the suggested 3-day composites (Entekhabi et al. 2014) still have spatial gaps. Thus, the 8-day composites of SMAP soil moisture were created, which contain the average soil moisture estimate from the samples within that period. Composites using the least number of days were preferred over monthly composites, for example, in order to highlight the more immediate interactions between precipitation events and soil moisture, as close in time to the events as possible. Likewise, 8-day composited averages were created for the TMPA precipitation data. The study period is from March 31, 2015 to June 23, 2016. Three SMAP daily estimates were unavailable (May 13, 2015, December 16, 2015, and May 1, 2016). In total, 448 daily files were compiled into 56 8-day composites for each dataset over the study period. Next, SMAP soil moisture's composites were subset to the TMPA's spatial coverage. In order to obtain uniform grid resolution between the datasets, TMPA's grid resolution of 0.25° by 0.25° was linearly interpolated to SMAP's EASE-Grid 2.0 nominal resolution of 0.36° by 0.36°. Such linear interpolation is a common technique of matching datasets spatial resolutions for further analysis in the hydrology community (e.g., AghaKouchak et al. 2011; Pan et al. 2019).

Finally, TMPA data were correlated to SMAP data, using MATLAB's "corrcoef" function. The formula used in "corrcoef" function to compute Pearson's Correlation Coefficient is shown below (Fisher 1958):

$$\rho(T,S) = \frac{1}{N-1}\sum_{i=0}^{N} (T_i - \mu_T)(S_i - \mu_S)\left(\frac{1}{\sigma_T}\right)\left(\frac{1}{\sigma_S}\right)$$

Where, ρ is the correlation coefficient between TMPA precipitation (T) and SMAP soil moisture values (S) per grid cell; N is the total number of grid cells; T_i is the precipitation value per grid cell; S_i is the soil moisture value per grid cell; μ_T is the mean of T; μ_S is the mean of S; and σ_T and σ_S are the standard deviations of T and S, respectively. Both Pearson's Correlation Coefficient and p-values indicating a confidence level of 95% were calculated for each grid location, except oceans and grids with missing data. After correlation coefficient values were calculated, significance tests (using p-values) were carried out to determine which coefficient values were statistically significant. The percentages of grids with statistically significant correlation values were calculated according to correlation strength. Three locations were selected for time series analysis, in order to display a region with a strong positive correlation value, an irrigated region, and a region with a negative correlation value.

To investigate how environmental factors affect soil moisture-precipitation interactions, results were spatially summarized according to land cover types and climate regimes. First, statistically significant correlation coefficient values were interpolated using linear interpolation to match MODIS Land Cover Classification grid resolution of 0.5° by 0.5°. Next, the land cover classification data were used to index correlation values according to their land cover type; the correlation values were spatially averaged, resulting in one average correlation value per land cover type. The same process was carried out for climate classification defined by the Köppen-Geiger climate classification, which results in one average correlation value per climate class.

Results

Figure 1 displays a sample 8-day composite obtained from TMPA daily products, spanning March 31, 2015 to April 7, 2015. Figure 2 displays a sample 8-day composite obtained from SMAP during the same period. These figures show the pattern that regions with the highest levels of precipitation (Figure 1) generally occur where regions experience the highest soil moisture levels (Figure 2). The strong relationship between these two figures indicates that elevated precipitation is generally associated with elevated soil moisture levels.

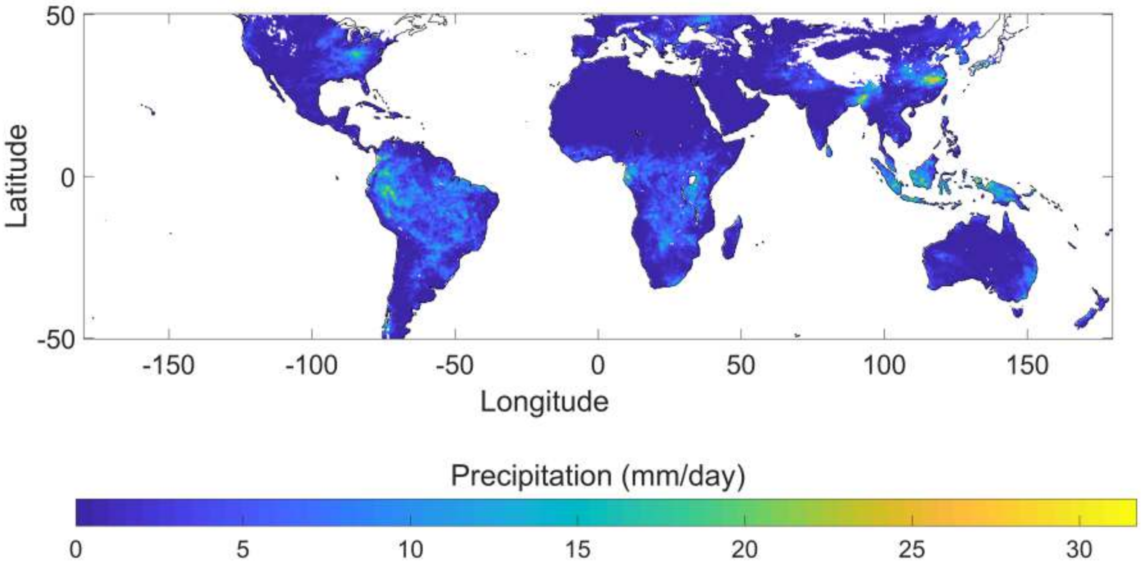

Figure 1. A sample 8-day composite of daily precipitation data obtained from TRMM 3B42 V7 from March 31, 2015 to April 7, 2015.

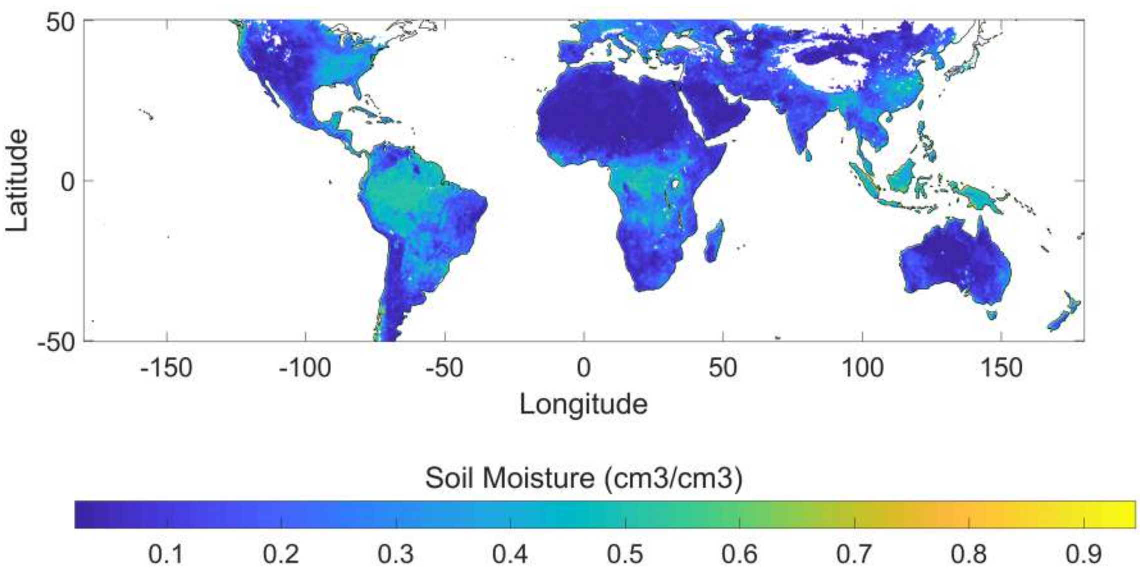

Figure 2. A sample 8-day composite of daily soil moisture data obtained from SMAP from March 31, 2015 to April 7, 2015.

Figure 3 displays Pearson's correlation coefficient for 8-day composites of the TMPA precipitation and SMAP soil moisture datasets in the study period. This figure shows a pattern of moderate to very strong positive correlations occurring in every continent. The strongest correlations occurred in Africa, Central America, the Middle East, Asia, Australia, the eastern portion of South America, and much of the Western United States. Moderate to weak correlations occurred in the Central and Eastern United States, Northern and Southern Africa, and north-east of the African Sahel. Additionally, moderate to weak correlations occurred throughout Europe, Southern Australia, Malaysia, Indonesia, and Papua New Guinea.

On the other hand, Figure 3 shows that the largest negatively correlated regions occurred in major river basins, such as the Amazon and Congo. This could be due to the physical process of hydraulic redistribution. Harper et al. (2010) documented that

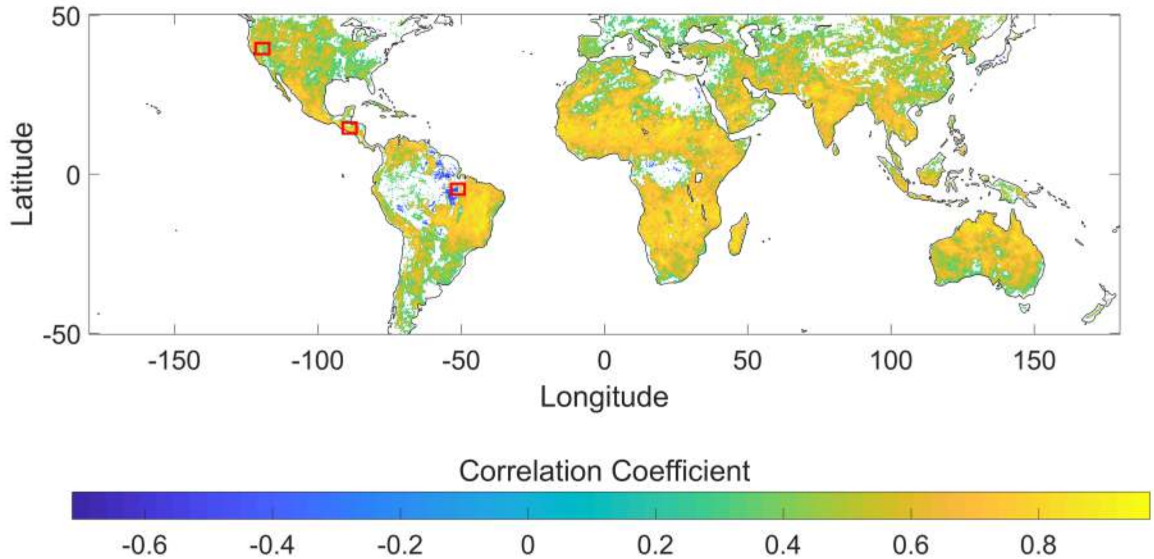

Figure 3. TMPA precipitation versus SMAP soil moisture correlation coefficients by grid cell with significant P values (< 0.05). 8-day composites spanning March 31, 2015 to June 23, 2016. The non-significant correlation coefficients are omitted and these grids are colored white. Red-colored rectangles located in Central America, Central California, and the Amazon Rainforest indicate time series locations for Figure 5.

Amazon trees with long roots perform hydraulic redistribution from deep to shallow soil, in order to survive dry seasons. Yan and Dickinson (2014) assert that a similar process occurs in the Congo River Basin, where deeply rooted trees perform hydraulic redistribution. In addition, non-positive correlations occur in Northeast Africa and Japan, and both coincide with river systems. The physical process of river transport creates conditions leading to an inverse relationship between precipitation and soil moisture: when precipitation occurs upstream, it would cause downstream portions of the river to expand, without downstream regions necessitating direct precipitation. Such is the case in Northeast Africa, where the Nile River is famous for its seasonal expansion. Heavy rains occur on the Nile River in Ethiopia and cause it to expand as it heads north into Egypt and Sudan (Conway 2000). Therefore, soil moisture along the Nile in Sudan and Egypt increases, independent of direct rainfall in Sudan and Egypt (Conway 2005).

Figure 4 displays the percentages of varying correlation strengths, which show that precipitation and soil moisture mostly correlate moderately to very strongly. 72.89% of the statistically significant grids displayed a moderate to very strong correlation, while 21.62% exhibited weak to very weak correlations. In addition to the prevalence of moderate to very strong correlations, the correlations are mostly positive, covering 93.07% of the globe, which is consistent with the previous literature (Findell and Eltahir 1997; Eltahir 1998; Zheng and Eltahir 1998). In these locations, as precipitation increases, soil moisture increases; or as precipitation decreases, soil moisture also decreases. The general trend of a moderate to strong correlation magnitude and a positive correlation direction supports the hypothesis that typically, precipitation leads to an increase in soil moisture. However, 1.44% of grids have negative correlations, indicating that soil moisture reacts to precipitation in an opposite way. Such negative relationships were observed by several other studies and were caused by different environmental and climatic factors (Cook et al. 2006; Guillod et al. 2015). For instance, Yang et al. (2018) specified that negative correlations occur in locations which have physical, limiting mechanisms such as having limited soil moisture, or being low in energy input.

One sample grid from each of the three locations, in Central America, Central California, and the Amazon Rainforest, was selected to show how SMAP soil moisture varies with TMPA precipitation for a region with a strong positive correlation, an irrigated region, and a region with

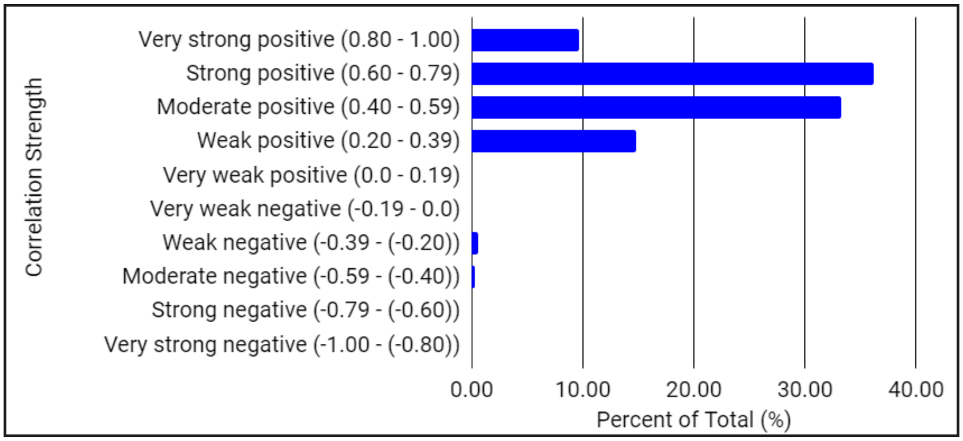

Figure 4. Bar plot of correlation strength by percent of total statistically significant grids.

a negative correlation, respectively. Figure 5a displays a time series of TMPA precipitation and SMAP soil moisture in Central America for the study period. This location represents a region where correlation coefficients are predominantly positive and moderately strong. The figure reveals a pattern that where precipitation rises soil moisture also rises. Figure 5b displays a time series in Central California, a heavily irrigated location. Patterns seen in the figure show that increases in precipitation coincide with increases in soil moisture, but increases in soil moisture also occur at times when precipitation does not occur. This dynamic is an expected scenario in the context of irrigation and watering of crop lands. Figure 5c displays a time series in the Amazon Rainforest, where concentrations of negative correlations occur. The figure reveals the pattern that soil moisture increases at times when precipitation is not present, which agrees with the findings from Harper et al. (2010) that top soil is moistened by groundwater during the dry season through the hydraulic redistribution process.

The average correlation coefficient by land cover type over the study period is shown in Figures 6 and 7 in order to understand how the precipitation and soil moisture relationship varies with the land cover. These figures reveal that precipitation and soil moisture are positively correlated under every type of land cover. The strongest positive correlations are found in land cover classes such as savannas, closed shrublands, woody savannas, mixtures of cropland and natural vegetation, open shrublands, and barren or sparsely vegetated. The land cover region showing the weakest positive correlation was permanent wetlands. These findings indicate that precipitation and soil moisture have the strongest correlations in regions of limited vegetation, whereas forests and densely vegetated regions have weaker correlations between precipitation and soil moisture. Figures 8 and 9 display the average correlation between TMPA precipitation and SMAP soil moisture, by Köppen-Geiger climate classification regimes. The same pattern was discovered as the land cover analysis, indicating that the precipitation and soil moisture correlation is positive across the climate regimes after averaging the correlation values per climate regime. These two figures reveal that South America, Africa, India, Australia, Central America, and parts of Europe have the highest correlation values. Also, precipitation and soil moisture have the strongest correlations in regions that are arid and dry or cold, and weaker correlations in humid, temperate locations.

Conclusion

This study assessed the relationship between precipitation and soil moisture using remotely sensed TRMM and SMAP measurements from March 31, 2015 to June 23, 2016. In order to calculate the correlation coefficients and their significances across the globe, 8-day composites of each dataset were created for coherent global coverage. Most grids showed a moderate to strong positive correlation between SMAP soil moisture and TMPA precipitation data. Precipitation and soil

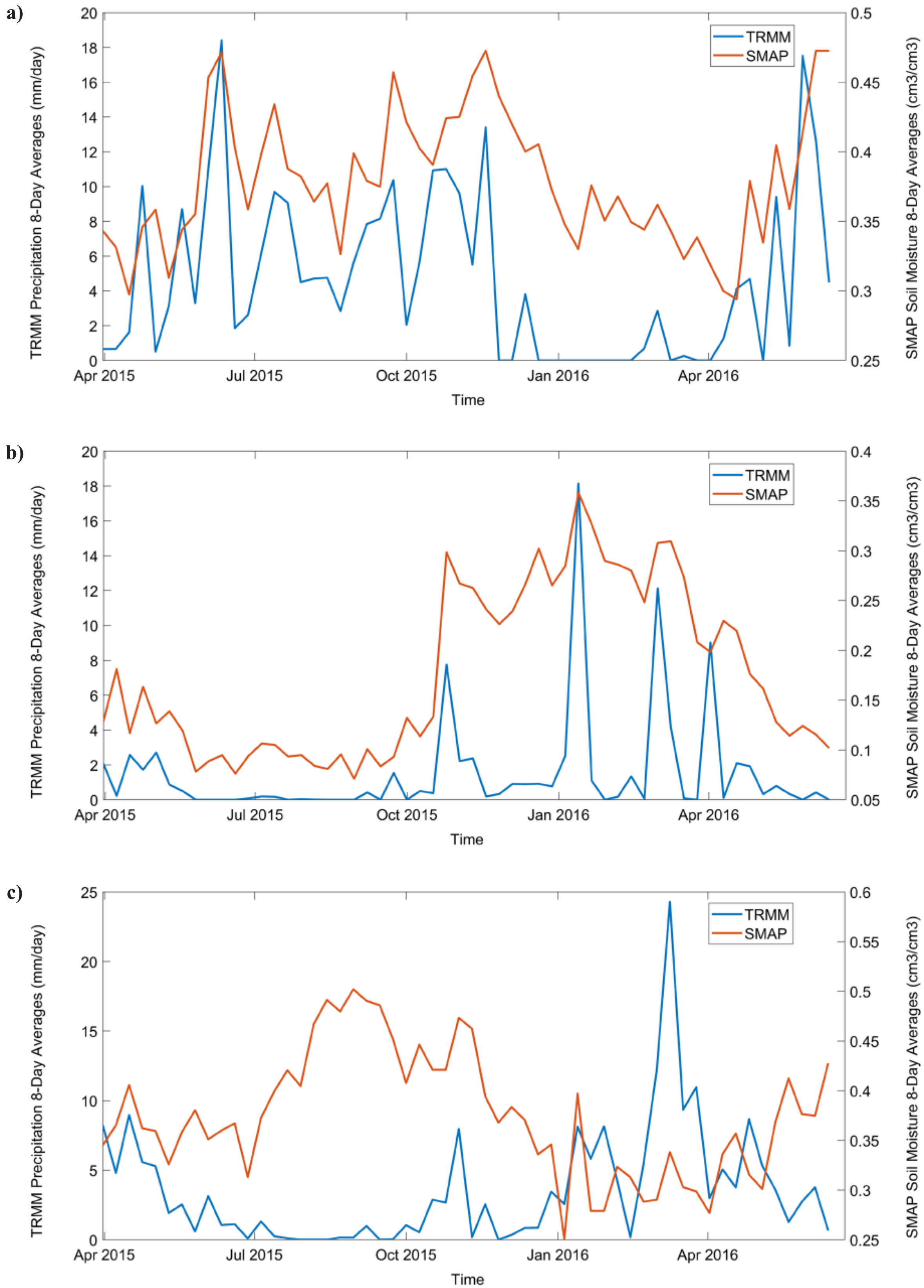

Figure 5. Time series for three locations in a) Central America, b) Central California, and c) Amazon Basin.

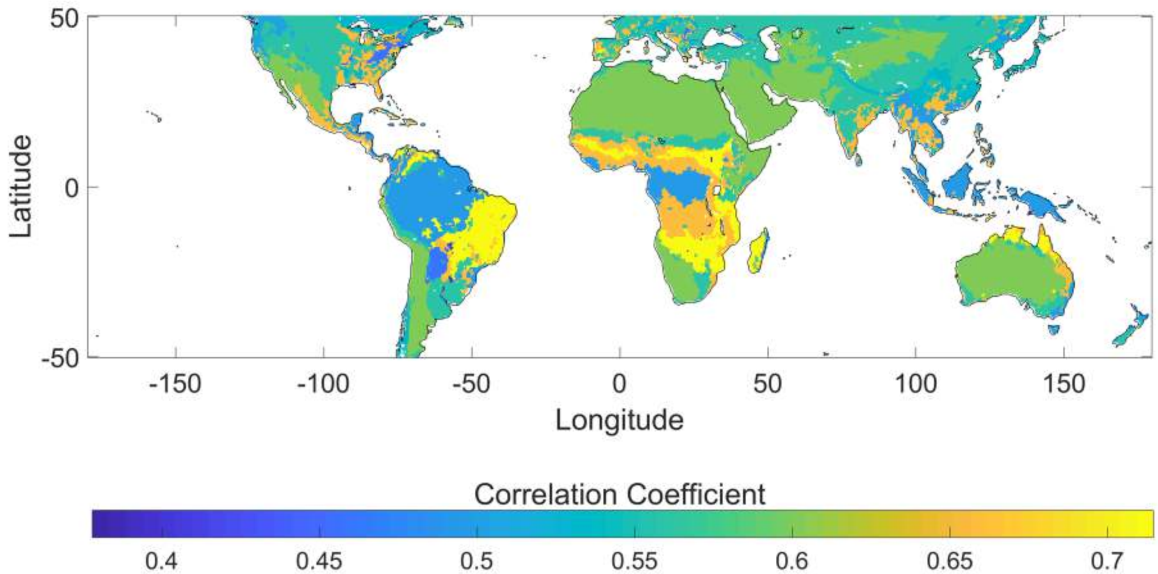

Figure 6. Average correlation coefficients by land cover type.

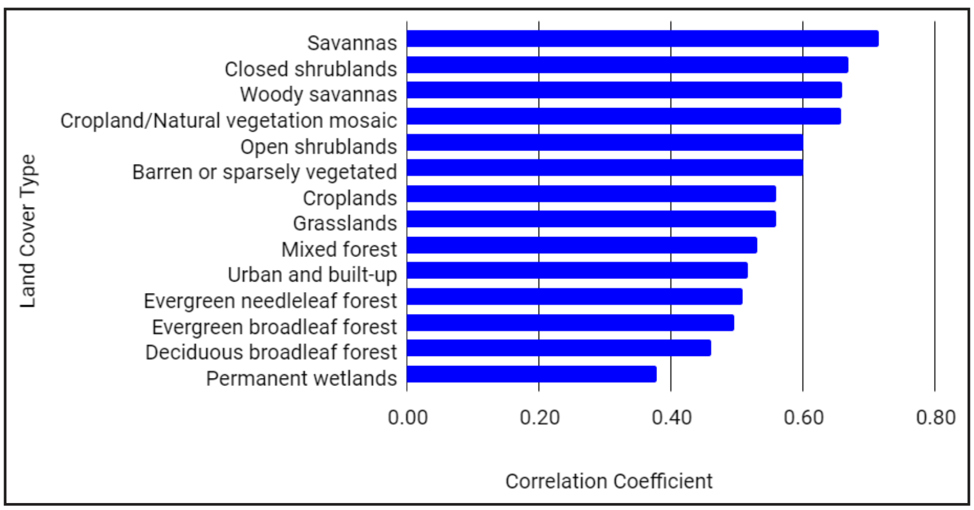

Figure 7. Bar plot of average correlation coefficient by land cover type.

moisture have the strongest correlations in regions of limited vegetation, whereas forests and densely vegetated regions have weaker correlations. Similarly, precipitation and soil moisture have the strongest correlations in regions that are arid and dry or cold, and weaker correlations in humid, temperate locations.

Overall, this study revealed that the relationship between precipitation and soil moisture goes deeper than what is seen on the surface. Although several other studies have revealed that negative correlations exist between precipitation and soil moisture (Cook et al. 2006; Guillod et al. 2015; Yang et al. 2018), the time series analysis conducted in this study reveals which of two mechanisms is causing negative correlations: either a) soil moisture increases while precipitation does not increase (i.e., decreases or stays the same) or b) soil moisture decreases while precipitation does not decrease (i.e., increases or stays the same). The time series helped explain that, specifically, in both the Amazon Rainforest and in Central California, soil moisture, at times, increased while precipitation did not increase. This study indicates that soil moisture and precipitation are not always positively correlated, and that the relationship

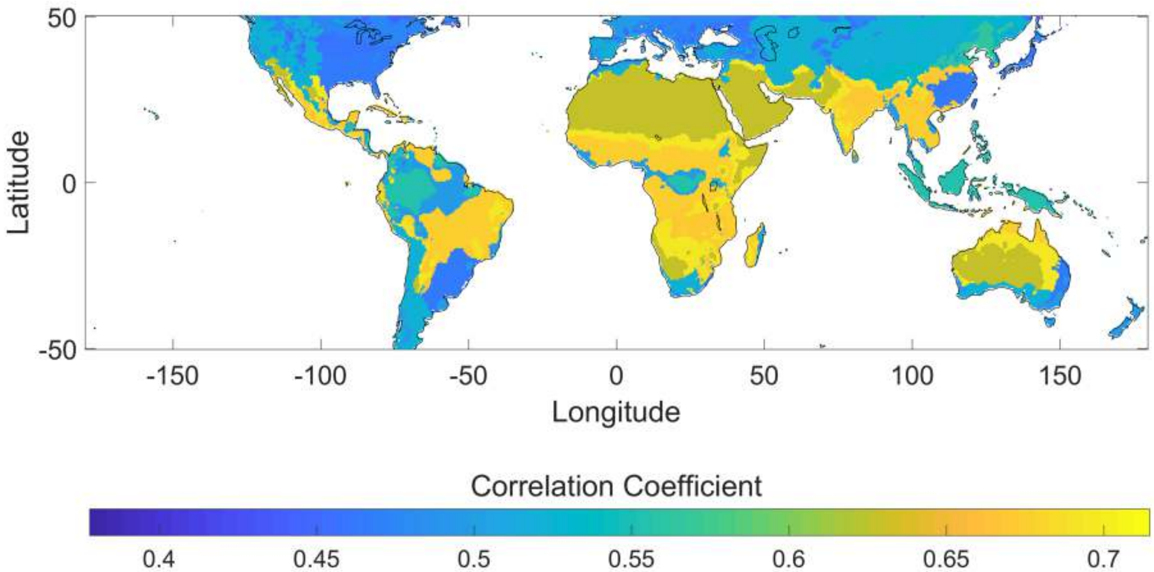

Figure 8. Average correlation coefficients by Koppen-Geiger climate classification regimes.

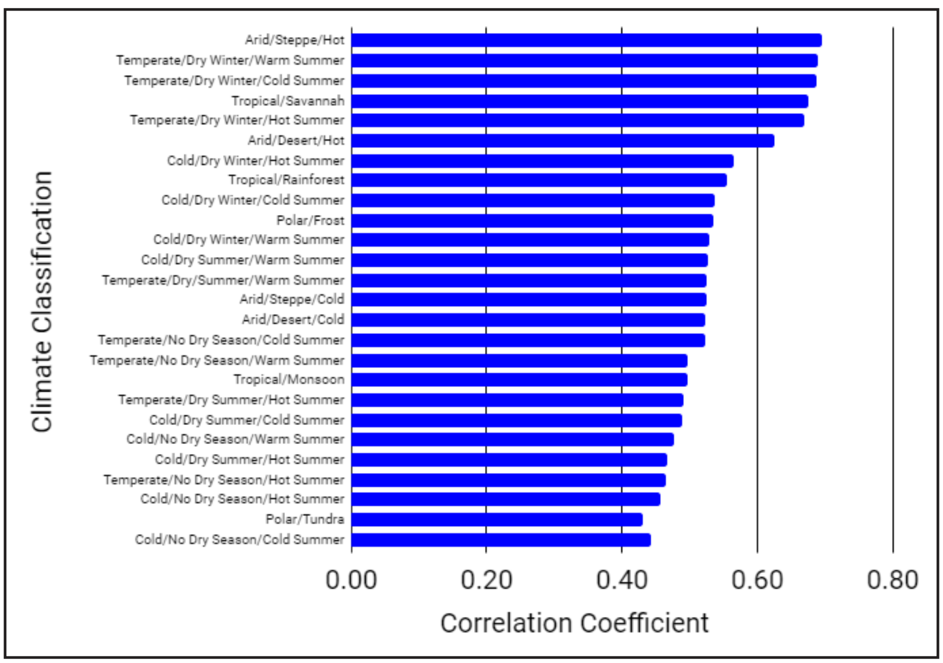

Figure 9. Bar plot of average correlation coefficient by Koppen-Geiger climate classification regimes.

between them tends to be inverse in major river basins, plausibly due to two physical processes, including hydraulic redistribution by tropical trees (Harper et al. 2010; Yan and Dickinson 2014), as well as river transport and expansion caused by upstream precipitation (Conway 2000, 2005).

Additionally, this study served as an informal validation of SMAP soil moisture data using TMPA precipitation data. TMPA precipitation helped validate SMAP soil moisture because in most locations on the globe, when moderate rain occurred soil moisture also increased, as indicated by predominantly positive correlations. The presence of negative correlations in this study may also add to the validity of SMAP data rather than taking away from it. For example, logically, irrigated regions should, at times, show an opposite relationship between soil moisture and precipitation. In addition, certain rainforests show an opposite relationship between soil moisture and precipitation, due to recent findings that rainforest tree roots transport groundwater to the top soil in order to survive dry seasons (Harper et al. 2010). Moreover, this study of incorporating landcover and climate regimes in our analyses further supports SMAP's credibility based on the different types of landcover and climate regimes. For example, savanna landcover and arid/steppe/hot climates experience a strong correlation between TRMM and SMAP because both precipitation and soil moisture are truly low in these environments, and both satellites were able to reflect those conditions.

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2020 UCOWR/NIWR
Annual Water Resources Conference
June 9-11, 2020
Graduate Hotel, Minneapolis, MN

Abstract Submission:

Abstracts for oral, panel, and poster presentations may be submitted electronically by Jan. 24, 2020. Abstracts should not exceed 300 words. If accepted and presented at the conference, the abstracts will be published as part of the conference proceedings.

The conference planning committee is pleased to invite abstract proposals for the 2020 UCOWR/NIWR Water Resources Conference. These sessions are an exciting part of the program, highlighting recent advances and transdisciplinary solutions to address complex water problems.

Near the headwaters of three continental basins, Minneapolis serves as a reminder that water connects distant places and diverse peoples. The committee encourages abstracts that frame water resource issues in the context of:

- Geographic transitions and spatial gradients in land use,population density, and climate.
- Inclusive engagement among stakeholders to address water competition, conflict, and inequities.

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Those interested in submitting an abstract should complete the online form at z.umn.edu/ucowr.

Abstracts will be evaluated by the Conference Planning Committee based on the timeliness and relevance of the topic. Notification of acceptance will be in late February.

For more info, visit www.ucowr.org.

General questions about the conference can be directed to Karl Williard (williard@siu.edu), Executive Director of UCOWR.

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