Colorado Water

August 2019

Hydrology Days 2019

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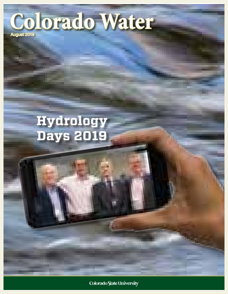

On the cover—
Neil Grigg, Mazdak Arabi, Jorge Ramirez and Pierre Julien pictured at the 2019 Hydrology Days annual meeting. Photo courtesy of Colorado Water Center. Background photos ©2019 iStock.com

References can be found in the online version of this newsletter at http://watercenter.colostate.edu/water-news

Cooperators include the Colorado State Forest Service, the Colorado Climate Center, and CSU's Water Resources Archive.

COLORADO **WATER**

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Director's LETTER

To advance the state of knowledge, scholarly research findings must be communicated beyond the lab to other scientists and eventually to the larger management community. While university researchers receive recognition for their work through the publication of results in academic journals, it is often in face-to-face settings that students and faculty clarify, communicate and expand their ideas, achieving deeper knowledge and greater impact. At Colorado State University, the annual AGU Hydrology Days event brings water researchers and students together on campus for three days to discuss their latest water research findings and learn from each other. Water researchers from government agencies, other universities, and the private sector are all welcomed as participants in the annual dialog on cutting-edge water research.

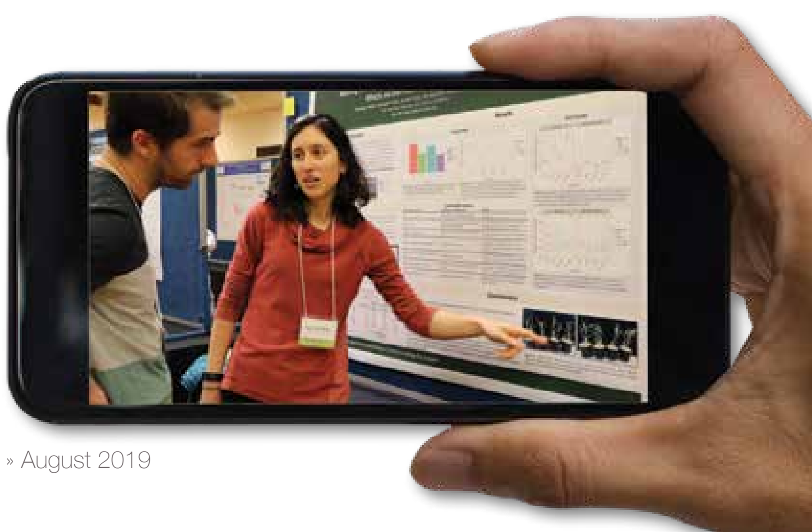
This year, the event celebrated Dr. Jorge Ramirez's career of contributions to the field of hydrology through a special symposium in his honor. After many years of service, Dr. Ramirez has stepped down from organizing the annual AGU Hydrology Days symposium at CSU. Dr. Mazdak Arabi has recently taken over as the organizer of Hydrology Days with a commitment to expand the event to include students and researchers from all water-related disciplines. Next year's Hydrology Days promises to be even broader and more inclusive as the organizing committee reaches across disciplines and universities to expand the program.

Showcasing student research through oral and poster presentations exposes students to the challenge of clearly communicating their work to their peers and professors—not an easy task. This year at Hydrology Days, student papers were juried by faculty in a competition to further hone and recognize the best research communications. Over 80 student papers were included in the program and the top 14 award winning papers are excerpted in this edition of *Colorado Water* newsletter. Congratulations to all of our student researchers and special recognition to the award winners. We look forward to what these students will achieve as their careers in water resources progress.

In the continuing effort to improve the water programs at CSU, this year we officially merged the Colorado Water Institute—one of the 54 Water Resources Research Institutes created by the federal Water Resources Research Act of 1964—with the CSU Water Center, which served as the focal point for CSU water faculty teaching, research, and outreach. This move brings the statewide efforts of the Institute, CSU Extension's water program, and the campus-focused Water Center together to strengthen CSU's water mission and impact while streamlining our communications and administration. The merged center will be known as the Colorado Water Center. Vice President for Engagement, Lou Swanson, stated, "the merger of these units better reflects the collaboration we already enjoy and will serve to increase the impact of our water scholarship on communities, wildlife, rivers, lakes and aquifers across Colorado and the West." Vice President Swanson officially retired from CSU in September 2019, capping a thirteen-year stint as the leader for engagement at the University, highlighted by his commitment to the communities of Colorado. Leaders like Dr. Jorge Ramirez and Dr. Lou Swanson make CSU a special place, building on the Land Grant University tradition, but with new ideas, fresh energy and initiatives. We acknowledge and appreciate these leaders, aspiring to continue their legacy of service to the people and natural resources of Colorado.

Reagan Waskom

Director, Colorado Water Center



Hannah Miller discusses her work with a Hydrology Days Conference attendee. Photo courtesy of Colorado Water Center.

Hydrology Days 2019 at a Glance

Sarah Millonig, One Water Solutions Institute, Colorado State University
Russell Dickerson, Walter Scott, Jr. College of Engineering, Colorado State University

Colorado Water Center

Hydrology Days Scientific Committee: Neil Grigg, Mazdak Arabi, Jorge Ramirez and Pierre Julien.

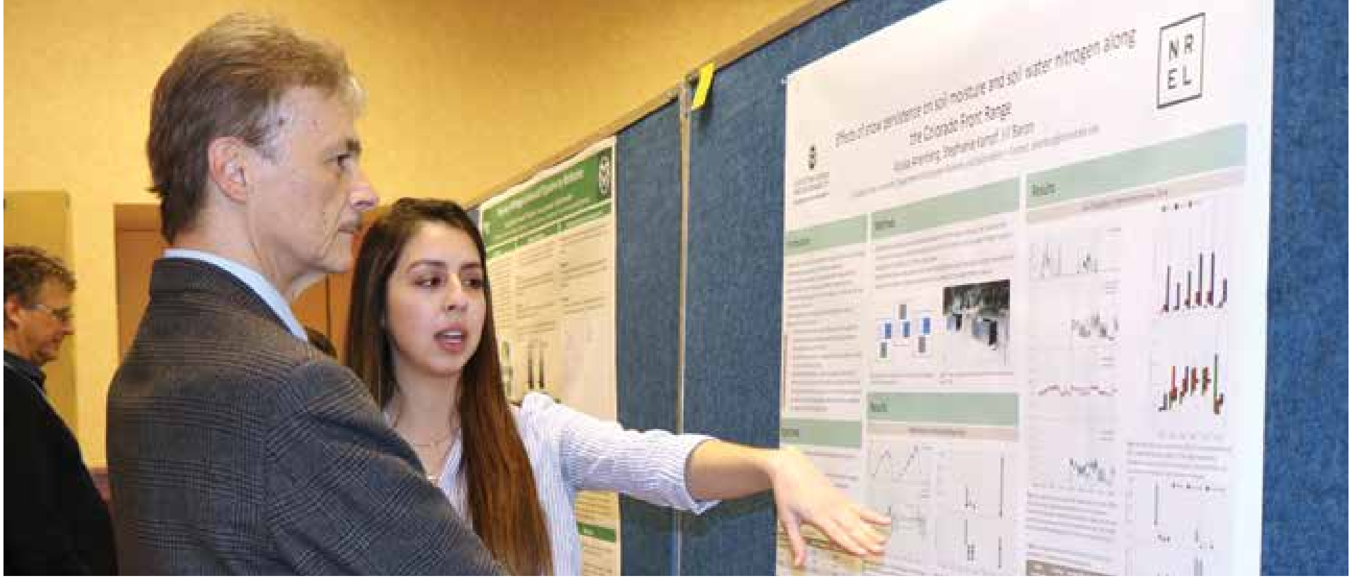
In March 2019, CSU hosted the three-day American Geophysical Union Hydrology Days annual meeting. The event generates a unique and energetic experience for students, faculty, and practitioners engaged in diverse and extensive water-related research topics. Hydrology Days (hydrologydays.colostate.edu) covers a broad range of water issues ranging from agriculture and water rights to climate change, urbanization, economics, and policy. The 2019 meeting was designed to bring together the abundance of ongoing water-related research currently under investigation at CSU and beyond.

The event was organized by CSU's One Water Solutions Institute (onewatersolutions.com) with support from the Colorado Water Center and the Department of Civil and Environmental Engineering. The meeting featured thematic sessions with oral presentations from researchers across campus, a scientific poster session, keynote lectures, and presentation of the annual Hydrology Days Award. In addition, a recognition session for Dr. Jorge Ramirez was conducted to acknowledge his revered contributions to both CSU and the overarching field of hydrology.

Each year, the Hydrology Days Award recognizes significant contributions to hydrologic science. Scientists and researchers are nominated by colleagues and experts in the field, making this a truly unique and humbling honor.

Twelve interdisciplinary research sessions were conducted to cultivate a community event for researchers to share results and discuss linkages between ongoing water-related scientific inquiries. The broad focus of the meeting featured aspects of the water cycle and its interactions with land surface, atmospheric, ecosystem, economic and political processes, and all facets of water resources engineering, management, and policy. Presentations were included on all topics in hydrology, related fields of science and linked systems including engineering, climatology, agriculture, economics, sustainability, and socio-ecological systems.

Each year, the Hydrology Days Award recognizes significant contributions to hydrologic science. Scientists and researchers are nominated by colleagues and experts in the field, making this a truly unique and humbling honor. The 2019 recipient is Bridget Scanlon, Senior Research Scientist at the Bureau of Economic Geology, Jackson School of Geosciences, Uni-



Graduate student Alyssa Anenberg (third place graduate poster award) shows Dr. Ramirez her research findings.

versity of Texas at Austin. Scanlon is a Fellow of the American Geophysical Union and the Geological Society of America and a member of the National Academy of Engineering.

As the Hydrology Days Award recipient, Scanlon delivered a keynote address on the implications and tools for management of water resources. Scanlon's lecture highlighted her research in water resources, global assessments using satellites and modeling, management related to climate extremes, and water energy interdependence.

In addition, two other distinguished researchers presented Borland lectures, with one keynote in hydraulics and the other in hydrology. Dr. Fotis Sotiropoulos (Hydraulics), Dean of the College of Engineering and Applied Sciences at Stony Brook University, presented research on hydraulic engineering in the era of big data and extreme-scale computing. Dr. Nandita Basu (Hydrology), Associate Professor of Water Sustainability and Ecohydrology at the University of Waterloo, discussed legacy human impacts on climate change and the future of water resources.

The event also provided student researchers their own showcase, a safe and supportive venue where students at different points in their careers could exchange ideas, give research presentations, and enhance their scientific communication skills. The showcase offered students an enriching environment to spark peer-to-peer learning and collaboration. More than 80 student presentations were scheduled over the course of the three-day event, including 57 oral research presentations and 28 scientific poster presentations.

A student presentation competition accompanied the 2019 meeting, the results of which are showcased in this issue. The Hydrology Days Scientific Committee is proud to recognize these student contributions to energize the event and is especially excited to feature their award-winning research in this special issue.

This year was marked by another milestone: Dr. Ramirez stepped down as the chair of Hydrology Days, and a special recognition session provided an opportunity to acknowledge his tremendous efforts organizing and leading the event for the last 19 years. In addition, the session celebrated his remarkable contributions to the field of hydrology. Esteemed colleagues and former students traveled from across the world to give short, anecdotal presentations highlighting relevant research and other examples of how he has contributed to the overarching field of study and influenced their professional endeavors and successes.

Over nearly three decades of service to Colorado State University, Dr. Ramirez has led numerous research, education, and training efforts to establish CSU as a leader in water science and technology. His academic scholarship has substantially expanded the University's research reputation in the fields of hydrology, hydrometeorology, and water resources planning and management, benefitting not only CSU students and his fellow faculty members but the profession as a whole.

Dr. Ramirez has an extensive record of significant contributions to curriculum and education program development and management of interdisciplinary research and training programs, as well as development of internationally recognized academic events. In addition to the leadership, mentoring, and global recognition he has brought to CSU, Dr. Ramirez has also broadened the reach of the University through engagement and collaboration with outside partners.

As evidenced by his exemplary service qualities which align directly with CSU's core mission, Dr. Ramirez was recently awarded the Oliver P. Pennock Distinguished Service Award, which recognizes meritorious and outstanding achievement of academic faculty. The award was formally presented to Dr. Ramirez on May 9, 2019.

Acknowledgements

Support for Hydrology Days was provided by the One Water Solutions Institute, Colorado Water Center, CSU Department of Civil and Environmental Engineering, and CSU Program of Research and Scholarly Excellence - Water Science and Global Solutions: *Water Information Systems for Education and Research (WISER)*.

Hydrology Days

Keynote Speakers

Bridget Scanlon

AGU Hydrology Day Award

Bridget R. Scanlon

Bridget Scanlon is a senior research scientist at the Bureau of Economic Geology in the Jackson School of Geosciences at the University of Texas at Austin. She has been with the University of Texas since 1987, and her current research focuses on various aspects of water resources—including global assessments using satellites and modeling, management related to climate extremes, and water-energy interdependence. She serves an associate editor for *Water Resources Research and Environmental Research Letters* and has authored and co-authored more than 100 publications. Dr. Scanlon is a fellow of the American Geophysical Union and the Geological Society of America and a member of the National Academy of Engineering.

In her keynote address at Hydrology Days, Dr. Scanlon explored how water resources management is becoming increasingly challenging within the context of climate extremes and change. Her studies look at trends in water storage using Gravity Recovery and Climate Experiment (GRACE) satellites and modeling, ranging from global to local scales. Likened to giant weighing scales in the sky, GRACE satellites have monitored monthly changes in land water storage globally since their launch in 2002. Her team has evaluated the reliability of global models by comparing modeled land water storage (snow, surface water, soil moisture, and groundwater) trends to storage trends from GRACE satellites. The satellites show that global land water storage, summed over 186 river basins, has increased over the past decade, although models show decreasing global water storage. This suggests opposing contributions to global mean sea level, with GRACE indicating a negative contribution to sea level and models indicating a positive contribution.

While there is considerable interest in global-scale analyses, water management generally occurs at the river basin scale, with models underestimating large decadal (2002-2014) trends in water storage relative to GRACE satellites. Comparing models with GRACE data highlights potential areas of future model development, particularly simulated water storage. The inability of models to capture large decadal water storage trends based on GRACE indicates that model projections of climate and human-induced water storage changes may be underestimated. What does this mean in reality? Take the Colorado River Basin as an example. This basin has been subjected to long-term drought. Transfer of water from the Colorado River to depleted aquifers using managed aquifer recharge has stabilized groundwater levels and stopped subsidence. However, such transfers may not be feasible in the future with continued drought, and implications for water resource management will need to be considered. The expansion of tools to assess and manage water resources should provide a more in-depth understanding of controls on water resources and increase the portfolio of management options to enhance resilience of water resources within the context of climate extremes.

Fotis Sotiropoulos

Borland Hydraulics Lecture

Fotis Sotiropoulos

Fotis Sotiropoulos has served as the dean of the College of Engineering and Applied Sciences (CEAS) and State University of New York (SUNY) distinguished professor of civil engineering at Stony Brook University since October 2015. His research focuses on simulation-based fluid mechanics in energy, environment, biology, and health. Dr. Sotiropoulos has made seminal contributions in environmental fluid mechanics, including sediment transport and scour; stream and river restoration; river flooding risk assessment and mitigation; wind, marine, and hydrokinetic energy systems; cardiovascular fluid mechanics; and aquatic swimming. Funded by the National Science Foundation, the Department of Energy, the National Institutes of Health, the Sandia National Laboratories, private industry, and other state and federal agencies, he has raised over $35 million for research and research facility development and renovation. He is a fellow of the American Society of Mechanical Engineers and the American Physical Society, twice winner of the latter's Division of Fluid Dynamics Gallery of Fluid Motion award, and a recipient of the Hunter-Rouse Hydraulic Engineering Prize from the American Society of Civil Engineers. Sotiropoulos has authored over 200 peer reviewed journal papers and book chapters, and his research results have been featured on the covers of several prestigious journals.

In his keynote address at Hydrology Days, Dr. Sotiropoulos highlighted recent advances in computational algorithms that, when coupled with exponentially growing computing power, are paving the way for developing a powerful simulation-based engineering science framework. This framework can be deployed to tackle a broad range of real-life hydraulic engineering flows. Multi-physics simulations—taking into account complex waterway bathymetry, energetic coherent structures, turbulence/sediment interactions and morphodynamics, free-surface effects, and flow structure interaction phenomena—are now well within reach and are beginning to impact engineering practice. Dr. Sotiropoulos provided an update on this progress, as well as specific examples to illustrate the enormous potential of simulation-based engineering science. This science can supplement and dramatically augment the insights gained from physical experiments. And while major computational challenges that lie ahead, there are enormous opportunities to take advantage of advanced algorithms, powerful supercomputers, and big data to tackle societal challenges. Restoration of aquatic environments, sustainable mitigation of the impacts of global environmental change, and development of efficient and environmentally compatible renewable energy systems may all benefit from these advances.

Nandita Basu

Borland Hydrology Lecture

Nandita Basu

Nandita Basu is an associate professor of water sustainability and ecohydrology at the University of Waterloo, and she studies the role humans play in modifying water availability and quality through changing land use and climate. Her work provides innovative solutions to water sustainability challenges by identifying and analyzing emergent patterns in landscape, hydrology, and biogeochemistry and the role humans play in modifying such patterns. Dr. Basu and her research group have used these patterns to develop parsimonious, minimum-calibration models that can effectively interface with climate and land-use change models to provide insights into water management on local and regional scales. Modeling in her lab is complemented by experimental research to develop pioneering, low-cost, passive water quality samplers for surface and groundwater applications. Dr. Basu also collaborates with ecologists, social scientists, and economists to explore other aspects of sustainable water management.

In her keynote address at Hydrology Days, Dr. Basu examined how water quality is under severe threat: from increasing incidences of algal blooms and hypoxic zones in inland and coastal waters, to climate change, wildfires, and emerging contaminants from rapid urbanization and concentrated livestock operations threatening our drinking water supplies. Despite widespread implementation of a range of conservation measures, the last few decades have seen a lack of improvement—and sometimes even a deterioration—of the water quality in surface and groundwater bodies. Dr. Basu's work shows that this lack of response can be attributed partly to legacy stores of nutrients that can accumulate in the landscape over decades of intensive agriculture and contribute to time lags between conservation measures implemented on the landscape and water quality benefits realized in receiving water bodies. Through a combination of top-down analysis using large datasets to identify patterns in landscape behavior and mechanistic modeling, her team has attempted to capture the ways in which long-term legacies of land use and management impact current dynamics in water quality. At the same time, they focus on the science of watershed management, exploring fundamental scaling questions, as well as more applied management questions on spatial configurations of wetlands and riparian areas and the role of these ecosystems in mitigating water pollution. From the Great Lakes to the Gulf of Mexico, from prairie wetlands to global biogeochemical cycles, from forest fires to urban water, this work demonstrates that, even as changes in climate and land use are leading us to a "new normal," where past assumptions may no longer hold, we also remain strongly bound by the past.

Assessment of Acoustic Flow Measurement Instrumentation for Mean Flow Measurements

Matthew Klema, Civil and Environmental Engineering, Colorado State University
Abdul Pirzado, Mehran University of Engineering & Technology
Timothy Gates, Civil and Environmental Engineering, Colorado State University
Karan Venayagamoorthy, Civil and Environmental Engineering, Colorado State University

Matthew Klema

Matthew Klema is a doctoral student in Civil and Environmental Engineering at Colorado State University. His main research focuses on fluid turbulence modeling under the guidance of Dr. Karan Venayagamoorthy at CSU's Environmental Fluid Mechanics Laboratory. The following research was presented as part of the Hydrologic Systems session at Hydrology Days and was awarded first place for oral presentations.

Introduction

River management and water allocation depend on accuracy of flow rate (discharge) measurements. The study of river systems and the forces that create evolution and change in a waterway also depend on the knowledge of discharge and the distribution of velocity in a flow. Humans have been estimating discharge, managing water, and observing the effects of water on the beds and banks of waterways for thousands of years. But how well do the most commonly used acoustic instruments actually perform in estimating discharges in a river or canal? The acoustic Doppler velocimeter (ADV) and the acoustic Doppler current profiler (ADCP) are two of the most popular classes of acoustic flow measurement instrumentation. These devices are sold by companies as a comprehensive solution for estimating discharge and velocity, but how well do they perform in comparison to a non-intrusive instrument?

Research Objectives

Laser Doppler Anemometers (LDAs) are non-intrusive flow measurement instruments that have very limited effects on the flow velocity, as they do not enter the flow. However, they are limited to scenarios where there is an unobstructed side view of the flow. This is usually only possible in a laboratory setting. The objective of this research is to precisely investigate the difference in the flow velocities measured by the LDA and the two most common classes of acoustic instruments in a controlled environment. Both the ADV and the ADCP are commonly used to make field measurements, but when they are placed in the water to make a measurement, they are intrusive, disturbing the actual flow they are intended to measure. While this might seem like a localized problem, the cumulative errors associated with such measurements can be significant, resulting in uncertainties in quantifying the actual flow. Testing these instruments over a range of flow velocities that are commonly encountered in the field or laboratory setting allows for a better evaluation of their efficacy.

Methods

All of the experiments were conducted in Environmental Fluid Mechanics Laboratory at Colorado State University in a recirculating 5-meter long, glass-walled, Armfield flume. Both the Nortek Vectrino I ADV and the Teledyne RDI StreamPro ADCP are downward-facing instruments. They were both tested for this study, mounted so that the instrument entered the flow from the water surface. A Dantec DopplerLite LDA was mounted on an Isel automated traverse system so that the laser could enter through the glass sidewalls of the flume and its movements could be controlled by lab computers. All three instruments determine the flow velocity by using the principle of Doppler shift in sound or light waves being scattered by particles moving with the water.

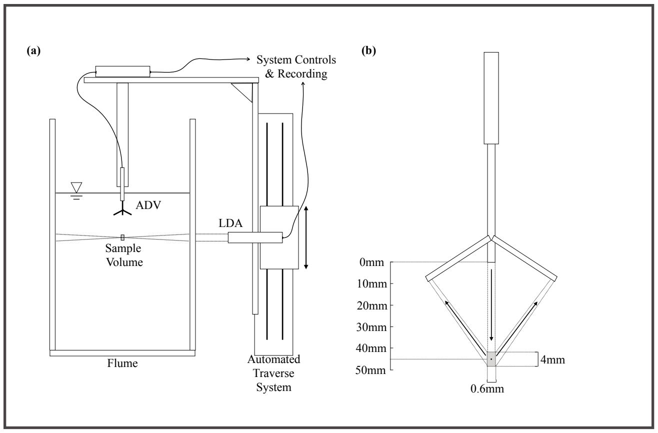


Figure 1: Diagram of the acoustic Doppler velocimeter (ADV) system

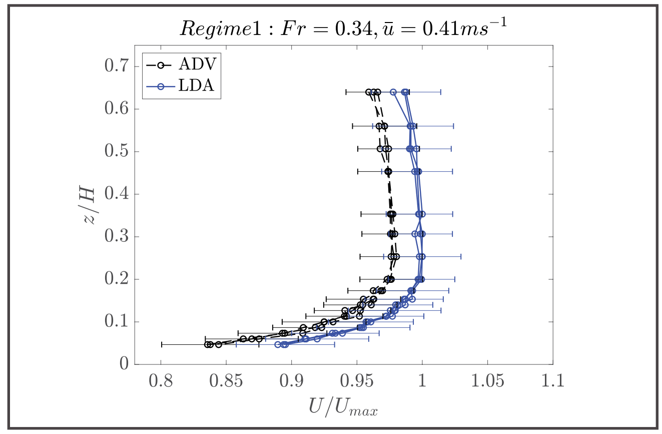


Figure2: Example of the velocity profiles measured by the ADV and LDA simultaneously

The center of the LDA and ADV sampling locations were calibrated to be coincident, and the instruments moved in unison (Figure 1). The Teledyne RDI StreamPro ADCP collected a profile of current velocities, from near the surface to 1-2 centimeters above the bed. This instrument was held stationary during the testing, with the head of the instrument just below the water surface; meanwhile, the LDA moved vertically, measuring at the same locations as the points measured in the ADCP profil. Measurements with each instrument were made at five different flow rates between 11.25 and 35.1 liters per second. At each flow rate the entire measurement profile was completed three separate times to ensure that the results were consistent and repeatable. Multiple ADV and ADCP instruments of the same make and model were also tested to confirm that the results were not a function of a faulty instrument.

Results and Discussion

The mean of the velocities (i.e., the average flow velocity) measured by the Nortek Vectrino I ADV show a mean under-prediction of 2.7% as compared the mean measured velocities of the LDA. These results assume that the ADV instrument is not impacting the flow velocity in the sampling volume of 45 millimeters (Figure 1) below the instrument. If the mean flow velocities measured by the ADV are compared to measurements made by the LDA of the same flow—but without the ADV in the water—the value measured of the velocity by the ADV varies as a function of the flow. At the lower flow rates and flow speeds, the ADV is much more accurate (the error is approximately 1%) than at the higher flow rates where the error is greater than 3.4%. Mean velocity measurements of ADCP as compared to the LDA showed approximately a 4% under-prediction but varied between 2.0% and 8.6%.

Since the ADCP instrument was held in a single location in the flume during the entire duration when the velocities were measured for a given flow condition, it was possible to assess the error associated with different sampling durations. For example, if sampling was only completed for five seconds, differences of up to 50% were found in the flow velocity at a single point in the profile when compared to the long-term average in some instances. Samples that used data collected for at least 15 seconds showed less than 10% difference from the long-term average.

Conclusions

Results show that both the Nortek Vectrino I ADV and the Teledyne RDI StreamPro ADCP under-predict the mean flow velocity when compared to the mean flow velocity measured with the Dantec DopplerLite LDA. Measurements made in the field or in the laboratory with acoustic instruments could be impacted as a result. Introduction of the Nortek Vectrino I ADV into a flow to make a measurement has a measurable impact on the flow velocity at the location the instrument samples. ADCP type instruments are commonly used to determine a discharge from the measured velocities. As a result of velocity under-prediction, the discharge measured by the ADCP will also be lower. This could have an impact on water budget management as well as on our understanding the fluid dynamics of a river or stream. The results also show that the total time of sampling also has an impact on the accuracy of the measurement. Due to the large standard deviations of measured velocities collected by the ADCP, it is necessary to consider longer sampling times.

Future Research

The results of these experiments present only the analysis of the data collected, highlighting mean flow. Measurements made by these instruments can also be used to determine turbulent quantities representative of the flow energy and dissipation. Future work will examine how these instruments behave in varying degrees of turbulence and accuracy of the collected turbulent flow characteristics.

Recovery of Nitrogen in Anaerobic Digestion by Nitrification

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Lucas Loetscher, Systems Engineering, Colorado State University
Sybil Sharvelle, Civil and Environmental Engineering, Colorado State University

Ismail Alhelal is a master's student in Chemical and Biological Engineering at Colorado State University. The following research was presented as part of the poster session at Hydrology Days and was awarded first place for graduate posters.


Ismail Alhelal

Animal wastes can cause environmental pollution when they are not managed appropriately. Manure piles, for example, release greenhouse gases such as carbon dioxide, methane, and nitrous oxide—all important contributors to climate change. Anaerobic digesters have been used to eliminate the environmental impacts of animal wastes, but they are not currently economically feasible, and more research is needed to overcome the primary challenges of this management approach.

One of the biggest challenges associated with anaerobic digesters is the toxicity of the ammonia (generated in the digestion of nitrogen-containing compounds in manure) to the microorganisms in the digester. Animal wastes like manure are rich in organic nitrogen components that convert to ammonia during anaerobic digestion, causing toxicity to methanogenic microorganisms and limiting the biogas yield in anaerobic digesters (Nakakubo et al., 2008).

Several approaches have been applied to solve the problem of ammonia toxicity in anaerobic digestion systems. The waste may be diluted with fresh water in the digestion system, but this requires a large amount of water and impacts economics and sustainability. Ammonia may also be removed from the anaerobic digestion system to control toxicity. The traditional and most economical way of removing the ammonia is volatilizing it from the anaerobic digesters then capturing it with an acid (Ozturk et al., 2003), but the use of acids is financially burdensome.

Therefore, this work aims to assess a new way to capture ammonia in an anaerobic digestion system. Whereas traditional methods use acids such as hydrochloric or sulfuric acid to capture ammonia, we used a nitrified solution instead of these strong acids to capture the ammonia. The main two benefits of using a nitrified solution instead of strong acids are 1) there is no free biological acid-forming reaction in the nitrification process, and (2) the nitrification process is a biological reaction in which organic fertilizer can be a product. In this work, a bench-scale version of the ammonia recovery system was designed that consists mainly of two units: a packed stripper column and a packed absorber column. The system is operated with different parameters to find the optimal operation conditions. The overall objectives for this project are to 1) improve the cost and performance of multi-stage anaerobic digestion (MSAD) by decreasing the ammonia toxicity in MSAD and 2) produce organic fertilizer through converting the removed ammonia to fertilizer, nitrate (NO_3^-).

Materials and Methods

A bench-scale ammonia recovery system was designed consisting of two units, a packed stripper column and a packed absorber column. The stripper is used to remove ammonia from the animal waste, and the absorber is intended to absorb or recovert the nitrogen that was removed by the stripper. Cattle manure leachate was used as a nitrogen source and was obtained from the Sharvelle anaerobic digestion laboratory at CSU. The amount of nitrogen in the manure was adjusted by adding ammonium chloride.

The stripper unit (500 ml flask) was operated at thermophilic conditions (52^{o}C) and examined in different pH ranges (8-12). A heating plate was used to heat the stripper, while a thermometer was used to measure the temperature of the stripper contents. The initial pH of the stripper was adjusted with sodium hydroxide. The leachate in the stripper was sampled over time to measure the ammonia concentration and pH.

The absorber unit (500 ml flask) was operated at room temperature (20°C) and examined in different pH ranges (2-4). Hydrochloric acid was used to adjust the initial pH in the absorber. Samples of the leachate in the stripper were removed over time to measure the ammonia concentration and the pH.

For both absorber and stripper samples, the ammonia concentration was measured using the Nitrogen, Ammonia Hach Test (Salicylate Method, Method 10031) while pH was measured using a pH probe.

Results and Discussion

The nitrogen recovery system was designed to reduce the cost of the anaerobic digestion process while producing a valuable product, organic fertilizer. By enhancing the performance of the nitrogen recovery system design and its operation conditions, process costs will decrease and performance will increase. Therefore, improving the recovery system is the objective of the bench experiments discussed here. Ammonia in water exists in two forms, free ammonia (NH_3) and the ammonium ion (NH_4^+). Each form can convert to the other one, and their conversion is a function of the solution pH. The amount of both forms are equal when the pH is around 9. However, NH_3 converts to NH_4^+ as the pH gets lower than 9, and NH_4^+ converts to NH_3 as the pH gets higher than 9. The ammonia conversion between the two forms can play a significant rule in the process of ammonia stripping and recovery. Therefore, the amount of ammonia stripped and recovered at different initial pH values is a main focus in both of the stripping unit and absorbing unit experiments.

High pH conditions enhance ammonia stripping but increase the cost due to the need to add a base. As the pH increases, ammonium in the wastewater converts to free ammonia, which enhances the ammonia stripping because ammonia is volatile.

Therefore, the stripping unit experiment aims to find an ideal but economic stripping pH.

The stripping unit experiment has two main objectives: to assess the stripping of ammonia at different pH levels to find the optimal pH and minimize the process cost, and to examine the pH change of the stripper due to the ammonia removal, as pH is an important parameter that should be maintained while removing ammonia. An ideal stripping pH was found to be at pH 10, as adding more base will not significantly remove more ammonia but would increase the process cost. Also of note, lower initial pH values have greater pH drops due to the ammonia removal. This can be explained by considering the buffering capacity, as higher pH solutions have higher alkalinity.

Low pH facilitates ammonia absorption but increases the cost due to the need of acid addition. Therefore, finding a suitable and economic absorbing pH is an objective of the absorbing unit experiment. A low pH in the absorber converts free ammonia to ammonium. Since NH_3 is more soluble in water than NH_4^+, converting NH_3 to NH_4^+ enhances ammonia absorption and ammonia recovery. Thus, the absorbing unit experiment also has two main objectives: to assess the absorption of ammonia at different initial pH values in order to find an appropriate and economic absorbing pH, and to examine the pH change of the absorber due to the ammonia absorption for process control purposes, as this helps to maintain the absorbing unit at the desired pH value.

Absorption of ammonia at pH 2 was significantly greater than at pH 4. This requires more acid to lower the process pH. Considering the pH change during absorbing, the pH rapidly increased due to ammonia absorbing for pH 2 and pH 4. Maintaining the pH in the absorber was the main challenge in the process design, as it sharply changes due to small amount of ammonia absorption. This suggests the need to modify the absorbing unit design to maintain the pH in the absorber.

Conclusions

The overall goals of the project (reducing the ammonia toxicity in anaerobic digestion and using the removed ammonia to produce fertilizer) can be achieved by designing a nitrogen recovery system. With optimal design and operation conditions, the recovery system can reduce the cost of the overall process. The stripping and absorbing of ammonia were examined at different pH values. The best pH for stripping was found to be 10 at 52 ^{o}C. For the absorbing unit, pH 2 solutions captured significantly more ammonia than those at pH 4. The absorbing unit results suggest that the recovery of nitrogen using a nitrified solution (which has a relatively high-absorbing pH, pH 7) might be limited due to the high-absorbing pH. However, the nitrified solution still has an economical advantage, as nitrification provides free acid.

These results also suggest that the pH in the absorber must be controlled, so a better process control is needed to maintain the pH. Ultimately applying these optimal conditions and design maximize the system's profit and performance.

This project is funded by Agricultural Experiment Station at Colorado State University.

Snow Surface Roughness Across Two Scales Considering Canopy Characteristics

Bradley M. Simms, Steven R. Fassnacht, and Eric S. Thomas
Ecosystem Science and Sustainability, Colorado State University

Bradley Simms

Bradley Simms is a recent graduate of the Watershed Science department at Colorado State University. He is continuing his education at the University of California, Davis in the Hydrologic Sciences master's program. His future research involves groundwater and surface water modeling in northern California with hopes of returning cold baseflow to streams for salmon migrations while also supplying local agriculture and municipalities. The following research was presented as part of the poster session at Hydrology Days and was awarded first place for undergraduate posters.

Introduction

Snow surface roughness is a measurement of micro-topographic variability of the snow surface structure at multiple scales. The physical roughness of the snow governs the transfer of wind energy to the surface, and its parameterization is crucial in the computations of the global energy balance—in climate models, and for estimating annual available water resources in the water-scarce West. Most current models assume the snow surface roughness to be a constant parameter. However, snow properties vary over many scales due to the variability in the interactions between the governing processes that controlling accumulation, metamorphism, and ablation (Deems et al., 2006). Identifying the natural scales controlled by these same processes may lead to more accurate estimations of small-scale snow surface roughness (SSR), which can in turn be used in complement with other tools, such as using remote sensing. This study builds on the methods of Fassnacht et al. (2009) with specific objectives to: 1) quantify the temporal variability of snow surface roughness at two scales; 2) quantify the spatial variability of SSR at two scales; and 3) compare spatial distribution patterns based on vegetation characteristics across the two scales, at the millimeter and meter resolution.

Data

Data from the NASA Cold Land Processes Experiment (CLPX) were used, including ground-based field measurements in the Colorado Rocky Mountains collected during four Intensive Observation Periods (IOPs) in late February and March of 2002 and 2003 (Elder et al., 2009). The Fraser Alpine one-square-kilometer intensive study area (ISA) was chosen due to its unique topography consisting of roughly 50% forest and 50% alpine (see Deems et al., 2006 for an aerial photograph of the ISA). The ISA was split into a ten-by-tengrid of equally sized blocks, and each was classified as forest or alpine using ArcGIS Pro to select land cover based on visual majority. Within each grid block, a meter-long snow surface roughness digital image was collected at a random location. Each measurement location remained consistent over each IOP. Airborne LiDAR data of the snow surface were captured at a native resolution of about 1.5 meters during IOP4 (March 25, 2003).

Methods

The image analysis technique developed by Fassnacht et al. (2009) was utilized to convert raw SSR board images into a detrended series of X, Y coordinates. The airborne LiDAR point cloud data were interpolated at a two-meter resolution using ordinary kriging, and then each grid block was detrended. From each snow roughness, the Random Roughness (RR), which is the standard deviation of the detrended surface, was computed. The RR of each of the 100 individual boards was compared for each IOP. The results

Table 1. Random Roughness board descriptive statistics for the entire Fraser Alpine study area, and the forest and alpine sub-sets area for the four different intensive observation periods (IOP).

	Entire Fraser Alpine ISA					Forest					Alpine				
Statistic	IOP1	IOP2	IOP3	IOP4	LIDAR	IOP1	IOP2	IOP3	IOP4	LIDAR	IOP1	IOP2	IOP3	IOP4	LIDAR
Max	15.62	11.27	22.90	26.30	3.76	9.51	10.21	9.03	14.08	3.76	12.49	11.27	22.90	26.30	2.78
Min	0.57	0.70	0.68	0.77	0.23	0.57	1.26	0.68	1.61	0.36	0.92	0.70	1.16	1.11	0.23
Mean	3.89	3.18	3.97	5.60	1.13	3.14	3.08	3.01	5.16	1.64	4.37	3.11	4.72	6.89	0.78
Std Dev	2.88	2.18	3.44	4.65	0.79	2.13	1.83	2.22	3.51	0.83	2.77	2.24	4.05	5.39	0.52
Median	2.91	2.56	2.83	4.22	0.96	2.41	2.60	2.25	4.48	1.66	3.66	2.54	3.04	5.21	0.63

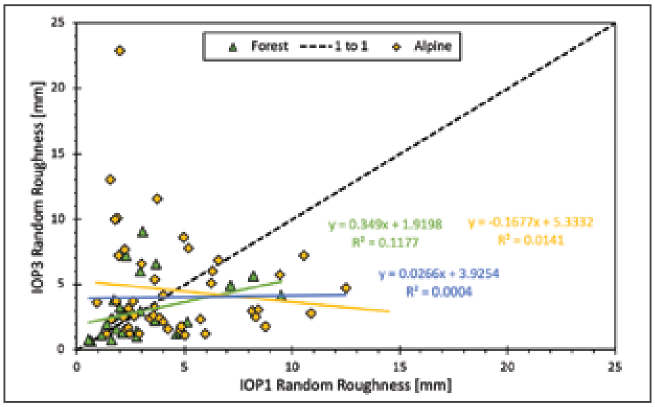


Figure 1. Random Roughness board comparison at identical locations for IOP3 and IOP4 split by land cover with best linear fit, and the best linear fit for all locations (blue line).

were then split into forest or alpine. Finally, the RR for each roughness board was compared to each LiDAR grid block.

Results

No temporal consistency in RR was observed at discrete, individual board locations across the entire study area or when they were split into forest and alpine pixels. Figure 1 shows the highest temporal correlation of identical board measurements over time. When looking at the entire distribution of RR across the one-square-kilometer study area, IOP1 and IOP3 showed similar RR, while IOP2 and IOP4 varied (Table 1). Split by land cover, the forested area displayed temporal consistency in RR, while the alpine area varied greatly over time (Table 1).

Across the entire study area distribution, the RR of IOP4 boards did not scale with the LiDAR snow surface (Table 1). When split by land cover, the forested area boards of IOP4 resulted in a relatively smooth surface, while the LiDAR showed a rough surface. The alpine area boards of IOP4 showed highly variable roughness, and the LiDAR exhibited relatively smooth surfaces when compared to the forested region (Table 1).

Discussion

Individual discrete board measurements showed almost no correlation over time and varied up to two orders of magnitude, further displaying that snow surface roughness is not constant. Across the entire study region distribution, IOP1 and IOP3 displayed similar mean RR, while IOP2 and IOP4 varied (Table 1). SNOTEL data closest to Fraser Alpine show that no snow accumulated three days prior to IOP1 and IOP3 measurements, while IOP2 and IOP4 measurements were collected immediately following large storm events. The varied physical properties of fresh snow versus snow that has interacted with wind may have greatly affected redistribution patterns and the surface roughness.

Wind redistribution following large storm events blows less dense, fresh snow, which may describe high mean RR for IOP4, while a lack of wind redistribution leaves a smooth snow blanket over the surface, which may describe the low mean random roughness across the study region for IOP2. The forested area saw lower and more temporally consistent board RR when compared to Alpine area across all IOPs (Table 1).

Consistent topography, vegetation, and wind sheltering within the sub-coniferous pine forest may allow for similar roughness characteristics throughout. Conversely, the exposed tundra experiences high wind speeds that produce highly variable surface roughness. While the board RR saw some temporal consistency split into land cover, the scale comparison with LiDAR did not. LiDAR roughness showed the opposite effect: high RR in the forest and smooth RR in the alpine region. The relatively coarse two-meter LiDAR resolution likely captured the variability of snow accumulation around the trees at different points and clumped the wavelike variability of the open alpine region. Board measurements consisted of a much smaller area within the forest and alpine regions and saw different scales of roughness variability. A future fractal analysis would determine whether the differing observed roughness values at the two scales are driven by the same physical processes.

Conclusion

This study aimed to quantify the spatial and temporal variability of snow surface roughness using the random roughness at two scales and evaluate the spatial distribution patterns over time by analyzing physical properties of land cover. Results suggest that snow surface roughness is highly variable over time and space; however, land cover may play a large role in the processes driving the spatial structure of the snow at various scales. Results indicate that snow surface roughness should not be treated as a constant value in hydrologic and climate models. Values over time and space vary up to two orders of magnitude and can affect model accuracy. Further research will include a fractal analysis between each board and LiDAR grid block to determine if the same processes are driving the varied roughness found in each land cover. Additionally, the analysis will be expanded to other locations throughout the Colorado Rocky Mountains to evaluate whether or not similar situations exist elsewhere.

Predicting the Impact of Soil Salinity on Crop Production: A Look at Traditional and New Approaches

Ansley J. Brown and Allan A. Andales, Soil and Crop Sciences, Colorado State University
Timothy K. Gates, Civil and Environmental Engineering, Colorado State University

Ansley Brown

Ansley "A.J." Brown is a Ph. D. Student at Colorado State University advised by Dr. Allan Andales and co-advised by Dr. Timothy Gates. He studies irrigation water and soil salinity management, crop growth and water flow model augmentation, and low-cost environmental sensor development. The following research was presented as part of the Agricultural Water & Conservation Practices session at Hydrology Days and was awarded second place for oral presentations.

We use them in our foods for taste, on sidewalks to melt ice, and in our houses for drywall. Salts are some of the most commonly used minerals found on the planet; yet, not many of us think of them as a threat to our global food security. Just as humans cannot drink salt water, plants have difficulty extracting water they need from the soil when too many salts accumulate in their root zones. It is estimated that nearly 2,800 soccer fields' worth of food-providing land is degraded each day around the world because of the over-accumulation of salt in farm ground as a result of poor irrigation management, inadequate drainage, and contaminated groundwaters. Scientists have identified ways to quantify crop yield losses due to salty soil through plot-based and greenhouse experiments involving different concentrations of salt. But what happens when these experiments are scaled up to a large field or an entire farm level, where there are many more factors controlling growth such as drought, irrigation amounts, fertilization, and weather? Often, it is too time-consuming and laborious to collect enough soil samples and yield measurements to apply the salinity tolerance models from these experiments on a commercial level. The goal of this research was to find new techniques to quickly and reliably predict crop yield losses on larger scales using electromagnetic induction and advanced statistical techniques in the Arkansas River Valley in Colorado.

Figure 1. Image of the EM38-MK2 electromagnetic induction device, coupled with handheld computer and GPS for mapping soil salinity in a newly planted alfalfa field near Swink, Colorado.

Figure 2. Visual comparison of a corn cob grown in a highly saline area (left) compared to a healthy cob (right) grown in an area unaffected by excess salt accumulation.

Experimental Methods

Salts are electrolytes (just like the kind found in sports drinks), meaning that they can conduct electricity when dissolved. Electromagnetic induction allows us to estimate salt concentrations in the ground by sending electromagnetic waves into the soil with a very small current and measuring the magnetic fields produced by simply walking over the ground. The EM38-MK2 instrument from Geonics Limited was used tp take these readings (Mississauga, Ontario, Canada; Figure 1). Collecting a few soil samples in conjunction with this ensures that what we are detecting is soil salinity and not any of the other factors that affect electrical conductance in the soil (e.g., soil texture and moisture content). This process was used to observe salinity in two corn fields (approximately 40 acres each) at the study site, where a wide enough range of salinity was observed to be confident about the degree to which the crop would be hindered by the accrued salts.

At the end of the growing season, we needed to see the impact soil salinity had on the corn growth. To observe this, 40 locations in each corn field were selected to manually collect corn cobs for yield measurement. Sample locations were found in all levels of salinity in each field so that the full range of effect on crop growth could be captured (Figure 2). Corn was then shucked and dried in an oven to obtain dry grain weight (i.e., to eliminate the variability of moisture content across yield samples).

Results and Discussion

By comparing salt concentrations to yields found in each field, we have been able to adapt some of the traditional and newer crop salinity tolerance models developed in the plot and greenhouse experiments to function over much larger areas on real farms. Results show that corn yields can be accurately predicted in fields where soil salinization is already a known problem (Figure 3). This is because electromagnetic induction readings can be biased by soil texture and moisture, so ground truthing would be recommended. This new methodology provides a potential solution to the scaling issue presented above.

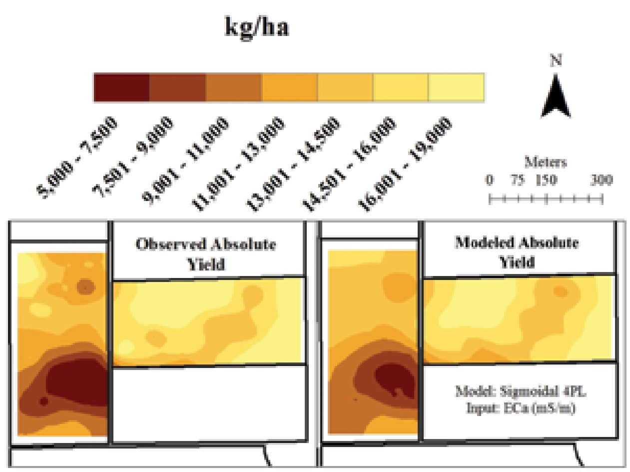


Figure 3. Maps of observed corn yield (left; kg/ha) from direct sampling compared to yield modeled using a sigmoidal four parameter logistic equation using EM38-MK2 derived bulk apparent soil electrical conductivity values as the predictor (i.e. no soil sampling performed).

Future research is moving forward with a focus on lowering the number of yield samples needed to obtain an accurate model, seeing if calibrated models will hold up over multiple growing seasons and accounting for different types of soil salts (specifically, the overestimation of soil salinity when gypsum salt is present) when predicting yield. This knowledge could provide a powerful management tool for farmers and agricultural consulting firms by providing insight about the need to change irrigation management practices or change crops to reduce salinity impact and allowing them to be more competitive in a local economy while simultaneously increasing global food security.

Evaluating the Effects of Green Stormwater Infrastructure on Urban Roadway Flooding

Katie Knight and Aditi Bhaskar, Civil and Environmental Engineering, Colorado State University

Katie Knight is a Masters student in Civil and Environmental Engineering at Colorado State University performing research on Green Stormwater Infrastructure (GSI) impacts on roadway flooding under Dr. Aditi Bhaskar. Katie received her Bachelors in Civil Engineering from the University of Washington in 2018, where she focused on hydrology and hydrodynamics. The following research was presented as part of the poster session at Hydrology Days and was awarded second place for graduate posters.

Green stormwater infrastructure (GSI) is a type of stormwater infrastructure that uses infiltration or harvest-based methods to reduce or delay runoff that enters the traditional stormwater network during a storm event. GSI is a broad category that includes detention ponds, vegetated and non-vegetated swales, rain gardens, green roofs, rain harvesting, permeable pavements, and bioretention cells (U.S. EPA, 2018). The effectiveness of single or small-scale GSI networks has been widely studied, but the impacts of GSI networks at an urban watershed or catchment scale have not yet been established (Jefferson et al., 2017). Studies of single or small-scale GSI networks have found that GSI is effective in mitigating the runoff of smaller storm events but lacks the capacity to mitigate larger storms (Qin et al., 2013).

Roadway flooding often occurs in urban environments due to the overloading of stormwater systems during storm events. Roadway flooding caused by overloaded stormwater networks can be catastrophic, causing damage to infrastructure and private property and an increased risk to human safety, but often flooding is less dramatic. Smaller-scale flooding, typically with depths below two feet, is referred to as nuisance flooding. Nuisance flooding does not result in impassable roads and rarely causes catastrophic damage; however, the effects of hazardous driving conditions and the load on infrastructure caused

Katie Knight on site at Little Dry Creek in Westminster, CO. Photo by Aditi Bhaskar.

Little Dry Creek at Westminster Station, part of the study location. Photo by Aditi Bhaskar.

by nuisance flooding are cumulative. A study examining the impact of nuisance flooding due to increased tidal inundation on the East Coast estimated that over 100 million vehicle-hours of traffic delays occurred due to the flooding in 2018 (Jacobs et al., 2018). This study will look at the effect of implementing a GSI network in Westminster, CO, on the occurrence of roadway flooding due to lower intensity, more frequent storm events.

To examine the impact of GSI networks on roadway flooding, a stormwater model for a catchment in Westminster, will be developed in PCSWMM, which is a software that uses the current version of the EPA's Stormwater Management Model (SWMM5) (CHI Water, 2018). First, a model of the current stormwater network is being developed using information in GIS and as-built documents provided by the City of Westminster. To decide where to add the theoretical GSI network to the stormwater model, critical link analysis will be used in combination with input from the City of Westminster's future stormwater management goals. Critical link analysis is a technique that uses results of a flooding model and traffic data to determine what areas of a stormwater network pose the greatest risk of impacting traffic due to flooding. Mitigating flooding at these critical links has been found to have a disproportionate effect on the overall impact of a storm event on traffic delays (Pregnolato et al., 2016b). A dual-drainage modeling approach will be utilized to capture the interaction between the subsurface stormwater drainage system and the surface overland flow pathways.

The goal of this study is to evaluate the effectiveness of a realistic GSI network at mitigating roadway flooding at a catchment scale. The extents of the stormwater model were determined by outlining the extent of the stormwater network in Westminster that drains to Little Dry Creek in between two USGS stream gages. These extents were carefully selected as the difference between the streamflow at the two gages allows for calibration and validation of the model. Additionally, the roadway flooding results will be compared to a compilation of social media posts and citizen science reports using Flood Tracker (anecdata.org/projects/view/556), which show events of roadway flooding by comparing model outputs to co-located reports. The results of this model evaluation and GSI impacts on roadway flooding will be used as inputs for a probabilistic traffic model to analyze the effect of roadway flooding on traffic patterns under hazardous conditions. This study is part of a growing field of research examining how management practices, such as GSI networks, can improve the resiliency of our urban systems.

A Hydrologic Analysis of Big Bear Creek Watershed in Iowa

Lily Conrad, Environmental Science, University of Northern Iowa
Steven Fassnacht, Ecosystem Science and Sustainability, Colorado State University

Lily Conrad graduated with a BS in Environmental Science from the University of Northern Iowa in May 2019, where she was mainly involved in water quality monitoring projects (Figure 3). Looking for more experience with data management and hydrologic modeling, she and Steven found common ground with Big Bear Creek watershed in central Iowa. The following research was presented as part of the poster session at Hydrology Days and was awarded second place for undergraduate posters.

Lily Conrad

Introduction

The Big Bear Creek (BBC) at Ladora watershed in Central Iowa drains 489 square kilometers of mostly agricultural land (Figure 1). This watershed was selected due to its "textbook" hydrologic processes—in particular, the rapid increases in streamflow in response to a rainfall event that is followed by a first-order decay recession (Figure 2). Currently, the land cover for this watershed is predominantly corn and soybean fields. Changes in streamflow characteristics were assumed to exist if climate change and/or land cover change has occurred over the more than 70-year period of record. Since land cover change was not assessed in this particular study, changes in runoff were compared to changes in precipitation, as the difference between the two, which is assumed to be evapotranspiration, and as water yield, which is the annual ratio of runoff to precipitation.

Methods

Historical daily streamflow data for BBC were downloaded from the USGS National Water Information System (nwis.waterdata.usgs.gov) for the 73 water years (October 1 to September 30 of any given year) from 1946 to 2018. Historical data were obtained from the NOAA National Climatic Data Center (ncdc.noaa.gov) for the Grinnell meteorological station, measured for 68 years from 1948 to 2018.

To investigate the streamflow recession after a rain event, a first-order decay function was fit to several peak flow events. This function was a reasonable fit, so to improve the fit, a linear segment was added (Figure 2c). Trends were analyzed using the Mann-Kendall test for statistical significance and the Theil-Sen's slope estimate (Gilbert, 1987). These tests are non-parametric analyses (i.e., they do not assume a specific probability distribution function). The MAKESENS macro (Salmi et al., 2002) was used to run the two statistical tests.

From these analyses, the statistical significance of each change (confidence level of $p<0.1$), the rate of change, and decadal slopes were computed for the BBC peak streamflow, mean runoff, and 7-day low flow. From the Grinnell meteorological data, trends in the annual precipitation, days with precipitation, and maximum and minimum temperatures were also computed. The subsequent correlation between runoff and precipitation were used to illustrate the evapotranspirative influence and the water yield (Table 1).

Results and Discussion

Mean and 7-day low flow values exhibited significant increase within BBC, whereas maximum streamflow change was not significant (Table 1). The amount of annual precipitation and number of days with precipitation (approximately five days more per decade) also increased significantly

Figure 1. Big Bear Creek watershed in central Iowa (inset) across Poweshiek and Iowa counties draining into the Iowa River. The meteorological station at the Grinnell airport is shown.

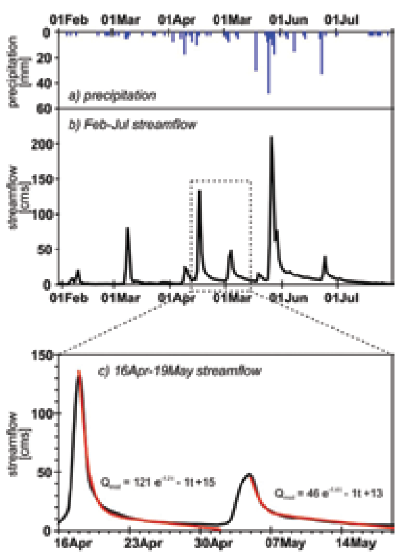


Figure 2. February through July 2013 a) daily precipitation at Grinnell and b) streamflow on Big Bear Creek, c) highlighting two storms in April and May 2013. A modified decay function is presented to model the recession limb of the storm hydrographs. Precipitation data are from the National Weather Service (ncdc.noaa.gov) and streamflow data are from the US Geological Survey (nwis.waterdata.usgs.gov).

over the period of record, while the temperatures were cooling, but not significantly (Table 1). Annual precipitation is increasing (approximately 21 millimeters/decade) at a greater rate than mean runoff (approximately 18 millimeters/decade), but the evapotranspiration increase of less than one millimeter/decade (not significant) did not account for the trend difference between precipitation and runoff. Further, the water yield significantly increasing by 1.7% per decade does not explain the trend difference. Future work will analyze precipitation trends for other stations in the area but must consider the much shorter period of record for most of these other stations. Subsequently, the meteorological data will be used to compute evapotranspiration, and land use data will be evaluated to understand changes over time.

Acknowledgements

The authors would like to express gratitude to the Vertically Integrated Project program (VIP.colostate.edu) at CSU for enabling this project's origin and collaboration.

Table 1. Summary of the Mann-Kendall significance test and Theil-Sen's slope estimate for the maximum, mean, and minimum 7-day low streamflow trends on BBC over the 73 water years of record from 1946 to 2018, and the Grinnell meteorological station for precipitation and temperature. N/S represents a trend that is not significant.

	significance	slope [per decade]	y-intercept
BBC 1948 to 2018 (73 years)			
peak streamflow [m^3/s]	N/S	0.898	80.7
mean runoff [mm]	$p<0.05$	17.6	2.79
7-day low flow [m^3/s]	$p<0.001$	0.0380	0.075
Grinnell 1949 to 2018 (68 years)			
annual precipitation [mm]	$p<0.1$	21.2	816
days with precipitation	$p<0.001$	4.8	84.2
maximum temperature [C]	N/S	-0.12	15.3
minimum temperature [C]	N/S	-0.03	2.56
precipitation and runoff comparison			
ET = P – R [mm]	N/S	0.854	643
WY = R/P [%]	$p<0.05$	1.69	0.199

Erin Dougherty is a Ph.D. candidate in Atmospheric Science at Colorado State University working with Dr. Kristen Rasmussen to study floods in a future climate. Their research was presented as part of the Global Environmental Change session at Hydrology Days and was awarded third place for oral presentations.

Erin Dougherty

Flood-Producing Storms in a Current and Future Climate Using High-Resolution Convection-Permitting Solutions in the United States

Floods are a major hazard across the world and are the second deadliest weather-related disaster in the continental United States (CONUS). Single flood events can cause massive destruction, with flooding from Hurricane Harvey (2017) alone resulting in $125 billion in damage. As population is projected to increase in flood-prone areas, and rainfall is expected to intensify in a future, warmer climate, it is expected that future floods will also become more severe. However, the regional details of how flood-producing storms might change in the future has not been explicitly examined. Thus, the goal of our research was to fill this gap by examining how the rainfall characteristics in flash flood-producing storms over the CONUS will change in future climate.

A flood-producing storm climatology over the CONUS from 2002-2013 developed by Dougherty and Rasmussen was used to select the top 25% most intense cases to examine in high-resolution (4-km) convection-permitting simulations. These simulations were continuous 13-year runs (2000-2013) and included the current climate forced by reanalysis data and a pseudo-global warming simulation, with a climate delta signal added to the reanalysis data to produce a realization of a future, warmer climate. These simulations show that future flash flood-producing storms produced more rainfall, particularly in the Southwest, Mid-Atlantic, and Southern Great Plains regions (Figure 1). The change in future rainfall was greater than change in storm area or duration, which were minimal. Results suggest that cities in the CONUS need to prepare for more intense future flash floods and that policy-makers and water managers need to take these results into account when updating water infrastructure.

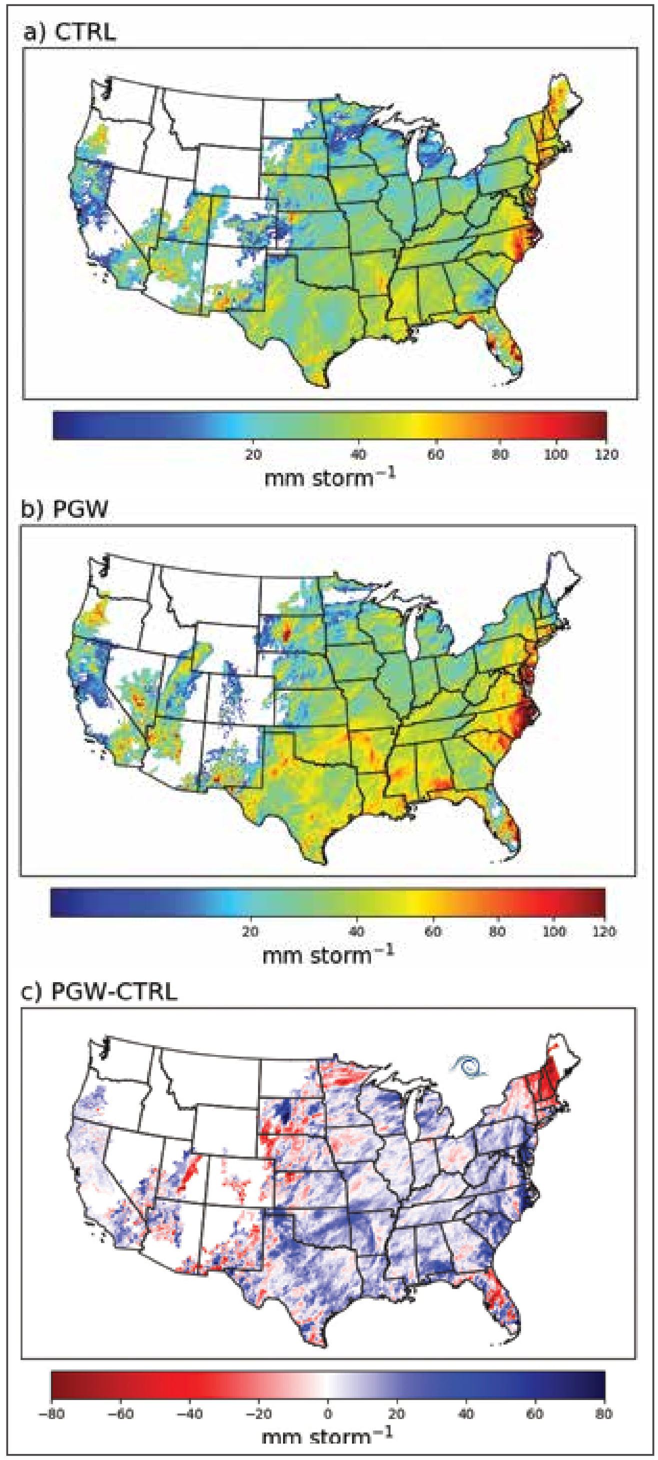


Figure 1: Average flash flood rainfall per storm over the continental United States from 2002-2013 in a) the current (CTRL) climate, b) the future (PGW) climate under the Representative Concentration Pathway (RCP) 8.5 emissions scenario, and c) the difference between the future and current climate (PGW-CTRL).

Zach Ferrie is an M.S. candidate with Colorado State University's Center for Contaminant Hydrology. His research interests include the Internet of Things (IoT) and big data processing as they pertain to contaminant hydrology. His research was presented as part of the Groundwater session at Hydrology Days and was awarded third place for oral presentations.

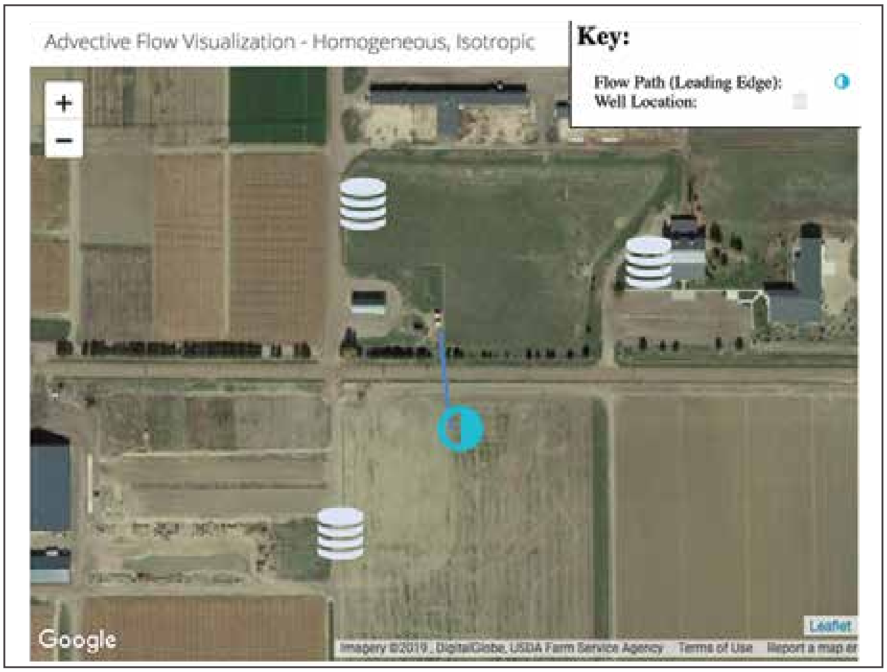


Figure 1. Real-time groundwater flow visualization. The blue line represents the historic groundwater flow path with the blue half circle representing the current location. Photo by Zach Ferrie.

Real-Time Visualization of Advective Groundwater Flow

As the understanding of our world increases we have found that previous releases of contaminants into soil and groundwater have adversely affected human health and the environment. As these contaminated sites mature, sometimes the best practice is to contain the contaminants and let them naturally degrade. In addition there is always the potential for mistakes to be made and contaminant releases still occur today. Long-term monitoring is becoming the primary factor governing how funds are spent to this end. Current best practices include either collecting data by hand or deploying pressure transducers and periodically returning to manually download the data. Unfortunately, infrequent data collection and processing is not conducive to timely responses to adverse conditions.

Figure 2. Zach installing a real-time sensor system at CSU's Agricultural Research, Education, and Development Center (ARDEC). Photo by Kelsey Provost.

By developing low-cost, cellular-connected data acquisition systems, large amounts of data can be gathered and processed in real-time. This reduces monitoring costs and quickens response times to adverse conditions. At CSU's Agricultural Research, Development, and Education Center (ARDEC), a preliminary study showed the benefit of these developments. Figure 1 shows the flow path of groundwater over time, which could be used to estimate the direction and rate at which groundwater contaminants move in real-time. The study also estimates the deviation from the estimated flow path due to instrument error. In this study, instrument error is shown to have little effect on altering the possible range of flow paths. Since sensors drift and become more inaccurate over time, the simulation can instead be used to estimate how many years it will take for sensor drift to effect the estimated flow path, causing it to become unreliable, giving one a better idea of when instrumentation needs to be replaced. This can save money or prevent inaccurate data from being used to make decisions.

Another novel addition is the integration of real-time alerts. By automating various alerts, site managers can be notified when conditions reach a threshold indicating the possibility of contaminants escaping site boundaries and entering the greater population. This allows for action to be quickly when the event occurs and can lead to greater safety for the public and save sites from costly mistakes.

Student Awards—Third Place Winners

HYDROLOGY DAYS

Marissa Karpack is a second year Master's student in Civil and Environmental Engineering at Colorado State University. She works with Dr. Ryan Morrison to study how people affect floodplain function. Their research was presented as part of the Global Environmental Change session at Hydrology Days and was awarded third place for oral presentations.

Marissa Karpack

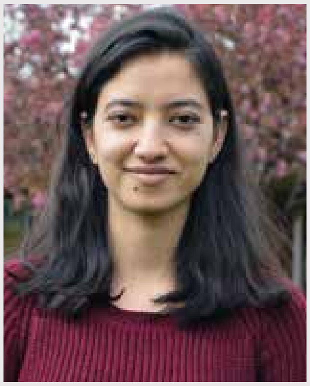
Quantitative Assessment of Floodplain Functionality Using an Index of Integrity

Floodplains are unique and vital ecosystems that are also among the most threatened landscapes globally. Floodplains perform a variety of functions, which include attenuating floods, connecting groundwater, regulating sediment, organics, and solutes, and providing habitat for a myriad of plants and animals. However, despite the important role that floodplains play in riverine ecosystems, humans have drastically reduced floodplain functionality by altering the landscape and river hydrology. To restore floodplains, a necessary first step is to understand where and how much human alteration has occurred.

We developed a methodology to assess floodplain integrity—the ability of a floodplain to perform essential functions—at a large spatial scale. Our method focused on using publicly available spatial datasets to measure the prevalence of stressors that reduce floodplain integrity. Using datasets that already exist instead of field studies means that this methodology can provide information about large regions, which we demonstrated by evaluating floodplain integrity for the entire state of Colorado. We computed a metric that quantifies reductions in floodplain functionality, mapped this metric for floodplains across the state, and then analyzed the results for patterns in floodplain health. Generally, we found that floodplains lower in the basin and in urban areas have more altered functionality.

Mapping of floodplain integrity in Colorado can help target restoration efforts to the areas and functions that are most in need. Additionally, this methodology was developed to be transferable so that it can be used to evaluate floodplain integrity in other regions, leading to more effective floodplain restoration projects—which in turn leads to healthy, functional floodplains.

Sujana Timilsina is a Master's student in Civil and Environmental Engineering at Colorado State University. She is a Fulbright Scholar from Nepal working with Drs. Jeffrey Niemann and Sara Rathburn to explore the hydrologic processes associated with soil saturation and debris flow initiation during the September 2013 storm in the Colorado Front Range. Their research was presented as part of the Hydrologic Systems session at Hydrology Days and was awarded third place for oral presentations.



Sujana Timilsina

Modeling Hydrologic Processes Associated with Soil Saturation and Debris Flow Initiation During the September 2013 Storm, Colorado Front Range

The extreme rainfall during September 9-13, 2013, resulted in more than 1,100 debris flows in the Colorado Front Range. Seventy-eight percent of those debris flows occurred on south-facing slopes (SFS). One reason for this pattern of debris flow occurrence may be that SFS were more commonly saturated than north-facing slopes (NFS) during the storm, as observed from limited soil moisture observations. This pattern of soil moisture contrasts with the pattern observed during the dry conditions, under which NFS are wetter than SFS. The objectives of this research were to explore the hydrologic mechanisms behind the saturation of SFS during the storm and determine the importance of soil moisture patterns in the initiation of debris flows. The Equilibrium Moisture from Topography, Vegetation, and Soil (EMT+VS) model was used to calculate the fine-resolution soil moisture pattern during the storm for an area in the Front Range covering 63% of the debris flow initiation locations. The model was used to test five hypotheses: (1) higher rainfall rates, (2) lower interception rates, (3) lower porosity, (4) thinner soils, and (5) reduced groundwater recharge on SFS. An infinite slope stability model was also used to generate factor of safety maps using the output from EMT+VS model. The results suggested that the primary reasons for wetter SFS were lower interception and groundwater recharge on SFS. However, the soil moisture pattern played a secondary role in comparison to vegetation and slope in the debris flow initiation pattern.

Figure 1. Snow manipulation chambers and monitoring instrumentation at the Mill Creek research site in Horsetooth Mountain Park. Photo by Alyssa Anenberg.

Alyssa Anenberg is a Watershed Science Master's candidate in Ecosystem Science and Sustainability at Colorado State University. Her research focuses on linking snow persistence and biogeochemistry in mountain regions and understanding the associated impacts of climate change on catchment hydrology. Her research was presented as part of the poster session at Hydrology Days and was awarded third place for graduate posters.

Figure 2. Alyssa Anenberg hiking in field equipment for installation at the Mill Creek research site in Horsetooth Mountain Park.

Figure 3. Tension lysimeters installed at the Mill Creek research site collect soil water following snow melt events. Photo by Alyssa Anenberg.

Effects of Snow Persistence on Soil Moisture and Soil Water Nitrogen along the Colorado Front Range

In the western United States, climate warming directly affects snowpack dynamics, resulting in decreased snow cover and earlier snowmelt. Prior research has shown that the timing and magnitude of snowmelt is an important control on soil water and nutrient availability, however snow and soil water dynamics in lower-elevation regions are not as well documented. The goal of this research is to understand how the duration of snow persistence affects soil moisture across an elevation gradient and how this gradient in snowpack affects soil water nitrogen.

Three research sites were established in the Colorado Front Range to monitor snow, soil moisture, and soil water nitrogen. The highest elevation site, Michigan River, is located in the persistent snow zone; the middle elevation site, Dry Creek, is in the transitional snow zone; and the lowest elevation site, Mill Creek, lies in the intermittent snow zone. Each site was equipped with soil moisture probes at five and 20 centimeters depth, soil temperature probes, snow depth poles monitored by time-lapse cameras, and ion exchange resin probes. The Mill Creek research site also contained nine snow manipulation chambers and 27 tension lysimeters to sample soil water nitrogen.

Results showed that snow persisted for longer periods of time as elevation increased and temperatures decreased. On average, soil moisture was greater at 20 centimeters depth than at five, and peak soil moisture occurred shortly after peak snow depth, coinciding with increased snowmelt. Ion exchange resin probe results showed that the highest nitrogen values were observed in June, during peak snowmelt when soil moisture was highest. Our hope is that this research will increase our understanding of how changes in the duration and quantity of snowpack affect the supply of soil water nitrogen in these mountain regions.

Student Awards—Third Place Winner

HYDROLOGY DAYS

Cibi Chinnasamy

Cibi Chinnasamy is a PhD student in Civil and Environmental Engineering at Colorado State University. Coming from India, a country of a billion people, he wants to understand the story behind water in cities. His research was presented as part of the poster session at Hydrology Days and was awarded third place for graduate posters.

Characteristics of Water Use Across 124 Urban Centers in the USA: What Did We Learn?

Globally, planning for future projections of urban water demand under the implications of extreme climate variations and population growth trajectories is becoming a major challenge to ensuring cities' sustainability. Resiliency of an urban water system depends on the physical availability of water, infrastructure and technology to use water efficiently, and the institutional agencies to bring equity in water management across different social and economic strata. By characterizing the historical patterns of municipal end-water uses in the residential and commercial, industrial, and institutional (CII) sectors, Cibi and his research cohorts have created temporal models to forecast urban water demand largely driven by population growth. Then, by incorporating different climate, land use, and socio-economic projections into this water demand model, they are able to take a glimpse at a range of possible future states of water systems ideal for a city. Equipped with this information, an array of water conservation and reuse strategies can be optimally designed and implemented for cities in different climatic and socio-economic clusters. But, challenges arise when one begins to start characterizing municipal water use across global cities, because unlike in the U.S., it is not common for many global cities to have piped, uninterrupted municipal water supply for domestic use. The vision for this research team is to characterize the nature of the global municipal water supply-demand chain and provide scenario-based pathways to safeguard our future cites by encouraging smart water use practices, designing efficient technology, and ensuring equitable functioning of institutions to enhance the resiliency and improve the well-being of life in the cities.

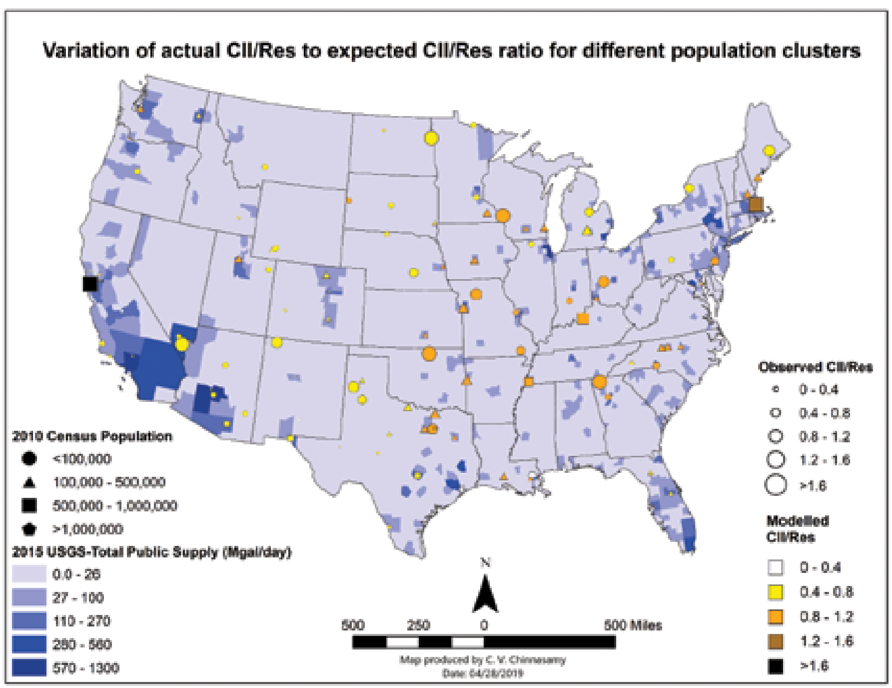


Figure 1. Map of the contiguous USA showing the variation in the CII to residential water use (CII/Res) ratio with the modeled CII/Res ratio across 125 cities. The CII/Res ratio is also represented in relation to the population size of the city.

Student Awards—Third Place Winner

HYDROLOGY DAYS

Danny White is a Master's student in Civil and Environmental Engineering at Colorado State University. Through his research, Danny aims to link hydrogeomorphic and ecological processes in riparian systems to inform the scientific practice of river rehabilitation. His research was presented as part of the poster session at Hydrology Days and was awarded third place for graduate posters.

Danny White

Sorting Patterns in Curved Channels: Flume Experiment Observations

Meandering rivers tend to exhibit bed surface sorting patterns, with coarse particles located in pools and fine particles located on bar tops. The mechanism by which this pattern emerges, particularly in gravel-bed rivers, remains poorly understood. We are conducting an ongoing flume experiment at the Colorado State University Hydraulics Laboratory in which channel bed morphology, flow velocity, and bedload transport have been precisely documented in a single-bend meandering channel with mixed particle-size gravel. The experimental channel is 1.35 meters wide, 15.2 meters long, and its centerline follows a sine-generated curve with a crossing angle of 20 degrees. Water and sediment input were held constant throughout the experiment at 104.8 liters per second (L/s) and 230 kilograms/hour (kg/h), respectively, and measurements were collected under quasi-equilibrium conditions, once the sediment input and output were approximately equal and the bed was essentially unchanging.

Velocity data collected through the flume indicate the presence of expected secondary circulating currents that contribute to selective lateral sediment transport in pools. Measured bedload sediment transport was high in regions of greatest shear stress, a parameter linearly related to flow depth and velocity. The highest sediment transport rates transition from the right side of the channel to the left as it travels downstream through the meander bend.

Figure 1. The single meander bend gravel-bed flume in operation at the CSU Hydraulic Laboratory.

Through visual observation of the bed surface, we noticed distinct sorting patterns with large sediment particles in the pool. As we further analyze the data collected, an improved understanding of the relationship between flow and sediment transport in meandering gravel bed channels can enhance stream channel design and habitat restoration.

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Student Awards—Third Place Winner

HYDROLOGY DAYS

Julie Dauer is a senior in Watershed Science in Ecosystem Science and Sustainability at Colorado State University. Julie was drawn to the idea of greywater reuse when she became aware of the recent legislation changes in Colorado and studies how water conservation in the Southwest can be addressed through technological efforts. Her research was presented as part of the poster session at Hydrology Days and was awarded third place for undergraduate posters.

Julie Dauer

Table 1. History of recent relevant water reuse laws, legislation, ordinances, and goals.

Year	Laws, legislation, ordinances, or goals
2013	House Bill 13-1044 passed: State Legislature Authorized the use of greywater in CO
2015	CO Water Quality Control Commission adopted Regulation 86 which permits local government to adopt an ordinance authorizing the use of greywater
2016	Denver City Council passed an ordinance that make Denver one of the first cities in the state to allow the use of greywater for residential, commercial, and industrial purposes
2018	House Bill 18-1069 passed: Reclaimed water can now be used for toilet flushing
2020	Denver's 2020 Community Sustainability Goal for Water Quantity: hope to reduce per capita use of potable water by 22%

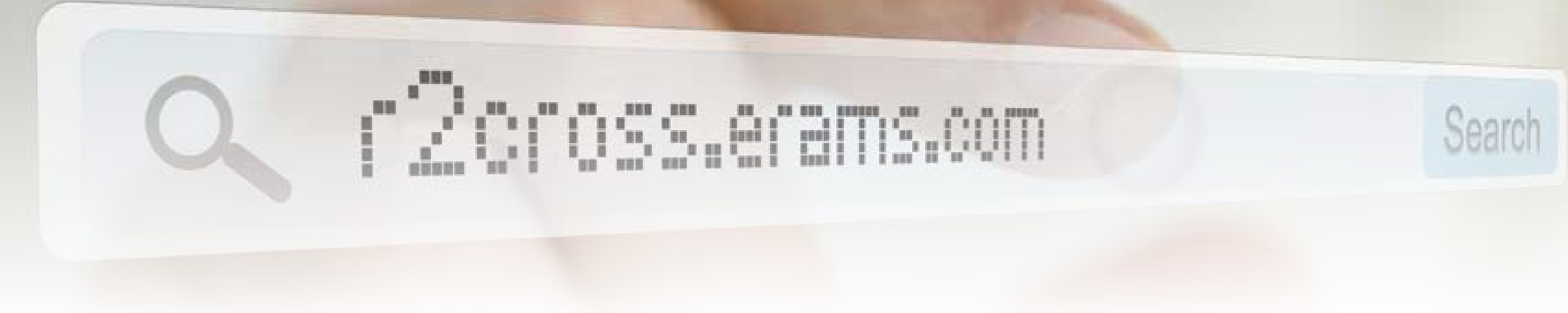
Table 2. Details of Colorado House Bill 18-1069 relevant to the Shower Water Reclamation System.

Section	Specifics
3	Defines 3 categories of water quality standards for reclaimed domestic wastewater, sets forth the allowable uses for each water quality standard category, and adds toilet and urinal flushing in multifamily residential and nonresidential structures as allowable uses for reclaimed domestic wastewater.
5	Authorizes the state plumbing board to promulgate rules governing the installation and inspection of toilet and urinal systems and structures for which reclaimed domestic wastewater is used.
6	Appropriates $25,054 in the 2018-19 fiscal year from the general fund to the department for use by the water quality control division to implement the bill.

A Shower Water Reclamation System To Address Colorado House Bill 18-1069

Across the United States, a person uses on average 235 liters of water per day for domestic purposes (Figure 1). Of this, about 25% is used for flushing toilets, while 19% is used by showering and 2% by bathing. People from areas of the world where flush toilets are not ubiquitous often wonder why high-quality, treated water is used to transport human bodily waste into the sewer system, and this research explored the potential to reuse shower and bath water for toilet flushing. Specifically, we examined new legislation in Colorado that now allows for some water reuse, an example system, related water quality issues, and the economics of implementation. An example shower water reclamation system (SWRS) would use a series of tanks and pumps (Figure 2a) to produce clean, treated water for showering and bathing, and the estimated cost for the system is $1,500. A similar system also considered reusing washing machine water in the toilet, which would flush greywater (Hodgson, 2012). At present, the price of water in the City of Fort Collins, CO, is $0.733 per cubic meter ($2.77/1,000 gallons) with a fixed price of $17.87 per month. Using an average use of 235 liters per day per person and 2.6 people per household (2019 data for Fort Collins of 165,080 people in 64,038 households), the average monthly household use is about 18,000 liters. Including the fixed price, this usage yields an average rate of $1.70 per cubic meter. By installing a SWRS, daily use savings would total $6.45 ($0.212 per day per household) (Figure 1). Using an approximate SWRS of $1,500 and an annual interest rate of 5%, the return period for Fort Collins is thus 13.5 years. In other cities where the water rates are higher—such as San Diego, CA, which has the second highest water rates in the U.S. (after Flint Michigan) and users pay 219% of those in Fort Collins—installing this system would have an ever shorter return period (just 7.3 years in the case of San Diego). While various assumptions have been made to determine the payback period, the authors feel that this is a viable project to reduce water use, and save money.

This project is part of the Vertically Integrated Projects program at Colorado State University (vip.colostate.edu).



Instream Flow Recommendations Web-Based Tool for Colorado

Panagiotis D. Oikonomou, Colorado Water Center, Colorado State University
Ryan R. Morrison, Civil & Environmental Engineering, Colorado State University
Rumpal Sidhu, One Water Solutions Institute, Colorado State University
Tyler Wible, One Water Solutions Institute, Colorado State University

Synopsis

The Colorado Water Conservation Board (CWCB) is responsible for determining instream flow rights in natural river systems throughout the State of Colorado. However, assessing how much water to leave in a water body to meet ecological instream needs for a reasonably healthy ecosystem is not a trivial task. The state currently uses the R2Cross method to determine the streamflow requirements for habitat protection. The R2Cross program estimates hydraulic conditions in the channel, at different flow depths, and compares them to habitat criteria to determine biological instream flow recommendations. The current article presents the development of a web-based version of the R2Cross model that offers a user-friendly, open-access interface for the CWCB and pertinent stakeholders who use the program. Additional features and enhancements were incorporated to the web-based tool that could further facilitate the evaluation of ecological needs at mountainous streams.

In the state of Colorado, all surface water and tributary groundwater are governed by the prior appropriation doctrine. It is a legal doctrine, which administers water rights based on the priority of beneficial use. Water is diverted from rivers and streams based on the water right system in order to satisfy multiple beneficial uses (agriculture, industrial etc.) related to human activities. In the 1970's there was a major public concern of the impact of anthropogenic activities to the environment and riparian health. At the time, there was a lack in the Colorado legal system to keep enough water in the streams in order to preserve the ecological functions. As a result, Colorado's Instream Flow Program originated in 1973 with the passage of Senate Bill 97 (SB 97). Under SB 97, the CWCB was vested with the authority to appropriate instream flow water rights in the State of Colorado (§37-92-102(3), C.R.S. (2002)). Instream flow water rights are held by the CWCB on behalf of the people of the State of Colorado to "preserve the natural environment to a reasonable degree." Today, the CWCB holds over 1,500 instream flow water rights covering approximately 8,500 miles of Colorado streams to help protect the natural environment.

Determining the minimum quantity of water for reasonably healthy ecosystems can be a challenging task due to hydraulic conditions, ecological criteria, and socio-economic considerations. In the State of Colorado, the R2Cross methodology is used to determine the streamflow requirements for habitat protection. It is based on one-dimensional geometric and hydraulic data collected in riffle habitat types. Riffles are defined as shallow sections in streams or rivers. They are the most vulnerable stream habitats types since they are the first to dry up in low flow conditions. The field data collected for a stream location consists of streamflow measurements, the cross-sectional channel geometry, the water surface slope, and steam bed's particle size distribution. The field data are used to model three key hydraulic parameters—average depth, average velocity, and percent wetted perimeter—and their levels are directly associated with the quality of health of the aquatic habitat.

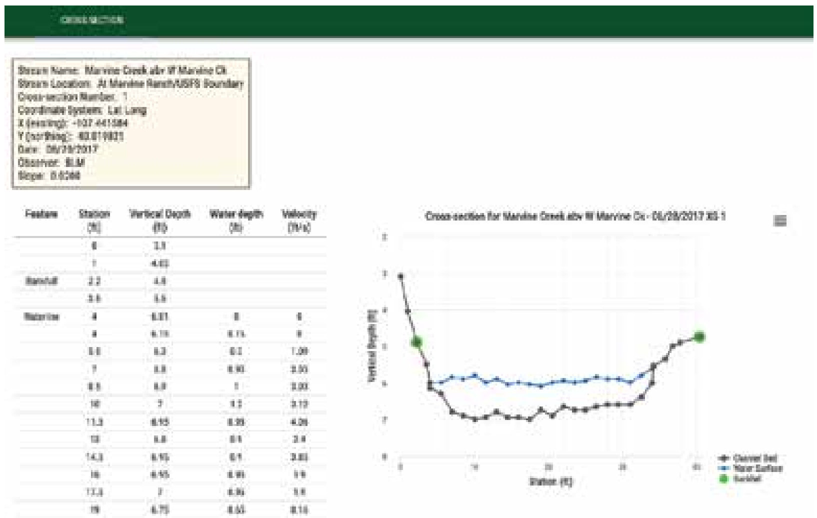


Figure 1: Cross-section tab showing information collected from the field data input form.

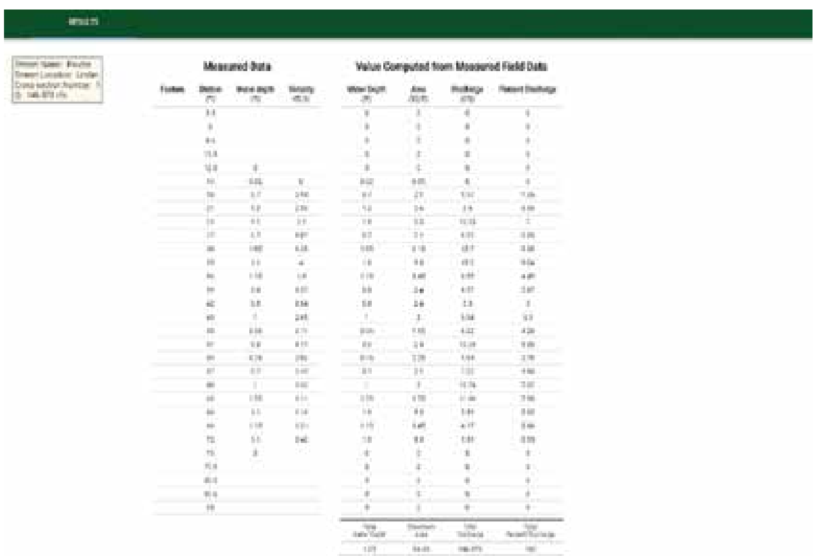


Figure 2: Results from the Discharge Calculator.

Figure 3: Results from the Particle Size Calculator.

R2Cross Update

R2Cross is a technique to determine minimum flows in a stream, and it has been used for the majority of the CWCB ISF appropriations over the last 45 years. We recently updated R2Cross with the purpose of providing a user-friendly, open-access interface for the CWCB and pertinent stakeholders who use the program. The updated R2Cross program is hosted in the eRAMS platform, an open platform supporting development of geospatially-enabled web applications for sustainable management of land, water, and energy resources. The tool is freely accessible at https://r2cross.erams.com.

The R2Cross model can be run using two different methods for calculating channel roughness. The default method is based on the variable-power resistance equation developed by Ferguson (2007; 2013), which considers depth adjusted roughness in the channel. The Ferguson method is the preferred approach in this update; however, if sediment size distribution information is not available, the user can use the Manning's equation to run the model. Along with this major update, additional features and enhancements were incorporated to the web-based tool that include:

1. Standard templates to import field data for the R2Cross model, discharge measurements, and pebble counts.
2. Dynamically generated figures and graphs illustrating cross-section information (Figure 1), R2Cross calculations, and habitat criteria selection.
3. A stand-alone Discharge Calculator that can be used to determine the discharge measured at a cross-section other than the one used in R2Cross. The results from the discharge calculator (Figure 2) can be used as a substitute discharge in the

R2Cross tool or can be used completely independent of the R2Cross tool.

4. A stand-alone Particle Size Calculator that can be used to determine statistical distributions of sediment sizes based on size classifications. The outputs from the particle size calculations (Figure 3) include a cumulative yield curve and sediment size histogram, a summary table by particle size type (i.e. sand and silts, fine gravel, etc.), as well as a summary metrics table of the sediment distribution including percent finer sizes (D50, D84), geometric mean, standard deviation, and gradation coefficient. Similarly, the results of the particle size calculator can be used completely independent of the R2Cross tool, or be used as input for the Ferguson method in the R2Cross tool.
5. Data layers and mapping tools to locate the cross-section and display information related to hydrography, stream gages, water right structures (Figure 4), and instream flow reaches (Figure 5).
6. Export tools for pdf reports, graphs, and Excel files of model output.

R2Cross outputs

The outputs of the main R2Cross program are displayed in four tabs, namely a Staging Table tab, R2Cross Summary tab, Supplementary Results tab and the Habitat Criteria & Results tab. The Staging Table displays hydraulic variables, calculated based on channel geometry and the roughness equation selected, for each stream stage between zero flow and bankfull (Figure 6). The next information R2Cros provides is a summary that compares measured and model cal-

Figure 4: Water right structures map (area shown: Fort Collins, CO).

Figure 5: CWCB map of instream flow rights (area shown: west of Horsetooth Reservoir near Fort Collins, CO).

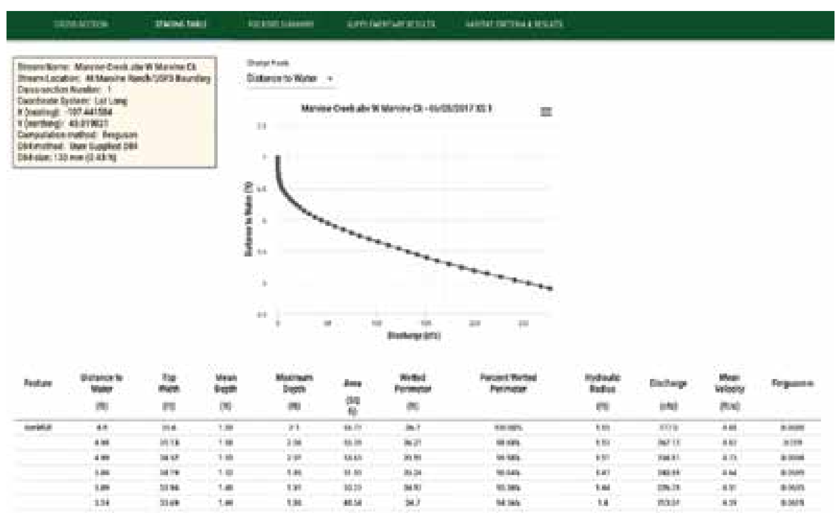


Figure 6: Example of information displayed in the Staging Table.

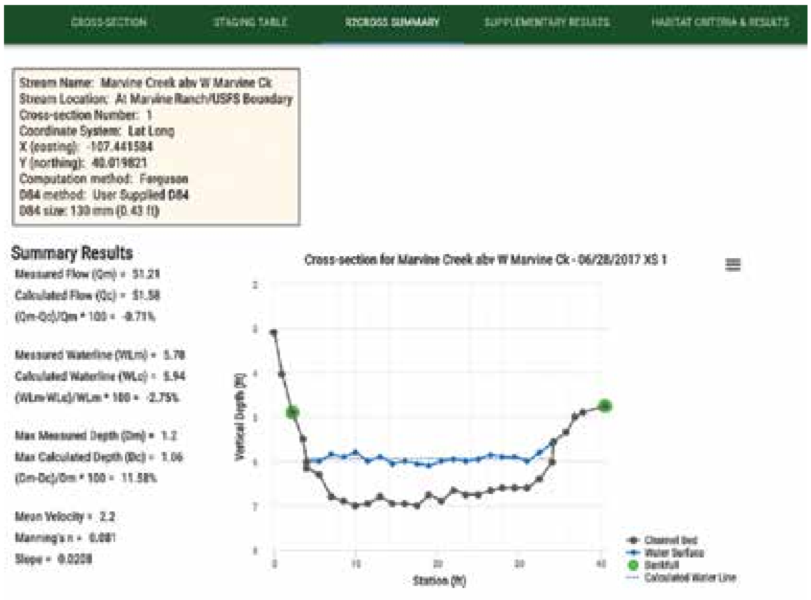
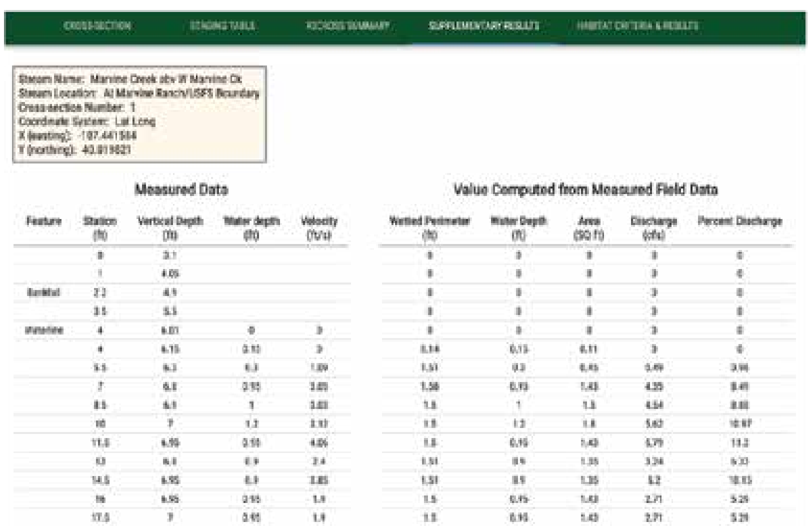


Figure 7: Example of information displayed in the R2Cross Summary.



Measured Data					Value Computed from Measured Field Data				
Feature	Station (ft)	Vertical Depth (ft)	Water depth (ft)	Velocity (ft/s)	Wetted Perimeter (ft)	Water Depth (ft)	Area (SQ ft)	Discharge (cfs)	Percent Discharge
	0	3.1			0	0	0	0	0
	1	4.05			0	0	0	0	0
Bankfull	2.2	4.9			0	0	0	0	0
	3.5	5.5			0	0	0	0	0
Waterline	4	6.01	0	0	0	0	0	0	0
	4	6.15	0.15	0	0.14	0.15	0.11	0	0
	5.5	6.3	0.3	1.09	1.51	0.3	0.45	0.49	0.96
	7	6.8	0.95	3.05	1.58	0.93	1.43	4.35	8.49
	8.5	6.9	1	3.03	1.5	1	1.5	4.54	8.88
	10	7	1.2	3.13	1.5	1.2	1.8	5.62	10.97
	11.5	6.95	0.95	4.05	1.5	0.95	1.43	5.79	11.3
	13	6.9	0.9	2.4	1.51	0.9	1.35	3.24	6.33
	14.5	6.95	0.9	3.85	1.51	0.9	1.35	5.2	10.15
	16	6.95	0.95	1.9	1.5	0.95	1.43	2.71	5.29
	17.5	7	0.95	1.9	1.5	0.95	1.43	2.71	5.29

Figure 8: Example of information displayed in the Supplementary Results.

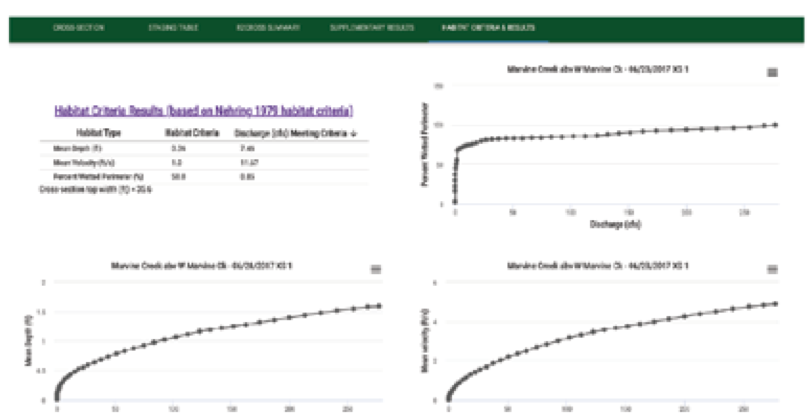


Figure 9: Example of information displayed in the Habitat Criteria & Results.

culated values. Measured variables refer to the characteristics measured in the field at the time the cross-section data were collected, while calculated variables are calculated by the model using the chosen equation (Figure 7).

The supplementary results tab contains two tables (Figure 8) that display: (1) measured data collected in the field (feature, station, vertical depth, water depth, and velocity), and (2) accompanying hydraulic variables calculated using the field surveyed data (wetted perimeter, water depth, flow area, discharge, percent of total discharge). Summaries of hydraulic variables are shown at the bottom of the table. The Habitat Criteria & Results output (Figure 9) contains a summary table of the three flow criteria based on the bankfull width of the R2Cross cross-section. This is a new key function that the updated R2Cross programs offers in order to facilitate decision process. The discharge necessary to meet the three hydraulic criteria is interpolated based on the staging table data. In addition, three dynamic graphs are included that show the relationship between these criteria and discharge. The table displayed in this tab allows the user to sort the results according to discharge.

Overall, it is believed that the web-based R2Cross tool's capabilities would assist State authorities and stakeholders to evaluate ecological needs at mountainous streams in order to make informed water management decisions that consider both socio-economic needs and preserving the natural environment.

Acknowledgments

This project was funded by the Colorado Water Conservation Board (CWCB). We appreciate the personnel of CWCB's Stream and Lake Protection Section for their collaboration and feedback throughout the development of the web-based tool.

Hydrology Days Extends Historical Legacy

Patricia J. Rettig, Water Resources Archive, Colorado State University Libraries

Photographs from the Colorado Water Resources Research Institute Records, Water Resources Archive, Colorado State University Libraries

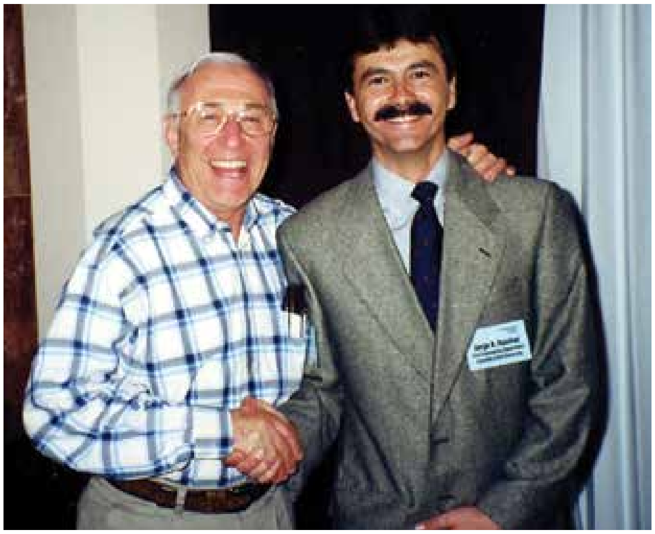
"I have often wondered for many years why (some) scientists from Denver, Boulder, or Fort Collins, for example, would travel long distances and incur large living expenditures to gather together and yet fail to meet locally. For this reason some of my colleagues and I have spearheaded this grassroots effort to promote scientific exchange at minimum cost."
– Hubert J. Morel-Seytoux

Hydrology Days, this effort spearheaded by CSU professor Hubert Morel-Seytoux, started in 1981 in the singular form—just one day on which to highlight current research on hydrology and related issues. The event gradually expanded to multiple days and successfully achieved Dr. Morel-Seytoux's original goals of reducing travel expenses and enabling student participation at a local professional meeting.

With these dual intentions of meeting locally and including students, Dr. Morel-Seytoux's creation of Hydrology Days carried forward Colorado State University's long-established strength in hydrological teaching, research, service, and engagement. It has now lasted nearly four decades, a testament to the success of the original impetus.

Held every spring, this professional event has expanded over time to include more student research as well as awards In addition to student awards, the Hydrology Days Award has recognized outstanding contributions to hydrology. In 1983, the inaugural awards went to Robert Glover, a civil engineer who developed mathematical equations applicable to groundwater flow analysis, including the formula bearing his name. In 2000, the award went to Dr. Morel-Seytoux, in part to recognize all of his work on Hydrology Days. Award recipients have also come from other universities, government, and industry in the U.S. and abroad.

The Borland Lecture, endowed by former Bureau of Reclamation employee Whitney Borland, became part of Hydrology Days in 2003 with the aim of bringing nationally and internationally recognized hydrology-related speakers to the event. The first Borland Lectures were by Jose Salas of CSU on "Characterizing the Dynamics of Drought" and John Dracup from the University of California at Berkeley on "Linking Drought Research to Water Resource Management Actions."



Hubert Morel-Seytoux congratulates Jorge Ramirez in taking over responsibility for Hydrology Days in 2000.

From the beginning, the American Geophysical Union (AGU) was a partner in Hydrology Days, with the event sponsored by the Front Range Branch, chaired by Dr. Morel-Seytoux. This group included members from Colorado, Wyoming, Utah, New Mexico, and Arizona. Meeting participation extended even further, demonstrating that people from beyond the region saw value in the event. While the main focus of the conference was on academia, individuals from government and industry also participated, including on the multidisciplinary organizing committee. In the 1990s, additional sponsors included the American Society of Civil Engineers and the American Water Resources Association.

Dr. Morel-Seytoux led the Hydrology Days effort through its first nineteen gatherings. Born in France in 1932, Morel-Seytoux was faculty in CSU's Civil and Environmental Engineering Department from 1974 to 1991, when he achieved professor emeritus status. By 1999, he was ready to pass the torch of Hydrology Days to someone new. A group came together to discuss such possibilities as having the AGU take the lead or having the event rotate among several institutions. It was soon decided that Hydrology Days was of great importance to CSU, as it provided a unique educational and professional experience for the students, as well as a time for the water faculty across various departments to come together.

Scientific discussions at Hydrology Days, undated.

Hubert Morel-Seytoux at lectern with Hydrology Days 1996 participant Sasa Tumic.

Hydrology Days 1996 was dedicated to CSU civil engineering professors Hsieh Wen Shen, Daryl Simons, and Everett Richardson, photographed with Hubert Morel-Seytoux (second from left).

In 2000, Jorge Ramirez took over the organization of Hydrology Days and managed the conference through 2018, transitioning the event this year to Mazdak Arabi. Dr. Ramirez has been a professor of Civil and Environmental Engineering at CSU since 1990, during which time he has made significant contributions to curriculum development and to the management of interdisciplinary research programs. Dr. Arabi has been a professor in the same department since 2007 and also serves as the director of the One Water Solutions Institute, which now sponsors Hydrology Days.

Ever since the second Hydrology Days, conference proceedings have been published, first as a traditional printed volume, then as electronic files and later online. Dr. Morel-Seytoux saw this as an important outcome of Hydrology Days, as much of the research represented state-of-the-art scientific results. Frequent themes among the papers show traditional hydrological topics along with increasing inclusion of technology applications, examination of how hydrology relates to current events such as drought, and growing interest in the leading experts of the recent past and their accomplishments.

Though typically not included in the proceedings, many Hydrology Days have featured prominent invited speakers, demonstrating the close faculty partnerships with state and federal agencies and using these to benefit students. Over the years, such speakers have included the Colorado Water Conservation Board director, the Colorado state engineer, the president of the Colorado Water Congress, a Colorado Supreme Court justice, and the manager of Denver Water.

Perhaps one of the few speeches still accessible is the one Denver Water manager Chips Barry gave in 1998, with the coincident April 1 date aiding his humorous approach to the topic "Hydrology in the Time of El Niño: A Fool's Errand?" The talk included Barry's summary of himself: "Actually—as you have no doubt concluded by now—I'm a hydrology, science, and computer moron. The titles of many of these [Hydrology Days] papers elude me completely. Thus it is only fitting that I should be the manager of one of the largest and most sophisticated water systems in the entire country." (CSU Hydrology Days, Chips Barry Papers, CSU Water Resources Archive http://hdl.handle.net/10217/90217)

While this was likely a memorable speech, there is no doubt that across the decades Hydrology Days has been significant to attendees, participants, and planners for a number of reasons. Future ones are sure to be the same. The year 2020 will bring both the 150th anniversary of Colorado State University and the fortieth convening of Hydrology Days. The institution and the event have long shared in the mutual benefits that carry forward an important part of CSU's water heritage.

For additional information on Hydrology Days, visit hydrologydays.colostate.edu or lib2.colostate.edu/archives/findingaids/water/wrri.html in the Water Resources Archive at Morgan Library.

Water Science and Engineering for Global Solutions: **A CSU Program of Research and Scholarly Excellence**

Neil Grigg, Civil and Environmental Engineering, Colorado State University

Water programs at the core of Colorado State's mission

As Colorado State University applies its missions in teaching and research, it engages with a diverse society with urgent needs in water resources management across the globe. From its earliest days, the university has recognized those needs and endeavored to address them in innovative and practical ways. This work provides a model for how a public university with a mission in engagement can assume unique roles to help with public issues.

The history of Colorado State's role is captured in the 1977 publication *Democracy's College in the Centennial State*, which explains how water knowledge has been a central theme at CSU since the 1870s, when Elwood Mead organized a course in irrigation engineering— the first course in water resources at Colorado State and even, perhaps, in the nation. Later, Mead, for whom the lake above Hoover Dam is named, laid the foundation for CSU's hydraulic engineering program. As another example, Charles A. Lory, the university's President from 1909 to 1940, had great influence on the school's water programs. He lived on a farm near Fort Collins and by age 15, he was working on irrigation tasks and was soon to be employed as a ditch superintendent. During the 1930s, his leadership was recognized on the national scene when he joined the National Resources Planning Board, with his name appearing on river basin studies of the period.

Fast forward to the 1960s, and we see that CSU's Hydraulics Laboratory had become a centerpiece of the water programs. International work ramped up as well: after India and Pakistan gained independence in 1947, there was a push to develop water project models, and several key dams were tested in the Hydraulics Laboratory. President William Morgan presided over the university's rapid post-war growth and served as chair of the Water Committee of the National Association of State Universities and Land Grant Colleges (NASULGC) at the time of the passage of the 1964 Water Resources Research Act. CSU's first doctorate in water resources was awarded to A. R. Chamberlain, who later became president and also served on the NASULGC water committee. During the tenure of president Albert C. Yates, the university's Water Plaza was built, and the Water Resources Archives were initiated in the Morgan Library. Also during President Yates' tenure, the Colorado Commission on Higher Education awarded the university for excellence in water resources programs, which were among the first set of CSU's Programs of Research and Scholarly Excellence (PRSEs).

Evolution of the PRSE in Water Resources

The idea behind the first PRSE in water resources was to create an organizing concept for university-wide water resources programs. Soon afterwards, this led to the CSU Water Center being organized in the mid-1990s, which became the focal point for this campus-wide effort. There was a natural organizational affinity between the Water Center and the Colorado Water Resources Research Institute (CWI), and the two entities were managed together. The two entities have now merged and are now called the Colorado Water Center, which is a division under CSU's Office of Engagement with support from CSU Extension, the Office of the Provost, the Agricultural Experiment Station, and the U.S. Geological Survey.

As the Water Center evolved during its first two decades, it took on the coordination missions that the initial PRSE proposed, and the PRSE began to focus on specific research issues. By 2010, its focus had shifted to environmental sustainability, and activity was focused on development of I-WATER, an ecological engineering program, and grant proposals that led to successful projects such as the CLEAN program (Center for Comprehensive, optimaL, and Effective Abatement of Nutrients) and the UWIN project (Urban Water Innovation Network). The PRSE funds were used to recruit graduate students and to acquire equipment for faculty research.

In 2017, the PRSE took on the name "Water Science and Engineering for Global Solutions". Its vision is to evolve into a highly effective and comprehensive research and scholarly hub at CSU with a focus on global water sustainability challenges. The idea is to capitalize on and advance CSU's strategic strengths in water science and engineering, while supporting the Colorado Water Center's mission of university-wide coordination of broad scholarly activity in water. The PRSE's work is envisioned to focus on the nexus of water sustainability and renewable energy in resource-constrained regions; future agriculture in rapidly urbanizing semi-arid regions; understanding change and transitions toward sustainability; and decision innovation and system integration.

These areas align with the direction of sustainability programs of major federal, state, and local funding agencies, such as the NSF Innovations at the Nexus of Food, Energy and Water Systems (INFEWS), USDA-NIFA Water for Agriculture, and EPA Safe and Sustainable Water Resources Strategic Research Action Plan. The PRSE will help to promote strategic projects for CSU faculty and students in the water, food, and energy sustainability arenas.

Recent PRSE activity

Recent participation in the PRSE program has been beneficial to the water research program in several ways. Perhaps most importantly, it has elevated CSU's water research mission and provided help to get projects supported.

Student support has been very helpful, beginning with use of annual funds provided through the Graduate School for student recruitment. PRSE funds were also used in 2018 to help support the 9th International Congress on Environmental Modelling and Software (iEMSs), a primary objective of which was to increase student participation by lowering fees as much as possible. This tripled student participation from previous years and helped overcome constraints on students participating from other parts of the country. Funds also supported ten student scholarships for on-campus housing, meals, and registration. The conference had 153 student participants from 88 institutions in 23 countries.

In addition to base support, the PRSE program offers the opportunity to compete for research grants, such as the CSU Water Information Systems for Education and Research (WISER) award.

More than 450 participants attended the event from over 230 institutions and 35 countries.

Under the theme "Modelling for Sustainable Food-Energy-Water Systems," the workshops held during the iEMSs Congress were helpful to train students and faculty with water modeling tools that can undergird future research efforts. These included SWAT-MODFLOW Coupled Surface-Subsurface Hydrologic Modelling; Modelling Uncertainty in Geographic Information Analysis; Introduction to SWAT+, a completely restructured version of the SWAT model; the eRAMS Web-based GIS Platform; the eRAMS Online Tools for Integrated Resource Management; and Web-Based Integrated Wind and Water Soil Erosion Simulation Tools.

As a further indication of how helpful the PRSE is to the water program at CSU, the 2019 Hydrology Days event offered its own showcase of student researchers and provided a supportive venue for students at different points in their careers to exchange ideas, give presentations and poster sessions, and enhance their scientific communication skills. More than 80 student presentations were scheduled over the three-day event, including 57 oral presentations and 28 poster presentations.

PRSE funds allowed any student to register for the event free of charge. This enabled the annual event to gain recognition as the leading water-related research event on campus. Some 57 student scholarships were also provided, with over 100 students from 11 institutions across four states and three countries. To encourage student participation in the event student awards were presented, and these are featured in this special issue of *Colorado Water.*

In addition to base support, the PRSE program offers the opportunity to compete for research grants, such as the CSU Water Information Systems for Education and Research (WISER) award. The goals of WISER, which is ongoing, are to develop cyberinfrastructure building blocks to collect, organize, and create accessible and scalable computing service for existing water and environmental modeling and analysis tools developed by CSU researchers and key partners; conduct workshops for students and researchers at CSU to deploy their data, analytics, and models as cloud computing web services; and promote CSU water and environmental programs as well as WISER technologies by providing dissemination and marketing opportunities at an international modeling and software congress.

Colorado Water Center Awards Innovative Research and Education Grants for 2019-2020 Academic Year

By Catie Boehmer, Salazar Center, Colorado State University

The Colorado Water Center conducts an annual call for proposals each January to provide seed grants for CSU faculty and researchers. The proposals are peer-reviewed by CSU faculty in a highly competitive pool. The proposals funded for 2019-20 academic year come from a broad range of disciplines, including engineering, natural resources, and agricultural sciences. These projects catalyze water research, education, and engagement through interdisciplinary collaboration and creative scholarship among CSU faculty and students. Congratulations to the awardees!

RESEARCH TEAMS

Harnessing the Power of the Crowd to Monitor Urban Street Flooding

Aditi Bhaskar, an assistant professor in Civil and Environmental Engineering, will lead a research team that hopes to harness the power of crowd-sourced monitoring to better understand urban street flooding. Not only will this method generate more robust on-the-ground data than is possible with sensors, this pilot project will also provide a foundation for integrating social media with a new Flood Tracker citizen science app (anecdata.org/projects/view/556).

Hydrologic drivers of peatland development and carbon accumulation in western Washington

John Hribljan, a research scientist in Forest and Rangeland Stewardship, and his team will investigate how peatlands in western Washington respond to changes in precipitation and temperature over time. Despite peatlands' significant role in global carbon storage, uncertainties remain in how these systems respond to hydrologic alterations from changing climate and land use. This research will inform regional wetland management and has far reaching implications for more northern peatlands.

The current and future state of water resources for the Colorado Rocky Mountains

Kristen Rasmussen, an assistant professor in Atmospheric Science, will use high-resolution modeling to investigate how predicted changes in climate will modify the snowpack and hydrology of the Rocky Mountains. By generating a better understanding of future snow dynamics—especially given snow's complex interactions with the atmosphere, land cover, and terrain—her team's work will also inform management efforts for Rocky Mountain National Park and surrounding areas.

The Internet of Soil: Developing Open-source, Low-cost, IoT Technology for Monitoring Soil Moisture

Jay Ham, a professor in Soil and Crop Sciences, was awarded the Center's inaugural Food-Water-Sustainability grant, which is funded in partnership with the School of Global Environmental Sustainability and the CSU Agricultural Experiment Station. Irrigation water management in agricultural and

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urban systems is currently hamstrung by a lack of affordable, real-time, soil moisture data; Dr. Ham's research team seeks to remedy this gap by using the Internet of Things and cloud computing to develop better technology and infrastructure for data collection, as well as education resources for researchers deploying these new tools. Backed by research to increase soil moist monitoring efficiency and sustainability, the end-product will be open-source and available for purchase online.

WATER CENTER FACULTY FELLOWS

The purpose of this type of grant is for individual faculty to implement water-related scholarship and build their capacity and progress in water research, education, and engagement.


Eric Engbretson, USFWS

Assessing gene flow of invasive brook trout to restore a meta-population of threatened greenback cutthroat trout in the upper Poudre River basin

Yoichiro Kanno, an assistant professor in Fish, Wildlife, and Conservation Biology, will provide scientific support for a significant greenback cutthroat trout restoration in the upper Cache la Poudre basin. Spatial population structure and movement of this species in the upper basin are poorly understood, and this research will quantify trout movement, identify habitat features that impact gene flow, and determine whether altered flows in the river's mainstem may hamper fish movement or isolate tributary populations.

Numerical modeling of evolving recharge-discharge sources in a multi-aquifer system

Michael Ronayne, an assistant professor in Geosciences, will study the hydrogeologic processes that control time-varying recharge within complex multi-aquifer systems. This research will examine how geologic heterogeneity impacts the alluvial-bedrock groundwater exchange, the conditions that give rise to unsaturated zones between the alluvium and bedrock, and the causes of aquifer "disconnect."

EDUCATION AND ENGAGEMENT PROJECTS

And, for the first time since its competitive grant program was launched at CSU in 2014, the Center will also fund two education and engagement projects: one led by Steven Fassnacht, a professor in Ecosystem Science and Sustainability, and the other by Amy Kremen, a research project manager in Soil and Crop Sciences.


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Kids Poetry on Water—Creating K-12 Curriculum Integrating Water Science and Poetry

Dr. Fassnacht's team will create high school curriculum that integrates water science and poetry, the impact of which will be twofold: students as well as their educators will gain a better understanding of the links between the humanities and the environment—specifically ecology, climate, and hydrology—and, they hope, students will be inspired to study water and environmental sciences at the college level.

Development and launch of a "Master Irrigator" education and training program in Northeastern Colorado

Ms. Kremen and her team will also develop curriculum, one for a "Master Irrigator" education and training program in Northeastern Colorado. Her project, complemented by state and local policy efforts, will target producers and crop consultants, encouraging them to adopt water-use efficiency and water conservation practices that will ultimately help push the region towards fulfilling its water conservation goals.


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2019 A Snow Year to Remember for Western Colorado

Peter E. Goble and Russ S. Schumacher
Colorado Climate Center, Colorado State University

Introduction

The winter of 2018-2019 may not have felt exceptionally snowy to many of us who reside on the Front Range. Here in Fort Collins, we received about a foot less snow than average over the cold season. However, those who recreate in the mountains during winter and those who reside in the mountains of western Colorado will cast this winter in an entirely different light. With much thanks to a span of six wet weeks in February and March, Colorado snowpack peaked well above average this year. In some locations, peak snowpack was greater than 150% of average. In this article, we will dive into some of the statistics that made 2019's snow year exceptional, frame it in the context of climate change and climate variability, and discuss the atmospheric patterns that allowed for such high snow totals.

Snow statistics

2019 was the snowiest winter for western Colorado in many years. High-elevation April 1 snowpack (liquid water content of snow) in major river basins across Colorado ranged from 120% of normal in the Yampa and White Basins to 157% of normal in the San Juan, Dolores, and San Miguel Basins (USDA NRCS, 2019). Average high-elevation snowpack in the San Juan, Dolores, and San Miguel Basins peaked on April 4 at 29.2 inches of liquid water content. This marks more than an eleven-inch departure from the normal peak snowpack of 17.9 inches. The wettest snowpack measurement sites in the state recorded over 50 inches of snowpack at peak. Were snowfall measured at these sites, it easily could have totaled over 800 inches for the season based on typical snow-to-liquid ratios (Baxter et al., 2005). Peak snowpack in the western San Juans, central Sangre de Cristos, and Uncompahgre Plateau was greater than over 90% of past years of record.

Figure 1: Skiers on Wolf Creek Ski Resort's Alberta Lift are buried in snow in the span of one short chairlift ride (February 22, 2019). The 24-hour snowfall report from this day was 28 inches. Photo by Jared Brewer.

How it happened

The snow started fast. October was a cold and wet month, but much of the snow received in October at high elevations melted after falling. What followed in November, December, and January was normal for western Colorado. A mix of high pressure with dry southwesterly flow and low pressure with Pacific moisture was observed. Precipitation each month was a mix of above- and below–average, de-

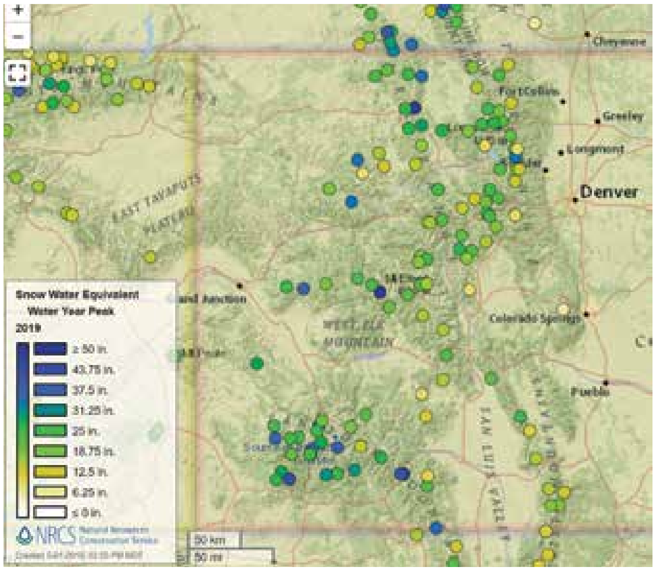

Figure 2: US Department of Agriculture Snowpack Telemetry (SNOTEL) stations in western Colorado shaded by peak measured snowpack in winter 2019.

pending on where the storms fell, and overall, snowpack at the end of January was near normal. In fact, northern mountain ranges had been slightly preferred for greater than normal snowpack to that point. Snowpack in the Yampa Basin, Colorado Main Stem, Gunnison Basin, and San Juan Basins were respectively 114%, 115%, 106%, and 85% of normal at the end of January (USDA NRCS, 2019).

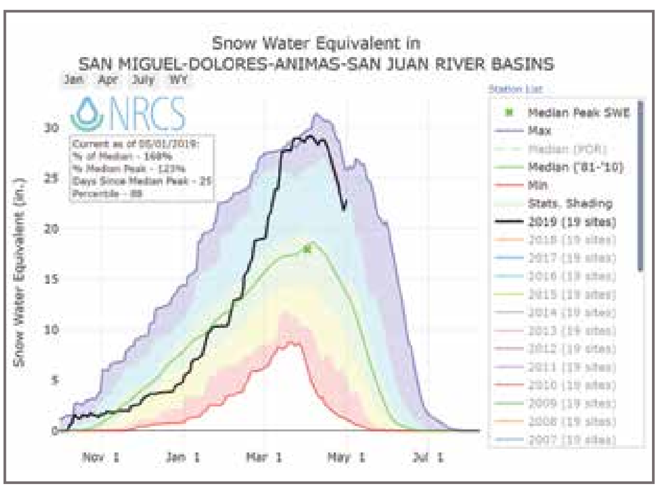

Figure 3: US Department of Agriculture water year 2019 snowpack accumulation time series as of May 1, 2019, for the San Juan Mountain Range in Colorado. The current year time series (black) is framed against the historical distribution (color shaded), median year of record (green line), low year of record (red line), and high year of record (blue line).

February and March is where things got interesting. This was driven by a semi-permanent low pressure system that spun off of the coast of southern California and a bitter cold mass of high pressure air over the intercontinent, blocking the low pressure from advancing. As a result, the proverbial door to the Pacific was left wide open. Colorado was impacted by six atmospheric river events in as many weeks (SCRIPPS, 2019). By the time those six weeks ended, southwestern Colorado was reporting more snowpack than any time since 2005 (USDA NRCS, 2019).

Atmospheric river events?

The American Meteorological Society Glossary defines an atmospheric river as "a long, narrow, and transient corridor of strong horizontal water vapor transport." It goes on to explain that these rivers are responsible for large precipitation events when forced over mountain barriers like the Colorado Rockies. Atmospheric river events are defined by how large a mass of water vapor is being carried through the atmosphere over a region at a given point of time. In this article, atmospheric column-integrated vapor transports greater than 300 kilograms per meter per second are being characterized as atmospheric rivers.

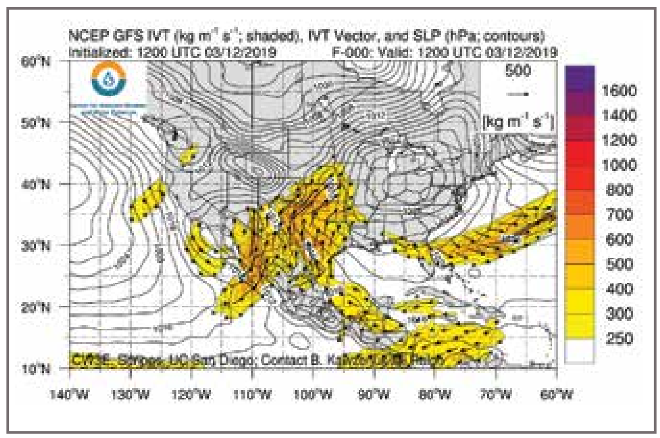

Figure 4: SCRIPPS Institute of Oceanography modeled atmosphere column integrated water vapor transport from the morning of March 12, 2019, primarily over North America.

Snowpack and climate change

Peak annual snowpack has been slowly declining in western Colorado over the last 60 years (Mote et al., 2018). Recent analyses have shown these declines to be significant in southwest and south-central Colorado with at least 95% confidence (Goble and Doesken, 2017). Given that both a warming climate and El Niño have more generally been correlated with lower snowpack years, 2019 highlights the stochastic nature of seasonal weather. It also underscores the importance of individual weather events. In the case of winter 2019, several large events, which can be categorized as atmospheric rivers, impacted the area in relatively rapid succession and acted to set this year apart from normal.

Snowpack and ENSO

The El Niño Southern Oscillation (ENSO) refers to the back-and-forth movement of warm sea surface temperatures in the equatorial portion of the Pacific Ocean. In an El Niño, warmer than normal sea surface temperatures extend to the western South American Coast. In a La Niña, warm sea surface temperatures are confined to the western Pacific, nearer Australia. This oscillation has ripple effects on the climate globally. Winter 2019 started as an ENSO-neutral year and developed slowly into a weak El Niño. In a classic El Niño setup, warm temperature anomalies spread all the way to the eastern coast of the Pacific. This El Niño was unique in that positive sea surface temperature anomalies stayed more over the Central Pacific, a setup referred to as a Modoki El Niño.

Historically, El Niño years yield wetter conditions in the spring and summer in Colorado but are actually correlated with drier winters in the western slopes (Lukas et al., 2014). Ultimately, correlation between ENSO state and peak snowpack in Colorado is weak (Goble and Doesken, 2017). The difference between Modoki El Niños and regular El Niños for western Colorado is not well understood (we have only a small sample size of Modoki El Niños). Six such events have occurred since 1950.

Impact on drought

2018 and 2019 have been marked by precipitation whiplash in western Colorado (Figure 5). Water year 2018 (October of 2017 through September of 2018) in western Colorado was a bad drought year. It was both the hottest and driest water year on record for Colorado west of the Continental Divide (NOAA NCEI, 2019). 2019, on the other hand, was the wettest cold season in western Colorado since 1980. More precipitation accumulated in western Colorado during the first six months of water year 2019 than the entirety of water year 2018. As of May 1, stream flows and soil moisture are above average in most of western Colorado with over half of the snowpack still left to melt. Colorado's largest reservoirs, which suffered big losses in 2018, are fast refilling.

Conclusions

The winter of 2018-2019 brought a robust snowpack to Colorado, particularly in the southwest. It is important to note that traditional seasonal indicators of climate variability (like ENSO) were not sufficient to see this coming and that our warming climate makes winter 2019 marginally more of an anomaly. This winter was set apart from a normal winter during a six-week time period between early February and mid-March in which a series of atmospheric river events unloaded large slugs of moisture over Colorado's mountains. The snow amassed during this period truly made 2019 a winter to remember.

Addendum

A slow melt: One of the most notable characteristics of the 2019 snow season was a delay in melt caused by cooler than average temperatures in May. Temperatures were 4-6 degrees cooler than normal across most of Colorado. It was the coldest May in Colorado since 1995 (NOAA NCEI, 2019). As a result, high volumes of snowpack remained into the summer season (Figure 6). This also had a notable impact on the timing of runoff, delaying peak streamflows by days or weeks.

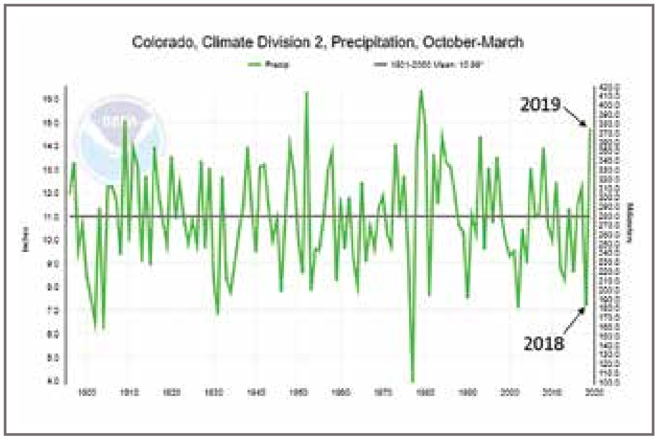

Figure 5: October-March precipitation averaged across western Colorado for 1895-2019 (NOAA NCEI 2019).

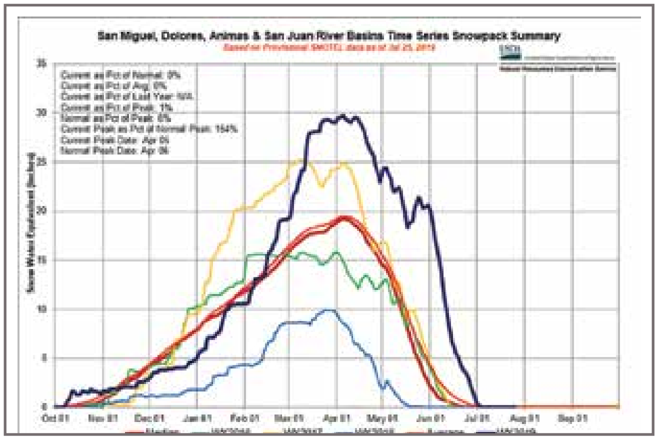

Figure 6: Time series of Water Year 2019 snowpack in southwest Colorado.

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2019: A Snow Year to Remember for Western Colorado

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