RESOURCE

engineering and technology for a sustainable world

Take a deep dive into

DIGITAL WATER

Also inside:
Annual Report

from the President

I began writing this column in Peoria, Illinois, as the ASABE 1/4-Scale Tractor Competition was wrapping up. This was the first time in three years that a full set of teams was present in Peoria. Although I've watched the teams from Penn State build their tractors and head off to the live event over the years, this was the first time I had attended the competition in person. Until I saw this year's event, I really didn't appreciate the effort that the organizing committee, the judges, ASABE staff, and the student teams and their advisors all put into the competition. I was very glad to have the opportunity to be there and experience first-hand the energy, the comradery, and the competitiveness.

This issue of *Resource* tackles "digital water" as the theme. Of course, water is a critical resource that is increasingly challenged by our growing population. As this issue shows, agricultural and biological engineers are leading the way in the use of digital technology to address water issues. We are pleased to have two guest editors, **ASABE members Debabrata Sahoo and Sushant Mehan,** handling this issue. They have solicited contributions from a variety of expert authors who describe a wide range of digital applications to water management, water quality monitoring, water resource modeling, and other topics under the umbrella of digital water.

This past year has seen a transition to a new normal. In-person ASABE events, which had been on hiatus since the spring of 2020, began to pick up last fall and further increased in the spring. Finally, after three years, we have an in-person Annual International Meeting! It may take a while for people to become comfortable getting together, and I understand why some of us may never have the same comfort level again. Regardless of whether or not you attend ASABE events, your affiliation with the Society is important. Our members contribute to solving the world's grand challenges, and that need will only increase.

As I finish my year as ASABE President, I want to share some observations about our Society. As in any group, there are always certain people who are willing to put extraordinary amounts of their own time into making the organization work. For ASABE, those people include the Board of Trustees, Council chairs, Technical Community chairs, and many others who volunteer their time, energy, and skill. We also have a dedicated headquarters staff, who are wonderful to work with. And we have members who make our profession known through their jobs and in their communities. Like many professional societies, ASABE faces challenges, especially related to maintaining membership. However, if we continue to make ourselves known for our ability to innovate and solve real-world problems, we will ensure our future.

Finally, I want to reiterate the importance of assuring all of our members that they have an important role in our Society and that their voices will be heard. The solutions we need often come from unexpected sources, so listen to unexpected ideas. New voices can offer new solutions, and they can help us avoid new problems.

Thank you for entrusting me with this leadership role. It has been a great pleasure, a great education, and a great honor.

Paul Heinemann
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events calendar

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ON THE COVER:
In this special issue we take a deep dive into digital water. Tap into your understanding of digital water—its current applications and its implications for the future. This issue is flooded with great insight.

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Special Issue: DIGITAL WATER

Guest Editors: Debabrata Sahoo, P.E., P.H.
and Sushant Mehan

DEPARTMENTS

Digital Water: Technologies to Understand Water as an Integrated System

Guest Editor Debabrata Sahoo, P.E., P.H.

When I travel down my memory lane, the place that first comes to mind is my village in India where I had fun as a kid with my parents and siblings. I loved puddling and fishing in the village pond, jumping into the river to cool off during the hot summers, stargazing on the banks of the river at night, pumping water for the villagers, and many other simple pleasures. In all those places, I see one element in common, and that element is water. Even today, as an adult, the places I visit with my family and friends are always connected to water. Hiking along streams, canoeing, and rafting are my favorite adventures. I'm sure you have had similar experiences. Water connects us!

Water is an essential element of living systems. It's fair to say that the foundations of human civilization are rooted in water. There is much evidence for how water played a critical role in our social evolution, from nomadic groups to agrarian societies to our modern industrial economy. And why not? After, all, more than 70% of the Earth's surface is covered with water. As humans became settled and societies have grown, our dependence on water has only become more evident.

Now our water systems, both natural and engineered, are facing unprecedented stresses, including water quality issues (e.g., pollution and algal blooms), demands from multiple sectors (e.g., domestic consumption, agriculture, and industry), impacts from extreme events (e.g., floods and droughts), disputes over water rights, and the environmental needs of local ecologies. There is an increasing demand for water from every sector.

Policies have been created and regulations have been implemented to address these water issues and ensure sustainable water resources, alleviate the impact of stressors, identify the sources of stress, and create accountability. However, despite these policies and regulations, we continue to face problems with water quality and quantity.

While many advances have been made in understanding water systems and addressing water problems, water still feels like one of the world's least explored elements. Many of the water issues listed above are related to the lack of comprehensive information on water systems at any given point. This information is essential for understanding and managing water resources. Unfortunately, the required information is often not collected due to inadequate resources. Even where information exists, it is often fragmented, unstructured, paper-based, or not available in a universal format.

In addition, water data are abundant for certain parts of the world, while scarce in other regions. Even worse, many water systems in numerous countries are not gauged, and no water quality data are being collected. Accurate modeling, comprehensive analytics, better management decisions, sound policies, and informed regulations all require high-quality data.

Fortunately, we live in a digital age in which all systems are interconnected, and water systems are no exception to the digital revolution. The most obvious example of digital water is the use of sensors to monitor and record water quantity and quality wherever water flows—in municipal treatment systems, in irrigation systems, as well as groundwater, stormwater, wastewater, and surface runoff and streamflow in the field.

Remote sensing, using satellites, manned aircraft, and UAVs, is another digital tool that is widely used to measure, monitor, and map water resources. The resulting data can be stored in local databases or in the cloud. Consistent data quality and compatibility assist in analytics and visualization. These datasets can also be used to develop computer models, which are another component of digital water. Communication tools, such as social media and online dashboards, help in disseminating the results.

These tools—sensors, databases, spreadsheets, and models—are not new. Water researchers have been using them for quite some time. However, the speed at which the tools for digital water have improved in recent years—with automation, big data analytics, cloud computing, machine learning, artificial intelligence (AI), deep learning, internet of things (IoT), machine-to-machine (M2M) communication, blockchains, and wireless platforms—has revolutionized the water industry.

Going forward, we will see even faster changes in digital water technology, and there will be new technologies that we haven't heard of today. We will use these technologies to monitor and improve every aspect of water systems, to answer relevant questions with a local focus as well as a global perspective, and to address the grand challenge of ensuring abundant clean water for the growing global population.

Imagine all the world's water systems digitally connected to provide citizens, scientists, engineers, policymakers, and regulators with real-time information on every drop of available water. Imagine universally formatted datasets, that can be accessed globally, and that can be used for information gathering as well as knowledge dissemination. Imagine digital twins of water systems, which is possible with emerging technologies. Imagine real-time modeling with immersive experiences coupled with virtual reality. Imagine models running uninterrupted using cloud computing and AI with data from water sensors and providing real-time analytics. The information generated by these tools will lead to better policies and regulations, creating a resilient and sustainable global village. The possibilities are endless!

In short, digital water can give us the information needed to meet the grand challenge of achieving sustainable water resources. Future generations will appreciate that.

To achieve this goal, we must recognize certain impediments to progress, including the adoption and adaptation of

technology, digitization of methods and processes, access to affordable technology (e.g., low-cost sensors, databases, and computing power), availability of trained people, willingness to share information, access to financial resources, as well as support from research institutions, universities, government agencies, and private entities. These are likely short-term impediments to digital water. In the long run, digital water will pay tremendous dividends.

In collaboration with young and energetic ASABE members and industry leaders, ASABE member Sushant Mehan and I have compiled a series of articles on the various aspects of digital water for this issue of *Resource*. Sushant has been a tremendous resource for this project, and I'm very much indebted to him. We aimed to allow researchers and engineers to explain the technologies that they are applying to digital water, and we encouraged our contributors to project their ideas into the future.

I would also acknowledge Dr. Debasmita Misra, and Dr. Raghavendra Jana for their informative suggestions. Their help is very much appreciated!

The articles in this issue will help all of us imagine the endless opportunities and myriad challenges that we need to address as agricultural and biological engineers. The breadth of the articles demonstrates the wide variety of water-related issues that we face today and that can be solved using digital tools. I hope these articles inspire you to make our world more sustainable for the future. If so, then my goal has been accomplished!

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Digital Water: The Future of Water Resources

Guest Editor Sushant Mehan

Water is essential for human life. Given that the projected global population will be at least nine billion by 2050 and the global air temperature will rise by 2-4°C, the availability of clean water is necessary for our survival, as well as for a prosperous economy. Before I go any further, I want to highlight some facts from the 2022 United Nations World Water Development Report:

"It is estimated that agricultural pollution has overtaken contamination from settlements and industries as the major factor in the degradation of inland and coastal waters. In the European Union, 38% of water bodies are under significant pressure from agricultural pollution; in the U.S., agriculture is the principal source of pollution of rivers; and in China, agriculture is responsible for a large proportion of surface and groundwater pollution by nitrogen."

Aren't those facts alarming? Will adequate water even be available in the next decade? I doubt it, unless some progressive new methods are included in our current research plans. Specifically, we must:

• Understand hydrophysical processes and cycles that require continuous monitoring.
• Access ecosystem properties that are currently inaccessible to us and our activities.
• Identify critically affected resource areas and ensure their sustainability.

These concerns inspired the theme of this special issue of *Resource:* Digital Water.

Digital water incorporates the many technological transformations that are taking place in the water resources sector. The terms digital water, smart water, and internet of water are often used interchangeably. Whatever the term, digital water means exploiting the power of big data using automation and artificial intelligence to build more resilient, secure, and economically viable water systems.

The strength of digital water lies in its use of smart sensors, edge computing, and digital algorithms that use real-time information to increase the reliability of decision support, regulatory compliance, water resources monitoring, and system modeling. Although digital water involves a higher initial investment than conventional water systems, it provides increased security, efficiency, and net returns while reducing operating costs and the need for human invention.

With more young professionals in the water resources sector and the emergence of a digitally literate generation, water customers and regulators will eventually demand digital innovations in their products and services to address water challenges. The implementation of digital water by municipal utilities would help them access, manage, and use the data necessary to ensure access to high-quality water.

Digital water will also help ensure reliable and efficient water services in response to the new normal of water scarcity and flooding. Like other recent innovations, digital water will require engagement, training, and vigilance to tap its full potential.

This special issue of *Resource* contains a range of articles on digital water, written by a variety of experts in the water resources sector. These articles will improve your understanding of digital water, its current applications, and its implications for the future. You will also be amazed to see how agricultural and biological engineers are applying digital water in their research, as well as the promising results they have achieved.

ASABE member Sushant Mehan, Department of Biological System Engineering, University of Wisconsin, Madison, USA, sushantmehan@gmail.com.

Further Reading
UNESCO. (2022). Groundwater: Making the invisible visible. United Nations World Water Development Report 2022. Paris, France: UNESCO. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000380721

A Mobile App for Cotton Irrigation Management

Srinivasulu Ale, Qiong Su, Jasdeep Singh, Sushil Himanshu, Yubing Fan, Blake Stoker, Eric Gonzalez, Bala Sapkota, Curtis Adams, Keith Biggers, Emi Kimura, and James Wall

The Texas High Plains (THP) and Texas Rolling Plains (TRP) regions collectively produce more than 30% of U.S. cotton. Irrigated cotton production in these regions is largely supported by groundwater from the underlying Ogallala and Seymour Aquifers. These aquifers have experienced substantial declines due to excessive pumping for irrigation and increased frequency of droughts. Projected warmer and drier summers in the future are expected to further exacerbate the problem due to higher crop water requirements. Groundwater conservation districts in the THP region have already enacted restrictions on groundwater pumping to prolong the usable economic lifetime of the Ogallala Aquifer. Therefore, IT-based decision support tools are needed for cotton producers in these regions to efficiently apply limited irrigation water and optimize crop yield, while complying with groundwater pumping restrictions.

Many tools have been developed for improving irrigation water use efficiency, but several drawbacks of these tools limit their widespread adoption. Some of these drawbacks include: (1) they are cumbersome and expensive, requiring extensive manual data collection and installation of sensors; (2) their lack of mechanisms to accurately apply irrigation water at a deficit and their reliance on limited data for making predictions; (3) their lack of accessibility, for example, some systems require proximity to established weather stations and associated support, limiting potential users by location; and (4) their narrow approach, such as relying only on crop models without any feedback from the field.

To address these drawbacks, we have developed a mobile app for a crop model- and sensor-based irrigation decision support system (called *idCROP*, for "irrigation decision support system for conserving resources and optimizing production") and validated it in the TRP region. In developing *idCROP*, our focus has been on providing an accurate and user-friendly tool that is freely available and provides users with actionable information about when and how much irrigation is required.

Irrigation prescriptions are generated by the crop model with minimal input from the user. The crop model pairs historic and forecasted weather with recorded irrigations to provide reliable irrigation recommendations that are optimized in real-time. The app generates prescriptions for several irrigation strategies that users can follow according to their water availability and economic goals. We have also tested on-farm sensors mounted on pivot irrigation systems to improve the accuracy of irrigation recommendations, although the app can be used without the additional sensor data. The prototype *idCROP* app has been deployed to a small group of evaluators on both iOS and Android mobile devices.

Crop model-based irrigation scheduling

With proper parameterization and evaluation, crop models can aid in irrigation scheduling by integrating data on climate, soil properties, crop genetics, and farm management practices. Crop models are also useful for forecasting the impacts of different irrigation scheduling strategies on crop yield and economic return. We employed the Decision Support System for Agrotechnology Transfer (DSSAT) model because of its wide applicability in deficit irrigation scheduling. An evaluated DSSAT CROPGRO-Cotton model with calibrated cultivar coefficients for three maturity groups (i.e., early, early-mid, and mid-full) is embedded in *idCROP*.

The overall architecture of *idCROP* is shown in the accompanying illustration. The app was developed using an Agile-based software engineering method, which involved rapid, iterative, feedback-focused software generation, resulting in a finished product that addresses the feedback obtained from subject-matter experts and end-users throughout the design and development process. This process enabled iterative refinement and expansion of the app, and it provided an expanded set of features and capabilities in an incremental fashion.

The app is organized into three major components: (1) data input from the user on initial field conditions, cultivar used, tillage, planting details (e.g., date, row spacing, and seeding rate), chemicals used, and harvest date; (2) data processing and computation to create input files and for execution of the DSSAT and economic models; and (3) generation and presentation of the results, including irrigation schedules, water use efficiency, and expected yield and net return.

The app provides two options for irrigation scheduling. The default option is crop model-based scheduling, with irrigation timing determined by model-simulated plant water stress. The irrigation timing can be improved by optional remote detection of plant water stress using a sensor platform mounted on a pivot irrigation system, which is discussed later.

Users can select any evapotranspiration (ET) replacement scenario to apply deficit irrigation based on their well capacities. The simulated seasonal irrigations and crop yields from the crop growth model are then used by the economic

model to estimate farm profits for the corresponding irrigation scenarios. To help users compare costs and benefits, *idCROP* presents both predicted yields and estimated profits for the different irrigation scenarios. With this information, producers can proactively make decisions about in-season irrigation and crop management to optimize crop yield and profit.

The resulting irrigation prescriptions are updated as the growing season progresses based on recorded irrigations, past and real-time weather data from the beginning of the growing season, and updated short-term weather for the remainder of the growing season. Users can change their irrigation strategy during the growing season, if necessary, based on the availability of irrigation water or changes in their goals.

Environmental data generation

Dominant soil types in the THP and TRP regions were identified, and soil files for the DSSAT model were created using data from the Official Soil Series Descriptions and Soil Survey Geographic (SSURGO) database. These developed soil files were used in *idCROP* to classify soil types for user selection. Cotton genotypic coefficients for different maturity groups were determined by evaluating the DSSAT CROPGRO-Cotton model based on variety trial data from Texas A&M AgriLife Extension. The developed cultivar files are included in *idCROP* so users can select the maturity group that best represents the cultivar they plant.

Real-time weather forecasts

Reliable short-term and seasonal weather forecasts are essential for irrigation decision-making and predicting future crop production. To ensure the reliability of weather data, *idCROP* combines weather data from four sources: (1) historic weather data until the day before the date of simulation (or app use) obtained from a nearby weather station; (2) real-time data from an on-site or nearby weather station; (3) daily short-term forecasted weather data for a 16-day period obtained from the Global Forecast System (GFS); and (4) daily seasonal forecasted weather data for six months obtained from the North American Multi-Model Ensemble (NMME) forecasting system. The short-term (16-day period) and seasonal (six-month period) forecasted data are updated every day and each month, respectively. As new data become available, they are automatically used in the app.

Economic model

An economic model based on an enterprise budget approach is embedded in *idCROP* to provide visual analytics for decision support and tradeoff analysis. The economic model enables the calculation of: (1) total revenue, which is based on the simulated crop yield and the harvested crop price estimated using the contract future market price at harvest time plus/minus the average price basis for each location during harvest, and (2) total cost, which includes both variable and fixed costs. Input prices for seed, fertilizers, herbicides, insecticides, and custom-hired machinery and equipment, provided by the enterprise budget for Texas A&M AgriLife Extension District 3, are embedded in *idCROP* by default, and these prices can be adjusted by the user. The total cost is calculated based on the price dataset and farm inputs.

Additionally, a sensitivity analysis is conducted within the app for each irrigation strategy to evaluate the net return (total revenue minus total cost) at alternative price levels. With these settings, users
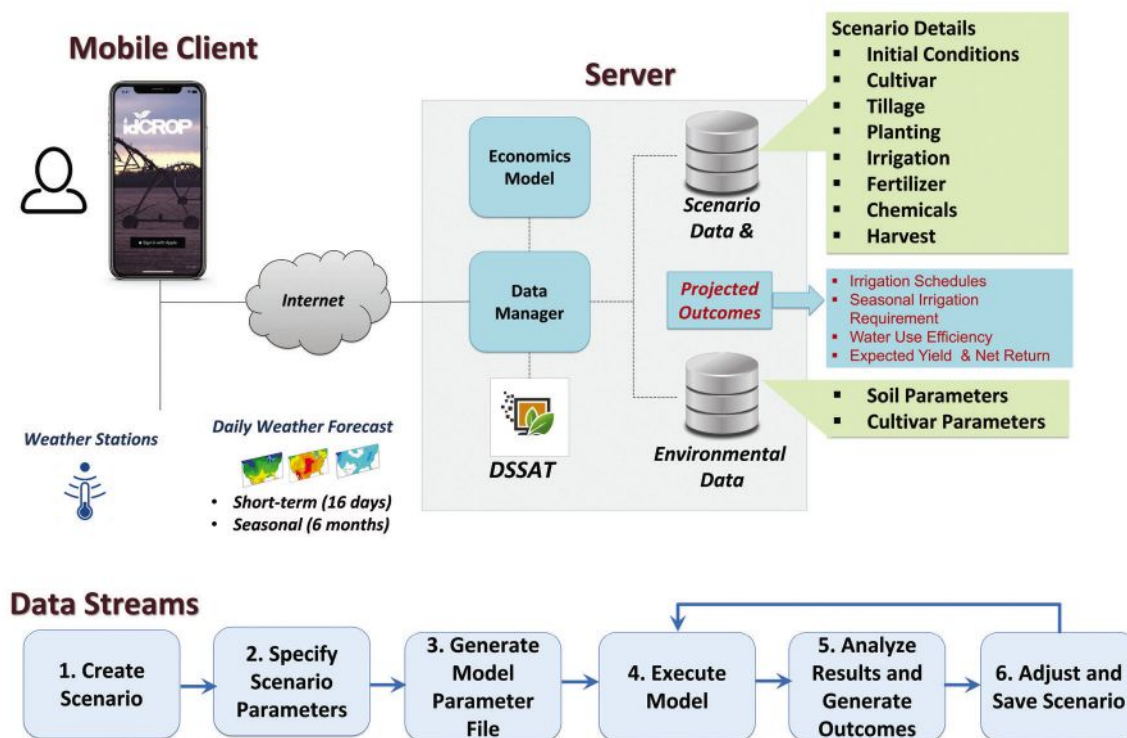
Crop-model-based irrigation scheduling and workflow.

can compare the net returns for selected irrigation levels and understand the changes in net return due to price fluctuation.

Sensor-based irrigation scheduling

Users of *idCROP* have an option to improve their irrigation prescriptions with the use of in-field sensors. For this sensor-based approach, a sensor platform is mounted on the pivot, allowing real-time measurement of canopy temperature and other data, which are transferred to a server using a datalogger and a wireless modem. These data, together with the real-time weather data, are used to calculate the water deficit index (WDI), a modified crop water stress
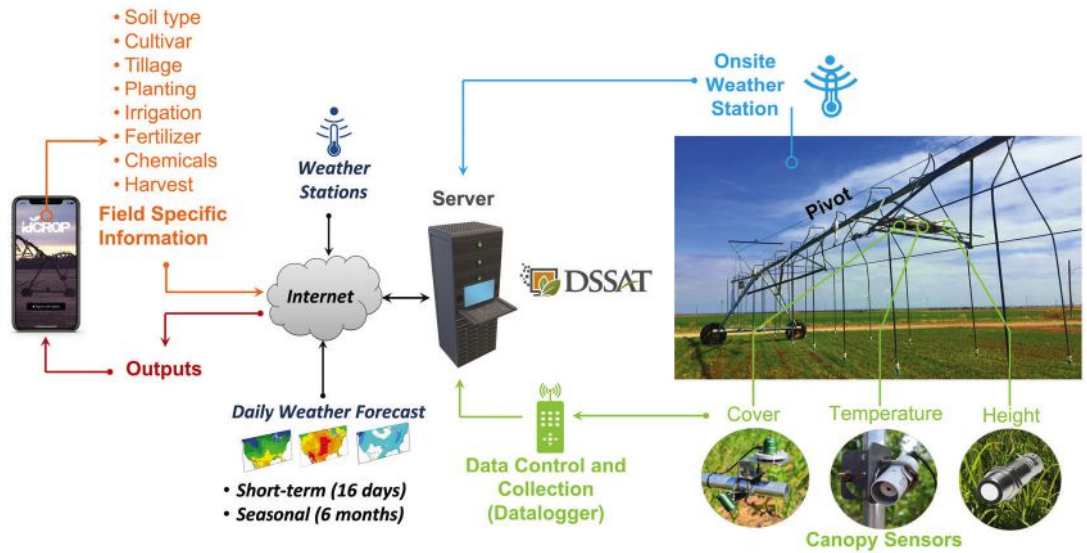
Sensor-based irrigation scheduling and workflow.

index (CWSI) that includes the effect of soil heat flux. Using field-calibrated relationships between the seasonal average WDI and cotton yield under different ET replacement scenarios, the WDI provides on-site corrections and improves the accuracy of the model-based irrigation schedules.

We also evaluated the integration of a mini weather station into the sensor system, which was highly effective. For users who do not have a mini weather station, *idCROP* will automatically acquire real-time data from the nearest weather station.

The next steps

Compared to other irrigation decision support systems, *idCROP* has several distinct benefits, including: (1) more reliable estimation of weather parameters for crop model simulation by using a combination of historic, real-time, and short-term forecasted weather data; (2) improvement in the site-specific accuracy of irrigation schedules by combining crop model-based irrigation scheduling with on-farm, non-contact sensor data; and (3) calculation of net returns, enabling users to choose an irrigation strategy that best fits their well capacities, yield goals, and economic goals.

The prototype version of *idCROP* has been tested and verified for cotton in the TRP region. Our future efforts will focus on developing and testing the app for the THP region. The system design allows modifications within *idCROP*, and there is scope to include other row crops and expand the use of *idCROP* to other crop production regions in Texas and beyond.

ASABE member Srinivasulu Ale, ASABE member Qiong Su, ASABE member Jasdeep Singh, ASABE member Sushil Himanshu, and Yubing Fan, Texas A&M AgriLife Research; Blake Stoker and Eric Gonzalez, Texas A&M Center for Applied Technology; Bala Sapkota and Curtis Adams, Texas A&M AgriLife Research; Keith Biggers, Texas A&M Center for Applied Technology; Emi Kimura, Texas A&M AgriLife Extension; and James Wall, Texas A&M Center for Applied Technology, College Station, USA. For more information, contact Srinivasulu Ale, srini.ale@ag.tamu.edu.

Ecological Engineered Treatment Technologies (EETTs) for Aquaculture and Wastewater

Natasha Bell, P.E., Randall Etheridge, P.E., and Steven Hall, P.E.

Coastal communities are facing many challenges related to climate change and sea level rise, including saltwater intrusion into cropland and damage from extreme weather events. In the U.S., these increasing events are threatening important sectors of the economy and valuable coastal ecosystems. Researchers at East Carolina University (ECU) and North Carolina State University (NCSU) have teamed up to help coastal communities overcome barriers to the expansion of aquaculture as an alternative land use for areas affected by sea level rise, and to increase the resiliency of the infrastructure used for wastewater treatment (WWT) from aquaculture and municipal sources.

Investment in adaptive and sustainable ecological engineered treatment technologies (or EETTs) for wastewater would support the coastal aquaculture industry by removing WWT barriers and increasing the resiliency of municipal WWT while protecting coastal water resources. EETTs, such as hybrid constructed wetlands, use naturally occurring plant and microbial processes to remove nutrients, such as nitrogen (N) and phosphorus (P), and other contaminants from wastewater. EETTs can provide low-cost alternatives to conventional treatment.

Although EETTs have been shown to effectively reduce contaminants, many questions remain about their design, implementation, and return on investment. In particular, changes in hydrologic conditions and temperature substantially influence treatment effectiveness. Therefore, there is a need to monitor the conditions within the treatment system and forecast future conditions so that the treatment processes can be optimized to maximize the removal of contaminants, pathogens, and solids.

The rise of aquaculture

Aquaculture is the fastest growing protein sector in the world, providing healthy protein and extremely efficient feed conversion ratios. As aquaculture expands, its effluent stream must be considered, especially as larger operations are developed. An additional challenge with marine aquaculture is that saltwater cannot be used for irrigating most plants. Hence, development of constructed wetlands with salt-tolerant plants (such as *Spartina alterniflora* and *Juncus roemarianus*) may be an effective approach for removing contaminants and potentially providing other benefits, such as habitat for wildlife and biomass for value-added processes.

The objectives of our project include development of pilot-scale, salt-tolerant constructed wetlands that can be scaled up for commercial application. Biomass growth rates, microbial communities in the root zone, and nutrient (ammonia, nitrite, nitrate, and phosphorus) removal rates will be monitored. Improved understanding and engineering design of these environmentally friendly systems should lead to greater sustainability for aquaculture and other agricultural and coastal enterprises.

The experiments are being conducted at the NCSU Marine Aquaculture Research Center (MARC) in Marshallberg, North Carolina, which is located on a tidal inlet with access to marine waters. The MARC includes two hurricane-resistant research buildings, which survived Hurricanes Florence and Michael with negligible damage, with over 8,000 square feet of interior space including a series of recirculating aquaculture systems ranging in volume from 400 to 10,000 liters per tank and ranging in number from 6 to 16 tanks for repeated experiments, as well as shop and construction space. The facility also features solar, wind, and backup generator power as well as a range of advanced waste treatment and testing facilities.

Staff, students, and faculty conduct experiments, raise fish, work with the equipment, and provide demonstration and outreach in a variety of areas including aquaculture, engineering, coastal studies, and automated systems. This site is also close to other coastal facilities where our collaborators are located, including the NCSU Center for Marine Sciences and Technology (CMAST) and NOAA's Beaufort Laboratory, providing further knowledge of the coastal environment and excellent hosts for enhanced aquaculture wastewater treatment.

The Marine Aquaculture Research Center (MARC) in Marshallberg, North Carolina.

The challenges facing wastewater treatment

Municipal wastewater treatment plants (WWTPs) can be disrupted by rainfall events of just 1 to 2 inches, not to mention severe storms and hurricanes. These disruptions result in increased input of nitrogen and phosphorus to nearby waters, which can contribute to harmful algal blooms. Many coastal watersheds are already considered impaired due to elevated N and P loading. These hydrologic and climatic challenges, paired with aging infrastructure and increasingly stringent regulatory limits, have incentivized WWTPs to seek alternative treatment options.

Identifying cost-effective WWT alternatives is necessary for improving the resiliency of coastal communities while maintaining affordable residential and commercial wastewater rates. In addition to applications in aquaculture, EETTs for WWT in coastal communities have potential to be more resilient, adaptable, and cost-effective than conventional WWT technologies, such as high-energy aerated reactors and membrane filtration.

ECU has partnered with the Greenville Utilities Commission WWTP, located in Greenville, North Carolina, to test pilot-scale hybrid constructed wetlands as an add-on technology to further reduce N and P concentrations in the released effluent. Hybrid constructed wetlands, which have been used mostly in Europe and Asia, are a promising treatment method that consists of varying zones of vertical and horizontal subsurface and surface flow.

Within each constructed wetland zone, the conditions are manipulated to support varying redox environments, allowing aerobic, anaerobic, and anoxic microbial transformation, uptake, and sorption of N and P to occur. Our team is exploring the potential for incorporating subsurface denitrifying bioreactors as well as novel N and P adsorbent materials (including natural, manufactured, and industrial byproducts) into hybrid constructed wetlands.

EETTs with active management

It is well known that factors such as temperature, retention time, and redox conditions alter the effectiveness of EETTs for removing nutrients. In the past, EETTs have not included active management, but installing EETTs onsite for wastewater treatment makes active management feasible. This active management can include lowering the water level in specific zones in anticipation of rainfall or retaining water in specific zones at night to increase the treatment effect when temperatures are lower.

Although municipal WWTPs may have the resources and expertise to actively manage EETTs, active management is likely to be more of a challenge for small aquaculture operations. Data-driven techniques, such as machine learning, can be used to actively manage EETTs while reducing the need for operator input. Data-driven techniques can incorporate data on the current conditions (water level, nutrient concentrations, etc.) in each treatment zone, future weather forecasts, and past treatment with the goal of reducing nutrient loads in the effluent. This approach can also help experienced operators improve the performance of existing systems. Most important, active management should increase the effectiveness of treatment and potentially reduce the land area required for installation of EETTs.

To manage these systems most effectively using machine learning techniques, data on the current conditions in each cell will have to be continuously available while the model is being trained and after the model is put into use. This data acquisition could be as simple as measuring water levels. However, regularly measuring the concentrations of the contaminants of interest would provide increased efficiency. Advances in sensor technology are making this possible.

Real-time measurement of treatment efficiency and automated active management of EETTs is becoming economically feasible as low-cost sensing technology and low-cost computing become more widely available. Small single-board computers will likely have the processing power required to run models that optimize treatment. Installing these computers onsite and matching the computing requirements to the needs will reduce costs and promote active management of EETTs.

Biosensors for real-time microbial management

Enhanced biological phosphorus removal (EBPR) is commonly used in municipal WWTPs to remove P from wastewater, with polyphosphate-accumulating organisms (PAOs) used for most P
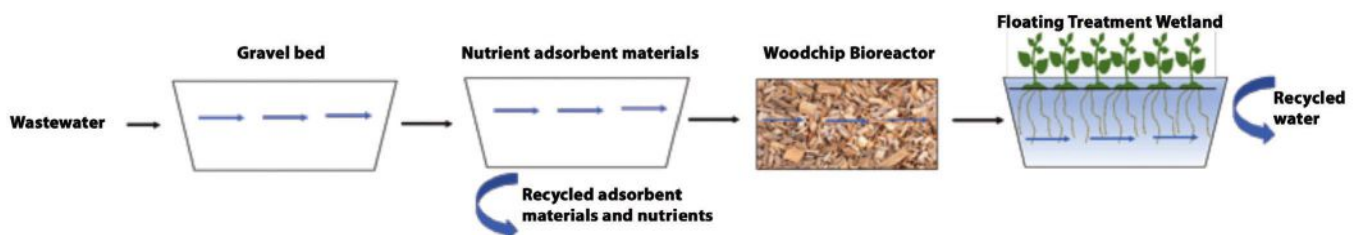
Schematic of a hybrid constructed wetland with four zones for wastewater treatment.

Six pilot-scale, three-stage hybrid constructed wetlands installed by an ECU Capstone engineering senior design team at the Greenville Utilities Commission wastewater treatment plant in Greenville, North Carolina.

removal. While EBPR can be extremely effective for P removal, irregularities at the WWTP (such as large rainfall events, unexpected inputs, etc.) are disruptive to PAO communities, which may require several days to recover.

While many WWTPs are beginning to deploy in-line sensing to detect effluent P concentrations, they would benefit from understanding how the PAOs are functioning in real-time so that adjustments can be made before high P levels are detected in the effluent. Inexpensive electrochemical biosensors are currently being developed by our team to monitor PAO functioning via sensing of P uptake on carbon electrode surfaces. The sensors will be tested at our partner WWTP and validated by comparing the results with data from a high-frequency nutrient monitoring system.

Interdisciplinary research and stakeholder engagement

Development and application of EETTs requires collaboration between researchers from a variety of disciplines, including engineering, natural sciences, and social sciences, as well as continued engagement with stakeholders. At ECU, interdisciplinary centers, such as the Water Resources Center and the Center for Sustainabl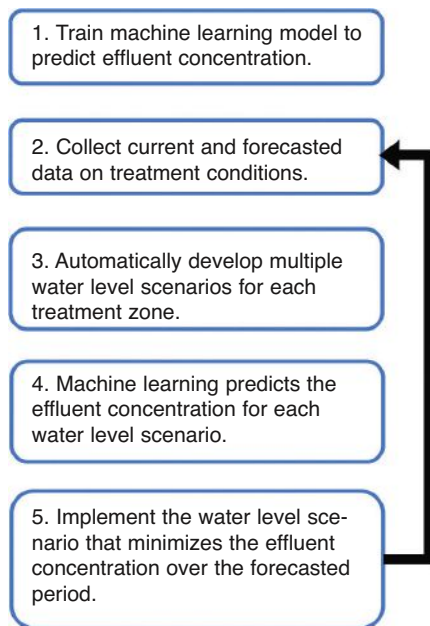e Energy and Environmental Engineering, are enabling these collaborations. To overcome barriers to the adoption of EETTs, our team is also engaged with an advisory board made up of aquaculture producers, state regulatory agencies,

biotechnology and water sensing experts, and environmental consultants.

In addition, community-based participatory research efforts have allowed our team to form partnerships with the agricultural and coastal communities. Extension and outreach are ongoing efforts, including extension publications and conferences that share best practices and enable farmers and operators to best use these new technologies.

Through sustained partnerships with North Carolina Cooperative Extension and the broader wastewater treatment commu-

1. Train machine learning model to predict effluent concentration.

2. Collect current and forecasted data on treatment conditions.

3. Automatically develop multiple water level scenarios for each treatment zone.

4. Machine learning predicts the effluent concentration for each water level scenario.

5. Implement the water level scenario that minimizes the effluent concentration over the forecasted period.

Flowchart of automated management of hybrid constructed wetlands.

nity, this work will lead to beneficial reuse of N and P byproducts from EETTs within agricultural industries, as well as the reuse of treated wastewater in a number of other industries, improving both the environment and the economy. These positive outcomes are a result of combining an interdisciplinary team, relevant stakeholders, and new technology to improve the resiliency of areas impacted by climate change.

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The Coming Wave of Aquatic Robotics

Sierra Young, John-Paul Ore,
and Steven Hall, P.E.

Behind the scenes, local municipalities and environmental agencies conduct the water testing needed to ensure public safety. While this is a critical service, it can also be resource-intensive and time-consuming, as many programs rely on manual sampling and data collection. This can mean that some water bodies are sampled only once a year, or even less.

Automated sensors can alleviate this issue; however, a single sensor only provides point measurements at a single location and can miss events of concern that happen in other areas of a large water body. Robotics can complement sensor-based monitoring by covering large areas, being deployed quickly, and collecting data autonomously, making things easier for the people who monitor water quality.

Robots on the water aid in sensing and sampling

There are many definitions of a robot, but broadly speaking all robots are some type of intelligence (i.e., they can make decisions or solve problems) embodied in an engineered system that can move and sense its environment. For monitoring water quality, robots that travel on the water surface, also known as unoccupied surface vehicles (USVs), can be used for direct sensing and sampling. These platforms have the ability to sense both above and below the water surface, capacity for large payloads, and by being operated remotely, they protect humans from potentially harmful environments.

USV technology is always advancing, and a wide range of commercially mature platforms are available for surveying in open water bodies, such as lakes and reservoirs. These platforms can be fitted with water quality sensors, hydrographic surveying equipment, and even water samplers for use in laboratory analysis. Some platforms are available with further development in mind, allowing users to integrate custom sensors and software for specific applications, such as algorithms to track pollutants or automation to explore unknown environments.

Flying robots reach remote sampling locations

As with any technology-based solution, there are tradeoffs. While USVs offer many benefits for water quality monitoring, they tend to operate at low speeds and have limitations for deployment, including required water depths and water surface velocities. An emerging solution for water sampling in difficult-to-access areas is the use of unoccupied aerial vehicles (UAVs), also called drones.

With UAVs, water sampling sensors can be mounted to a long tether and deployed over the water. Rotorcraft UAVs are used for this application so that the vehicle can hover above the water to deploy a cable-suspended pump and sensors. By flushing the pump and tubing at each sampling location, these systems can also reduce the risk of cross-contamination.

Current UAVs have a range of up to several kilometers and can fly multiple preprogrammed missions with the operator only needing to specify the target GPS locations. However, given the risk associated with operating UAVs over open water, research is still ongoing regarding safe sensing and operating methods for UAV-based systems, including both passive and active sampling.

A few commercially available solutions are making their way into the market, from water sampling systems that integrate with commercial UAV platforms to the development of aerial water samplers as a provided service. Regardless of the sampling method, UAV-based water samplers show great promise in their ability to reduce sampling time and reduce the cost per sample.

Emerging uses for robotic sampling

Collecting water samples autonomously with aerial and surface vehicles has great potential for conventional laboratory analysis as well as for

A Heron USV (Clearpath Robotics, Inc., Kitchener, Ontario, Canada) awaiting deployment in an intercoastal shellfish growing area that is being monitored for potentially harmful concentrations of bacteria.

onboard analysis in the field. Some emerging applications of robotic sampling that our team and our colleagues are exploring are discussed below.

Sampling for laboratory analysis

Coliform: The economic impact of waterborne pathogens in seafood production is estimated to be $300 million per year. When high coliform levels are detected in water systems that include coastal aquaculture, the production managers must prohibit harvesting, potentially causing the loss of entire harvests. Because aquatic coliform testing requires culturing bacteria from water samples for up to 24 hours, the collected samples must be transported to a laboratory for processing. Our team is developing surface and aerial technologies to perform coliform sampling in shellfish growing areas, with the long-term goal of improving water quality predictions and deploying robotic sampling in response to coliform risks.

eDNA: Environmental DNA (eDNA) and RNA (eRNA) is an established tool to confirm the presence of an invasive species, and it has recently been used to characterize the distribution of aquatic species in an ecosystem. Aerial collection of water samples for laboratory analysis makes it easier to bypass barriers to waterfront access, and it increases the number and spatial range of samples that can be collected by a single operator. This is particularly useful in sensitive ecosystems, such as wetlands, where conventional sampling methods may be disruptive.

Sampling for onboard analysis

Zebra mussels: Zebra mussels are an invasive species that has had a severe economic impact. Their juvenile form, called veligers, can often be detected by filtering water through micron filter paper. We have shown that a UAV sampling platform can filter water samples in flight. These samples can then be examined by an expert to determine the presence of veligers and estimate the population density. This approach could be coupled with computer vision to provide automated population density estimates within minutes of deployment.

Nitrates: High nitrate levels in surface water systems, largely due to excess fertilizer application in agricultural systems, have been linked to harmful algal blooms. Although nitrate analysis has traditionally required lab kits (or gas chromatography for more precise measurements), new LED-based sensors allow nitrate levels to be monitored directly. By combining robotic deployment with LED-based water analysis, it will be possible to increase the spatiotemporal resolution of future nitrate datasets, leading to improved understanding and prediction of harmful algal blooms.

Looking forward to multi-robot systems

Regardless of the application, robotic monitoring reduces the required sampling time, improves the data collection, and enhances the resulting insights, allowing better management decisions. As the technology advances, we are looking for ways to enable robots to work together with humans, and thereby combine the benefits of different robotic systems with human expertise. For example, when a surface vehicle used for mapping water quality parameters encounters an area it cannot access, perhaps due to shallow water or obstructions, the system may call for a UAV to aid in collecting data in the inaccessible area. Alternatively, to extend the range of aerial systems, USVs can be used as docking and recharging stations for UAVs.

This concept of collaborative robots, or "co-robots", capitalizes on the use of different robotic systems to gather more data and enhance human decision-making, and it is an active area of research for our team. Moving forward, we eagerly anticipate the further development and use of

An Echoboat 160 (Seafloor Systems, Inc., Shingle Springs, Calif.) deployed for hydrographic surveying and water quality measurement.

robots and automated systems to advance water quality monitoring and continuously protect critical water resources.

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Digitizing Crop Water Use with Data-Driven Approaches

Abhilash Chandel, Basavaraj Amogi, Lav Khot, Claudio Stockle, and R. Troy Peters

Conventionally, crop evapotranspiration (ET) or water use is estimated using generalized crop coefficients and weather data. The estimation of ET can be supplemented by soil water budget, soil moisture, canopy stomatal conductance, stem water potential, and eddy covariance flux measurements. However, most of those point-sampling methods are not spatially scalable, which is necessary to realize the heterogeneous variability in a given crop at plant level. Emerging ground and remote sensing techniques can help with this challenge.

Satellite-based remote sensing with energy balance models can provide geospatial ET maps, but those maps are somewhat restricted by the low spatiotemporal resolution of satellite imagery, by occasional cloud cover, and by the long imaging intervals. For timely irrigation management, growers need timely mapping of crop water use or ET at high spatiotemporal resolution. To achieve this goal, unmanned aerial vehicles (UAV) or manned aircraft equipped with optical sensing offer a promising alternative to satellite-based remote sensing. These low-altitude remote sensing platforms allow on-demand data collection, and when the aerial imagery is combined with localized weather data, spatial ET maps can be derived for near real-time decision support. With millimeter-scale spatial resolution, these ET maps can be scaled down to the individual plant level or even to leaf level.

Similar to remote sensing, thermal and RGB imaging using a smartphone combined with edge computing can monitor crop water stress at the individual plant level. The following examples provide an explanation and some highlights of our ongoing research with combinations of remote sensing and smartphone-based technologies.

Mapping water use in a field crop

Using data from UAV imagery, we have successfully mapped the water use for a range of irrigated field crops, including alfalfa, spearmint, and potato. For example, an experimental potato crop was irrigated at four levels (40%, 60%, 80%, and 100% of ET), as calculated from non-stressed crop coefficients and reference ET from weather data. The box plots on the next page show the variation in ET as a result of the four irrigation treatments, and the field map (at 7 cm pixel^{-1} resolution) clearly shows higher ET for the potato plants irrigated at the 100% and 80% levels as compared to the 60% and 40% levels.

To derive the map, we used multispectral and radiometric thermal imagery collected in the 2018 and 2019 growing seasons. The acquired images were stitched together using photogrammetry and mapping software to generate crop reflectance and temperature orthomosaics. Those orthomosaics, along with a digital elevation model and open-field weather data (air temperature, relative humidity, wind speed, solar radiation, and precipitation) from the nearest WSU AgWeatherNet station, were used as inputs to a modified METRIC energy balance model.
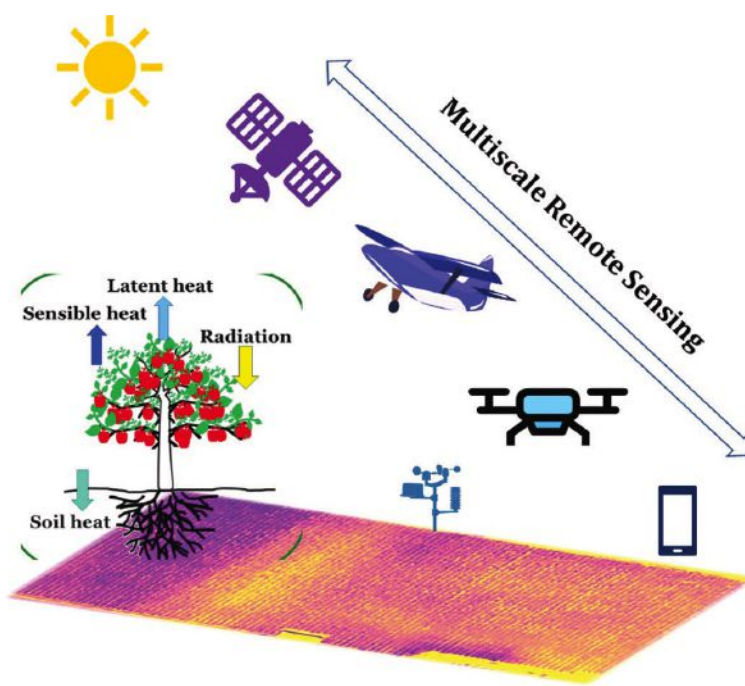
Multiscale and multimodal approaches for mapping crop water use.
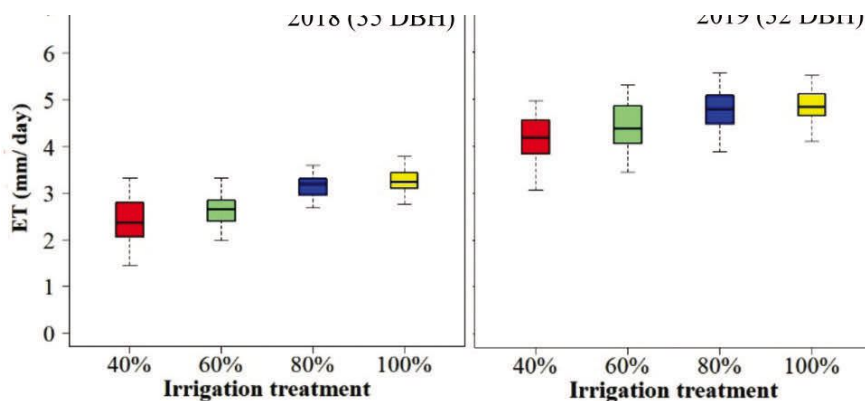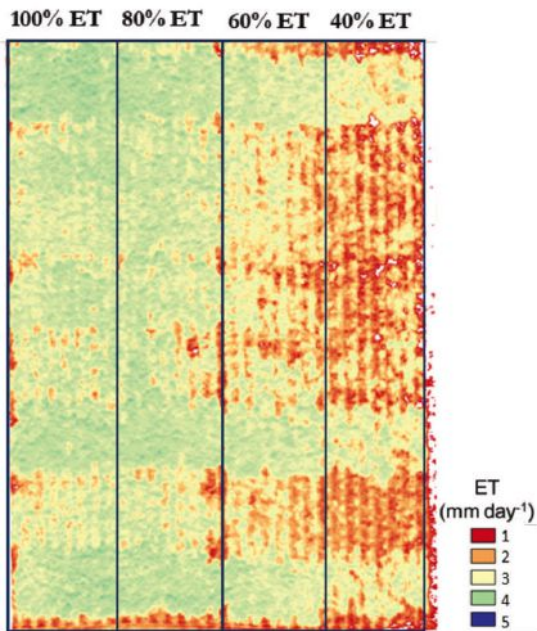
High-resolution (7 cm pixel^{-1}) crop water use map derived from UAV imagery and box plots of ET variability for potato plants irrigated at different rates in the 2018 and 2019 growing seasons.

Mapping water use in an orchard

We also have successfully mapped ET for a modern apple orchard by including multiscale spectral and thermal infrared imagery from UAV (7 cm pixel^{-1} spatial resolution), manned aircraft (20 cm pixel^{-1}), and satellite (3000 cm pixel^{-1}) in the energy balance model. The ET values derived from the UAV imagery had the highest correlation (r = 0.9) with the ground reference water stress measurements from a micro-tensiometer, followed by the satellite imagery (r = 0.8) and the manned aircraft imagery (r = 0.6).

The strong correlation for the UAV imagery, compared to the manned aircraft imagery, was probably due to the data quality. The UAV imaging was conducted before operation of the overhead sprinkler system for evaporative cooling, which wets the crop canopy, resulting in an altered temperature profile. Because imaging with the manned aircraft often coincided with or immediately followed the evaporative cooling events, the water use mapping with the manned aircraft may have been erroneous. Estimates from the satellite imagery lacked the spatial resolution needed for site-specific decision making.

We also evaluated the influences of localized and non-localized sources of weather data on the estimated water use for individual apple trees. Overall, UAV imagery with localized weather data enabled leaf-scale water use mapping, while the manned aircraft imagery enabled tree-scale mapping, and the lower-resolution satellite imagery enabled orchard-scale mapping.
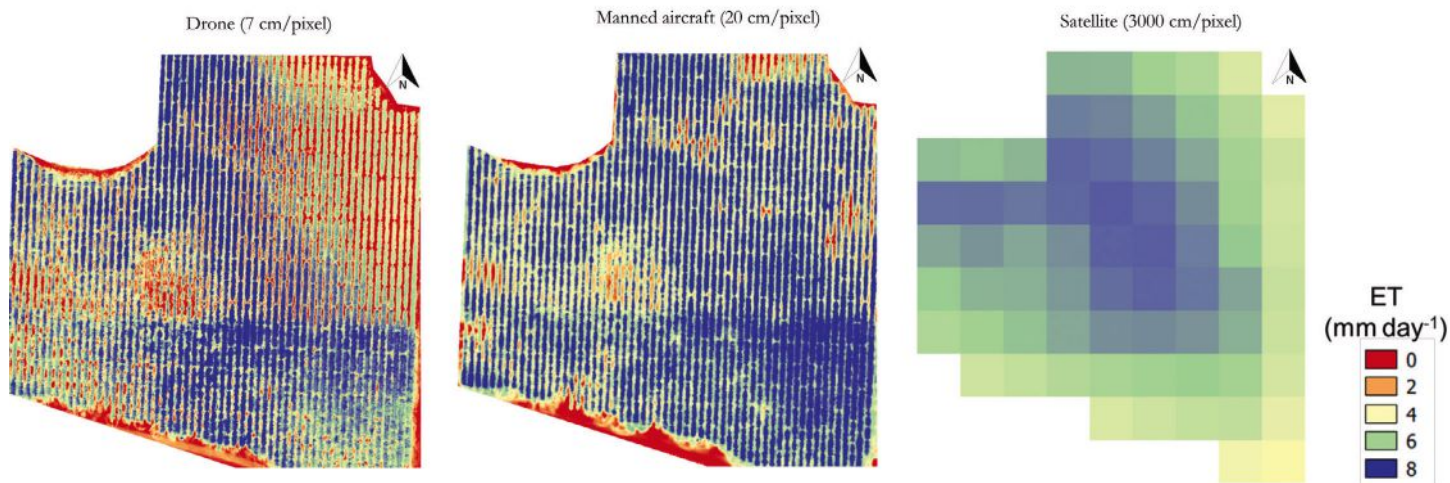
Crop water use maps of an apple orchard at 98 days before harvest using imagery from UAV, manned aircraft (from Ceres Imaging), and Landsat 8 satellite remote sensing.

Smartphone imaging for water stress

Similarly, we evaluated smartphone-based thermal-RGB imaging for mapping the crop water stress index (CWSI) in grapevines. The grapevines (cv. Cabernet sauvignon) were irrigated at 40%, 60%, 80%, and 100% of ET, as calculated from non-stressed crop coefficients and reference ET from weather data. The deficit irrigation treatments were applied at 60 cm depth, while irrigation at 100% of ET was applied at the surface. Smartphone imagery (in geotagged radiometric JPEG format with 0.9 mm pixel^{-1} spatial resolution) was collected for each treatment, and a custom algorithm was developed to extract the CWSI. The algorithm used localized weather data from the nearest WSU AgWeatherNet open-field weather station.

Overall, the CWSI estimates were lowest for the grapevines irrigated at 100% of ET and highest for the grapevines irrigated at 40% of ET. CWSI variations were also observed in the top, middle, and bottom zones of the canopy, which can be attributed to sun exposure levels. This in-field, on-demand, and portable sensing approach can be used for real-time CWSI estimation and site-specific irrigation scheduling.

The path forward

When combined with biophysical models implemented on edge or cloud computing platforms, these technologies allow digitizing of crop water use and monitoring of water stress in near real-time. The full potential of these technologies can be realized by addressing the following challenges: (1) capture and use of localized weather data and reduced empirical dependence on biophysical models; (2) compensation for biases in thermal imagery induced by atmospheric dynamics; (3) upscaling from UAV to other flexible remote sensing platforms for timely capture of crop physiology responses (including thermal infrared imagery) without interference from management operations (such as irrigation or evaporative cooling); and (4) end-user empowerment through apps for visualizing multiscale and multimodal data on hand-held mobile devices.

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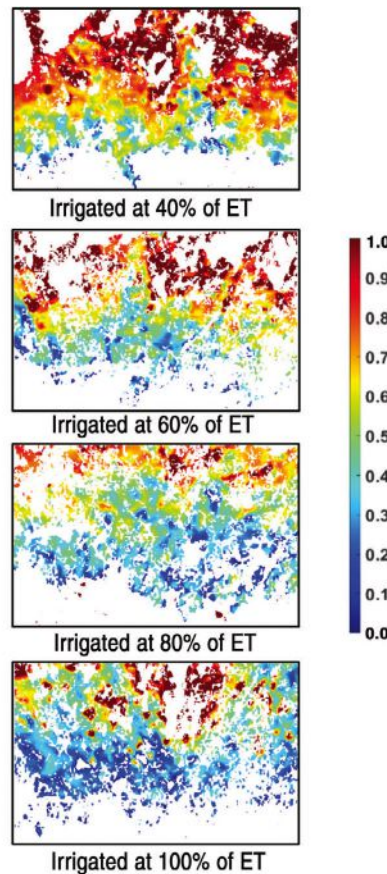
Using smartphone-based thermal-RGB imaging to map the crop water stress index in grapevines with four irrigation treatments.

Irrigated at 40% of ET

Irrigated at 60% of ET

Irrigated at 80% of ET

Irrigated at 100% of ET

The Importance of Sensors in Water Quality Research and Monitoring

Robert Hjort and Carmen Gomes

Agriculture is one of the largest global consumers of freshwater. Competition for water with the growing global population and increasing industrialization have resulted in water shortages, compounded by increasing water pollution. Water pollution is responsible for one-sixth of the global population lacking access to clean drinking water, which disproportionally affects low-income countries. To address the challenge of clean water access, many countries have established regulations to reduce pollution and have funded research initiatives for water purification in remote and low-resource areas.

Water quality monitoring is important for quantifying water pollutants and for determining the effectiveness of preventive and corrective strategies. However, monitoring water quality is challenging because most methods are laboratory-based and are therefore unsuitable for continuous sampling in remote and low-resource areas. Most methods also require sample pretreatment, exogenous reagents, or technical expertise, which increases the cost and hinders consistent monitoring.

Sensor systems that combine sensor data with analytics for decision support are a promising solution for remote and low-resource areas. Of particular interest are autonomous, low-maintenance sensor systems that provide continuous monitoring and that do not require sample pretreatment or reagents. Efforts to improve sensor performance (i.e., accuracy, response time, detection limit, concentration range, etc.) using new materials and scalable fabrication methods to reduce costs are also being explored.

In this article, we describe two types of sensors that have been used in field conditions to monitor water quality. The first type of sensor was developed to monitor nitrate in surface water using inexpensive ion-selective electrodes, while the second type, called biosensors, supports decision-making when pathogenic microorganisms are detected in irrigation water. The example sensors are at different maturity levels, offering insights into the development process. Finally, we provide some insights on remaining challenges in the development and deployment of water quality sensors.

Monitoring nitrate in surface water

Ions are found in all natural water sources but can become problematic when high concentrations or toxic ions are detected. Toxic ions found in water, such as mercury, lead, and cadmium, are heavily regulated and require precise equipment for detection at low concentrations (parts per billion). More benign ions that are toxic at high levels but tolerable at low levels require monitoring, particularly in agricultural and recreational settings. Monitoring of fertilizer ions (nitrogen, phosphorous, and potassium) is important due to their economic, environmental, and public health impacts.

Farms operate with narrow profit margins, and fertilizers are one of their largest expenses. Assessing nutrient levels before, during, and after fertilizer application is a useful method for maximizing crop yield and soil health while controlling cost. Solid-contact potentiometric ion-selective electrodes (sc-ISEs) based on polymeric ion-selective membranes can provide continuous in-field nutrient monitoring.

Ion-selective electrodes are composed of an electron-conducting transducer substrate, an ion-selective membrane, and a reference electrode. The membrane is selective toward free primary (target) ions in solution through the use of chemical compounds called ionophores. The sensor output signal is the difference in potential between the membrane/transducer interface and the reference electrode, which is assumed constant, and is typically measured with a high input impedance voltmeter under open-circuit conditions.

PVC is the most common material for polymeric membranes due to its chemical inertness and compatibility with a wide range of ionophores that are selective to organic and inorganic ions. Several research groups are currently focusing on optimizing polymeric membranes, developing alternative materials, and addressing issues with leaching of membrane components, water uptake, and biofouling. Alternative polymeric membrane materials include acrylate polymers and silicone rubbers, which have unique properties that can make them suitable for particular applications.

The transducer is critical to the overall stability and reproducibility of sc-ISEs. Conducting polymers such as poly(3,4-ethylenedioxythiophene) (PEDOT), polypyrrole (PPy), and poly(3-octylthiophene) (POT) are commonly used for solid-contact transducers. Their advantages are their ability to form ohmic contact with high work function materials, ease of deposition (e.g., electropolymerization or solution casting), and formation of an electroactive material with mixed ionic and electronic conductivity, enabling the transduction of an ionic signal into an

electronic signal. High surface area materials, such as micro/nanostructured carbon, form another type of sc-ISE transducer that is based on purely capacitive transduction. These materials, such as graphene, are a promising option for sc-ISE transducers because they are amenable to roll-to-roll manufacturing.

The stability and reproducibility of a sensor are affected by the material chosen for the electron-conducting substrate. Properties such as electrical conductivity, surface chemistry, and surface impurities significantly impact the quality of sc-ISEs. A recent method for producing a multi-layer graphene-like material, laser-induced graphene (LIG), was used for the development of inexpensive sc-ISEs for nitrate monitoring in surface water samples. These LIG-ISEs had a low detection limit for nitrate (0.373 ±0.089 ppm) and had performance comparable to an EPA-accepted analytical method when analyzing water samples from two lakes. The LIG-ISEs were immersed in the water samples for five weeks and showed good performance for the first three weeks, after which the polymer membrane began to delaminate from the LIG surface.

The overall durability of ISEs has been the main focus in developing this technology, with a design goal of monitoring ions in the field for several months at a time. The development of a water layer between the polymer membrane and the underlying electrode, biofouling of the polymer membrane, and leaching of the polymer membrane's chemical components are some of the top challenges for ISEs.

Pathogens and indicator bacteria

Pathogenic microorganisms are another area of concern for water quality, with annual global deaths and severe illnesses estimated in the millions and economic costs of at least one billion dollars. Ingestion of or contact with water contaminated with infectious agents such as bacteria and viruses are the main cause of these illnesses. Although there has been significant improvement in global access to clean water, disease outbreaks still occur and cause considerable healthcare and financial burdens, even in economi-

cally developed regions such as the U.S and the European Union.

Many methods exist for the detection of microorganisms in water, including spectroscopic methods, electrochemical methods, culturing and colony counting, and polymerase chain reaction (PCR). Although culturing and colony counting is considered the gold standard, extensive time is needed for reliable results, and false negatives can occur when working with viable but non-culturable microorganisms.

Reliable sensors for pathogens, like sensors for other targets, must be selective to the target, sensitive (i.e., detection limits within the regulatory requirements), reproducible, relatively rapid, and inexpensive. Electrochemical biosensors are coming to the forefront by meeting many of these requirements. Biosensors are differentiated

from other sensor types by their incorporation of biologically derived recognition agents (e.g., antibodies, enzymes, nucleic acids) that selectively bind with the desired target. The biological element is immobilized onto the sensor. During binding events with the target, the voltage, current, or impedance is monitored and used to quantify the target concentration.

Highly conductive precious metals such as gold, platinum, and silver are commonly used for the electrodes in biosensors for immobilization of the recognition agents. For example, a smartphone-based potentiostat was integrated with platinum interdigitated microelectrodes that were biofunctionalized with *Listeria* aptamers to develop a real-time sensor for hydroponic irrigation water. The sensor needed 27 minutes to analyze a 100 mL sample,
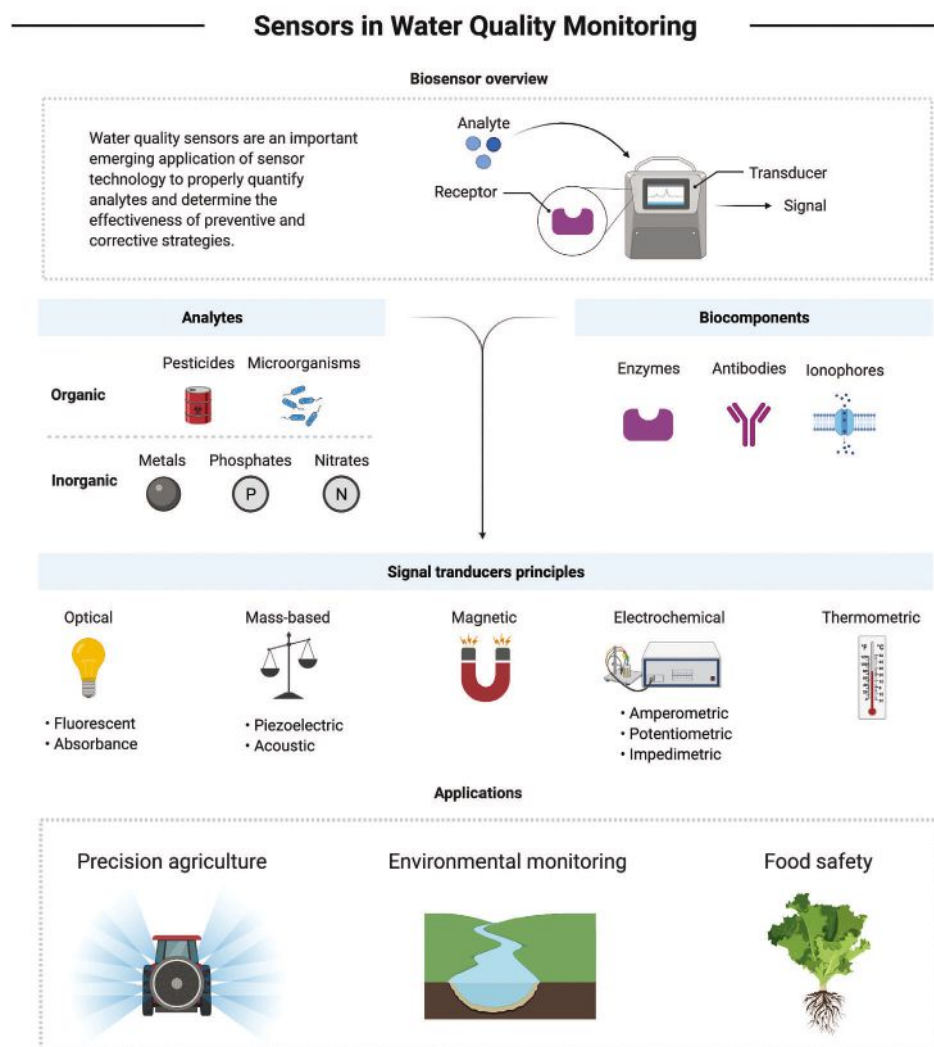
An overview of water quality sensors (*figure created using Biorender*).

which is much faster than colony counting, which can require 24 to 48 hours.

The system had a low detection limit of 23 ±4 CFU mL^{-1} and an operating range of 10^2 to 10^6 CFU mL^{-1} using sample volumes that followed regulatory standards. The sensor demonstrated reusability after rinsing in a strong basic solution (up to five times) and limitless reuse after removing the aptamers with Piranha solution followed by adsorption with fresh aptamers. Furthermore, the sensor was integrated with a flow-through system capable of pumping 10 mL min^{-1} of hydroponic solution for automated analysis.

Automation of sensors through cyber-physical systems is a large area of sensor research. Cyber-physical systems allow easy and continuous monitoring of samples and better decision support. A recent study provides an example of a semi-automated system for a rapid (17 minutes) and label-free (reagent-free) impedimetric biosensor for detection of *E. coli*. The metal-nanocarbon hybrid electrodes were loaded with temperature-responsive polymer nanobrushes, allowing capture of *E. coli* in food and hydroponic water samples. The polymer nanobrushes could have different terminal groups, facilitating the immobilization of bioreceptors, in this case antibodies and lectins.

The cyber-physical system developed in that study, called Sense-Analyze-Respond-Actuate (SARA), used nanomaterials and smartphone-based electroanalytical testing of the samples. A flow-through system was developed using a series of pumps that were triggered by electrochemical events at the surface of the biosensor, reducing problems with sample handling and providing on-site decision support based on data provided to the user via the smartphone app. SARA is an in-situ system and does not require sample extraction and transport to an analytical laboratory. Furthermore, the acquisition system is based on an open-source smartphone tool, which provides access to users with no need for unique equipment.

The system had a detection limit of 58 ±13 CFU mL^{-1} and an operating range of 50 to 200 CFU mL^{-1} for 100 mL water samples and enabled *E. coli* monitoring within the regulatory requirements for irrigation water, which dictate that *E. coli* concentrations must not exceed 126 CFU per 100 mL^{-1} without further responsive action.

Remaining challenges

Monitoring of water quality is essential for access to clean drinking water and for environmental protection and natural resources management. While a multitude of sensors have been developed around the world in the past few decades, very few have achieved widespread application due to various hurdles, including the incompat-ibility of operation in real-world conditions, and high fabrication and operating costs, consequently reducing market penetration and return on investment, compounded by a lack of integration with other technologies to provide actionable information to the user. Thus, the important factors for in-field water quality sensors are the control electronics and data transmission technologies, in addition to algorithms for processing large amounts of data to properly interpret the results for actionable decision-making.

Remote sensing, such as satellite and UAV imaging, in combination with in-field water quality sensors at different spatiotemporal scales can provide better understanding of the human impact on water resources and improve the predictability of hydrological models. Much work remains to be done to deploy water quality sensors in remote and low-resource areas.

Overall, water quality sensors play a key role in providing access to clean water, supporting water research, and preserving natural resources. They can also drive societal change, particularly in remote and low-resource areas, by providing evidence-based information that can influence public policy.

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Finding Solutions in Data Floods and Data Droughts

Young Gu Her, Sandra Guzmán, and Kati Migliaccio

Young Gu Her using a flowmeter to measure the flow velocity along the cross-section of a stream in Haiti.

The advances in sensing, computing, and communication technology over the past few decades have created extraordinary amounts of data—a data flood. Data are quickly created and widely available. Unmanned aerial vehicles can monitor large areas, and many satellite images are now open access, providing high-resolution spatial and temporal imagery. Smartphone apps allow us to upload images and receive real-time status reports. Palm-size processors can perform as many tasks as our home PCs, and wireless communication allows us to monitor operations from almost anywhere in the world.

The "data flood" metaphor perfectly illustrates the vast amounts of data that are available today, particularly in water research and hydrology. However, in addition to vast quantities of data, there are also vast differences in data quality, and the quality can vary among datasets as well as within a dataset. Thus, the first step in using digital water data is assessing the data quality.

Data floods and useful information

As you have probably learned from your own experience, having a lot of data does not necessarily mean having a lot of information. Raw data can contain errors, noise, outliers, and biases due to the limitations of the sensors and data collection methods, as well as human error. In addition, data quality can vary among different data sources because different researchers have different methods and purposes for data collection and evaluation.

The "data flood" metaphor is especially appropriate because the biggest challenge with digital water has become identifying which data, from many different datasets, are most useful for the task at hand with the least uncertainty and the most efficiency (i.e., the least time and money). The new challenge created by the vast quantities of available data requires new solutions, including statistical methods and AI with machine learning. These techniques are becoming essential for researchers in digital water who need to determine which data sets are best for the factor of interest, whether that factor is time, money, accuracy, or something else.

As agricultural and biological engineers who regularly collect and use water data, we recognize the need to establish guidelines for evaluating data quality and interpreting data with appropriate uncertainties, given the complexities present in data sets from multiple sources. Likewise, methods that consider multiple data sets can find better solutions, compared to decisions based on a single data source.

As evident to anyone who has worked with large data sets, data management is a significant consideration in converting data into information. New technologies, such as AI and machine learning, have rapidly evolved with the advances in data acquisition, computing resources, and statistical methods. Many of these methods can be applied with a "black box" approach, and users must be mindful of the risks of casual application. In particular, AI and machine learning are not useful for determining causation. However, AI can capture nonlinear processes that might be misrepresented by linear models. This ability has many applications in hydrologic systems.

For example, representation of the water dynamics across a soil profile requires characterization of complex media. Machine learning can incorporate multiple input data structures without the

need for assumptions about the governing equations of soil-water dynamics. This ability can provide rapid insights for practical management, especially at the field and sub-field scales where data are collected in real-time. Combined with an understanding of the physical processes, AI and machine learning can provide monitoring and control, such as in cyber-physical systems. Another example is the incorporation of stakeholder feedback as part of the data flood, where AI can provide technical assistance.

Supervised machine learning applications are particularly susceptible to input limitations. Expert knowledge can prevent the incorporation of biases embedded in the input data, which could be learned by the algorithm, leading to AI solutions that provide misleading information due to overfitting or estimating with unrelated data. To better explain the mechanisms behind the data, data-driven approaches can be informed by physically based approaches. Data-driven methods emphasize present data, while theory-driven methods emphasize past knowledge. Either approach alone is likely to be biased toward its own emphasis. Data-driven methods can thus lose their interpretability. Theory-driven methods can provide context for interpreting the results of data-driven methods.

With AI and machine learning tools, we have a new responsibility to ensure that these tools are used judiciously and balanced with other methods. Our expertise with the complex non-linear processes that occur in biological systems should inform the selection of the data used to train AI applications. The contributions of water resources engineers, technology professionals, and computer scientists in the selection of data can also contribute to the development of optimal methods for data quality monitoring and filtering when using these new applications.

Given the rapidly changing digital world and the new data tools, creating useful information for decision making requires researchers to understand how the stakeholders will interpret the information provided. Collaborations that incorporate

the social perspective are critical as data sources and evaluation methods grow in complexity, and as the users of this information are less familiar with the analysis methods. Researchers who collect and analyze data may not have the domain expertise or people knowledge to anticipate how the information will be interpreted. Therefore, multidisciplinary approaches are needed for digital water to provide the best information for decision makers.

Working with data droughts

We can now collect water data at any time interval desired, at as many locations as desired, and with as many data types as desired. As a result, data limitations are no longer based on the availability of data but rather on the quality of data, specifically on how the data can be converted to useful information. However, while much of the developed world has this capability, there are still parts of the world that do not. Thus, while engineers and researchers must be able to work in data-dense locations and address the special challenges that exist in those circumstances, we must also be able to function in locations with limited data resources.

In some parts of the world, water data are not a flood but rather a drought. Even rainfall data may be scarce in some developing countries. Some types of data, such as flow discharge data, are also expensive to collect, no matter the location. In these scenarios, global datasets, physically based approaches, statistical methods, and comparative assessments can be particularly useful. Global-scale remotely sensed datasets can help researchers estimate and predict the water conditions in remote areas, and new data portals provide ready access to water-related estimates, measurements, and images from national and international organizations, including:

- NASA's Data Pathfinders (https://earthdata.nasa.gov/learn/pathfinders)
- The Water Quality Portal of the National Water Quality Monitoring Council (https://www.waterqualitydata.us/)
- The Water Data Portal of the International Water Management Institute (https://waterdata.iwmi.org/)

- World Bank Water Data (https://wbwaterdata.org/).

Although there is no calibration-free simulation model, process-based modeling tools can still help us predict and understand water cycles in ungauged areas. When detailed modeling is not an option, statistical interpolation or even extrapolation using regressions, indexes, and geostatistical models can be an alternative. Comparative studies can use the characteristics of different areas to determine the similarities and differences between areas. Machine learning and AI can find hidden resemblances between gauged and ungauged areas and relate existing data to ungauged areas, maximizing the utility of historical data.

The best, and most expensive, way to acquire digital water data is to measure it. Big data methods and meta-analyses can help with identifying study areas and creating plans that can fill gaps in the data that are needed to answer a research question, thereby minimizing the required data collection.

However, there is no single best approach for all data droughts. Successful studies consider all available data and

Sandra Guzmán using a smartphone app to assess soil water status.

other information, including indirect observations, hydrological rationale, and expert knowledge, to improve their accuracy and assess uncertainty. Explicit communication about data limitations, efforts to overcome them, and the resulting implications is a big part of this collective expertise.

The future of digital water

Access to digital water data is still evolving, with further growth and new applications on the horizon. The future will bring unprecedented amounts of data, which will require new methods for data handling, automation, and analysis. In addition, the conventional methods, such as physically based approaches and statistical models, will still be important.

The flood of new data requires new methods for data communication and data sharing. Cloud computing can provide a platform for sharing data and software and thus improve the reproducibility of numerical experiments and modeling. Computer programming is already the second language of research, and it will continue to improve research efficiency and productivity in the future.

Each region of the Earth has its own hydrological particularities; thus, each regional water issue is unique. Likewise, the water data and the most appropriate tools also vary among different regions. The amount of available data, whether a flood or a drought, adds additional complexity. How do we ensure that data analysis and decision making use the optimal amount and optimal quality of data? And how do we create guidelines for data evaluation, especially for less experienced users? Given the diversity of water issues and the variations in data availability, these questions need to be considered carefully. As agricultural and biological engineers, we have a prominent role in guiding the use of digital water data to help the world manage, protect, and conserve its water resources, whether in data floods or data droughts.

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WADING BACK IN

I write this annual report with optimism for our Society. We are not without our challenges, but the last two years have been disruptive in so many ways and for everyone. One could argue about what was most disruptive to the entire global community in the past couple of centuries, but even world wars may not have the same type of reach to all "corners" of the world as this pandemic did. And like the rest of the world, our Society struggled, we learned, and now we move along in a new way. The presence of members together in section meetings, student rallies, and conferences starting in the fall was an indication that we try our best to protect ourselves and assume risk, but still desire to gain the benefits of in-person interactions.

I believe ASABE is strong, but we continue to face challenges. Our financial position in the past year is almost enviable. One might attribute this to luck of the markets, but it is also the savvy of those within the Society that make wise investments and careful management of our holdings. Our membership numbers have dropped slowly but steadily over time, but we are finding ways to encourage students to join and are reaching out well beyond our membership with far-reaching and important initiatives. Although we are investigating ways to enhance our income, loss of membership is certainly a concern for both the strength of the Society and the finances.

Internal Societal challenges aside, I think we can all agree that the relevance of our Society and what we do to meet the issues of a changing world is increasing, and fast. The initiatives that have bloomed over the past couple of years, with strong outward facing engagement, are increasing the recognition of our Society and what agricultural and biological engineers contribute to solving critical problems. We need to leverage these opportunities into membership growth and outside support.

In the past year, I have sought to send a message of the importance of providing an environment where all of our members feel welcomed, and therefore will thrive within the Society. It is an assumption that because someone is a member of our Society, they are entering a welcoming and safe environment. But the reality is that not all members feel that way. Status quo is not sufficient; it is only through paying attention and applying ongoing concerted efforts will we grow our membership and strengthen our retention.

As part of the effort to make all members feel welcomed in the Society and have their voices heard, the Board of Trustees approved placing the issue of student voting on the annual ballot. This was initiated in response to graduate students requesting the right to vote, and we felt that including undergraduates was

Life's a Beach! Among the many events this past year that brought attendees out from virtual environments to in-person encounters was the Florida section meeting. President Paul Heinemann, shown at right, was happy to join section members Adam Watson and Kati Migliaccio in Sand Key, near Clearwater.

an appropriate step. The measure did not receive the two-thirds majority of those voting to pass. Our next step is to see if we can determine the reasons why this failed, to learn more about members' concerns related to student voting.

This past year saw a huge increase in the number of members who chose to complete the detailed membership demographic survey initiated in 2020. The increase from just over 100 responses to well over 800 is encouraging and gives us much more insight into the diversity of our membership. The main purpose of this is to help us better serve the needs of our members.

My year as president began with virtual engagement, starting with the incoming Board of Trustees meeting after the annual meeting, in July 2021. But the fall brought change, and I was able to attend in-person meetings starting in November and continuing into the spring. And with invitations to present virtually to several hybrid and in-person meetings, I was able to connect with far more ASABE-related and external

Meetings & Conferences

2021 Annual International Meeting (Virtual)

2021 6th Decennial National Irrigation Symposium

2022 Agricultural Equipment Technology Conference

With Coronavirus still a significant presence in 2021, virtual events comprised 80% of all meetings held. This includes 15 specialty and 14 section/regional events and compares to 1 and 9, respectively, in 2020.

Event registrations totaled 3753, an 83% increase over 2020. The chart at right breaks down attendance by event.

Section/Region 17%
Annual Meeting 42%
Specialty Events 41%
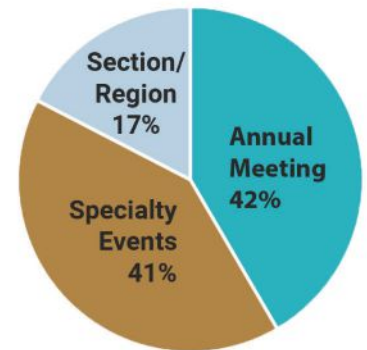
Realizing that online, hybrid, and distance learning increased the disconnect between students and the Society, we took action to engage the undergraduate population, with initiatives that resulted in an 84% increase in the number of student members.
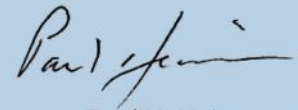
Overall membership numbers remained strong in 2021, with retention increasing five percentage points over the prior year.

Members found a new way to network, learn, and advance the profession through a Member Hour initiative, a series of live webinars, on a variety of topics, that cumulatively drew more than 600 participants over the past year.

With focus on growing ASABE as a welcoming and safe community, we collected more than 1800 demographic data points from our members, all provided voluntarily and confidentially. The data, to be used only in aggregate form, will help inform us in planning programming and policies that benefit members.

groups than if the virtual option were not available. Events I was able to attend in person included the Board of Trustee meetings, the North Carolina section, AETC, the Florida section, and the ¼-Scale Tractor Competition. Virtual connections included a presentation for an undergraduate course at Virginia Tech, the Texas and Oklahoma sections, the YPC leadership retreat, and the Philippine Society of Agricultural and Biological Engineers convention. By the way, the PSABE convention is quite something, full of pageantry and fanfare, as well as high energy.

This past year has been a great learning experience, and I very much appreciate the support from the ASABE executive director, professional staff, the Board of Trustees members, and all the other members who have contributed to our Society. Thank you.

Paul H. Heinemann

Paul H. Heinemann
ASABE President 2021-2022

Irrigation Systems Management is our newest open-access text and is available for download as individual chapters or as a whole and on Amazon as print-on-demand. A downloadable instructor kit also is available for a fee.

Transactions of the ASABE has been renamed *Journal of the ASABE,* to provide a clear reflection of the journal's peer-reviewed content and eliminate any confusion created by the word *transactions,* which some interpret as conference proceedings.

The Journal Editorial Board hosted a workshop, Associate Editor Best Practices, at ASABE's 2021 annual meeting. This roundtable discussion focused on best practices for associate editors as part of handling manuscripts for the ASABE journals. Future workshops are being scheduled.

Our editor in chief, Garey Fox, is providing a free literature review service that authors may request when submitting journal articles. Authors receive a list of recent key articles in ASABE journals to assist with manuscript preparation. There is no obligation to incorporate suggested citations into the article.

Standards

Participation
2000 Individuals

ASABE Activity
284 standards published
36 approved projects for new or revised

ISO Engagement
15 ISO committees
438 published international standards
86 approved projects

ASABE has formally applied to the Standards Council of Canada for accreditation as a Canadian Standards Developing Organization.

As always, we remain grateful to the supporters of ASABE's Standards program.

Additionally, a new award, the IDEA Award, was endowed by Robert and Yvonne Gustafson to recognize members who make significant contributions toward inclusion, diversity, equity, and access.

Our two major initiatives, the Alliance for Modernizing African Agrifood Systems and Circular Bioeconomy Systems, made strides by setting up structure, planning meetings and workshops, and launching distinctive logos. For CBS, a name change provides a crisper expression of the original, Transforming Food and Agriculture to Circular Systems.

We leveraged our partnership with DiscoverE to promote the profession's leadership in CBS, taking the opportunity to sponsor this year's Future City competition, the theme for which was "Waste-Free Cities." ASABE members across the country engaged as judges at regional and the national finals competitions.

REVENUE - December 31, 2021
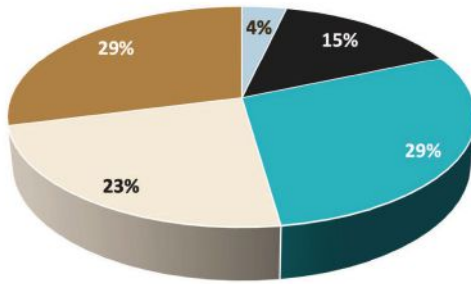
- Foundation: 4%
- Meetings & Conferences: 15%
- Society: 29%
- Standards & Technical: 23%
- Technical Publications: 29%

EXPENSES - December 31, 2021

- Foundation: 5%
- Meetings & Conferences: 9%
- Society: 42%
- Standards & Technical: 20%
- Technical Publications: 24%

Statement of Financial Position
December 31, 2021 and 2020
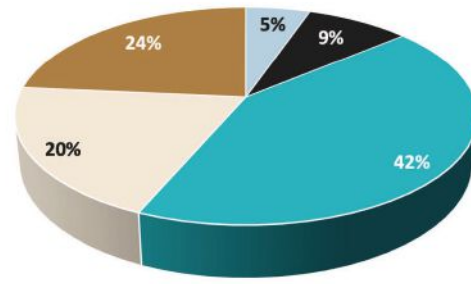
	2021	2020
ASSETS		
Cash	$2,139,424	$2,048,866
Accounts Receivable	19,980	32,395
Book Inventory	59,220	67,702
Due from (to) inter-fund (special projects)	0	0
Due from (to) inter-fund (other)	(94,780)	(109,573)
Property & Equipment	213,091	233,077
At cost, less $1,231,686 accumulated depreciation in each year		
Total Assets	$2,336,935	$2,272,467
LIABILITIES AND FUND BALANCE		
Accounts Payable & Accrued Expenses	561,403	554,151
Unearned Revenue: Dues & Sales	1,019,152	961,936
Fund Balance	756,380	756,380
Total Liabilities and Fund Balance	$2,336,935	$2,272,467
RESTRICTED RESERVE BALANCE	$2,962,985	$2,638,940
REVENUE	3,189,715	3,146,074
EXPENSES	3,094,935	3,036,501
SURPLUS	$94,780	$109,573

ASABE

Real-Time Monitoring, Modeling, and Control of Water Resources

Dayton Marchese, P.E.

Opti Monitoring
Continuous Monitoring

Opti Plus
Continuous Monitoring
and Adaptive Control

**Third Party
Integrations**

Opti Platform

Beaver Creek
Trunk Lines

Beaver Creek
Sewershed

The smart sewershed in Albany, New York, is monitoring and controlled by OptiRTC, a provider of digital stormwater management solutions.

The water resources industry is experiencing a digital revolution in which data and information are increasingly used to perceive the world, assess the situation, and then determine the course of action. Specifically, advances in communications and control technologies have led to significant improvements in three aspects of water digitization: real-time monitoring, modeling, and control.

Many of the improvements to date have focused on one of these three aspects. During the next era of digital water adoption, previously isolated monitoring, modeling, and control technologies will be integrated into water resources management, resulting in better understanding of water systems, quicker action, and improved social, economic, and environmental outcomes.

From technologies to integrated solutions

Advances in monitoring, modeling, and control technologies have resulted in improved operations and outcomes for municipalities and utilities. Sensors reporting real-time or near real-time (e.g.,

daily) data using cellular, radio, or satellite links have enabled operators to gain a trusted view of their systems. Hydrologic and hydraulic (H&H) models calibrated with field measurements and leveraging statistically derived design storms have enabled engineers and water resources managers to evaluate alternatives and design drainage systems. Control technologies have evolved from passive systems (e.g., relying on channel slopes and pipe diameters to control flows) to active systems with pumps, actuated gates, and valves that allow operators to take remote control of civil infrastructure.

Pushing the envelope further, water resources professionals have coupled various aspects of monitoring, modeling, and control technologies. Integrating real-time monitoring with modeling has given rise to live modeling, in which real-time sensor data, weather radar, and other environmental inputs inform H&H modeling in real-time. Utilities, government departments, and emergency response agencies use live modeling at the city scale (only recently available with advances in computing power) to forecast flood conditions as storms approach and take preparatory action.

Live modeling is particularly useful for informing immediate action because the data inputs are real-time field measurements (e.g., current water levels) instead of statistical averages like those used in many H&H design models. Like live modeling, integrating real-time monitoring with real-time control systems has resulted in more advanced control logic that uses observations from throughout the drainage network to drive action.

With three-way integrated solutions combining monitoring, modeling, and control, real-time data (water levels, flow rates, radar rainfall, weather forecasts, etc.) can feed continuously running live models that in turn inform the actions of automated control systems. These actions include draining stored water in advance of storms to create additional flood storage, or holding water during storms to alleviate pressure on downstream systems. Targeted actions specified by the control systems and the resulting field observations are sent back to the live models for use in subsequent model runs. This continuous process of monitoring, modeling, and control results in faster action and better outcomes for municipalities and utilities.

Improved environmental and economic outcomes

One municipality that leverages integrated monitoring, modeling, and control is Albany, New York. Like many cities in the northeastern U.S., Albany experiences flooding and combined sewer overflows. To address these issues, the city implemented a type of data-driven stormwater management called continuous monitoring and adaptive control (CMAC). Stormwater facilities (lakes, ponds, underground vaults, etc.) enhanced with CMAC are equipped with sensors and actuated flow-control devices. A cloud-based software platform analyzes the local weather forecast and site data, models the projected sewershed response in Albany, and automatically drains the stormwater facilities in advance of storms to create capacity.

During storms, Albany's CMAC systems meter flow into the receiving sewer at the lowest rate possible to provide capacity relief downstream. The first three of Albany's CMAC sites reduce wet weather discharge into the sewer system by 63.6 MG per year, compared to only 9.8 MG per year that would have been captured with traditional best management practices (BMPs). Because enhancing stormwater BMPs is generally less expensive than

A solar-powered stormwater control panel that uses cloud-based real-time control software.

building new infrastructure, Albany was able to capture that additional stormwater for $0.005 per gallon, compared to an estimated $0.47 per gallon with traditional stormwater management.

Another utility that uses CMAC to improve stormwater management is the Beckley Sanitary Board in Beckley, West Virginia. The Beckley Sanitary Board converted a dry detention pond into an adaptively controlled smart pond and increased annual sediment capture from 0% to 62%. This project also helped Beckley reduce flooding at the downstream intersection of Ewart Avenue and Robert C. Byrd Drive from an average of four or five times per year to less than once per year. The cost to the utility was approximately $0.02 per gallon managed, compared to $0.36 per gallon with traditional management.

Resilient design and operations

One of the fundamental functions of water resources professionals is infrastructure implementation, which generally follows a linear process: model, design, build, and maintain. With the adoption of digital water technologies, engineers and designers are no longer so tightly bound to this process. Previously permanent features of water resources infrastructure, such as normal pool elevations or maximum discharge rates, are editable in the software that controls the infrastructure. This represents a shift away from the traditional linear model to a cyclical process in which water resources infrastructure is regularly optimized as new data are collected, environmental conditions change, and regulations evolve. With digital water control technologies, modifying civil infrastructure after construction is as easy as changing software settings.

Take Ormond Beach, Florida, for example. In Ormond Beach's Central Park, there are five interconnected lakes with a

A stormwater control structure with a remotely actuated valve for automated real-time control.

combined capacity of 250 acre-feet that are an aesthetic and recreational amenity for the community. These lakes also provide flood risk mitigation for the surrounding neighborhoods. Before Hurricane Irma in 2017, Ormond Beach's CMAC system analyzed the local weather forecast, read real-time water level data from the site, and simulated the storm response. Based on that information, the lakes were drawn down to create capacity. The result was no flooding in Central Park during Hurricane Irma. According to Ormond Beach Public Works Director Shawn Finley, "Making information available on demand allows us to make better decisions."

In addition to design improvements, communities are realizing significant operating efficiency from implementing digital water solutions. For example, stormwater maintenance is often triggered when a field technician inspects a faulty facility and generates a work order. Crews are then deployed to fix the issue. The challenge with this process is that the time between failure and inspection can be months or even years. Meanwhile, the stormwater pond may not be functioning at all, resulting in poorer water quality, increased flood risk, or increased likelihood of catastrophic failure.

With real-time monitoring contextualized with site-specific information, facility failures can be automatically identified. Moreover, the integration of control technologies means that action can be taken.

Luke Stevens, an environmental specialist at the Beckley Sanitary Board, reviews real-time environmental data from a CMAC stormwater facility.

For example, if an automated diversion structure existed upstream of a failing stormwater facility, a real-time monitoring and control system could identify the critical failure point and route stormwater flows away from the failing facility until the anomaly was inspected and corrected.
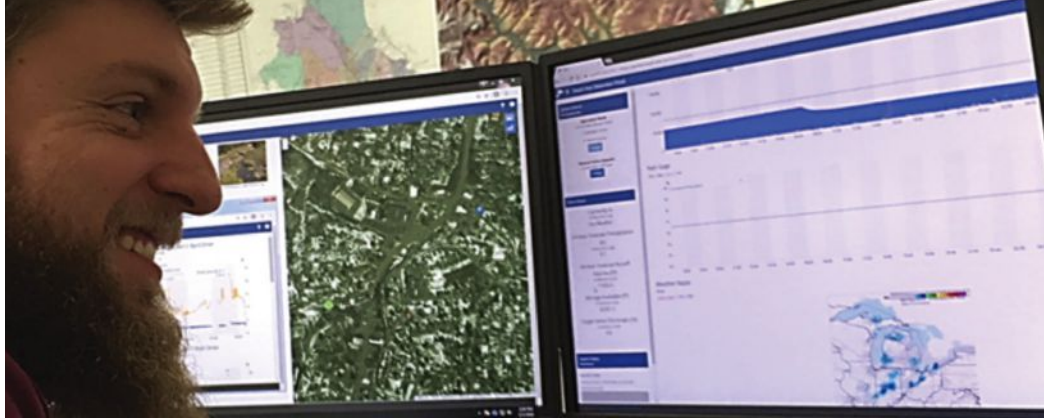
Integrating monitoring, modeling, and control also allows decisions to be made more rapidly as conditions change. Instead of requiring a person to interpret field conditions (e.g., water levels and rainfall radar) and decide on an action, which limits the decision frequency to maybe once a day, automated systems can process information and take action as frequently as the data reports. For example, a new weather forecast is available from NOAA every 15 minutes. An automated system can update control decisions for stormwater infrastructure with each new weather forecast and each new sensor reading.

Rethinking data, information, and knowledge

Integrating monitoring, modeling, and control enables a restructuring of how people interact with data and information. In water resources, data are collected and analyzed, information is extracted and influences action, and the results of that action are integrated into institutional knowledge. Traditionally, people have been heavily involved in every aspect of this process, including collecting field data, analyzing the data, and interpreting the resulting information.

Real-time monitoring largely replaces people in the data collection step. Live modeling provides data analysis and information extraction, and real-time control enables action. This technology-enabled shift means that an organization's most critical resource, its people, can focus on the most complex part of the process: interpreting outcomes and generating institutional knowledge.

How people look at data will also evolve with the rise and likely decline of digital dashboards. Dashboards are a necessary interim step in enabling digital water solutions, but dashboards are not the end goal. Instead, relevant data from seemingly disparate systems will be linked through application programming interfaces (APIs) or other tools to generate action. For example, roadway flooding captured by traffic cameras will be used to calibrate live models and trigger automated action to reroute traffic away from other roads that are predicted to flood, all without people in the loop.

Most of the data on today's dashboards will be used primarily by software. The only information that will need to be surfaced to people will be that which requires critical decision-making, so that operators only have to address challenges for which there is no pre-existing and pre-engineered solution. This is how change is affected, process improvements are made, and the water resources industry evolves.

Opportunities to accelerate digital water adoption

Civil engineering is a traditionally slow-moving industry. Water resources infrastructure is critical, and failures can lead to poor water quality, property damage, and loss of life. Water resources infrastructure is also long-lasting, and the drainage networks installed today will continue to shape communities for decades to come. Because of this, public works departments and utilities are particularly cautious with technology adoption. One way for key decision-makers to mitigate risk and improve the level of service through technology adoption is by finding trusted academic and private-sector partners with which to innovate.

Another way to accelerate digital adoption in the water resources sector is to advocate for the innovation of regulatory frameworks. Many digital water technologies do not fit into existing regulatory frameworks, leaving communities without incentives to adopt technology despite the improved environmental outcomes. One way to address this is for regulators to establish clear guidance for new technologies to achieve regulatory approval, possibly through testing and validation by trusted third-party entities with deep industry expertise.

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Sustainable Use of Groundwater in Agriculture

Isaya Kisekka

The greatest threat to the sustainability of irrigated agriculture in the U.S. is drought due to climate change, which has resulted in groundwater overdraft as farmers turn to groundwater as an insurance against drought. Some of the most productive agricultural regions in the U.S., such as California's Central Valley and the High Plains Aquifer region, are experiencing unprecedented levels of groundwater overdraft. Groundwater is also threatened by salinization and nitrate contamination associated with irrigated agriculture. Sustainable use of groundwater to meet the growing global demand for food, fiber, and biofuels while ensuring co-benefits for the environment and human health remains a grand challenge.

Aquifer overdraft and contamination have also resulted in significant social problems. Rural farming communities are particularly affected because they have fewer financial resources with which to dig new or deeper wells or diversify their water supply. Other problems associated with aquifer overdraft include land subsidence and infrastructure damage, harm to groundwater-dependent ecosystems, and negative impacts on rural agricultural economies.

To address these groundwater supply and quality issues, many U.S. states have enacted laws that will have a significant impact on the sustainability of irrigated agriculture. In 2014, California enacted the Sustainable Groundwater Management Act (SGMA). For the first time ever, California was given a framework for sustainable groundwater management. Under SGMA, water users need to bring their basins into long-term balance and avoid undesirable effects from excessive pumping by 2040. In addition, groundwater quality regulations, such as the Salt and Nitrate Control Program, are now in effect in parts of California to regulate nitrate leaching and salinization, a big part of which has been blamed on nonpoint-source pollution from agriculture operations.

Growers, water managers, and policymakers need tools that allow them to achieve sustainable use of groundwater in agriculture while meeting other social needs, such as an adequate nutritious food supply. Our research group at UC Davis is leading a multi-disciplinary and multistate USDA-NIFA SAS project to develop sustainable irrigated agricultural systems in the southwestern U.S. and to develop models and decision support tools for sustainable use of groundwater. Below are some examples of the projects being conducted by our research group to achieve these objectives.

Water management tools that address the needs of stakeholders

In collaboration with growers and groundwater sustainability agencies in the Central Valley, we are assessing and improving models for satellite-based remote sensing to estimate the evapotranspiration (ET) of applied irrigation water. The proportion of total ET that is attributable to applied water (ET_{app}) is used by some groundwater sustainability agencies in California to allocate and track groundwater use by growers on a field-by-field basis.

In one study, we are evaluating single-source and two-source energy balance models and comparing them against eddy covariance measurements of ET in an almond orchard. Our results show that if energy balance models are properly parameterized and integrated with soil hydrology models, they produce ET estimates comparable to ground-based measurements. Information from this study is
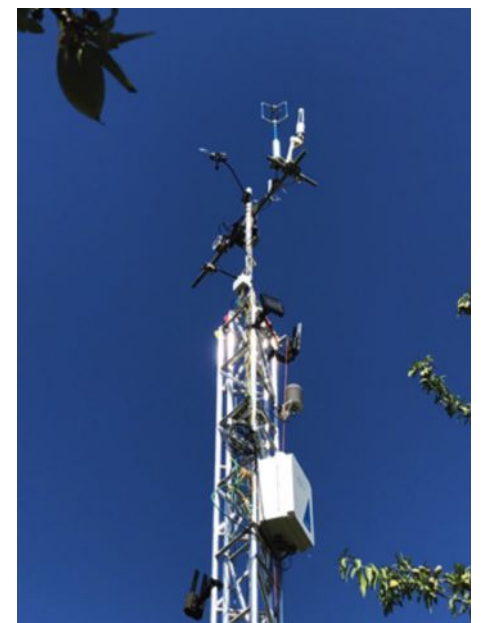
An eddy covariance flux tower installed in an almond orchard for validating remotely sensed evapotranspiration estimates.

Proximal sensing of orchard-scale soil moisture using a cosmic ray neutron probe in an almond orchard near Corning, California.

useful to groundwater sustainability agencies in the absence of water flow meters they use remote sensing to monitor water allocations on a field by field basis..

In a related study focusing on helping growers cope with limited water supplies, we are evaluating precision irrigation management in specialty crops, including almonds, walnuts, and processing tomatoes. We have developed a framework that combines monitoring of the soil, plant, and ET using ground-based sensors, proximal sensors, and remote sensing. We tested this framework in six almond orchards in the Central Valley. Our results show that it is now possible to use recent advances in soil water sensing technology (i.e., cosmic ray neutron probes in ~11 acre blocks) to monitor soil water at the orchard scale, thereby overcoming the limitations of point measurements.

New stem water potential (SWP) sensors, including osmometers and micro-tensiometers, for direct measurement of SWP were also investigated at several sites as a potential replacement for the pressure chamber, which is a scientific standard for measuring water status in tree crops but is very labor-intensive. We observed good accuracy between the SWP sensors and pressure chamber measurements, although proper installation is critical. We developed a model to upscale individual tree SWP measurements to the entire orchard using machine learning. Remote sensing and aerial imagery were also used to estimate high-resolution spatial evapotranspiration maps at scales ranging from an individual tree to the entire orchard. Growers can use these maps to refine their site-specific irrigation scheduling.

Monitoring of nitrate leaching to groundwater

Nitrate contamination of groundwater is a major problem worldwide, including in the U.S. Innovative monitoring techniques are needed to assess the impacts of irrigation and nitrogen management on nitrate leaching to groundwater. In this study, we are evaluating monitoring practices for nitrate leaching based on a deep vadose zone monitoring system (VMS), groundwater monitoring, and field-scale nitrogen balance assessments. This study is being conducted in collaboration with the USDA-NRCS Conservation Effects Assessment Project (CEAP), water quality coalitions, and commercial growers.

The study site is a commercial processing tomato field in Yolo County in the Central Valley. Between 2019 and 2021, the field was in a crop rotation of triticale and processing tomato. Historic water and nitrogen mass balances were performed using grower information, remote sensing, meteorological data, and nitrogen uptake coefficients. Since November 2019, water and nitrogen inputs and outputs have been continuously measured, and field-level water and nitrogen mass balances have been performed. In addition, a unique deep vadose zone monitoring system (VMS) was installed in the 2020-2021 season, and nitrogen movement was monitored from the root zone, through the deep vadose zone, and to the groundwater.

The deep VMS was able to detect deep percolation and nitrate leaching after an atmospheric river in October 2022 produced heavy rainfall in northern California (114 mm in 48 hours). This novel approach for continuous monitoring of nitrogen leaching from irrigated agriculture could easily be adopted in other regions dealing with nonpoint source nitrate contamination of groundwater.

Summary

Major aquifers in irrigated agricultural regions are experiencing unprecedented overdraft because water is being extracted at a higher rate than it can be replenished by precipitation or recharge from streams. Sustainable use of groundwater in agriculture is critical for achieving global food security. At the groundwater basin scale, practices that can enhance the sustainable use of groundwater include managed aquifer recharge, water demand reduction through groundwater allocation restrictions, and the development of groundwater
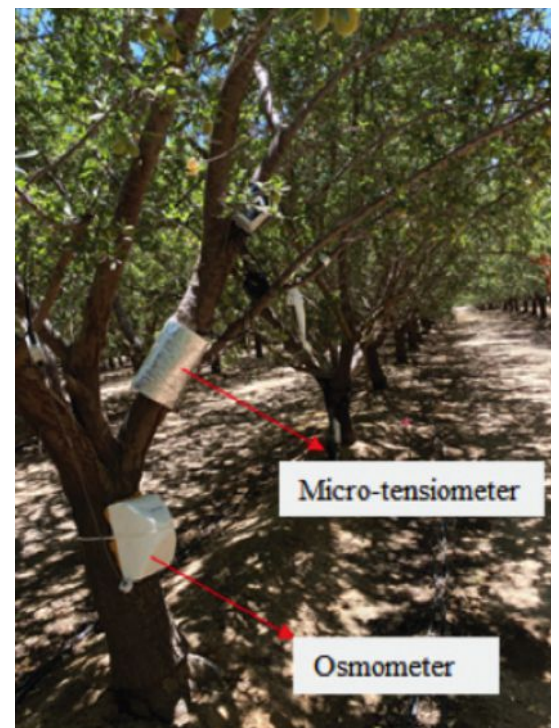
Automated monitoring of almond tree water status (stem water potential) using a micro-tensiometer and osmometer as replacements for a labor-intensive pressure chamber in an almond orchard near Arbuckle, California.
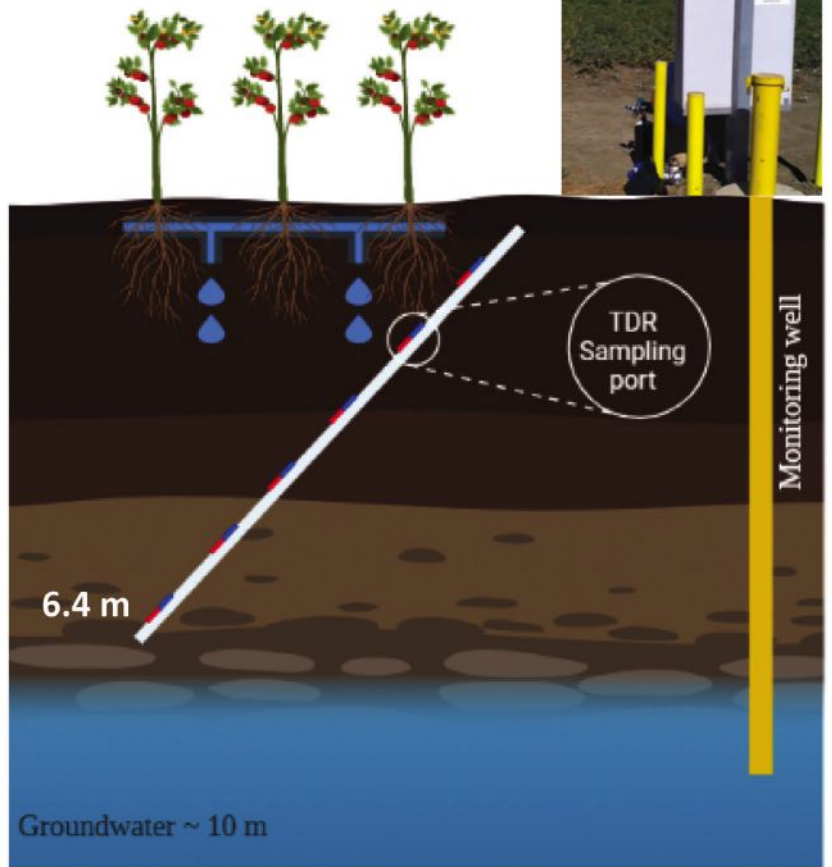
Installation of a deep vadose zone monitoring system (VMS) for continuous monitoring of nitrate leaching to groundwater in a processing tomato field near Esparto, California: (A) insertion of the VMS into the soil, (B) wetting the sampling port prior to insertion into the soil, and (C) the control panel for collecting soil pore water samples.

trading and markets. At the farm level, regenerative agriculture practices, precision irrigation, and multi-benefit land repurposing, such as conversion of previously irrigated land to other land uses, can help growers cope with limited water.

Water quality issues also need to be addressed to protect groundwater-dependent ecosystems as well as communities that depend on groundwater for their drinking water supplies. Most of all, sustainable groundwater use in agriculture

will require building trust and cooperation among the stakeholders.

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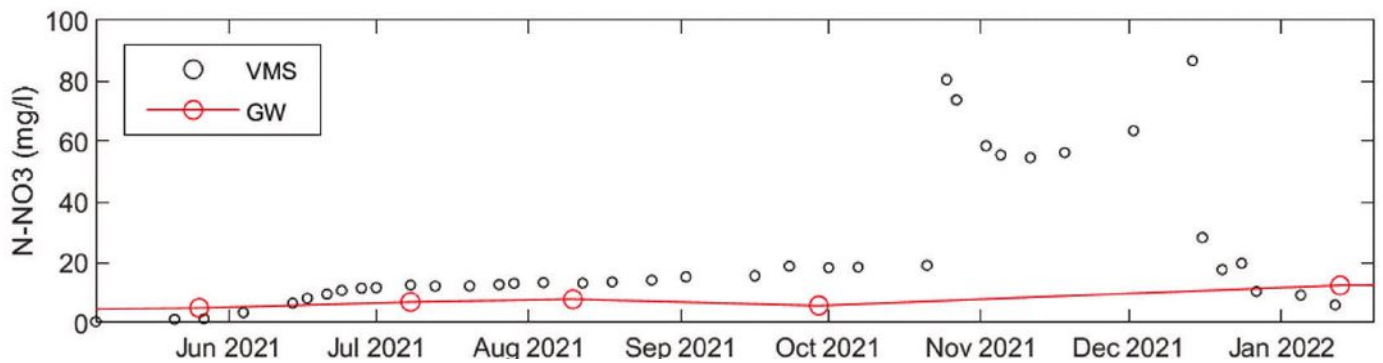
Nitrate leaching in the deep vadose zone measured by the VMS increased significantly after heavy rainfall in the fall of 2021 and the red line indicates nitrate concentration in groundwater.

The Rise of Cyberinfrastructure for Environmental Applications

Venkatesh Merwade, Adnan Rajib, I Luk Kim, Lan Zhao, and Carol Song

The global population is expected to reach approximately nine billion by 2050. Sustainable agricultural production will play a critical role in feeding the growing population and maintaining food security. At the same time, climate will continue to change and pose unprecedented challenges, in the form of extreme floods and droughts, to agricultural activities. Creating and maintaining food security in the coming years will demand innovations to increase agricultural production without impacting the Earth's other resources, such as land, water, and biodiversity. Significant innovations are already being made in agricultural production, including the use of precision agriculture, automation, and conservation practices, among others.

One of the tools that will play a critical role in enabling innovations in agricultural production is cyberinfrastructure, specifically the use of the internet and computational resources for handling big data and simulation models. Purdue University is a global leader in creating cyberinfrastructure for enabling innovations for climate change and water resources, which are connected to sustainable agricultural production. In this article, we highlight some of the tools and technologies that are hosted on WaterHub (https://mygeohub.org/groups/water-hub) for supporting the agricultural and environmental communities.

SWATShare

The Soil and Water Assessment Tool (SWAT) is a widely used modeling tool for simulating hydrology, water quality, best management practices, and crop management around the globe. SWATShare (https://mygeohub.org/groups/water-hub/swatshare) is a platform-independent resource for online publication of SWAT models for sharing model results with a wider community, enabling further development and enhancement of models, providing access to high-performance computing (HPC) resources to perform auto-calibration, and visualizing model results using geospatial and time series plots.

In addition to providing the above functions, SWATShare acts as a community
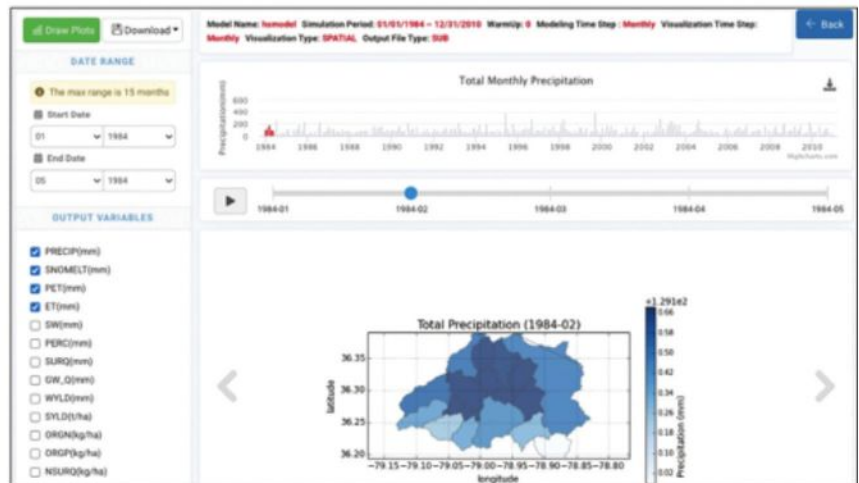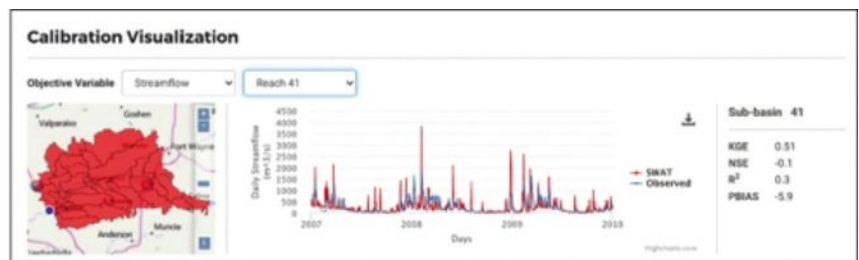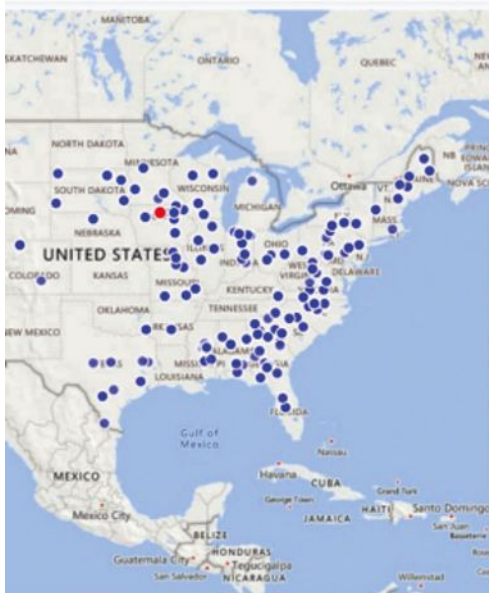
The SWATShare image on the left shows the areas for which SWAT models have been published. The images on the right show time series and geospatial plots.
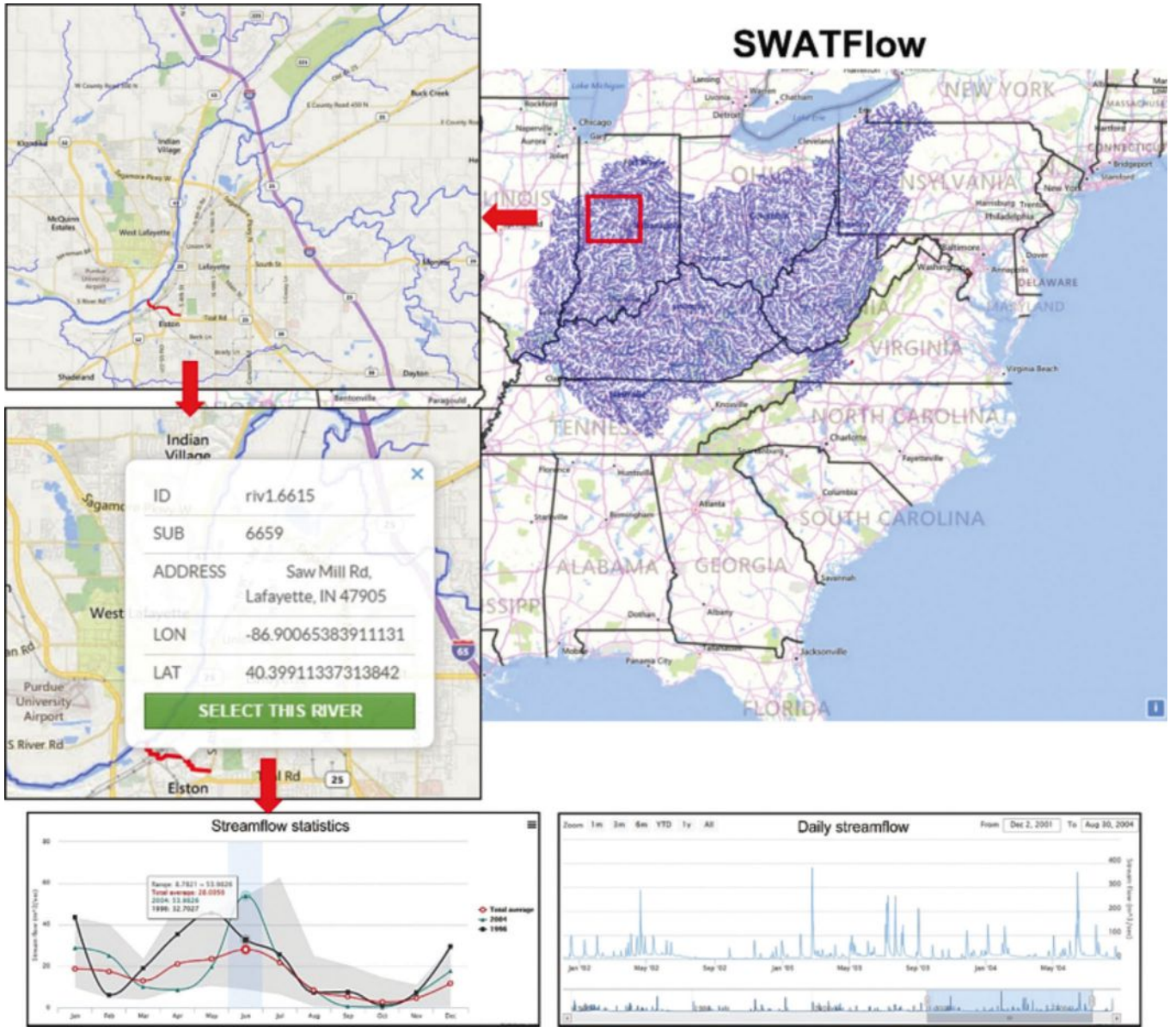
The SWATFlow interface showing the NHDPlus stream network in the Ohio River Basin and streamflow plots for a selected reach.

resource for creating a public repository of SWAT models for users around the globe. Considering the enormous efforts that go into creating an accurate model for simulating water and environmental conditions in a given region, SWATShare enables multiplication of these efforts across multiple domains to address water and agriculture-related questions from researchers, educators, and decision-makers.

SWATFlow

SWATFlow (https://mygeohub.org/groups/water-hub/swatflow) is a platform for publishing SWAT modeling results that can be visualized dynamically for any stream in the model. The current version of SWATFlow includes SWAT results using the high-resolution National Hydrography Dataset (NHD) for the Ohio River Basin (ORB). The SWAT model for the ORB was created through multi-site calibration using 70 years of data. Users can select any reach in the ORB and look at the historical daily streamflow hydrograph for that reach. For major stream reaches in the region, users can also see the flood inundation map corresponding to the flow. The flood inundation library for the ORB was created using the 2D LISFLOOD-FP model.

Users can also upload their own SWAT models to SWATFlow to dissemi-nate the model results through the SWATFlow dynamic visualization platform. This platform has already been adopted to disseminate streamflow information for the Quilca-Chili-Vitor and Camana river basins in Peru (www.agry.purdue.edu/hydrology/projects/nexus-swm/en/web_tools.html).

HydroGlobe

Most environmental models are calibrated using limited data, which primarily include streamflow observations at a few locations in the watershed. Remotely sensed Earth observations provide data related to many hydrologic fluxes that can
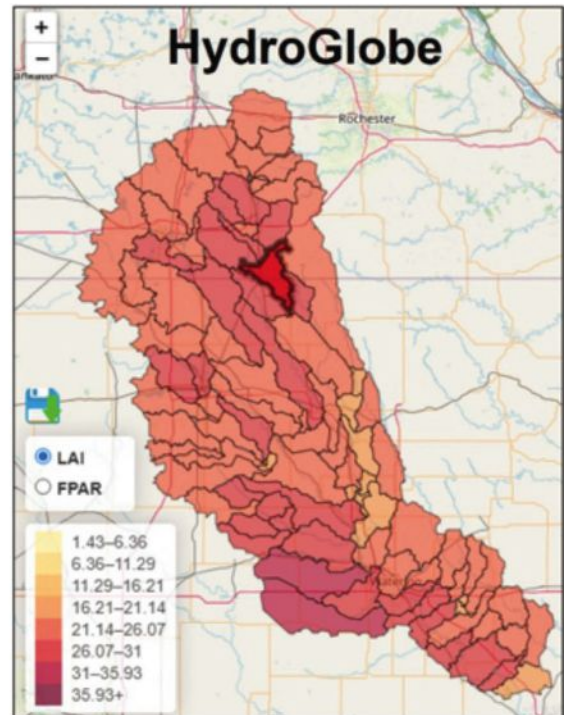
HydroGlobe interface showing a map of Leaf Area Index (LAI) created by processing MODIS data.

be used to improve and calibrate models such as SWAT. However, inconsistent storage structures, data formats, and spatial resolutions among different sources of remotely sensed observations limit their integration with hydrologic models. Available web services can help with downloading and visualization of bulk data, but they are not sufficiently tailored to meet the degree of interoperability required for direct application of Earth observations in hydrologic modeling at user-defined spatio-temporal scales.

HydroGlobe (https://mygeohub.org/tools/hydroglobetool) minimizes these processing tasks and delivers ready-to-use data from different Earth observation sources. HydroGlobe can provide spatially aggregated time series of Earth observations using the following inputs: data source, temporal extent in the form of start/end dates, and geographic units (e.g., grid cell or sub-basin boundary) and extent in the form of GIS shapefiles. HydroGlobe currently supports multiple data sources, including surface and root zone soil moisture from SMAP (Soil Moisture Active Passive Mission), actual and potential evapotranspiration from MODIS (Moderate Resolution Imaging Spectroradiometer), and precipitation from GPM (Global Precipitation Measurements).

Education and Workforce Development

While platforms such as SWATShare, SWATFlow, and HydroGlobe provide useful resources for the modeling community, creating, using, and sustaining such resources require training in cyberinfrastructure. Such training is currently not included in the engineering programs at most universities. At Purdue, we are using MyGeohub to host educational materials in the form of self-paced course modules that anyone can complete to learn how to program and create tools such as HydroGlobe for accessing, processing. and visualizing time series and geospatial data.

These modules train students on how to access publicly available data related to climate, streamflow, topography, soil, and land use by writing simple scripts in Python using the Jupyter Notebook environment hosted on MyGeohub. Students are also trained on how to make their research findable, accessible, interopera-ble, and reusable (FAIR) so that it can be used by a wider community. Students at many universities in the U.S. and around the world have completed these modules in MyGeohub and have learned to incorporate FAIR principles in their research.

The continued growth of cyberinfrastructure is providing unprecedented opportunities for the agricultural community to access and process big data. Access to high-performance computing resources is enabling environmental simulations at multiple scales. This article provides just a few examples of how cyberinfrastructure is being used to make SWAT models, their results, and related tools accessible to a broader community. As the technology continues to evolve, we will need to keep pace with it by providing training in the technology for the current and next generation of users.

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Using Cumulative Indicators to Detect Management Effects on Water Quality

François Birgand

One of the most difficult tasks that water researchers and engineers have faced is detecting, documenting, and quantifying the effects of a particular management practice (such as land use change) or BMP implementation on water quality. One of the major difficulties has been the lack of sufficiently frequent water quality data. However, with the availability of continuous water quality sensors, this lack-of-data problem has dwindled.

So what should researchers and engineers do with the higher-frequency data? To take full advantage of sensor data, are some indicators more pertinent than others? These questions are not as simple as they sound, and the answers may not be obvious. In particular, I suggest that some previously overlooked cumulative indicators should be considered as powerful tools to identify trends and detect the impacts of management on water quality.

Since the 1960s, hydrologists have had the ability to monitor flow rates and water tables on a nearly continuous basis. This has allowed researchers to establish the full story of hydrological phenomena, from which it has been possible to derive underlying mechanisms and create simulation models. I use the term "full story" for a reason. Hydrologists are keenly aware of the importance of measuring flow all the time because much of the flow volume can be exported in a relatively small proportion of the time, and at unpredictable times. In small watersheds, as much as 50% of the

> ❝ In a way, measuring hydrological phenomena is like watching a suspenseful movie, in which certain scenes are critical to understanding the plot. If you miss those critical scenes, you won't get the full story. ❞

volume can be exported in just 10% of the time, and that proportion of time decreases with decreasing watershed size.

In a way, measuring hydrological phenomena is like watching a suspenseful movie, in which certain scenes are critical to understanding the plot. If you miss those critical scenes, you won't get the full story.

Historically, to measure concentration data, in contrast to flow data, hydrologists had little choice but to collect water samples, either manually or automatically, and then analyze the samples one by one in the lab. That labor-intensive process yielded concentration data of much lower frequency (two or three orders of magnitude lower) than that of flow data. As a result,

our understanding of the processes involved and our development of tools to model water quality lagged behind those for water quantity. It's as if we were trying to understand the full story of a complicated movie from a collection of still images. It was not easy to detect how much the story had changed, or if it had changed at all.

Recently things have gotten better. Thanks to water quality sensors, researchers now have access to the full story on water quality as well as quantity, although the observations may still be a bit blurry because the sensors are not perfect. Hydrologists equipped with full and nearly continuous hydrographs and chemographs now have the data they always dreamed of having! So things should be easy now, right? Unfortunately, the availability of continuous sensor data has created a new challenge.

Mesmerized by the richness of information embedded in the sensor data, with concentration variations occurring in synchrony with flow variations, hydrologists have been in a frenzy of activity to analyze the relationships between concentration and flow, or the famous C-Q relationship. However, as we analyze the C-Q relationship for the information that it may reveal, it remains unclear whether this approach, i.e., analyzing the hysteresis loop formed by C = f(Q) over months or during flow events, has helped us decipher the processes at work in watersheds. This uncertainty is forcing us to think about the nature of the flow and concentration data, and the reasons why extracting trends from these analyses may be difficult.

I've always been fascinated by the ability of agronomists to quantify the effects of fertilization or pesticide treatments, with relative ease, from randomized research plots. Agronomists commonly report treatment effects of less than 5% with surprisingly narrow confidence intervals. What are they doing right, and what are we hydrologists missing?

I suspect that the difference is in the nature of the indicators used. For agronomists, the difference in yield between the treatment plots and control plots is often the indicator of choice. Mathematically, the mass yield of corn grain corresponds to the integration over time of the instantaneous productivity of a corn plant or a small plot during the growing season. The instantaneous productivity varies between night and day, as well as between sunny and cloudy skies, between warm and cold days, and there is also a treatment effect because of the applied treatment. If agronomists were able to measure the instantaneous productivity and compare it from one plot to the next, they would likely have a hard time distinguishing the treatment effect from all the other day-to-day effects.

Instantaneous productivity is much less indicative of the treatment effect because of its inherent variability, which is associated with highly variable driving factors. In contrast, overall production is a cumulative indicator, and instantaneous productivity is its mathematical derivative. The overall production, i.e., the mathematical integral of instantaneous productivity over time, is a more robust indicator of the treatment effect.

In other words, the different indicators are fundamentally different. Agronomists have demonstrated that cumulative indicators, such as crop yield, are robust. In contrast, derivative indicators, such as instantaneous productivity, are not robust because they are noisier and more sensitive to inherently variable drivers.

By analogy, I suggest that the individual concentration values measured by hydrologists, or even the indicators derived from individual event hydrographs and chemographs, correspond to the instantaneous productivities of crops and are very noisy derivative indicators. If that is the case, then overall indicators, such as cumulative flow volume or cumulative concentration load, ought to be more robust and more pertinent for detecting and quantifying the effects of management on water quality.

Do we have any evidence for that? Actually yes, and some of the evidence has been in existence for quite a while. Double-mass curves have long been used to detect drift and malfunction in flow monitoring instruments. The effect of treatment can also be detected in the break of the slope of a double-mass curve.

At North Carolina State University, we have been using these cumulative indicators for a while, and we have been able to quantify the effects of stream restoration on water quality, the impact of afforestation on water yield, and other effects. While agronomists only have access to end-of-season production data, hydrologists have access to time series data of cumulative loads and flow volumes. This creates an opportunity to detect breakpoints in the cumulative curves, as well as seasonal trends and patterns.

New tools, including statistical tools, are needed to analyze these cumulative indicators. In addition, the full time series of flow and concentration must be measured to calculate them. This means that robust methods to fill in missing data must be developed and agreed on. There is still much work to do in this area. However, we are convinced that cumulative indicators hold great value in hydrology, and we encourage researchers to use them.

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Digital Water and Its Impact on Sustainability

Khaleel Muhammed and Aavudai Anandhi

Digital water is an emerging research direction that involves using technology to manage water use. The digital water ecosystem is described by the International Water Association (IWA) as being composed of many stakeholders, including the public sector, peer groups, investors, industry associations, and academic institutions. In this brief article, we first describe the relationships among the aspects of digital water and then explain how digital water can be used to make water use more sustainable.

Aspects of digital water

The diagram on the next page adapts the digital water ecosystem described by the IWA into an illustration of the three aspects of digital water. The three aspects are industry, innovation, and information technology (IT). Each aspect can be fur-

ther broken down into more specific components. Industry includes components such as water and wastewater treatment utilities, agriculture, manufacturing, as well as human components like finance and training. Innovation involves developing new methods, ideas, and products. IT is the use of computers, communication devices, and infrastructure to process, store, and exchange data.

The desire to move toward a more sustainable society drives resource-intensive industries such as agriculture, water utilities, and steelmaking to change their practices. This creates the need for innovation. Innovation is led by teams within industries and by cross-sector collaboration.

Innovation has led to new methods and technologies to monitor water use, including cyber-physical systems such as smart water grids that use sensors, meters, and actuators distributed throughout the water infrastructure. Smart grids enable more efficient water management and infrastructure planning. The grids collect data on water consumption, flow rates, peak demand times, and pipe pressures in real-time, which can then be transferred and analyzed. The transfer of data is automated using radio transmissions like the Global System for Mobile communications (GSM) and General Packet Radio Services (GPRS). Interpreting large amounts of data can be tedious, so robotics and IT are promising tools for automating repetitive tasks.

Alongside real-time data analysis, other IT applications for digital water include cloud-based computing for the delivery of databases, analytics, and intelligence over the internet; remote sensing, such as using satellite imaging to detect and monitor the physical components of an area; and virtual or augmented reality, which provides a cost-effective way of simulating real-world situations to test alternative scenarios. Digital twins (DT) also fall into the category of virtual reality. DTs are digital replicas of a physical system that mimic the system's behavior. DTs

are a safe way to simulate the impact of abnormal events.

These information technologies can be used in combination to gather, distribute, and analyze data from both natural and artificial water networks. New methods and technologies bring new uncertainties, so the impact of new digital water solutions must be assessed before adoption.

Impact on Sustainability

Managing water resources is important for meeting the increasing water
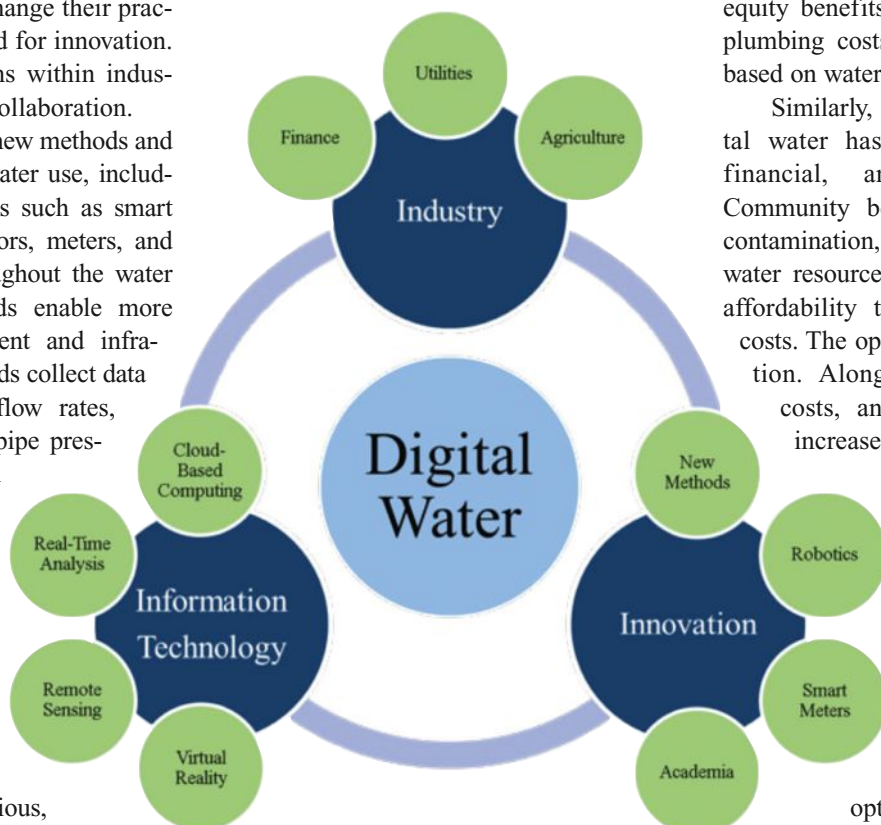
The three aspects of digital water.

demands for agriculture, industry, and personal use. Irrigated agriculture uses 70% of freshwater globally. The three agricultural production categories that use the most water are cereals (27%), meat (22%), and dairy products (7%). These water use values may change, as the global consumption of milk is expected to increase by 19% by the year 2050. Using technology to perform analyses is an efficient way to optimize water use as well as predict changes in water use due to climate change, population growth, and economic development.

A recent literature review asserted that digital water offers 77 benefits to sustainability. These benefits are grouped into three categories: environmental, economic, and social equity benefits. Environmental benefits include energy benefits associated with improved management, planning benefits due to increased knowledge and development of new algorithms, and water benefits from better monitoring. Economic benefits include reduced health and safety incident costs, reduced labor costs, and improved revenue forecasting. Social equity benefits are derived from reduced plumbing costs and customized products based on water use.

Similarly, the IWA suggests that digital water has community, operational, financial, and resiliency benefits. Community benefits are reduced water contamination, increased conservation of water resources, and increased long-term affordability through reduced operating costs. The operational benefit is automation. Along with reduced operating costs, another financial benefit is increased revenue. The resiliency benefits are derived from the adaptive nature of digital water systems. For example, high-resolution remote sensing promotes efficient irrigation of urban and agricultural landscapes by determining location-specific irrigation amounts for optimum plant health.

Optimizing global water use is important for sustainable development. The move toward digital water is the next logical step for optimizing global water use, considering the increased demand for water, global population growth, land use changes such as urbanization, and the reality of climate change.

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FarmBeats:
Digital Water for Agriculture

Sara Malvar, Anirudh Badam,
and Ranveer Chandra

Agriculture accounts for about 70% of global freshwater use, and this percentage is expected to increase to meet the demands of the growing population. However, most of this water is wasted, particularly in the distribution process. Only 15% to 50% of irrigation water reaches its intended destination. At the same time, climate change is increasing water loss via evapotranspiration, increasing the risk of drought in many parts of the world. This confluence of factors makes it vital to improve the efficiency of irrigation so that farmers can produce enough food to feed the global population of nine billion predicted by 2050. Even today, about 1.2 billion people live in severely water-constrained agriculture areas.

Although attention has focused primarily on water quantity, serious water quality problems in many parts of the world are responsible for the worsening water crisis. The pesticides and fertilizers used in agriculture can contaminate both groundwater and surface water, as can livestock wastes, antibiotics, silage effluents, and processing wastes. Agriculture has already surpassed cities and industries as the leading cause of inland and coastal water pollution in most high-income nations and many emerging economies. The most frequent chemical contaminant in the world's groundwater aquifers is nitrate from agriculture.

Agriculture-related water pollution has immediate negative health consequences, such as the well-known "blue baby" syndrome, in which excessive nitrate levels in water induce methemoglobinemia in infants. Certain broad-spectrum and persistent pesticides have been widely banned due to chemical buildup in water and the food chain, although similar pesticides are still used in agriculture, especially in developing countries.

One of the biggest challenges in water management for agriculture is the lack of visibility. There is little information about how much water is used on a given farm, or how much contamination the farm is causing to nearby waterways. Furthermore, even with this information, it is difficult to determine how much of the water, or fertilizer and chemicals, were actually needed on the farm.

Our vision

Our vision is to create a digital platform that can monitor on-farm water use, estimate the leaching of nitrogen and chemicals, and enable data-driven methods for precision agriculture, including precise use of irrigation water, fertilizers, and chemicals. This digital platform will enable growers to monitor and manage their impact on water.

Creating such a platform is extremely challenging. Ideally, we would place sensors at multiple strategic locations and connect them to the cloud. However, such a solution would be extremely expensive, and cumbersome to use, for several reasons:

Connectivity: Many farms and rural watersheds do not have good internet access. Additionally, nearly 40% of the world's population is not connected to the internet. We could use satellite connectivity, but that technology is very expensive.

Affordability: Current on-site sensor systems are cost-prohibitive. Each sensor typically costs several hundred dollars or more, and creating a soil moisture map would probably require one sensor every 10 meters.

Tech readiness: Many smallholder farmers are not literate and their technology skills are low, so the digital platform needs to translate the raw data into usable insights.

Data privacy: One of the biggest barriers to data acquisition and sharing is the lack of trust about data usage and consumer protection.

For over seven years, we have been doing research and development on FarmBeats, a digital platform for data-driven agriculture. We are inventing new technologies to connect farms, aggregating data from multiple sources (satellites, sensors, drones, tractors, weather stations, etc.), and developing new artificial intelligence methods to convert the data into useful insights by predicting the future state of the farm.

One of the key applications for FarmBeats is managing on-farm water use. In this article, we describe the tools in FarmBeats that can help regulators and researchers map on-farm water use, model the impacts of fertilizers and chemicals on water contamination, and manage water use efficiency. FarmBeats brings the latest technology to water, including internet of

things (IoT) sensors, internet connectivity, aerial imagery, artificial intelligence, edge and cloud computing, and blockchain.

IoT sensors

Commercially available IoT sensors can monitor various aspects of water, including soil moisture, water quality, and contaminants. However, the challenges with commercially available sensors are their cost and reliability. To address the cost challenge, we are developing new methods to leverage Wi-Fi for sensing soil moisture, so that growers will be able to monitor the soil moisture with their smartphones. We are also developing methods to make the sensors more reliable, leveraging the fall curves of these sensors. Using these methods, we can determine if a sensor reading is faulty.

Internet connectivity

Internet access is a challenge for smallholder farmers in developing countries due to the lack of connectivity and affordability. We propose the use of a technology called TV white spaces (TVWS) to extend internet coverage across several miles. TVWS refers to the unused regions of the TV broadcast spectrum that can be exploited to provide long-distance Wi-Fi access. Using TVWS is especially appealing for rural areas that have numerous unused TV channels, in comparison to metropolitan areas where TV antenna towers are typically located.

TVWS can provide hundreds of Mbps of bandwidth in remote locations. Furthermore, because TV signals operate in the lower frequency bands (UHF and VHF), they can travel greater distances under dense crop cover. At the same power level as Wi-Fi, we can get more than four times the coverage. In deployments on farms in the U.S., we have achieved more than 15 miles of connectivity using this technology. Our vision is that smallholder farmers can set up an antenna, on their house or on a grain silo, and achieve reliable long-distance internet connectivity.

Aerial imagery

As part of FarmBeats, we are enabling the use of aerial imagery from a variety of sources. Current remote sensing suffers from three bottlenecks that we address in our platform. First, existing satellite imagery is limited by cloud cover. We have developed a new capability, called SpaceEye, that can reconstruct satellite imagery through clouds using AI to fuse imagery across optical and synthetic aperture radar satellites.

Second, aerial imagery only captures a few spectral bands, which is not sufficient to map soil moisture at different depths. We have invented a method that combines sensor data with aerial imagery to create heat maps for different spectral bands.

Third, unmanned aerial vehicles (UAV) are expensive, especially for smallholder farmers. We use a method, called Tethered Eye, with which a grower can attach a smartphone and battery pack to a helium-filled balloon that is tethered to the ground. The grower can walk the farm land with the balloon, and Tethered Eye uses computer vision to stabilize the motion and create UAV-quality images with a low-cost platform. Tethered Eye allows growers to identify water quality problems, detect leaks and floods, and create custom heat maps for monitoring soil moisture and scheduling irrigation.

Artificial intelligence

AI can augment the knowledge of stakeholders so that they can make more informed decisions. For example, the integration of data and numerical models can create a digital twin of an actual water distribution network for testing different scenarios in real-time. When combined with software as a service (SaaS) platforms,
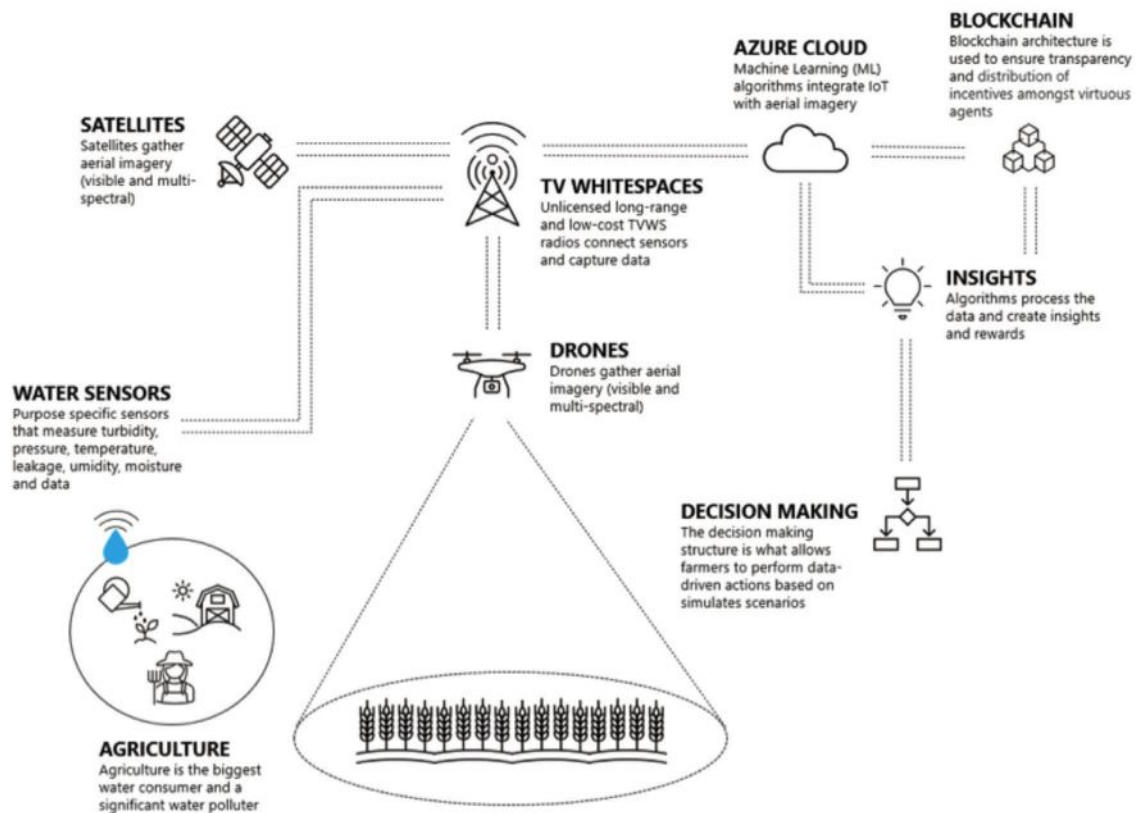
The FarmBeats for Water system uses sensors, satellites, drones, TV whites spaces, edge and cloud solutions, blockchain, and AI to provide insights to farmers and enable data-driven smart water revolution.

sensors, and communication networks, AI allows water utilities to operate in a more strategic and cost-effective manner, including better project planning, real-time tracking of resource losses, more efficient collection and distribution networks, and maximum revenue capture and customer satisfaction.

As part of FarmBeats, we leverage AI to create multiple insights. FarmBeats can combine sensor data with aerial imagery to create heat maps of farms, waterways, and watersheds. It can also perform microclimate prediction by combining local weather forecasts with sensor data. This can provide better irrigation timing, chemical application, and water management. We have also developed a low-code, no-code platform that can empower non-specialists to quickly develop AI models.

Edge and cloud computing

Instead of transmitting all the data to the cloud, which may be prohibitively expensive, we send it to an Azure IoT edge device. The data can then be processed at the edge, such as stitching an orthomosaic from UAV imagery, rather than sending terabytes of data to the cloud. Powerful data transfer technologies, such as Visage, that run at the edge and enable interactive analytics on UAV data are part of FarmBeats. At a higher level, the benefits of IoT coupled with edge computing enable real-time decision-making. The edge improves sensors by expanding their capabilities beyond data collection to information processing that delivers actionable insights. Timely notifications from such systems are crucial for identifying critical situations and reducing water losses.

Blockchain

Secure blockchain solutions reduce the dangers of hacking and data destruction, and they promote transparency and the transition of water utilities to an ever-expanding menu of digital water technologies. The transition of water utilities to digital water technology opens up exciting new prospects. The use of sensors and big data by utilities requires data reliability, accessibility, and analytics, which may be controlled in part using blockchain platforms.

FarmBeats leverages a public blockchain infrastructure in which smart contracts represent the interests of different water stakeholders and regulate the distribution of incentives among virtuous agents. AI can be combined with the system to predict water use and reward agents who follow the predictions. The same architecture would also ensure that water quality measurements are sent to the blockchain as soft contract inputs, allowing water to be discharged only after the necessary treatments are performed and ensuring that regulatory and environmental wastewater policies are followed.

FarmBeats allows stakeholders to capture data from a variety of vantage points, including rainwater, surface water, groundwater, and other sources, and provides AI tools for analyzing the use and waste of water resources. Of course, not all water risks can be addressed by farmers or depend exclusively on farmers' decisions. Some water risks rely on public-sector interventions and initiatives. Governments need to enact strict environmental and water management laws, monitor industries and farms, and incentivize the efficient use of water. We believe that a digital water platform, like FarmBeats, can provide the knowledge needed to drive these interventions, regulations, and subsidies.

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Using Fiber Optics for High-Resolution Measurement of Soil Water Content

Chadi Sayde

Increasing the productivity and profitability of agricultural land, while reducing the environmental impact of production intensification, can be achieved by increasing the efficiency of agriculture water use. Enhancing water use efficiency can also improve the economic competitiveness of agricultural production systems by reducing nutrient losses, energy demand, and labor costs while improving yield quality and quantity.

Acknowledging the importance of increasing the efficiency of agricultural water systems, researchers have devoted significant effort to improving the efficiency of agricultural water use. However, most of this effort has been limited to improving the efficiency of specific components of the water supply chain, following water from storage, through conveyance and distribution, to on-field application, but stopping short of where water matters most: the root zone.

In fact, all efficiency indicators are based on aboveground measurements, and subsurface homogeneity is assumed, i.e., the water application uniformity measured aboveground is assumed to propagate unchanged through the root zone. This assumption is due to the inability of current technology to track soil water content and movement beyond a point location. Due to this limitation, the design and management of irrigation and drainage systems are commonly conducted with the assumption of subsurface homogeneity, ignoring the profound impact of heterogeneity.

Additionally, mitigating the effects of climate change on agriculture requires better understanding of the field-scale response to the increasingly unpredictable timing, frequency, and intensity of precipitation. In particular, it is crucial to improve our understanding of two key moisture-controlled processes: (1) precipitation partitioning into deep percolation, surface runoff, and root zone storage; and (2) vegetation water stress. At the field scale, this understanding will allow us to optimize water addition, retention, or release depending on the particular field and crop conditions. This also applies at the watershed level for improving our understanding of basin-wide hydrological responses and for forecasting flood events, especially in response to the expected increase in high-intensity precipitation.

Several studies have shown that the dynamic spatial patterns of soil water content from the 1 m to 1,000 m scales, i.e., from individual plant scale to field scale, will have dramatic effects on hydrologic response. However, these patterns are exceedingly difficult to determine, holding back scientific progress in understanding basic hydrologic processes. Current technologies for characterizing soil water content across the root zone are only available at the point scale, while large-scale remote sensing technologies, such as satellite or UAV-based systems, are limited in their temporal frequency, spatial resolution, and ability to measure soil moisture below the top few centimeters.

Motivated by the lack of technology that can characterize soil water dynamics from individual plant scale to field scale, our research group at North Carolina State University is focusing on developing technologies that allow high-resolution measurement of soil water content. In particular, we are using fiber optic distributed temperature sensing (FO-DTS),

A specially designed plow system to install FO-DTS cable with minimal soil disturbance.

which measures temperatures along a fiber optic cable that can extend for more than 5 km in length, with high spatial (every 0.125 m) and temporal (every 1 s) resolutions. The ultra-high density of temperature measurements provided by FO-DTS allows us to use temperature as a tracer to reveal key environmental processes, such as soil water content distribution in the field, at high resolution.

The principle of measuring soil water content using FO-DTS is based on observing the thermal response of soil to heat perturbation. The heat perturbation can be generated within the buried fiber optic cable through controlled electrical heating of the cable's metallic sheathing. The heat perturbation can also originate from the diurnal thermal cycle propagating through the soil profile. FO-DTS is used to measure the change in temperature along thousands of meters of buried cable. Heat transfer models can then be used to estimate soil water content from the measured soil thermal response. The FO-DTS sensing cables are typically installed in the field using a specially designed plow system to minimize soil disturbance and allow the soil to heal rapidly around the installed cables.

Several published articles have highlighted the feasibility of using FO-DTS for high-resolution measurement of soil water content with unprecedented measurement density. Nevertheless, despite the potential of FO-DTS technology, those articles also point out the challenges associated with applying this technology in field conditions. Significant effort is needed to calibrate long lengths of FO-DTS cable due to the non-linear relationship between the soil thermal conductivity, which FO-DTS measures, and the soil water content. This relationship can also vary across a field, even over short distances, due to the spatial variability in soil properties such as bulk density and soil texture.

So far, specialized expertise and extensive laboratory and field efforts are

Soil moisture sensors installed next to FO-DTS cables for calibration purposes.

needed to perform calibration, which makes data collection expensive, even for relatively homogeneous soils. The high cost associated with calibrating and operating FO-DTS has limited its applicability for soil moisture measurements. Realizing the challenges associated with the current status of FO-DTS technology, our group is working on two separate fronts to simplify the calibration process: (1) developing a new data analysis method that eliminates the need for time-consuming laboratory calibration of the FO-DTS system, and (2) designing a new sensor system that eliminates the need for soil-specific calibration.

On the first front, a machine learning approach has been developed that can accurately calibrate long lengths of cable from three to four point sensors that are strategically located in the field according to feedback from the detailed thermal measurements provided by the FO-DTS system. This approach has been successfully tested in a large FO-DTS installation in an agricultural field. The FO-DTS system calibrated using the machine learning approach was able to provide detailed soil moisture measurements with an accuracy of 0.03 m^3 m^{-3}, which is comparable with most commercially available soil moisture point sensors.

On the second front, a novel FO-DTS design has been developed and tested in the laboratory and in the field. This novel design is based on a dual-needle heat pulse approach in which heat is applied along a heating cable and the temperature increase

is sensed by another FO-DTS cable that is maintained at a constant distance from the heated cable. The advantage of this design is that the thermal response is a function of the soil heat capacity, which changes linearly with water content in most cases regardless of soil type.

Extensive laboratory and field testing demonstrated the capability of the dual-probe design to sense changes in soil moisture with an accuracy of 0.02 m^3 m^{-3} and without the need to perform soil-specific calibration. Due to the complexity of the design, the current version of the dual-probe FO-DTS cable must be installed by digging a trench in the field, rather than the less-intrusive plow system used for the single-probe FO-DTS cable. Additional research is being conducted to design a plow system that can accommodate the geometry of the dual-probe system.

The simplified calibration and reliable operation of the FO-DTS method for measuring soil moisture are very encouraging. This is an important step toward making this technology available for use in agricultural and environmental applications, with tremendous possibilities for precision management of our water resources. At its current state, this technology can provide the high-resolution measurements needed to bridge the gap in measuring soil water content at the intermediate scale (1 m to 1000 m) in most field conditions.

The next challenge is how to handle, store, transmit, analyze, verify, and visualize the tremendous amount of data generated by the FO-DTS system. In some deployments, the raw data generated by the FO-DTS system has exceeded 5 GB per hour, creating a tremendous challenge for providing timely feedback for precision irrigation and water management. That said, the rapid advances in computational power, mobile connectivity, cloud computing, and data analytics offer hope that the challenges of managing big data will be effectively solved in the near future.

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# Hunting for Hotspots with Electromagnetic Induction
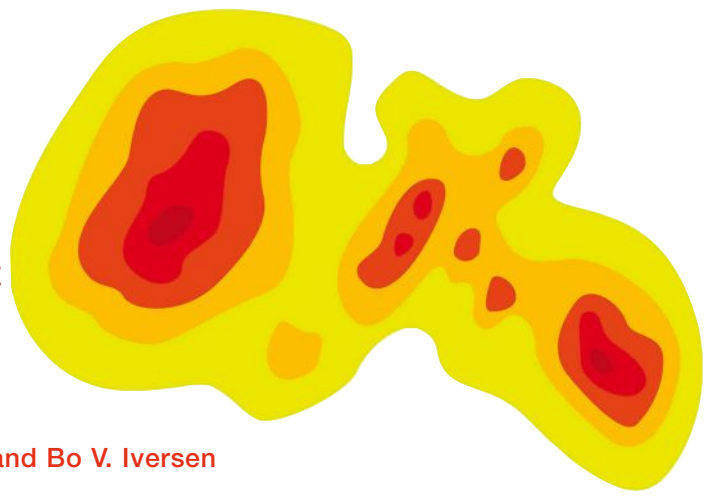
Maria Isabel Senal, Triven Koganti, Anders Bjørn Møller, and Bo V. Iversen

In soil biogeochemistry, the term "hotspot" refers to certain patches within a soil volume that are characterized by significantly higher biogeochemical reaction rates. The term is commonly used to refer to denitrification hotspots, which are patches of intense reduction of anaerobic nitrate to nitrous oxide (i.e., denitrification). The term was introduced by McClain et al. (2003), although the concept had been around years earlier, when Parkin and Berry (1994) described the denitrification rates around earthworm castings.

Biogeochemical reactions in the soil, particularly denitrification processes, are highly spatially variable and are therefore fickle parameters to measure, with values ranging across several orders of magnitude even within a small soil volume. To make it even more complicated, the measurement method strongly influences the obtained values.

Therefore, the idea of mapping hotspots when describing soil biogeochemical processes is an exciting prospect. By mapping hotspots, mitigation efforts and interventions could be concentrated at specific locations, which is a more cost-effective and sustainable strategy for nitrogen management in agriculture. It also complements the pursuit of precision agriculture, which supports the ultimate goal of increased food production with sustainable use of the soil.
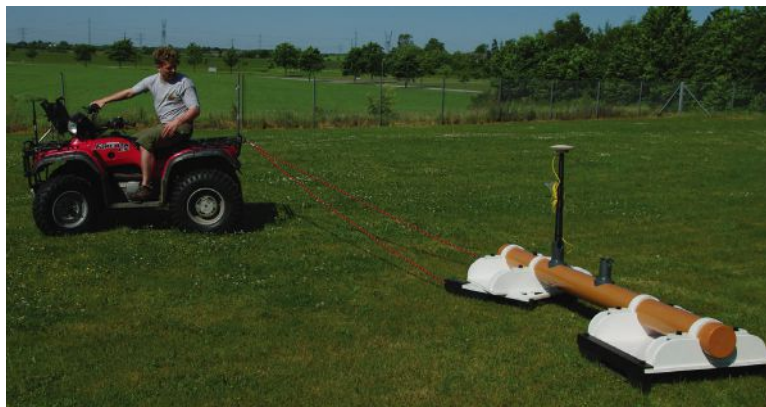
The Dualem-21S instrument used for soil electrical conductivity measurements (from Koganti et al., 2020).

With the adoption of the EU Drinking Water Directive and the pursuit of the European Green Deal, there is ever-increasing pressure to better understand and assess the extent of biogeochemical processes, particularly denitrification. However, quantifying hotspots and incorporating them into biogeochemical models remain challenging. While the lack of thorough understanding of the dynamics and the influencing factors is one of the major causes of this difficulty, the lack of extensive, fine-scale assessment of the influencing factors also contributes to the difficulty.

The promise of electromagnetic induction

Mapping soil electrical conductivity (EC) through electromagnetic induction (EMI) is a promising technique that can provide fine-scale assessment at the landscape or catchment scale. With significant instrumentation development in the last few decades, EMI is gaining popularity and seeing extensive uses. EMI was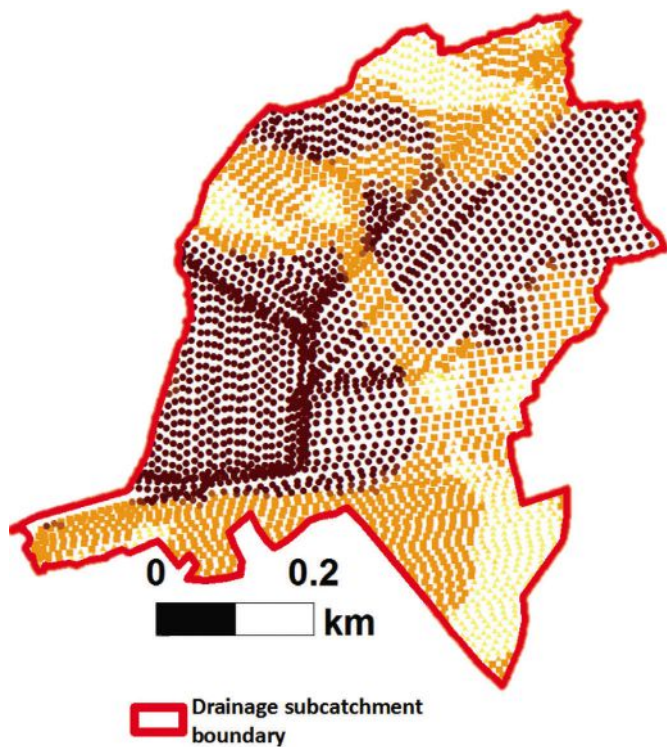 initially used to assess the salinity of soils. Its applications have been further expanded to assess other soil parameters, such as water content, texture, and organic matter content. The ease of use and cost-effectiveness for field-scale investigations is one of the major advantages of the EMI method.

To explore the utility of EMI in assessing the variability of soil nitrogen and nitrogen processes, we collected EC measurements within the root zone using a Dualem-21S conductivity meter in an artificially drained, agricultural subcatchment in the eastern Jutland peninsula in Denmark. The high EC measurements collected in certain areas correlated well with reduced redox conditions and relatively low nitrate concentrations. To take this further, we used fine-scale EC measurements to create zones within the subcatchment using two clustering methods: unsupervised iterative self-organizing data (ISODATA) clustering and optimized hot spot analysis.

The results were promising. The two clustering methods were able to distinguish zones that could be deemed nitrate reduction hotspots. This could be an indication that dismissal of the root zone's ability to reduce nitrate before it infiltrates into the drains could lead to overestimation of the amount of nitrogen leached, as is the case with the traditional understanding of transport processes in the area.

One of the advantages of the method that enabled the use of the two clustering techniques was the high number of fine-

Zones generated with optimized hotspot analysis of electrical conductivity (EC) measurements in the Fensholt subcatchment in Denmark.

scale measurements from the EMI instrument. Given that the clustering techniques are readily available through geographic information system (GIS) platforms, this method could be easily adapted to other sites. With further development of EMI and other fine-scale geophysical techniques, it might also be possible to investigate the correlation between soil EC and the entire nitrate reduction profile in other artificially drained agricultural areas.

More than denitrification measurement

In our mapping of hotspots, we decided to refer to these areas as nitrate reduction hotspots, rather than denitrification hotspots, because the denitrification rates measured with denitrification enzyme assays were not significantly higher than those in the surrounding areas. While there was insufficient evidence to exclude the presence of other potentially dominant nitrate reduction processes, such as dissimilatory nitrate reduction to ammonium (DNRA), we believe that the overall flow patterns due to the topography and the presence of potential anoxic microsites play a larger role than biologi-

cal processes in attenuating nitrate within the root zone of the subcatchment.

This explanation seems to be in contrast with the conventional understanding of a hotspot, which is defined as an area characterized by intense reaction rates. This discrepancy may also be due to the measurement method, as *in situ* measurements may capture the actual magnitude of denitrification at the study site better than laboratory assays. Thus, hunting for hotspots should not be limited to simply measuring biogeochemical rates, and it should always be a complement of multiple hydrogeological and biological parameters.

While our study was highly empirical, we believe that it can provide a guide to further improve nitrate reduction models for root zone areas. We have high hopes that near-surface geophysical techniques will aid in incorporating nitrate reduction hotspots into biogeochemical models, which will improve our management of soil and water resources.

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Further Reading

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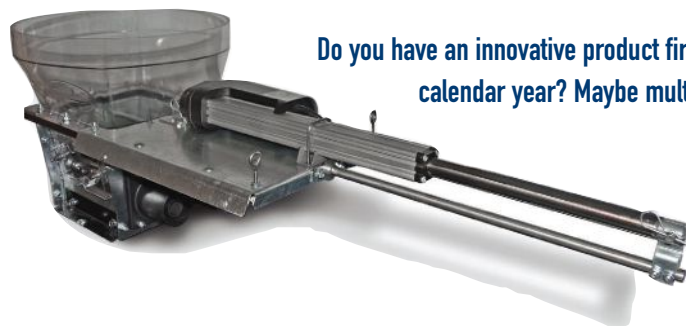
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