EARTH SCIENCE
APPLIED SCIENCES

# 2019 ANNUAL SUMMARY

NASA Earth Science Applied Sciences Program

WATER RESOURCES
& AGRICULTURE

# *2019 Annual Summaries for the Applied Sciences Program Water Resources Applications Area and the Agriculture Applications Area*

**Table of Contents**

# I. INTRODUCTION

The Earth Science Division's (ESD's) Applied Sciences Program promotes efforts to discover and demonstrate innovative and practical uses of Earth observations. The program funds applied-science research and applications projects to enable near-term uses of Earth observations, formulate new applications, integrate Earth observations and related products in practitioners' decision-making, and transfer the applications to stakeholders. The projects are carried out in partnership with public- and private-sector organizations to achieve sustained use and sustained benefits from Earth observations.

The Applied Sciences Program's applications themes are currently focused on five of the nine Societal Benefit Areas (SBAs) of the interagency Group on Earth Observations: Health (including Air Quality), Disasters, Ecological Forecasting, Water Resources, and Agriculture.[1] The program includes climate-related influences and impacts within each of these themes and has cross-cutting elements such as Wildfires and Capacity Building.

The Applied Sciences Water Resources Applications Area and the Applied Sciences Agriculture Applications Area are two separate program elements that work in tandem to address the world's water and agriculture issues. Information about both of these program areas is presented here as the topics often overlap and stakeholders and end-users benefit from cross-program coordination. The water- and agriculture-related challenges of today and tomorrow cannot be addressed without Earth observations. NASA provides a unique perspective providing Earth Observations for use by natural resource managers to better inform life-saving decisions.

The Applied Sciences Applications Areas support the integration of NASA Earth observations and technologies into management tools for the water and agriculture communities. The Water Resources Application Area currently supports a diverse range of projects addressing topics including drought monitoring and mitigation, snow monitoring and runoff forecasting, water quality, soil moisture, groundwater change, and climatic and ecological impacts on water resources. The Applied Sciences Agriculture Applications Area focus on agricultural land use, sustainability, and productivity. The agriculture program element aims to improve each of these areas as well as the methods and products that provide actionable information and insight about them from farm to global scales.

[1] The nine USGEO SBAs are Agriculture, Climate, Disasters, Ecological Forecasting, Energy, Health, Oceans, Water Resources, and Weather.

## *Water Resources*

NASA's free and open exchange of Earth-observing data helps engage and improve integrated observation networks and enables national and multinational regional water cycle research and applications. Satellite and airborne observations and hydrometeorological models can be applied to enhance information from surface observation networks, and these models play a critical role in providing information on water resources—especially in data-sparse regions.

NASA satellite and modeling products provide a huge volume of valuable water resources information extending back more than 50 years across a broad range of spatial (local-to-global) and temporal (hourly-to-decadal) scales. Many of these products are also available in near real-time (see *https://earthdata.nasa.gov*).

The primary objective of NASA's Water Resources Applications Area is to discover, demonstrate, and transfer innovative uses and practical benefits of NASA's Earth science observations, research, and technologies for improved water management to the water resources management community. To accomplish this objective, NASA partners with a diverse range of organizations (e.g., federal agencies, universities, NGOs, and industry) in the United States and internationally to ensure cost-effective and beneficial solutions are provided to water resources managers.

*Western Water Applications Office (WWAO)*

The Applied Science Program's Western Water Applications Office (WWAO) is a NASA program based at the Jet Propulsion Laboratory in Pasadena, California. WWAO's mission is to develop game-changing water applications that help solve the most important and pressing water issues faced in the Western United States. WWAO delivers NASA's capabilities—remote-sensing data, expertise, and tools—directly to decision makers who can make use of them across a host of Western states and water basins. WWAO is part of a larger effort within NASA to forge an "applied-science mindset" that maximizes the societal benefits of NASA's capabilities and projects. More details are at https://wwao.jpl.nasa.gov/.

With its fleet of satellites and remote-sensing expertise, NASA has a unique set of eyes over our planet that can help solve water challenges affecting people's lives. The WWAO is on a mission to improve how water is managed in the arid western U.S. by getting NASA data, technology, and tools into the hands of water managers and decision makers.

## *Agriculture*

In November 2017, the Applied Sciences Program selected the Harvest Consortium, led by the University of Maryland, to receive funds over a five-year period through the Agency's Research Opportunities in Space and Earth Science (ROSES) grant program. NASA Harvest is a

multidisciplinary program commissioned by NASA and led by the University of Maryland to enhance the use of satellite data in decision making related to food security and agriculture from farm to global scales, both domestically and worldwide. The consortium aligns with NASA's priority to make its Earth observations freely and openly available to those seeking solutions to important global issues such as food security, changing freshwater availability, and human health.

Through a multidisciplinary consortium of partners, NASA Harvest is advancing the use of satellite data in decision-making processes related to agriculture in the U.S. and to solve food security issues around the globe in conjunction with other agencies and aid organizations. NASA partners with operational agencies such as the U.S. Department of Agriculture (USDA), the U.S. Agency for International Development (USAID) and the National Oceanic and Atmospheric Administration (NOAA)—along with international organizations and private industry—to advance the use of remotely sensed data for more informed decision making.

With these investments in building local capacity to use Earth observations to understand our agriculture, water, and climate systems, NASA is making a lasting impact on food security and people's livelihoods—both here and abroad. A diverse consortium, NASA Harvest concentrates its efforts in the United States and Eastern Africa, focusing on innovation in field data collection, public-private partnerships, artificial intelligence and machine learning, and data integration and sharing through open platforms.

# II. OVERIEW AND ASSESSMENT OF 2019

The Water Resources and Agriculture teams continued to make strides in addressing critical water and agriculture challenges in the U.S. and globally throughout 2019. Each applications area supports a portfolio of research projects; educates the communities on the benefits of Earth observations in natural resources management; supplies leadership by contributing to international, interagency, and regional working groups; and actively advances relevant technology and capabilities through various program initiatives for the betterment of society. The hard work and dedication of applications area team members is evidenced by the awards received by program staff and PIs during 2019 (see highlights in the text box below).

In his February 12th speech at the World Agriculture Expo, NASA Administrator Jim Bridenstine conveyed how NASA's Water and Agriculture Application Areas are working together to address these critical issues. The Administrator's talk and slides included material from both application areas including work on evapotranspiration, the Airborne Snow Observatory, and how Uganda

harvests Earth data to enable proactive, timely food-security decisions. This work was again highlighted through Administrator Bridenstine's interview with CNBC.

## 2019 Individual Awards

**Program Manager Dr. Bradley Doorn** – **Exceptional Service Medal** as part of the 2019 NASA Agency Honor Awards for his exceptional leadership of the Applied Sciences Water Resources and Agriculture Programs.

**Associate Program Manager John Bolten -** John was selected as a recipient of a prestigious 2018 **Arthur S. Flemming Award** from the George Washington University Trachtenberg School of Public Policy and Public Administration in the Applied Science and Engineering category for achieving advances in applying satellite remote sensing, land surface modeling, and data assimilation for water resources management, agricultural forecasting, and flood monitoring and impact assessment.

**Associate Program Manager Christine Lee** – Christine received the **Early Career Public Achievement Medal** of the 2019 NASA Agency Honor Awards for her achievement in developing and advancing applied science concepts for NASA programs, missions, and projects.
Christine also received **the Voyager Award** for EV mission formulation and applications, for her participation in and contributions to the EV proposal as a science / applied science team member.

**PI JT Reager** – JT received the **Presidential Early Career Award for Scientists and Engineers** (PECASE) for his groundbreaking analysis of the way water moves around the globe. The PECASE Award is the highest honor given by the U.S. government to early-career government scientists and engineers who demonstrate the capacity for innovative science and cutting edge exploration.

**PI Bill Kustas –** Bill received the **2019 Hydrologic Sciences Award** at the American Geophysical Unions' Fall meeting for outstanding contributions to the Science of Hydrology over a career, with an emphasis on the past five years.

**PI Christ Peters-Lidard** – Christa was selected to be an **American Geophysical Union fellow** in 2019. Fellows are members whose visionary leadership and scientific excellence have fundamentally advanced research in their respective fields. AGU Fellows are recognized for their scientific eminence in the Earth and space sciences. Their breadth of interests and the scope of their contributions are remarkable and often groundbreaking. Only 0.1% of AGU membership receives this recognition in any given year.

**PI Amir AghaKouchak** - Amir received the **American Geophysical Union's Macelwane Medal**. The medal is given annually to a small group of early career researchers for significant contributions to the geophysical sciences. The AGU recognized AghaKouchak for his fundamental and innovative contributions to the study of hydrologic extremes and compound natural hazards

**Harvest Eastern Africa Lead Catherine Nakalembe** – Catherine was an inaugural winner of the **2019 GEO Individual Excellence Awards**. This award recognizes scientists who have dedicated their valuable time, resources, and energy towards highly impactful missions with palpable results.

## *Water Resources*

Calendar year 2019 was very productive, including the completion of four projects, and the selection of thirteen new projects from NASA's Research Opportunities in Space and Earth Science (ROSES) A.36 solicitation bringing the total portfolio to 34 projects at its height. In addition to supporting funded projects spanning topics such as drought, climate impacts on water resources, water quality and streamflow forecasting/flood monitoring, the Water Resources Applications Area was also very active in national and regional water resources community groups in the U.S. (Western States Water Council, National Drought Resilience Partnership) and internationally. The team engaged with the operational, policy, and practitioner communities as well as Earth-science communities, attending multiple practitioner meetings and conferences such as the American Geophysical Union's Fall Meeting, Western

States Water Council Water Information Management Systems Workshop, California Open Water Data Symposium, Integrated Hydro-Terrestrial Modeling Workshop, 21st William T. Pecora Memorial Remote Sensing Symposium (Pecora 21) and the 38th International Symposium on Remote Sensing of Environment (ISRSE-38), American Water Resources Association Conferences, National Drought Forum, World Water – Tech North America Summit, National Soil Moisture Meetings, and Committee On Earth Observation Meetings, among others.

The Water Resources Applications Area includes the WWAO. WWAO addresses water management issues with an innovative program focused on stakeholder engagement and dynamic response to water management challenges in the western U.S. WWAO is part of a larger effort within NASA to forge an "applied-science mindset" that maximizes the societal benefits of NASA's capabilities and projects. WWAO does this by:

1. Identifying Needs in western water management for information and decision support;
2. Making Connections between stakeholders and NASA scientists, technology, tools, and data;
3. Building Projects tailored to meet those Needs, engaging with stakeholders from beginning to end;
4. Transitioning water applications and technology into an operational, sustainable state for long-term impact.

## *Agriculture*

NASA's agriculture activities throughout 2019 were led by NASA Harvest. NASA Harvest is a consortium jointly managed between NASA and the University of Maryland. Harvest addresses key agriculture needs and pushes the utilization of Earth observations for agriculture, both domestically and internationally.

In 2019—the program's second year of operation—NASA Harvest supported 26 funded projects and maintained more than 50 collaborations with public and private partners interested in leveraging their resources to further this critical mission. Harvest partners use Earth-observing satellites and other tools to monitor crop health and conditions (e.g., weather patterns, soil moisture) and predict where crop loss will likely occur due to floods, drought, and other extreme weather. Armed with this information, farmers can protect their livelihoods and decision makers can work to prevent food shortages and destabilizing spikes in food prices and commodity crop markets.

For example, a private company called Applied GeoSolutions worked on crop resilience and conservation in Arkansas. A university partner working on crop-yield forecasting in the Midwest developed an approach to collaborate and exchange information with U.S.-based farmer associations. Working with another university partner and local agriculture agencies, Harvest led training sessions to develop national-scale crop monitoring programs in Kenya, Tanzania,

and Rwanda, and initiated a partnership to create early warning systems for crop health in Mali, Burkina Faso, and Niger.

# III. PORTFOLIO OF RESEARCH PROJECTS

## *Water Resources*

The Applied Water Resources Application Area managed 40 active projects in 2019, including six WWAO projects. Of the 40 active projects, 28 projects were funded through ROSES solicitations. Four projects were completed in 2019.

Seven projects from the A.45 ROSES solicitation were active in 2019, including the four projects that ended this year. The A.45 solicitation aimed to develop improved forecasts of water supply anomalies in the mid-term (30–180-day outlooks). The remaining three projects from A.45 will continue in 2020 as will the eight projects selected from the ROSES 2016 A.37 solicitation focused on water quality and agricultural water use.

In 2019, the program also awarded grants for thirteen new projects through the A.36 ROSES solicitation to support applied research to monitor and assess local and regional water quality and quantity for improving water resource risk assessment, economic planning, investment planning, and policy making.

The Water Resources Applications Area also manages four international projects through GEOGLOWS, an element of the Group on Earth Observations solicitation sponsored by NASA's Applied Sciences Program. The application area manages two relevant projects that are funded through the ECOSTRESS solicitation and manages a joint project on Cyanobacteria with NASA's Research and Analysis Program, the Environmental Protection Agency, NOAA, and USGS.

Descriptions of all the projects in the Water Resources Application Area's portfolio are included in Appendix A.

Projects show progress by advancing through Application Readiness Levels (ARLs). The ARL assesses the maturity of Earth science applications projects and allows NASA to track integration of Earth science into decision making by articulating expected advancement along a continuum from fundamental research to application and sustained operations. Of the 34 projects within the portfolio that are not funded by WWAO, 32 projects report ARLs.

The table at right shows the ARL distribution of these projects at the end of the Calendar Year 2019, including the final ARL achieved by the four completed projects, and the status of the 28 ARL-tracked projects that will continue into 2020. Fourteen of the projects began in 2019, which is reflected by the high number of projects at a low ARL level.

Even though the A.36-funded projects received their funds at the end of the calendar year, 15 projects within the portfolio advanced one or more ARL in 2019.

*ARL Levels of the 32 ARL-tracked projects managed by the Water Resources Program in 2019*

| ***ARL*** | # of active projects at the end of 2019 | # of projects that closed in 2019 |
|---|---|---|
| ***9*** | 0 | 2 |
| ***8*** | 0 | 0 |
| ***7*** | 0 | 0 |
| ***6*** | 5 | 2 |
| ***5*** | 5 | 0 |
| ***4*** | 7 | 0 |
| ***3*** | 7 | 0 |
| ***2*** | 4 | 0 |
| ***1*** | 0 | 0 |
| ***TOTAL*** | **28** | **4** |

*WWAO Project Portfolio*

In 2019, WWAO continued to fund six water projects in the implementation phase. These projects reported significant technical achievements and end-user interactions, as highlighted below. WWAO's water projects address core issues facing the western U.S. now and in the future: water availability, water consumption, drought, and water forecasting. Project partners include farmers, local and tribal communities, and water managers, decision makers, and agencies at the federal, state, and local levels. The six WWAO-funded projects are listed below and are summarized in more detail in Appendix A.

- *Operational Evapotranspiration for the State of New Mexico*
  Goal: Develop operational evapotranspiration data for New Mexico so it can better monitor drought conditions, process water-rights applications, and refine its water-budget modeling.

- *Satellite-Based Irrigation for Better Crop Management*
  Goal: Use satellite data to help farmers in California and beyond grow food in more sustainable ways—e.g., with less water and fertilizer.

- *Drought Monitoring in the Navajo Nation*
  Goal: Use satellite data to improve the Navajo Nation Department of Water Resources Drought Report, which is presented to emergency managers and used to allocate drought-relief dollars throughout each chapter in the Navajo Nation.

- *High-Resolution Soil Products for Multiple Stakeholders*
  Goal: Harness soil-moisture data from satellites to improve measures of soil moisture at both ground-level and in the root-zone for agricultural and other partners.

- *NASA's Airborne Snow Observatory (ASO) and Automated Water Supply Model*

Goal: Harness data from NASA's ASO to improve runoff forecasts in California's Sierra Nevada and Colorado's Rocky Mountain range. Such forecasts help reservoir managers meet often-conflicting needs for drought planning, ecological flows, groundwater recharge, and flood prevention.

- *Snowpack Representation in the Colorado Basin River Forecast Center (CBRFC) Model*
  Goal: Use data from NASA's ASO to improve streamflow forecasts by refining how snowpack is represented in the CBRFC's snow model.

### *Agriculture Program*

In 2019, the program's second year of operation, NASA Harvest supported 26 funded projects and maintained more than 50 collaborations with public and private partners interested in leveraging their resources to further this critical mission. Harvest partners use Earth-observing satellites and other tools to monitor crop health and conditions (e.g., weather patterns, soil moisture) and predict where crop loss will likely occur due to floods, drought, and other extreme weather. The list of projects funded by NASA Harvest can be found at **https://nasaharvest.org/projects**

## IV. PROGRAM MANAGEMENT

The Water Resources and Agriculture Applications Areas grew throughout 2019. To support and connect researchers and stakeholders, the programs hosted team meetings and events for community members. The program areas grew the community by further developing relationships and collaborating with new partners. In 2019, WWAO initiated the WWAO Water Alliance and NASA Harvest expanded the consortium, adding new funded partners, three new formal collaborators, and identified several other unfunded collaborators. At the end of 2019, Harvest also announced a new partnership with Farm2050.

### *Program Events*

*Compass Communications Workshop*

On March 26-27, 2019, the Applied Sciences Communication team hosted a workshop for the Water Resources and Agriculture Applications Area staff and funded PIs. Grounded in the latest research on science communication, the training was designed to help participants best articulate the relevance of their applied science and applications activities

to diverse audiences including journalists, partners, policymakers, the public, and other scientists. The small workshop (20 people) was hosted in Washington DC and was facilitated by the science communications firm, Compass Science Communications.

*2019 Annual Water Resources and WWAO Team Meeting*

The annual NASA Water Resources and WWAO team meeting was held in Portland, Oregon, July 15-19. More than 85 participants from the Water Resources science and user community participated, with local stakeholders from the Pacific NW region joining in person. The overarching purpose of the meeting was to provide a forum for the NASA-supported water resources community of PIs, water resources partners, and stakeholders to exchange information, share updates, and collaborate on remote-sensing applications for water resources management.

NASA Water Resources Program Manager Dr. Brad Doorn opened the meeting with an introduction highlighting the vision and strategic direction of the program, which was followed by a series of presentations on addressing water resource issues across the U.S. made by PIs from the NASA Applied Sciences Water Resources portfolio. These presentations covered topics such as: improving estimates of crop water demand to support irrigation and agricultural applications; snowmelt-streamflow estimates for water supply forecasting and flood assessments; and water quality applications including detection of algal blooms and modeling of nutrient loading. Highlights included the communications training activities and presentations from PIs on the technology transition process and their experiences leading applied science activities.

WWAO team member Savannah Cooley chaired a panel on Applications Transition. The panel members shared advice on how to effectively transition NASA (water) science from research to operations, and what they have learned about transitioning applications/technology to sustained use by a non-NASA partner or end-user.

*WWAO Technology Transfer Workshop*

In August 2019, the Western States Water Council (WSWC) and WWAO hosted a joint workshop on Technology Transfer in Irvine, California. Workshop goals were to understand how different agencies approach the technology transfer and Research to Operations (R2O) process, to identify best practices, and to discuss existing barriers to the successful infusion of a new capability into operational water management systems at state and federal levels.

The workshop was opened by Rep. Grace Napolitano, who spoke about the critical value of water data and the importance of collaboration between state and federal agencies to advance the use of water data in water management, planning, and policy. About 70 people attended in-person and remotely. Attendees included PIs and project teams supported by

NASA (CyAN, Western ET, ESI, ASO, Sierra Snow, Fallowed Area Mapping) and representatives from federal (USGS, NOAA, USBR, EPA) and state (California DWR, Wyoming State Engineer's Office, Oregon Water Resource Department, Nebraska Department of Natural Resources) agencies.

The workshop drove home the point that technology transfer is very challenging, and that it is never too early think about project transition. Examples of truly successful R2O do exist, but successful endeavors can take a decade of concerted effort from different stakeholders to achieve.

A key best practice that emerged from the workshop discussions was the importance of broadening (and sustaining) communications in projects with a NASA Applications Readiness Level (ARL) of around 5 to 7. Such communications should involve representation from senior management and IT staff at the operational/partner agency. Involvement of these parties would allow adequate lead time for budget and IT planning processes to ensure that the financial and technical resources required for technology transfer could be secured.

The gathering was a first step to developing a broader community and initiating discussion around R2O in (western) water management. Many of the best practices and key takeaways represent starting places for action at WWAO, WSWC, and the other participants' institutions. These takeaways and next steps are summarized in the 2019 Technology Transfer for Water Management in the Western United States Workshop Report. Effective implementation of these lessons learned will require significant time, resources, and planning. For this reason, WWAO proposes to host regular meetings (for instance, an annual workshop) on the topic.

*NASA Harvest Conference and All Hands Meeting*

Over 200 stakeholders attended the Harvest Conference on June 25th that was kicked off by NASA Administrator Jim Bridenstine, Director of Applied Sciences Lawrence Friedl, and Harvest Director Inbal Becker-Reshef. Partners from NASA, USDA, USAID, UN FAO, European Commission, EU, European Space Agency, World Bank, IDB, private companies, NGOs, universities, foundations, agriculture trade orgs, and representatives from ministries of agriculture from five countries helped set priorities for Earth observation related to agriculture and food security. Key themes included: the role of EO in informing agricultural markets, early warning and capacity building in food-insecure regions, the importance of and challenges inherent to forming and sustaining public-private partnerships and data sharing, and improved coordination for better domestic and international agriculture policy.

The public meeting proceeded and followed a Harvest All Hands Meeting on June 24 and 26, 2019, which facilitated cross-consortium communication and resulted in increased collaborations with partners on cross-cutting activities.

## *Public Private Partnerships*

*WWAO Water Alliance*

In 2019, WWAO continued its momentum in establishing a Water Alliance of private and non-profit water partners focused on common goals. The alliance is a group of hand-picked private companies and non-profit groups that are involved in western water management and infrastructure and that can potentially partner with WWAO to 1) forge innovative collaborations, and 2) help transition the technology and capabilities developed by WWAO's Water Projects into the water management processes of stakeholders.

Following efforts in 2018 to define a shortlist of target organizations, identify synergies, and reach out to a variety of stakeholders, in 2019 WWAO recruited ten mainly private-sector-based entities to take part in its Industry-Based Water Needs Assessment. Participants included Esri, Tetra Tech, WaterStart, AECOM, Quantum Spatial Inc., California Water Services Group, Parsons Engineering, Jacobs Engineering, Maxar Technologies, and the Freshwater Trust. These entities focus on everything from geospatial data and analytics, to infrastructure services and solutions, to water treatment and flood management, to water conservation and ecosystem restoration, and technology and innovation acceleration.

Akin to the Needs Assessments that WWAO has been conducting in the public-sector sphere, the private-sector process will first involve carrying out a detailed Water Needs Survey for each potential partner organization via a series of in-depth interviews. Following analysis by the WWAO team and depending on the potential synergies identified, WWAO plans to host either an Industry Water Needs Assessment Workshop for multiple alliance partners or hold a number of one-on-one meetings to identify specific areas of collaboration with NASA and potential pilot activities.

*NASA Harvest Partnerships*

Public Private Partnerships (PPP) have emerged as high-priority innovation mechanisms for reaching Harvest's goals. Private sector organizations and NGOs presented on PPPs and related topics at Harvest's 2019 Conference included Swiss Re, Gro Intelligence, 6thGrain, East African Grain Council, Maxar, Manobi, Lutheran World Relief, ICPAC, Gates Foundation, Planet, and Applied GeoSolutions. Key themes included the need for co-development of technologies and services; demonstrating value for private sector, farmers and end users; building trust and collaboration through shared vision and goals and clear intentions; working with corporations across the value chain; and making data available for public interests and research.

Throughout 2019 Harvest led a considerable effort to engage partners in the program's thematic concentrations (crop yield and condition, crop type and area, food security and early warning) and crosscutting activities (Harvest's domestic strategy, markets and trade,

regional efforts, existing programs, public-private partnerships). The goal is to evolve strategies and outcomes for end users in each area to ensure more successful uptake of Earth observations in agricultural applications.

One example of these partnerships is a joint project between Swiss Re and Harvest to use in situ data gathered by Swiss Re to validate and calibrate remote sensing information to improve yield forecasting methods. The partnership kickstarted a cost-shared data collection campaign. As a second example, NASA Harvest hosted an event, "Partnerships for a Sustainable Future," in collaboration with Planet and Farm2050, to bring together forward-thinking agriculture companies from across the value chain to tackle how public, private, and academic sectors can work together to build and advance sustainability commitments.

# V. COMMUNITY LEADERSHIP

Water Resources and Agriculture Applications Area team members are truly leaders in the field. The program staff represent the community at countless domestic and international conferences and events, enabling program scientists to advance research while simultaneously building bridges and channels of communications with potential partners and stakeholders. The program furthers the uptake of EO for water and agriculture by contributing to multiple regional, domestic, and international committees and boards.

WWAO and Harvest each took giant leaps in closing the gap between EO capabilities and EO use in decision making by identifying needs of stakeholders in their respective communities. In addition, key staff are representing the program to the world through leadership opportunities on international, interagency, and regional committees and by showcasing the EO applications during invited media interviews (see text box below).

## *Water Needs Catalog*

With four river-basin-based needs assessments (California, Upper and Lower Colorado, and Columbia basins) under its belt, as well as a rapid needs assessment that was performed soon after WWAO's launch, WWAO has amassed a water needs catalog containing around 150 high-priority water needs and 40 detailed use cases. An important thrust in the coming months will be to build an online database to house these data, to share internally and externally, and to help shape the development of future water projects in 2020 and beyond.

### In the Media in 2019

- Live interview for ABC Radio National. Associate Program Manager John Bolten discussed the efforts by NASA Goddard Space Flight Center and the NASA Applied Sciences Program to monitor and address Australian agriculture and water resource needs including SMAP and GRACE applications for improved water resource management, and activities by the NASA ESD to study changing climate and extreme events.
- Interview in Texas + Water. Texas+Water Editor-in-Chief, Dr. Todd Votteler, interviews Dr. John D. Bolten, Associate Program Manager of Water Resources for the NASA Applied Sciences Program.
- NASA Harvest Director gives interview on Podship Earth Podcast. NASA Harvest Program Director, Dr. Inbal Becker-Reshef, was recently featured on Episode 73: Crop Circle on the nature, Earth, and environmentally-focused podcast series Podship Earth hosted by Jared Blumenfeld, California's Secretary for Environmental Protection. In the interview, she touches on various topics related to satellite remote sensing for informing agricultural and food security decisions.
- Released in early 2019, Program Manager Brad Doorn and Associate Program Manager John Bolten provided interviews for Story Corps.

## *Harvest Portal –Data and Knowledge Sharing*

Harvest Hub members built a web app using Amazon Web Services (AWS) for the Group on Earth Observations Global Agricultural Monitoring Inititative (GEOGAM) which ingests vegetation indicies, soil moisture, rainfall, and temperature data. It runs completely in the cloud, can be deployed in multiple countries, and is the backend for the Harvest Portal. Hub members also completed a cost analysis of the AWS implementation, a report for NASA detailing the costs and architecture styles, and built a full GeoNode implementation for Latin America that indexes, archives, and aids in the discovery/access of EO-datasets and related materials such as papers, webinars, and training documents. The platform will be expanded globally under Harvest. Harvest PI Gary Eilerts compiled an initial all-crop archive of sub-national agriculture statistics for: Bangladesh, Belize, Bhutan, Bolivia, Chile, Cuba, Gambia, Ghana, Nepal, New Zealand, Pakistan, Paraguay, and Swaziland and loaded data into the Famine Early Warning System (FEWS) Data Warehouse.

## *Committees and Boards*

The water resources and agriculture application area staff represent NASA by participating in various committees, boards, and leadership organizations. These organizations range from international organizations and interagency working groups to regional/local committees. Some examples (not exhaustive) include, WESTFAST, NIDIS Interagency Working Group, National Soil Moisture Network, Interagency Water Working Group, National Drought Resiliency Partnership,

the California Subcommittee on Water Quality, the United Nations Framework Convention on Climate Change, and the steering committee for the 2019 Pecora/ISRSE Conference.

# VI. MAJOR ACCOMPLISHMENTS

## *A.36 Water Resources Projects Kickoff*

The Water Resources Program implemented a solicitation in the NASA ROSES 2018 calls for proposals. This solicitation was focused on advancing the use of satellite observations and hydrologic modeling to monitor and assess local and regional water quality and quantity for improving water resource risk assessment, economic planning, investment planning, and policy making. Furthermore, this solicitation sought the development of sustainable solutions that incorporate solid business/organization models that strive to incorporate performance metrics and the fiscal realism of sustained operations.

NASA selected 13 projects for awards, totaling approximately $9 million over three years. This solicitation will support three-year projects (first-year award with two option years) to develop applied research for transition to a public or private organization for sustained use in decision making and services to end-users. Projects will aid the nation by demonstrating the capacity of operational organizations to use Earth observations for water-related economic risk and policy related to water resources. These projects all began commenced in 2019.

## *OpenET Annual Meeting and Tech Team*

Associate Program Manager Forrest Melton organized and co-led the OpenET Annual Meeting and Tech Team Meeting at the Desert Research Institute in Reno, Nevada. The meetings were attended by five NASA-supported research teams (25 scientists), as well at 65 representatives from the Western Water Management Community, including small family farms, state water management agencies, state regulatory agencies, local irrigation districts, federal agencies, conservation NGOs, and program managers from the Walton Family Fund and the S.D. Bechtel Jr, Foundation. The OpenET project team presented an overview of the OpenET Beta Platform, Communications Strategy, and Long-term Sustainability Plan. The project team obtained feedback from the project partners and Western water management community, and developed plans for the next six months of the project and platform development.

## *Cyanobacteria Assessment Network (CyAN)*

Changes in water quality can be challenging to detect, even in communities where routine monitoring occurs. Observing changes across multiple locations and during various times can be difficult, resulting in missed events such as the sudden development of cyanobacterial harmful algal blooms that may pose environmental, animal, and human health issues. The Cyanobacteria Assessment Network (CyAN) is a multi-agency project (EPA, NASA, NOAA, and the USGS) to develop an early warning indicator system to detect algal blooms in U.S. freshwater systems using historical and current satellite data. It puts the power of satellite technology in the hands of communities so they can detect changes in cyanobacterial harmful algal blooms. The research supports federal, state, and local partners in their monitoring efforts to assess water quality to protect aquatic and human health. CyAN provided daily, weekly, and true-color satellite data from the European Commission's Copernicus Program Sentinel-3A Ocean and Land Color Instrument (OLCI) to 32 state departments of health or environment with webinar trainings and technical assistance, as requested in 2019.

Methods for quantifying the cyanoHAB annual magnitude, temporal frequency, spatial extent, and lake occurrence have been developed and published. In 2019, CyAN made the satellite imagery available to the public through a mobile application that experienced 1000+ downloads and received a 4-star rating in  less than six months on Google Play. As a result, data from this project is connected to the Oregon Cyanotoxin Drinking Water Rule, as well as Utah, Idaho, Colorado and Wyoming health advisories. Information provided by CyAN allows communities to make decisions that may reduce the societal costs linked to decreased water quality such as illness, missed days of work, or possible drinking water contamination. In 2020, the project will complete a national validation of the ability to derive chlorophyll relevant to trophic status reporting, compare satellite cyanoHAB detection against state issued health advisories and reported toxin concentrations, and the mobile application will be mirrored on a web-based platform to reach more end-users.

## *Satellite Enhanced Snowmelt Flood Predictions in the Red River of the North Basin*

The objective of the project is to improve the NCRFC's operational flood prediction in the Red River Basin (RRB) by using NASA products to update the NWS's operational forecasting models (SNOW17 model and Sacramento Sac-SMA) with spatially distributed estimates of state variables, including snow water equivalent, snow melt phase, snow-covered area, and meltwater partitioning parameters based on antecedent soil moisture. Once proven on the RRB, the same techniques will be available for use elsewhere within the NCRFC area of responsibility and at the remaining 12 RFCs. This NASA support is directly responsible for building the capacity of the NOAA NCRFC to use satellite observations in the snow melt flood predictions. This capacity will serve the northern great plains region and the nation extremely well in years to come. NASA products were used in support of operations throughout the winter 2018/2019 and are currently being used for the 2019/2020 snow

season. All indicators suggest that these remotely sensed snow products will continue to be part of the river forecasters suite of observational datasets considered in the updates of river model forecasts. The prototype application system has been transitioned into the partner's decision-making system. In winter 2018/2019, products were transitioned to NCRFC staff with the agency scientists making and interpreting weekly datasets with support from UNH.

## *Forecasting in Africa and the Middle East (FAME)*

The project examined drought forecasting in MENA (Middle East and Northern Africa). Droughts are critical factors affecting food insecurity, regional instability, and conflict, especially for MENA. The project team developed, evaluated, and transitioned a seasonal water deficit forecasting system using downscaled and bias-corrected GEOS-5 forecasts and land surface models in the NASA Land Information System (LIS). In 2019 the project reached an Application Readiness Level (ARL) of 9. Moving forward, the Famine Early Warning System Network (FEWS NET) is continuing forecasts and using the FAME products at monthly climate forecast discussions to support food aid decision-making.

## *Integrating GRACE and GRACE Follow On Data into Flood and Drought Forecasts for the Continental U.S.*

This project developed, refined, and is now routinely generating 1-3 month soil moisture and groundwater wetness/drought forecast maps for the contiguous U.S. This unique approach integrates data from GRACE, GRACE-FO, and other observations within a land surface model that is subsequently forced into the future by downscaled seasonal climate predictions. The products are now being widely disseminated by the National Drought Mitigation Center through a public facing website. The value of these wetness/drought products for streamflow prediction was demonstrated by project partners at NOAA's North Central River Forecast Center, who continue to work on ways to integrate the products into their operations. UNL developed a map template and new NDMC webpage for distributing the drought forecast products. NOAA/NCRFC used historical GRACE DA groundwater and SWE, in addition to soil moisture, in experimental retrospective forecasts and demonstrated value added.

## *Columbia River Basin Needs Assessment*

Partner-driven tools start with relationships. And as in all relationships, listening is key. In 2019, WWAO continued to listen to the needs of western water managers, decision makers, and stakeholders through both formal needs assessments and ongoing strategic partnerships.

Following on from its previous work in the western U.S., WWAO undertook a needs assessment in the Columbia River Basin (CRB) to identify, catalog, and understand high-priority needs of water stakeholders in and around the basin, as well as the obstacles to meeting those needs. The assessment was part of WWAO's ongoing push to catalog water needs in the west using a basin-

by-basin approach. By the end of 2019, WWAO had surveyed four of the ten major river basins – California, Upper Colorado, Lower Colorado and Columbia – in the continental western U.S. (west of the 100th meridian), and surveys of other basin assessments will continue apace in 2020.

WWAO's CRB Needs Assessment commenced in March 2019 with a study that summarized publicly-available information about stakeholders in the CRB who could potentially benefit from NASA's remote-sensing research and data. In April and May, a series of interviews were conducted with twenty-two stakeholders representing a cross-section of policymakers, planners, water management officials, and end users in the CRB. These interviews helped establish a greater understanding of stakeholders' water responsibilities and the limitations they currently face in providing maximum value to their clients, customers, members, or constituents. The surveys were used to identify, at a first pass, important water management and data challenges within the CRB and information gaps that impede decision-making progress.

Then in September 2019, WWAO convened a two-day Needs Assessment Workshop with stakeholders in Portland, Oregon to dig deeper into the issues identified. At the workshop, a variety of NASA resources and capabilities were presented. Stakeholder representatives collaborated to identify and prioritize key water management issues, and developed an initial set of 54 needs. These needs were then organized into four broad categories: Agriculture, Water Quality, Water Supply, and Watershed Health. Discussion and analysis resulted in a shortlist of 14 'use cases' to move forward for further study.

Notably, the Agriculture and Water Supply groups both developed use cases based on evapotranspiration (ET). ET is a critical element in water management within the CRB and, indeed, within other western U.S. river basins. From an agricultural perspective, accurate estimation of ET is crucial to the proper administration of water rights for irrigation. Agricultural irrigation is a major consumptive use of water within the CRB, and different crops, climatological conditions, and irrigation methods can create enormous variability in agricultural ET values. On a larger scale, however, accurate estimates of ET are important for determining water availability throughout entire regions and for large-scale water use planning and forecasting. It was therefore not surprising that ET was selected as a use case by two different stakeholder groups at the workshop. ET over land and water was a key priority identified in the Colorado River Basin in 2018 which is now being pursued through an FY19 project concept.

## *Global Collection of Sub-national crop production statistics*

A NASA Harvest and USAID FEWSNET Collaboration led by PI Gary Eilerts looks to gather a global collection of sub-national crop production statistics. The team created a unique analytic tool and historic baseline that collected crop production statistics for 145 countries since 1980. The tool has information on approximately 3.5 million area, yield, and production data points from over 3,500 original data source documents.

In 2019, the project team finished compiling an initial, complete all-crop archive of sub-national agricultural statistics for approximately 30 new countries including: Argentina, Australia, Belarus, Bosnia-Herzegovina, Brazil, China, Colombia, Croatia, Egypt, Estonia, Georgia, Guinea-Bissau, Hungary, India, Japan, Kosovo, Kuwait, Lithuania, Moldova, Montenegro, Myanmar, North Macedonia, Palestine, Serbia, Slovakia, Slovenia, Spain, and Ukraine. These datasets have been loaded or are being loaded into the FEWS Data Warehouse. This information provided crop data to IFPRI SPAM, USDA IPAD, and Applied GeoSolutions for a variety of applied work including the compiling, analyzing, and assessment of the baseline changes in the last 10-years of Chinese sub-national agricultural statistics.

### *Crop Mapping and improved yield modelling.*

A Harvest project improved the yield model applied at subnational (errors 20%) and national levels (errors 11%) and improved the yield model applied at subnational (errors 7%) and national levels (errors 5%) in Germany for 2001-2017. Crop mapping -Generation of winter wheat maps for Russia at 250 m spatial resolution for 2015-2019 and Germany for 2000-2018. Improved yield model applied at subnational (errors 20%) and national level (errors 11%) in Russia (Figure 1) for 2001-2017. Improved yield model applied at subnational (errors 7%) and national level (errors 5%) in Germany (Figure 1) for 2001-2017. Lobell's group continued their work with One Acre Fund to apply our maize yield estimates to evaluate their interventions in Kenya and Tanzania region, and post-doc Dienes is working on field-scale crop type and yield estimation in the U.S. Corn Belt, comparing Scalable Crop Yield Mapper results with USDA county statistics, doing data validation with ground data, and assessing conservation tillage impacts on maize yields.

## VII. INTERNATIONAL ACTIVITIES

### *Group on Earth Observations Global Water Sustainability (GEOGLOWS)*

GEOGLOWS is a Group on Earth Observations (GEO) initiative designed to support the development and sustainable use of the world's water resources by bringing together those who need information to make better decisions with those who can provide relevant and robust information. This process involves data, analysis, product development and distribution, and support for the use of data products and research results to explore new applications and solutions to existing and emerging needs.

The Applied Sciences Program is managing four GEOGLOWS projects from a competitive ROSES solicitation. 1) *AmeriGEOSS Cloud-based Platform for Deployment of GEOLOWS*, PI-Daniel

Ames, Brigham Young University; 2) *Optimizing the Indus Basin Irrigation System,* PI-Karl Rittger, University of Colorado; 3) *Risk and Capacity Development for Two Indian River Basins*, PI-Venkat Lakshmi, University of Virginia; and 4) *Surface Water Changes over the Lower Mekong*, PI-Hongki Lee, University of Houston.

## *HARVEST Regional Activities*

Throughout 2019 Harvest has been working with government entities in Eastern Africa, including collaborations with Ministries of Agriculture on national-scale crop monitors in Kenya, Tanzania, and Rwanda with Harvest partners UCSB, SERVIR, ICPAC, RCMRD and other local partners. Harvest also worked with Lutheran World Relief and the Gates Foundation on developing crop monitoring and early warning systems in Mali. Harvest is now engaging with the United Nations Framework Convention on Climate Change (UNFCCC) team that leads the National Adaptation Plans (NAP) development on the integration of EO as part of the broader suite of tools for Agriculture, to supplement the IIASA/FAO Global Agroecological Zone (GAEZ) system, and also to extend the active decision support provide by climate services work/early warning systems that focus on delivery of weather/climate information to users. Harvest also engages with the Agricultural Monitoring in the Americas (AMA) working group which consists of representatives from nine countries and intergovernmental authorities.

## *Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM)*

NASA Harvest, in its capacity as a key contributor to GEOGLAM, will be working to address Agricultural Market Information System's (AMIS) formal request that GEOGLAM observe countries where there is high uncertainty in production forecast. In 2013, AMIS requested that GEOGLAM provide monthly consensus crop conditions on the four major commodities (wheat, rice, soy, maize) in countries responsible for 80-90% of global production. Since then, GEOGLAM has published the Crop Monitor for AMIS bulletins, which are one of the most valuable components of AMIS's Market Monitor. In 2019, GEOGLAM published Crop Monitor for AMIS bulletins and Crop Monitor for Early Warning bulletins, with new special reports and updates about flood impacts in Iran and Iraq, the start of the U.S. 2019 spring/summer season, Southern Africa 2018/2019 summer crops in April, and special report on East Africa 2019 main season crops in June. In addition, the Harvest team has actively engaged with the Committee on Earth Observations (CEOS) via the GEOGLAM Secretariat. In 2019, Harvest delivered final GEOGLAM requirements and CEOS Response to GEOGLAM request to CEOS in September 2019, closing out a three-year action.

# VIII. LOOKING AHEAD

The Water Resources Applications area looks to 2020 as a year of growth, expansion, and an opportunity to strengthen application impacts. In addition to supporting the 16 high-impact projects, the new selections from ROSES 2018 solicitation in the portfolio, and the two new Ecostress projects, the program will also broaden its breadth of non-traditional partnerships.

In 2020, WWAO will grow, deepening its reach and impact in the water and applied science arenas. Needs assessments will be carried out for the Rio Grande and Missouri River Basins and WWAO's project formulation process will continue to be refined. In 2020, WWAO will complete its first Industry-Based Water Needs Assessment and begin to define collaborations and/or pilot projects with the private sector. In 2019, WWAO began establishing an interagency network of experts that can facilitate effective R2O in water management. In April 2020, WWAO will continue this work by co-hosting with the Western States Water Council (WSWC) a second R2O workshop in Irvine, California. The workshop will bring together NASA scientists and partners from federal and state agencies that have experience with technology transfer. Finally, in 2020, WWAO plans to conduct a survey to quantify the size of the ET market to contribute to the assessment of viable operational pathways for ET-based information.

NASA will sign a Memoradum of Understanding (MoU) with the United States Department of Agriculture as a commitment to partner and work together in the coming years. Harvest will facilitate many activities that fall under the MoU to strengthen Harvest's domestic agriculture activities. Harvest will also look to expand partnerships in 2020 and continue to support research in applied science for the agriculture community.

# IX. APPENDIX A: WATER RESOURCES 2019 PROJECT UPDATES

**Project Title**: Advancing Drought Onset Detection and Seasonal Prediction Using a Composite of NASA Model and Satellite Data

**Principal investigator:** Amir AghaKouchak, University of California, Irvine

**Project year:** 5

**Year-end ARL:** 5

**Project description:** The primary goal of this project is to improve drought monitoring and prediction in California through: a) using NASA's Atmospheric Infrared Sounder (AIRS) relative humidity and water vapor to improve drought early-onset detection and prediction, b) developing a multivariate modeling framework for composite drought assessment, and c) developing a framework for quantitative and probabilistic assessment of drought by integrating satellite data into an analog-based drought prediction model. The project is being conducted in close collaboration between UC Irvine and investigators from the California Department of Water Resources (CDWR).

**End Users/Partners:** California Department of Water Resources (CDWR)

**Data sources, models, technology:** NASA Atmospheric Infrared Sounder, MODIS SST, VIIRS SST, land-atmosphere models, stochastic modeling techniques.

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**Project Title:** An AmeriGEOSS Cloud-based Platform for Rapid Deployment of GEOGLOWS Water and Food Security Nexus Decision Support Apps

**Principal Investigator:** Daniel P. Ames and Norm Jones, Brigham Young University

**Project Year:** 2

**Year End ARL:** 5

**End Users / Partners:** José Mauro (Brazil-INMET), Pierre Guillevic (University of Maryland), Dardo Fontanella (INTA-Argentina), Jaime Bernal (CORPOICA-Colombia), Silvano Pecora (WMO)

**Project Description:** We are extending our open source environmental web app development system, Tethys Platform, creating an app warehouse for rapid deployment of water resources decision-support-system web apps and creating new specific decision-support web apps for our collaborators in Latin America.

**Data sources, model, technologies:** Our core technology is the Tethys Platform, which is a collection of open-source web development tools for spatial and temporal data management and visualization. Data sources include ground observations of streamflow, water quality, ground water, and flood observations, as well as satellite data from GRACE, MODIS, and others.

**Major Accomplishments in 2019:**

- GEOGloWS Global Streamflow Pilot: We have developed a GEOGloWS Global Streamflow Pilot project including streamflow forecast for the Americas, Africa, India, and parts of Southeast Asia. These streamflow forecasts are based on ECMWF 15-Day weather forecasts and the RAPID streamflow routing method. Forecasts are generated daily and are available for retrieval via web application programming interfaces (APIs). A 35-year retrospective analysis is used to identify flood return periods and flag high-risk forecasts.
- Global HydroViewer Web Applications: We have developed several open-source web applications using the Tethys Platform and have deployed them for users in Colombia, Nepal, the Dominican Republic, the La Plata Basin and other locales. These web applications provide end users with access to forecast data, in situ observations, and remotely sensed data.
- Ground Water Management Apps: Our GRACE app has been improved to automatically check for new GRACE data files, extract time series for specific locations, and to estimate ground water variation over large basins. Our Groundwater Level Mapping Tool app allows users to view time series of groundwater levels at wells throughout an aquifer. The application also interpolates the well data to create a map of groundwater levels that can be viewed at different time steps, allowing users to visualize changes in groundwater levels over time.
- App Warehouse: We have created a prototype app warehouse using the HydroShare.org data store as a back-end catalog and a custom Tethys web app for app discovery. We have partnered with a local company, Aquaveo, to continue this development, focusing on an automated app install to simplify acquisition and use of apps by our partners in Latin America.

**Relevant project websites / links:** http://worldwater.byu.edu/, http://www.hydroshare.org/ http://tethys.byu.edu/

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**Project Title**: Remotely Sensed Water Storage for Agriculture and Regional Security and The Global Reservoir and Lake Monitor (GREALM)

**Principal investigator:** Charon Birkett, NASA/GSFC

**Project year**: 1 (Water Storage) and 3 (GREALM)

**Year-end ARL**: 2 (with respect to new water-storage products) or ARL 4 (with respect to new Sentinel-3A water-level products).

**Description:** This project provides a range of surface water products related to lakes, reservoirs, and wetlands in a near real time framework. It also offers a longer-term set of observations via integration of historical data sets. Products include water level, water extent, hypsometry and bathymetry, and water storage. A range of new status indicators will also be output to highlight current normal or anomalous conditions. Products are used by various PI and collaborative stakeholders to assess global water storage for agriculture in terms of irrigation potential, for consideration of fish catch potential, and for highlighting food/water/energy deficits that could potentially influence regional stability.

**End users:** USDA Foreign Agricultural Service (FAS), US Army Corps of Engineers (USACE/ERDC), National Geospatial Intelligence Agency (NGA), Dept. of Defense Intelligence Information System (DoDIIS), and several wetland researchers and agencies including members of Wetlands International and the Food and Agriculture Organization of the United Nations (FAO).

**Data sources, models, technology:** The project uses a variety of multi-platform satellite data sets including radar altimeters (the NASA/CNES TOPEX/Jason series and the ESA/ISRO/CNES SARAL and Sentinel-3 series), and multi-spectral imagers (MODIS 250m), and Digital Elevation Models such as SRTM and Tandem-X. Future instruments will also integrate data from the Sentinel-3B, Sentinel-6 Michael Freilich (launch 2020), and SWOT (launch 2021) missions.

**Major accomplishments in CY 2019:**

- The Global Water Monitor site is a new web portal for access to the new storage and status indicator products and the test wetland surface water level products. The web portal was finalized in 2019 and became operational. While serving as a backup to the USDA/GREALM portal, this new facility offers enhanced information to serve a much wider variety of stakeholders.
- The 10-day-resolution surface water level products for lakes/reservoirs underwent an upgrade to Version 2.5 to maintain climate index quality time series, and the team commenced delivery of new 27-day-resolution operational products from the ESA Sentinel-3A satellite.
- With a new project-team structure, an alpha-version software module, designed to utilize MODIS imagery from the NASA LANCE facility and follow similar image processing of the NASA/GSFC Global Flood Monitor service, was constructed. Still in test mode there is a

specific focus on resolving technical issues relating to cloud interference and partial lake coverage. The module will ultimately be merged with the altimetric processing chain to form the much higher-level hypsometry and storage products for lakes.

- In 2019 the Global Water Monitor portal also delivered surface water level products for a number of wetland sites, notably for the Usangu region in Tanzania. Through collaborative efforts these products became the basis for a study on water resources management in the light of competing agriculture, fishery, hydro-electric power, and wetland ecology needs. The web facility also delivered surface water level products for a selection of river reaches in Alaska as part of the NASA/USGS-funded "Remotely sensed Streamflow and Water Resource Management Agency Operations" Applied Sciences project.

**New Publication:**
Tortini, Noujdina, Yeo, Ricko, Birkett, Khandelwal, Kumar, Marlier and Lettenmaier, Satellite-based remote sensing dataset of global water storage change from 1992 to 2018, submitted to Earth System Science Data (Copernicus Publication), In Press 2019.

**Relevant Websites**:

- The USDA CropExplorer/Global Reservoir and Lake Monitor https://ipad.fas.usda.gov/cropexplorer/global_reservoir/
- The Global Water Monitor https://water-monitor.sgt-inc.com/

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**Project Title**: High-Resolution Soil Moisture Monitoring for Improved Vineyard Water Resource Management

**Principal investigator:** Wade T. Crow, USDA-ARS

**Project year**: 1

**Year-end ARL**: 4

**Description:** This project seeks to provide high-resolution (i.e., daily, 30-m) soil moisture information to guide in-season irrigation decision support for vineyards equipped with variable-rate drip irrigation (VRDI) systems in the Central Valley of California. The primary water resource decision for these systems concerns when to start irrigation in the late spring/early summer. While the quality of many grape varieties benefits from the introduction of moderate levels of water stress (associated with the delay of irrigation), excessive stress can permanently damage the grape-carrying capacity of vines. The key to balancing these two concerns is the availability of timely, accurate and high-resolution soil moisture products that can only be produced by the assimilation of high-resolution remote sensing products into a soil-water balance model.

**End Users:** The primary end user is from the project E&J Gallo Winery. However, E&J Gallo sources most of their grapes from a very large external grower network that cultivates a significant fraction of the total Californian vineyard acreage. As a result, our system is being designed with the eventual goal of serving this (much larger) secondary end-user community.

**Data Sources:** Satellite-based retrievals of surface soil moisture, derived from synthetic aperture radar (SAR) observations, and surface evaporative fluxes, derived from thermal/infrared land surface temperature (LST), form the backbone of our approach. Thermal-infrared satellite data from the NOAA GOES and VIIRS, NASA MODIS, and USGS Landsat sensors are utilized to retrieve LST at a range of spatial scales. In anticipation of the potential future availability of routine, 200-m, surface soil moisture retrievals from the NASA/ISPRO NISAR mission, surface soil moisture fields are acquired from ESA Sentinel-1 SAR imaging of E&J Gallo vineyards.

**Major Accomplishments in CY19:** This project formally started in early 2019. The major accomplishment during its first year was publication of a proof-of-concept, peer-reviewed journal article (Lei et al., 2020) outlining our novel data assimilation and remote sensing approach. Project personnel also presented updates on the project at the April 2019 GRAPEX workshop in Modesto, California and the November 2019 National Grape Alliance Workshop on Sensor Technology in Sacramento, California. Both workshops were attended by key end users and provided important outreach opportunities.

**Plans/Expectations for CY20:** Planned 2020 activities are focused on operationally implementing the data assimilation system described in Lei et al. (2020). Current plans call for this system to be initialized on May 1, 2020 and provide weekly, 30-m resolution estimates of root-zone (0 to 60-cm) soil moisture estimates for two separate E&J Gallo vineyards located near Ripperdan, California and Lodi, California. Data products will be delivered operationally to end users (described above) via the existing "ET dashboard" interface. E&J Gallo has agreed to provide timely feedback on the data quality and format of the product. We will complete weekly data delivery less than one-week behind the real-time acquisition of observations.

**New Publication:**

Lei, F., Crow, W.T.**,** Kustas, W.P., Dong, J., Yang, Y., Knipper, K.R., Anderson, M.C., Gao, F., Notarnicola, C., Greifeneder, F., McKee, L.M., Alfieri, J.G., Hain, C. and Dokoozlian, N. Data assimilation of high-resolution thermal and radar remote sensing retrievals for soil moisture monitoring in a drip-irrigated vineyard. *Remote Sensing of Environment*. 239. 111622. https://doi.org/10.1016/j.rse.2019.111622. 2020.

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**Project Title**: Enhancing Water Resource Management in Alaska: Integration of Remotely Sensed Streamflow Data into Resource Management Operations

**Principal investigator**: Jack Eggleston, USGS Hydrologic Remote Sensing Branch

**Project year**: 1

**Year-end ARL**: 3

**Project description**: This primary goal of this project is to develop the workflow for operational space-based streamflow (discharge) measurement. The Alaska DOT and National Weather Service Alaska-Pacific River Forecast Center are long-term partners of the USGS and are representative of the hundreds of government agencies in the U.S. whose operations depend on streamflow data. This project plans to operationalize space-based methods for USGS river monitoring in Alaska and operationalize use of remotely sensed streamflow data by other public agencies in Alaska. We plan to develop an ensemble approach for computing river discharge by leveraging multiple satellites and discharge algorithms and develop operational workflows for remote sensing data that can be adopted outside of Alaska—nationally and globally.

**End Users/Partners**: NWS Alaska-Pacific River Forecast Center, Alaska DOT, USFWS Alaska National Wildlife Refuge System, Alaska Department of Fish and Game

**Data sources, models, technology**: NASA JASON altimetry, Landsat, land-surface interpretation modeling (DSWE), open-channel hydraulics modeling techniques. Project plans to incorporate additional data sources including Sentinel-2, ICESat-2, SWOT.

**Major accomplishments in CY 2019**: The project team convened the first team meeting at the USGS Alaska Science Center in Anchorage, September 24-25, 2019 for the project kickoff and coordination and end-user engagement (USGS, NASA/GSFC, and end-users NWS, USFWS, AK DOT, and AK Fish & Game in attendance). Following the kick-off meeting the team finalized the selection of the project study sites for computing remotely-sensed discharge (RSQ). The team established a test website for serving TOP/POS/JASON riverine altimetry data for this project; assembly of altimetry data for study gages is an ongoing task. All available (as of December 2019) dynamic surface-water extent (DSWE) data products for our study sites were downloaded and are being processed using newly-developed analysis scripts. We identified candidate flow-computation algorithms to be evaluated, and those evaluation efforts are ongoing. A provisional model has been developed for application of DSWE to Sentinel-2 data and preliminary results were presented at the American Geophysical Union's Fall meeting in San Francisco, California.

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**Project Title**: Optimizing Reservoir Operations for Hydropower Production in Africa through the use of Remote Sensing Data and Seasonal Climate Forecasts

**Principal investigator:** Mekonnen Gebremichael, UCLA

**Project year:** 5

**Year-end ARL:** 5.5

**Project description:** In 2014, this project was selected for four-year funding as part of the A.45 Water Resources solicitation. This project aims to improve reservoir operations for hydropower production for multiple utilities in East Africa by utilizing remote-sensing data and seasonal climate forecasts in respective decision support systems.

**End users/partners:** Ethiopian Electric Power Corporation, Ethiopian Water Works Construction Enterprise, Tanzania Electricity Company, National Meteorological Agency of Ethiopia

**Data sources, models, technology:** 1) Precipitation Data: TRMM 3B42RT, NMME seasonal forecasts, THORPEX Interactive Grand Global Ensemble (TIGGE) ensemble weather forecasts from eight global centers, NASA's Global Data Assimilation System, Global Livestock Environmental Assessment Model (GLEAM) evapotranspiration data; 2) Model data: NASA's Land Information System and Noah-MP Land Surface Model

**Relevant project websites/links:** http://nasa-ucla.rap.ucar.edu/

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**Project Title**: Eco-Hydrological Modeling Using Field-Based and Earth Observations to Assess Water Use Efficiency and Support Agricultural Water Resources Management

**Principal investigator:** Pierre Guillevic and Jean-Claude Roger, University of Maryland

**Project year:** 3

**Year-end ARL:** 5

**Project description:** The goal of this project is to develop an integrated modeling platform using Earth observations to simulate large-scale hydrological processes and food production in support of water use decisions and agricultural policy. The approach is based on the use of field and Earth observations to calibrate the APEX and SWAT eco-hydrological models, and climate simulations to forecast crop condition and yield through the crop season. The primary outcomes and results for stakeholders will be potential water management best practices to improve water use efficiency and prevent excessive losses of water and nitrogen to the environment.

**End users/partners:** G20 GEOGLAM and NASA Harvest initiatives, agriculture and water ministries in Tanzania and South Africa, water management consortiums and farmers in Argentina, Tanzania, and South Africa. Natural Resources Conservation Service, Bureau of Reclamation and farmers in the U.S. Irrigation consulting and management companies in the U.S. and New Zealand.

**Data sources, models, technology:** APEX and SWAT models; satellite data from MODIS, Landsat, GPM, Sentinel, and ECOSTRESS; meteorological data from NCEP and NASA; ground-based measurements from project partners.
**Relevant project websites/links:** http://agwater.umd.edu

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**Project Title**: Development of a Global Evaporative Stress Index Based on Thermal and Microwave LST towards Improved Monitoring of Agricultural Drought

**Principal investigator:** Christopher Hain, NASA MSFC

**Project year:** 3

**Year-end ARL:** 6

**Project description:** We propose to develop a global agricultural monitoring tool, with a focus on providing early warning of developing vegetation stress at relatively high spatial resolution (5-km) for agricultural decision makers and stakeholders. This tool is based on remotely sensed estimates of evapotranspiration retrieved via energy balance principles using observations of land-surface temperature (LST). The Evaporative Stress Index (ESI) represents anomalies in the ratio of actual-to-potential ET generated with the thermal remote-sensing based Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model. The LST inputs to ESI have been shown to provide early warning information about the development of vegetation stress, with stress-elevated canopy temperatures observed well before a decrease in greenness is detected in remotely sensed vegetation indices.

Whereas many drought indicators based on precipitation or atmospheric conditions capture meteorological drought, the ESI is one of few indicators of agricultural drought that reveals actual vegetation stress conditions realized on the ground. As a diagnostic indicator of actual ET, the ESI requires no information regarding antecedent precipitation or soil moisture storage capacity—the current available moisture to vegetation is deduced directly from the remotely sensed LST signal. This signal also inherently accounts for both precipitation and non-precipitation related inputs/sinks to the plant-available soil-moisture pool (e.g., irrigation, tile drainage), which can modify crop response to rainfall anomalies. Independence from precipitation data is a benefit for global agricultural monitoring applications due to sparseness in existing ground-based precipitation networks and time delays in public reporting. Even as

satellite precipitation monitoring has closed some of the observational gaps, these data are usually provided at coarse resolution with their accuracy dependent upon extensive calibration with ground-based precipitation estimates.

**End users/partners:** National Drought Mitigation Center, USDA Foreign Agricultural Service, International Center for Biosaline Agriculture's MENA Regional Drought Management System, G20 GeoGLAM Crop Monitor Initiative for the Agricultural Information System (AMIS), NASA SERVIR, Agriculture and Agri-Food Canada (AAFC)

**Data sources, models, technology:** The primary input to the original ALEXI modeling system is the time-differential change in mid-morning LST, typically obtained from geostationary satellites. To facilitate global mapping applications, new methods have been developed to estimate the mid-morning change from day-night temperature differences available from a single polar-orbiting thermal infrared sensor. In addition, a new cloud gap-filling technique using Ka-band retrievals of LST allows coverage in persistently cloudy equatorial regions. The project will exploit several NASA and NOAA Earth Science research datasets including: 1) land-surface products from the MODIS instruments on NASA's Terra and Aqua satellites and the VIIRS on the Suomi National Polar-orbiting Partnership (NPP) platform, 2) microwave Ka-band observations from a number of national and international platforms, and 3) meteorological information from the NOAA Climate Forecast System Reanalysis modeling systems, which provide operational production and retrospective analyses back to 1979.

**Relevant project websites/links:** Global ESI in NASA SERVIR Data Catalogue: http://catalogue.servirglobal.net/Product?product_id=198

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**Project Title**: Precipitation, Water Management, and Algae Blooms in South Florida Estuaries

**Principal investigator:** Chaumin Hu, University of South Florida

**Project year:** 1

**Year-end ARL:** 3

**Project description:** The project is designed to meet the water management needs by the SFWMD and USACE, with the ultimate goal of incorporating state-of-the-art remote sensing, physical-biological models, and historical information in their existing DSIS.

**End users/partners:** South Florida Water Management District (SFWMD)

**Data sources, models, technology:** TRMM, MERIS, MODIS, OLCI

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**Project Title**: Enhancing National Security Decision-making Processes for Regions Vulnerable to the Impacts of Flash Droughts Through Greater Use of NASA Resources

**Principal investigator:** Eric Hunt, Atmospheric and Environmental Research

**Project year:** 1

**Year-end ARL:** 4

**Project description:** Use the NASA MERRA-2 reanalysis data to develop a global flash drought climatology based on evaporative stress. The end product is for global use and the goal is to develop a global flash drought climatology for use by national security stakeholders.

**End users/partners:** South Florida Water Management District (SFWMD)

**Data sources, models, technology:** NGA, Department of Army, Department of Air Force

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**Project Title**: Operational Remote Sensing of Agricultural Water Use in Cooperation with Western State Water Resource Agencies for Improved Water Management

**Principal investigator:** Justin Huntington, Desert Research Institute

**Project year:** 3

**Year-end ARL:** 6.5

**Project description:** Reporting of evapotranspiration (ET) from irrigated agriculture in the western U.S. is increasingly being required for surface and groundwater-use inventories, estimating historical pumpage, as well as supporting water rights, transfers, and management. Crop conditions vary significantly in time and space due to crop phenology, management, stress and fallowing. Satellite imagery with sufficient spatial resolution can be used to observe crop conditions and estimate ET. The objective of this project is to develop an open-source cloud computing software framework, OpenET, that allows water agencies to operationally produce and analyze satellite-based ET data for day-to-day operations. OpenET also assists special studies with the aim of improving water management through enhanced knowledge of historical and current consumptive use and hydrologic budgets.

**End users/partners:** Nine western state water resource agencies: Nevada Division of Water Resources, Utah Division of Water Resources, Wyoming State Engineer's Office, Montana Department of Natural Resources, Texas Water Development Board, California Department of

Water Resources, California Water Control Board, Idaho Department of Water Resources and Oregon Water Resource Department

**Data sources, models, technology:** Landsat, Sentinel-2, METRIC and SIMS, Google Earth Engine, web visualization and data dissemination, open-source code repository

**Major accomplishments in CY 2019:**

- State end-users tested and implementation of standalone Python model versions of METRIC (pyMETRIC and pySIMS) and ran models on local computers to produce ET maps. Oregon Department of Water Resources integrated pyMETRIC ET results into a USGS groundwater modeling project for groundwater management. pySIMS was finalized and state testing will begin in CY 2020.
- Deployed eddy covariance station in Oregon over a field of alfalfa, performed energy balance closure analysis, and performed comparisons between in-situ ET estimates, and pyMETRIC, pySIMS, and SSEBop remote sensing ET models.
- Populated geodatabase with field-level ET results for each study area.
- Developed software on Google Earth Engine to operationally produce ET datasets from multiple models, including METRIC, SIMS, SSEBop, PT-JPL, and disALEXI.
- Shared all software on the open GitHub repository. All water agency partners have downloaded, tested, and implemented pyMETRIC and pyQAQC weather station software programs.
- Co-developed a user interface to explore ET data from multiple ET models across the western U.S.
- Continued collaboration with NASA, non-profit, and various university and government partners to leverage this work and support the OpenET project - www.etdata.org
- Relevant project websites/links: www.etdata.org; https://github.com/DRI-WSWUP; https://github.com/orgs/Open-ET; https://landsat.gsfc.nasa.gov/mapping-water-use-nationwide-with-landsat/

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**Project Title**: Satellite Enhanced Snowmelt Flood Predictions in the Red River of the North Basin

**Principal investigator:** Jennifer Jacobs, University of New Hampshire

**Project year:** Completed

**ARL:** 8/9

**Description:** In 2014, this project was selected for four-year funding as part of the A.45 Water Resources solicitation. The objective of the project is to improve the NCRFC's operational flood prediction in the Red River Basin by using NASA products to update the NWS's operational forecasting models (SNOW17 model and Sacramento Sac-SMA) with spatially distributed estimates of state variables, including snow water equivalent, snow melt phase, snow-covered

area, and meltwater partitioning parameters based on antecedent soil moisture. Once proven on the RRB, the same techniques will be available for use elsewhere within the NCRFC area of responsibility and at the remaining 12 RFCs.

**End users:** North Central River Forecast Center

**Data sources, models, technology:** SMM/I, AMSR-E, AMSR2, SMOS, SMAP, MODIS, SNODAS

**Major accomplishments in CY 2019:**

- This NASA support is directly responsible for building the capacity of the NOAA NCRFC to use satellite observations in the snow melt flood predictions. Products were used in support of operations throughout the winter 2018/2019 and are currently being used for the 2019/2020 snow season. All indicators suggest that these remotely sensed snow products will continue to be part of the river forecasters suite of observational datasets considered in the updates of river model forecasts.
- Transitioned the prototype application system into the partner's decision-making system. In winter 2018/2019, products were transitioned to NCRFC staff with the agency scientists making and interpreting weekly datasets with support from UNH. Development of the UNH satellite product workflow was completed in October 2018. The workflow was then thoroughly tested at UNH, documented, disseminated upon completion for use at the RFC, and NCRFC staff received training
- Despite three changes in project leadership throughout this project, the UNH team maintained continuity and support from the NCRFC. After Dr. Pedro Restrepo's retirement, Michael DeWeese, Hydrologist-in-Charge of the NCRFC, continued to lead the project team. Michael DeWeese or his staff continued to participate in weekly (winter) weekly or biweekly (non-winter) project conference calls. Michael DeWeese retired in December 2018 and Mr. Brian Connelly stepped into his position and become our lead contact at the NCRFC.
- The system's capability and improved results have been presented to many of our end-user partners, are currently documented in papers, and presented at regional and national conferences. Project results have been communicated through forty-five publications and presentations including 14 refereed journal articles. Fifteen of these communications include NOAA NCRFC and NOHRSC scientists as co-authors.
- The early-career scientists supported through this project gained technical skills that have allowed them to move into highly competitive professional positions and to develop the ability to work with stakeholders that will serve them throughout their careers. Ph.D. candidate, Eunsang Cho, was awarded the University of New Hampshire, Dissertation Year Fellowship for 2018-2019, will graduate in Spring 2020, and plans to continue research as a postdoctoral scientist at NASA Goddard Space Flight Center (pending). Project postdoctoral scientist, Samuel Tuttle, has accepted a tenure track Assistant Professor position at Syracuse University (Fall 2020). Project postdoctoral scientist, Ronny Schroeder, began a tenure track Assistant Professor position at Emery-Riddle University (Fall 2019).

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**Project Title**: Integration of InSAR with Airborne Geophysical Data for the Development of Groundwater Models

**Principal Investigator:** Rosemary Knight, Stanford University

**Project Year:** 1

**Year-end ARL:** 2

**Project Description:** The goal of this work is to improve the quality and usefulness of groundwater models by incorporating information derived from interferometric synthetic aperture radar (InSAR) data and airborne electromagnetic (AEM) data. These improved groundwater models can then be adopted by water agencies to predict and assess changing conditions (e.g., climate, land use) and the outcomes of possible water management actions; this process is key to achieving sustainable groundwater management. We will test the utility of including INSAR and AEM data in groundwater modeling in two study areas, both located in California's Central Valley. The first study area centers on Butte County in the northern end of the valley, the second study area encompasses the Kaweah Subbasin in the southern end of the valley.

**End Users / Partners:** Ryan Smith (Missouri University of Science and Technology), Claudia Faunt (USGS), Tom Launkes (NORCE), Butte County Department of Water Resources and Conservation, Mid-Kaweah Groundwater Sustainability Agency, Greater Kaweah Groundwater Sustainability Agency, East Kaweah Groundwater Sustainability Agency, California Department of Water Resources, California State Water Board, GEI Consultants, GSI Consultants.

**Data Sources, Models, Technology:** SAR data (Sentinel 1a & 1b, Envisat), AEM data, Central Valley Hydrologic Model (CVHM), Kaweah Groundwater Model, and auxiliary ground-based datasets (including GPS and well-based datasets).

**Major Accomplishments in CY 2019:**

- Preliminary processing and inversion of AEM data in both study areas.
- Detailed processing and inversion of the AEM data in the Butte Study area. Working with our local partners we have investigated the impact of various inversion parameters on the resulting resistivity models, and how these could be used to answer key hydrogeologic questions in the study area.
- Preliminary processing of the InSAR data in the Kaweah study area using both Sentinel and Envisat data.
- Acquisition and preliminary investigation of well-water-level database in Kaweah Subbasin.

- First annual project meeting. Our first annual meeting was an important opportunity to get all project partners and stakeholders up to speed on the planned work for this project and further develop the relationships that will be critical to the success of this project
- Presentation of results: there have been five presentations of results related to this project, including one at the NASA Water Resources Program Meeting (July 2019), two at the Groundwater Resources Association of California Annual Meeting (September 2019), and two at the Fall American Geophysical Union Meeting (December 2019).

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**Project Title**: Monitoring Vineyard Water Use and Vine Water Status with Land Surface Temperature for Improved and Sustainable Water Management from Field to Regional Scales

**Principal Investigator:** William P. Kustas USDA-ARS Hydrology and Remote Sensing Lab

**Project Year:** 3

**Year End ARL**: 7

**End Users / Partners:** E&J Gallo Winery, National Grape & Wine Initiative, Almond Board of California.

**Project Description:** The proposed project will refine and apply a multi-scale remote sensing toolkit for mapping crop water use and crop stress for improved irrigation scheduling and water management in vineyards in the Central Valley of California managed by E&J Gallo. This toolkit will be available to other wineries and orchard growers for improving water management and irrigation scheduling.

**Data sources, model, technologies:** We are combining Earth observations from GOES, VIIRS, MODIS, and Landsat satellites together with unmanned aerial vehicles (UAVs) in energy balance modeling systems utilizing land surface temperature. Model results are being validated with biophysical, soil moisture, and micrometeorological measurement of fluxes from leaf to canopy to whole vineyard blocks at selected experimental vineyards.

**Major Accomplishments in 2019**:

- The data fusion/ET toolkit was applied over the three GRAPEX vineyard experimental sites having a significant north-south climate gradient and containing different vine varieties, trellis designs, soil properties, and topography. Comparisons with micrometeorological data indicate satisfactory model performance at all sites, with mean absolute errors on the order of 0.70 mm/day, similar to past GRAPEX studies. Spatiotemporal analyses illustrate the ability of the thermal-based multi-sensor data fusion approach to characterize heterogeneity in ET both within a vineyard and over the surrounding landscape. Findings will assist in the development of strategies for integrating ET mapping

into the operational irrigation management framework, providing actionable information regarding vineyard water use and stress at the field and regional scale and at daily to multi-annual timescales.

- There were 14 manuscripts published as part of the GRAPEX Special Issue in *Irrigation Science*. (Irrigation Science (2019) 37:221–226 https://doi.org/10.1007/s00271-019-00633-7). Research results span from vine canopy to landscape scales covering vine biophysical processes, vine and interrow turbulent and energy balance exchange, application of remote sensing from UAV and satellite for surface energy balance, and ET modeling and stress detection from vine canopy to the regional scale.
- A peer-reviewed paper in *Remote Sensing* was published in September 2019 on the application of the ET toolkit over the Ripperdan 720 variable rate drip irrigation (VRDI) system, which enables differential water applications at the 30x30 m scale. Results indicate derived weekly total ET from the thermal-based data fusion approach (i.e., the ET toolkit) match well with observations. The thermal-based method was also able to capture the spatial heterogeneity in ET over the vineyard due to water stress events imposed on two of the four vineyard blocks. These transient stress events were not reflected in the vegetation index-based crop coefficient method for estimating ET, highlighting the value of thermal band imaging in monitoring actual crop water use.
- During the 2019 growing season, a pilot irrigation experiment was conducted at the Barrelli Ranch in Sonoma county over multiple high-value vineyards comparing the water use and irrigation management strategy currently run and operated by E&J Gallo with water use estimates from the ET toolkit integrated into the existing irrigation scheduling dashboard. Preliminary results indicate the ET toolkit performance in assessing vine water use and scheduling weekly irrigation rates matched closely with that of the experienced viticulturalist and irrigation manager at the Barrelli Ranch. This result suggests that the ET toolkit can provide operational capabilities for irrigation scheduling requiring minimal “hands-on” vineyard monitoring with an experienced water manager and viticulturalist.

**Selected Publications:**

Kustas, W.P., Agam, N., Ortega-Farias, S. (2019) Forward to the GRAPEX special issue Irrigation Science. https://doi.org/10.1007/s00271-019-00633-7.

Knipper, K., Kustas, W.P., Anderson, M.C., Alsina, M., Hain, C., Alfieri, J.G., Prueger, J.H., Gao, F., McKee, L.G., Sanchez, L. 2019. Using high-spatiotemporal thermal satellite ET retrievals for near-real time water use and stress monitoring in a California vineyard. Remote Sens. 11:2124. http://doi:10.3390/rs11182124.

Aboutalebi, M., Torres, A., McKee, M., Kustas, W.P., Nieto, H., Alsina, M., White, A., Prueger, J.H., McKee, L.G., Alfieri, J.G., Hipps, L.E., Coopmans, C., Dokoozlian, N. 2019.

Incorporation of unmanned aerial vehicle (UAV) point cloud product into remote sensing evapotranspiration models Remote Sensing. https://doi.org/10.3390/rs12010050.

**Relevant project websites / links:** https://ars.usda.gov/grapex

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**Project Title:** Evaluation of Risk and Capacity Development for Two Indian River Basins

**Principal investigator:** Venkat Lakshmi, University of Virginia

**Project year:** 2

**Year-end ARL:** 5

**End users/partners:** Karnataka Department of Water Resources

**Project description:** Ganga river basin (GRB) in the Indian subcontinent is one of the most heavily irrigated lands in the world. According to 2005 report by Central Water Commission (CWC), 57% of the net irrigated land in India lies inside GRB. Furthermore, GRB is also one of the most populous river basins in the world, supporting almost 400 million people of India. With increasing use of fertilizers in agriculture and untreated sewage waste from the booming industries, there is need to assess the water quality and the contamination in surface water. We use the Soil Water Assessment Tool (SWAT) to model the hydrology of the river basin. For water quality analysis, SWAT is able to simulate the impact on hydrology, sediment, and nutrients load due to physical changes brought in the large ungauged river basins. We hypothesize that numerous small, rain-fed rivers in the Indo-Gangetic floodplain that are flowing predominantly through agricultural land are important non-point source of Nitrogen(N) and Phosphorus (P) and will control the nutrient budget of large river system. The SWAT model is used to simulate flow and nutrient/sediment concentrations of nitrogen/nitrates, phosphorus, and sediment in the upper reach at Uttarkashi and Rishikesh; in the middle reach at Kanpur, Lucknow, and Varanasi; and Farakka at the lower reach. The SWAT model is calibrated at a daily/monthly time step for flow and monthly scale for water quality parameters. We analyze the water quality in the basin using a widely used Water Quality Index (WQI) considering pH, TDS, BOD, COD, hardness, nitrates, carbonates, and silicates. We also use gridded climate data from Indian Meteorological Department (IMD) and water quality data from CWC, SRTM 90 m DEM, a 300 m Land use/land cover map from Climate Change Initiative (CCI), and a 7 km soil map from Food and Agriculture Organization (FAO).

Our study used the water quality from CWC, which has many missing data values. Therefore, we decided to use SWAT to calibrate the model based on the data that we had. Further efforts include the use of our calibrated model to calculate Water Quality Index under the climate change scenario.

**Data sources, model, technologies:** TRMM, GPM, rain gauge data, streamflow data, SWAT

**Major Accomplishments in CY 2019:**

- Preliminary results suggest that the upper reach of the Ganga River basin does not show degradation in the water quality over the analysis period because the portion of the Ganga River from the origin to Rishikesh does not have much influence on human activities, as it is located in the midst of the densely forested mountains.
- Middle reach locations – Kanpur and Varanasi show significant degradation of the water quality with Varanasi showing the most adverse conditions. Between Rishikesh and the middle reach (Kanpur and Varanasi), the Ganga river basin passes through very densely populated cities of Uttar Pradesh. The anthropogenic activities along the river near these cities have led to this degradation of water quality.
- Farakka, on the other hand, being the most downstream location does not show as adverse degradation as Varanasi. The river reach going downstream from Varanasi confluences with Kosi river flowing from Nepal, which brings in more fresh and clean water. Therefore, although the Farakka location has significant water quality degradation, it is not as extreme as the degradation at Varanasi.

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**Project Title**: Maximizing Utility of Remote Sensing for Water Quality Monitoring and Resource Management in California's Water Systems

**Principal investigator:** Christine Lee, NASA Jet Propulsion Lab

**Project year:** 2

**Year-end ARL:** 4

**Project description:** This project was initiated in 2017 as part of the A.37 Water Resources solicitation. The objective of this project is to operationalize implementation of water quality algorithms to support water quality monitoring and management in California. This project focused on three products: turbidity (a bulk indicator of water column scattering and absorption), chlorophyll-a (phytoplankton pigment), and temperature. These variables are all important to management of water quality and resources in California's water systems; turbidity and temperature are integral to water quality compliance measures, motivated by the need to minimize detrimental impacts on endangered species such as the Delta smelt. Chlorophyll can be used to complement tracking of algal blooms (harmful or beneficial).

**End users:** This project includes agency/stakeholder partners from California Department of Water Resources, Metropolitan Water District, and the U.S. Geological Survey. We have also been engaging the California Department of Fish and Wildlife as part of this project.

**Data sources, models, technology:** Landsat, Sentinel 2A/B, ECOSTRESS for remote sensing; California Data Exchange and USGS data for in situ

**Major Accomplishments in CY2019:**

- Validation and application of turbidity products in a decision use case, related to management of water flow operations to improve habitat quality. Satellite-derived turbidity (FNU estimates) and in situ fixed water quality stations' turbidity values are well-correlated with NTU stations and FNU stations, with R2=0.55(NTU/N=549) and 0.71(FNU/N=443).
- Validation and application of temperature products to track thermal habitat suitability for endangered Delta smelt. Validation of Landsat-series water surface temperature utilized 20 years of radiometer data from Tahoe and the Salton Sea (R2=0.96). Application utilized thermal tolerances of Delta smelt, along with two non-native fish, to evaluate a 35-year record of changes in thermal habitat. These datasets map to evaluation of water temperature impacts (and habitat quality) relative to changes in water flow operations.
- Transition and operationalization of data processing to 34N-run servers have been initiated

**Relevant project websites/links:** https://nasa.baydeltalive.com

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**Project Title**: Monitoring Surface Water Storage Changes over the Lower Mekong with Multiple Satellite Techniques

**Principal Investigator:** Hyongki Lee, University of Houston

**Project Year:** 2

**Year-end ARL:** 5

**Description:** The goal of this project is to provide comprehensive understanding of surface water storage changes using a suite of satellite data and model and aid decision-making tools in lower Mekong countries. Specific applications include monitoring and forecasting of river discharges, inundation extents, and water level changes.

**End Users:** National Center for Water Resources Planning and Investigation (NAWAPI) of Vietnam, National Hydro-Meteorological Service (NHMS) of Vietnam, Ministry of Water Resources and Meteorology (MOWRAM) of Cambodia

**Data sources, models, technology:** SAR (Sentinel-1, ALOS-1/2) and InSAR, Altimetry (Jason-2/3, Sentinel-3), a hydrological catchment model (HYPE)

**Major accomplishments in CY 2019:**

- The project team delivered lectures on hindcast and forecast of daily inundation extents at the Asian Disaster Preparedness Center (ADPC) and visited NHMS of Vietnam for potential implementation of discharge forecasting using the Ensemble Learning Regression method (Kim et al., 2019) during June 3 – 4, 2019.
- The study about hindcast and forecast of daily cloud-free inundation extents over the Tonle Sap Lake using Sentinel-1 and Jason altimetry data through Empirical Orthogonal Function (EOF) analysis has been accepted in Remote Sensing of Environment (Chang et al., 2020). Animation of daily inundation for 2011 can be viewed from https://youtu.be/9m3YTRvrPyY.
- The study about daily discharge estimation using multi-mission altimetry data and Ensemble Learning Regression over the Mekong River has been published in Remote Sensing (Kim et al., 2019). It shows that the new method can provide more accurate discharge estimates downstream of Tonle Sap Lake where complex hydraulic conditions exists.
- A manuscript about streamflow predictions from the HYPE (Hydrological Predictions for the Environment) model set up over the Great Mekong region (Mekong Basin and all the basins in Vietnam) using satellite observations and a regionalization approach is currently under review for the Journal of Hydrology (Du et al., 2020).

**Plans or expectations for 2020:**

- The project team will collaborate with the other GEOGLOW PI Nelson to implement the forecasting system of inundation extents in the Tethys environment. In parallel, the project team will also collaborate with other SERVIR-Mekong scientists to implement the forecasting system under the Hydra-Floods system (https://github.com/Servir-Mekong/hydra-floods), leveraged from PI Lee's SERVIR project.
- The project team will also implement the forecasting system of river discharges using the Ensemble Learning Regression over the Mekong River. The project team will collaborate with NAWAPI and NHMS of Vietnam toward operationalizing the product. The pilot web portal developed by NAWAPI (http://waterportal.vaci.org.vn/) will be augmented to provide the service.
- Based on the identified needs from NAWAPI of Vietnam (Dr. Duong Du Bui), the project team will investigate the impact of land use change and sediment delivery to the reservoir using the HYPE model and satellite observations. The project team aims at delivering the complete HYPE model to the agency by end of this year.
- In-depth capacity building for NAWAPI, NHMS of Vietnam, and MOWRAM of Cambodia in June 2020 to implement the applications developed above. PI will collaborate with SERVIR-Mekong to support the training.

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**Project Title**: Integrating NASA Earth Systems Data into Decision-Making Tools of Member Utilities of the Florida Water and Climate Alliance

**Principal investigator**: Christopher Martinez, University of Florida

**Project year**: 1

**Year-end ARL**: 3

**Project description**: This project seeks to improve water allocation and storage decisions by public water utilities through the development of a real-time monitoring product and integration of high (10-km) resolution regional seasonal forecasts centered over Florida. The real-time monitoring product will use NASA Earth science products to anticipate the likelihood of early or late onsite/demise of seasons in peninsular Florida (which has very distinct wet and dry seasons). Customized dynamical seasonal climate forecasts will be provided that incorporate multiple NASA satellite- and model-based products. An extensive set of retrospective forecasts (reforecasts) from 2000-present for the winter (dry) season will be produced as part of this project. Reforecasts will serve in developing a robust bias correction of the forecasts, which has been previously demonstrated by the investigators to be critical for effective use of forecasts in hydrologic applications.

**End users/Partners**: Florida Water and Climate Alliance (FloridaWCA) including Tampa Bay Water and the Peace River Manasota Regional Water Supply Authority

**Data sources, models, technology**: SMAP, SMOS, TRMM, MODIS, GHRSST, NMME, MERRA 5 2.0, CFSR, ASDC

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**Project Title**: Operational production of long-term enhanced soil moisture information for USDA-FAS using hydrologic modeling and remote sensing

**Principal investigator**: Iliana E. Mladenova, NASA Goddard Space Flight Center
**Project year**: 1

**Year-end ARL**: 3

**Project description**: The project aims at improving the accuracy and resolution of the U.S. Department of Agriculture-Foreign Agricultural Service (USDA-FAS) root-zone soil moisture (RZSM) information by utilizing alternative NASA resources, including hydrologic models, forcing data, and satellite-based soil moisture data sets. The main objective of the project is to enhance the spatial resolution of the USDA-FAS RZSM information by utilizing the enhanced Soil Moisture Active Passive (SMAP) soil moisture product and the 10 km U.S. Air Force (USAF) precipitation

and temperature data or the GPM IMERGE product. This enhancement is expected to greatly improve the accuracy of the USDA-FAS crop stress alarm models. The project will also assess the possibility of further enhancing the USDA-FAS RZSM information by evaluating the skill of alternative physically-based hydrologic models (i.e., NASA Land Information System [LIS] Noah-Multi-Physics [Noah-MP] Land Surface Model).

**End users/Partners**: U.S. Department of Agriculture-Foreign Agricultural Service.

**Data sources, models, technology**: SMAP, SMOS, USAF, GPM IMERGE, Palmer Model, NASA LIS Noah-MP.

**Major accomplishments in CY 2019**:

- The newly developed USAF 10 km forcing data was released officially in November 2019. A preliminary meeting was held at NASA with the NASA LIS team that developed the product for USAF. The meeting allowed the team to become familiar with the new 10-km product and provided them with information about formatting, latency, distribution options, etc. The team gained access to the data and began preliminary evaluation of its quality. Several routines have been developed to process the 10-km data, extract the necessary fields needed to run the model, and ingest the data into the USDA-FAS Palmer model.
- Several discussion have been held with USDA-FAS in regard to outlining potential new ancillary datasets (i.e., soil properties, land cover, elevation, etc.) that meet the enhanced model grid spacing. These datasets have to be identified prior to running the model. USDA-FAS and NASA have to carefully coordinate these activities, as both agencies should use the same ancillary data to run the open loop (i.e., the model run alone without assimilation). Suggested datasets include the 10-km Available Water Content (AWC) data layer from Harvest Choice and the land cover datasets from the GAEZ v3.0 project.
- The model has been successfully modified to ingest the 10-km USAF forcing data. Currently, runs are conducted using the existing ancillary soil properties and elevation datasets. The team is conducting preliminary evaluation analysis to assess the quality of the enhanced 10-km Palmer soil product (open loop) and compare its performance relative to the existing 25-km soil moisture product.
- Major challenges related to the generation of the 10-km enhanced model output are: (1) available storage space for storing the complete archives of the fine resolution SMAP 9-km data and the 10-km USAF forcing data, and (2) generating parallel processing routines that will allow the model runs to speed up.

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**Project Title**: Analysis of Agricultural Water Supply-Demand Imbalance During the Unprecedented California Drought Using NASA Satellite Data

**Principal investigator:** Noah Molotch, University of Colorado, Boulder

**Project year:** 3

**Year-end ARL:** 6

**Project description:** The overarching goal of the project is to characterize anomalies in water supply and demand using a combination of NASA satellite observations and NASA physically-based land surface models. The annual water supply-demand imbalance is ingested into existing California Department of Water Resources (CDWR) operations and the jointly-produced information is distributed to multiple stakeholders across California. Additional project objectives include migration of remotely sensed SWE and ET analyses into the CDWR computational environment; and to conduct quantitative and qualitative assessment of the utility of the SIMS ET and MODIS-based snowpack information to inform water resource decisions during drought.

**End users/partners:** 87+ stakeholders including the California Department of Water Resources, NASA-JPL, U.S. Fish and Wildlife Service, San Francisco Public Utilities Commission, Pacific Gas and Electric, Kings River Water Association, Kings River Irrigation District, City of Bakersfield, Sacramento Municipal Utility District, Turlock Irrigation District, U.S. Bureau of Reclamation, Merced Irrigation District, Kaweah Delta Water Conservation District, J.G. Boswell Company, Modesto Irrigation District, Tulare Irrigation District, James Irrigation District, Friant Water Authority, Nevada Irrigation District, El Dorado Irrigation District, Southern California Edison, Los Angeles Department of Water and Power, Inyo County Water Department, The Watershed Center, U.S. Department of Agriculture, Natural Resources Conservation Service, National Oceanic and Atmospheric Administration, National Park Service, Truckee River Reservoir System Federal Water Master, University of California at Merced, and the Desert Research Institute.

**Data sources, models, technology:** The project is using MODIS-based snow water equivalent (SWE) estimates from a variety of models and Landsat- and MODIS-based ET estimates from the NASA Satellite Irrigation Management Support project (SIMS) and from the Numerical Terradynamic Simulation Group (NTSG) from 2000 through present. Land surface height anomalies as measured by Global Positioning System (GPS) sensors are also being analyzed.

**Major accomplishments in CY 2019:**

- Based on direction from our stakeholders we have streamlined our data analysis and distribution. We have improved our real-time SWE model for reporting season 2020.
- The California DWR has funded us to continue to produce our Sierra Nevada real time SWE product for the upcoming snow season. We have issued real-time SWE reports in the Southern Rockies since 2018 with funding from the Western Water Assessment (WWA). We have also produced data and analyses for the Wyoming State Engineers Office inside our third model domain in the Northern Rockies, which includes the headwaters of the Missouri River.

- We are leading an analysis of changes in land surface height (mm level) as influenced by seasonal and inter-annual precipitation anomalies. Land surface height anomalies are measured by Global Positioning System (GPS) sensors.
- We are continuing to fine-tune both the supply side (SWE) and demand side (ET) using models and NASA datasets, and co-developing project data sets and California DWR water supply-demand forecasts to be temporally and spatially consistent. Analysis of MODIS-based ET and vegetation productivity data is ongoing and shows interesting elevational patterns related to the recent drought.
- We are publishing a number of papers in peer-reviewed journals. We have a paper in review in which we are co-developing a reanalysis of the February, 2017 Atmospheric River event based on DWR guidance and in conjunction with the University of California at San Diego, Scripps Institution of Oceanography, Center for Western Weather and Extremes; and another paper where we examined how basin-wide snowpack volume and its seasonal maximum varies historically across western North America and how those metrics may respond to end-of-century warming.

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**Project Title**: Assessing the Need for Fire-related Decision-support Tools for Water Management in the Pacific Northwest, USA

**Principal Investigator:** Julie Padowski, Washington State University

**Project Year:** 1

**Year-end ARL:** N/A

**Project Description:** Fire disturbances in the Pacific Northwest (PNW) are projected to increase under a changing climate and are a major cause of increased erosion, runoff, suspended sediment, nutrient release, and debris flows in forested watersheds. Fire-related threats to water quality and quantity are of particular concern to drinking water providers in this region, who rely on forested watersheds to provide clean drinking water to millions of people. This project is a needs assessment that uses focus groups and surveys to collect information from drinking water providers and other water managers throughout the PNW to better understand what remotely sensed data and decision support tools would be needed to help managers make more timely and effective decisions about minimizing wildfire-related impacts to water resources. Results from this assessment will help poise our team to work with the latter-stage NSF-funded FireEarth modeling framework to integrate relevant, rapidly updatable NASA Earth observation data into decision-support tools to help water utility managers plan for and deal with wildfire risks and impacts.

**End Users / Partners:** Drinking water providers (e.g., Seattle Public Utilities, Portland Water Bureau) and watershed managers.

**Data Sources, Models, Technology:** Needs assessment results indicate that NASA products including Landsat, MODIS, SMAP, and AVIRIS could greatly aid water managers by integrating existing, relatively static geographic characteristics (e.g., slope, soil type) readily available to water managers with updateable remotely-sensed data that can provide new information on environmental conditions at temporal and spatial resolutions needed to make current decisions. NASA data will be a critical part of this decision-support tool, helping managers monitor and use vegetative stress, soil moisture, temperature, and fuel conditions to predict current areas of fire risk and explore the effectiveness of potential responses through modeled scenarios.

**Major accomplishments in CY 2019:** The team met with nine different water utility representatives to discuss: 1) current concerns and issues related to fire; 2) plans, strategies or actions that are currently being implemented, or are underway, for dealing with wildfire; and 3) what information or tools would be most helpful for managing wildfire in source watersheds. Participants showed a particular interest in data and decision-support tools that could help them understand where fires will burn, where pre-fire mitigation strategies (e.g., fuel treatments, forest thinning) could help prevent fires from occurring, and what severity of post-fire water quality issues they should anticipate. They emphasized that a decision support tool that could help them communicate risk to other watershed land owners (and to politicians and the public) would be extremely helpful.

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**Project Title**: Predicting Middle Eastern and African Season Water Deficits using NASA Data and Models

**Principal investigator:** Christa D. Peters-Lidard, NASA Goddard Space Flight Center

**Project year:** Completed

**Year-end ARL:** 9

**Project description:** The main objective of the project was to develop the NASA Hydrological Forecast and Analysis System (NHyFAS) to support our end-user partners, including the U.S. Agency for International Development (USAID) and U.S. Army Corps of Engineers (USACE) in the Middle East and Africa. The system is based on and uses existing and mature NASA and NOAA Earth-science capabilities. The primary goal of delivering seasonal drought forecasts to the Famine Early Warning Systems Network (FEWS NET) has been achieved.

**End users/partners:** USAID, USACE, and International Center for Biosaline Agriculture (ICBA)

**Data sources, models, technology:** NASA's GEOS and NOAA's CFS seasonal forecasts, LIS, Catchment Land Surface Model (CLSM), Noah-MP land surface model, ASCAT, SMAP, GRACE, MERRA2, CHIRPS

**Major accomplishments in CY 2019:**

- Routine seasonal forecasts, including both GEOS and ensemble streamflow prediction (ESP) forecast methods, were set up to generate close to near-real-time hydrological seasonal forecasts for USAID's FEWS NET community. The routine NHyFAS forecasts continue to generate live forecast products of agricultural drought indicators, such as soil moisture percentiles, which are provided via a public website for the FEWS NET end-users: https://lis.gsfc.nasa.gov/projects/nhyfas
- FEWS NET regional scientists in Africa have continued to use the routine products since August of 2018 in their regional forecast assessments and monthly feedback to USAID food security analysts. Project team members continue to receive feedback from the regional scientists to enhance existing products and provide additional forecast products to support their decision-making processes.
- A custom instance of NHyFAS is now supported by USAID and routinely run by the NASA-based FEWS NET team that maintains the system's hydrological seasonal forecasts for the Africa continent. The NASA FEWS NET team has also been expanding on the system to include additional North American Multi-Model Ensemble (NMME) model member forecasts.
- Also, the overall system or its components have been incorporated to support other efforts, such as SERVIR's West Africa LDAS and Hindu Kush-Himalaya Subseasonal to Seasonal Forecast system.

**Plans/expectations for 2020**

- Expand NHyFAS to support the NMME suite of ensemble model members to drive the multi-hydrological model ensemble seasonal forecasts.
- The NHyFAS forecast products are being more heavily used by the FEWS NET regional scientists who provide feedback to the USAID food security analysts on a monthly basis.

**Publications**

Arsenault, K., Shukla, S., Hazra, A., Getirana, A., McNally, A., Kumar, S., Koster, R., Zaitchik, B., Badr, H., Jung, H. C., Narapusetty, B., Navari, M., Wang, S., Mocko, S., Funk, C., Harrison, L., Husak, G., Verdin, J. V., and Peters-Lidard, C. C., 2020: A NASA modeling and remote-sensing based hydrological forecast system for food and water security applications. *Bull. Amer. Meteor. Soc.,* Accepted.

Shukla, S., Arsenault, K. R., Hazra, A., Peters-Lidard, C., Koster, R. D., Davenport, F., Magadzire, T., Funk, C., Kumar, S., McNally, A., Getirana, A., Husak, G., Zaitchik, B., Verdin, J., Nsadisa, F. D., and Becker-Reshef, I., 2019: Improving early warning of drought-driven food insecurity in Southern Africa using operational hydrological monitoring and forecasting

products, *Nat. Hazards Earth Syst. Sci. Discuss.*, https://doi.org/10.5194/nhess-2019-267, in review.

Getirana, A., H.C. Jung, K.R. Arsenault, S. Shukla, S.V. Kumar, C.D. Peters-Lidard, I. Maigari, and B. Mamane, 2020: Satellite gravimetry improves seasonal streamflow forecast initialization in Africa. *Water Resour. Res.,* Accepted, doi:10.1029/2019WR026259

**Relevant project websites/links:**
https://lis.gsfc.nasa.gov/projects/nhyfas
https://lis.gsfc.nasa.gov/blog/fame-project-research-applications-ongoing-success-story

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**Project Title**: Advancing Water Supply Forecasts in the Colorado River Basin for Improved Decision Making

**Principal investigator:** Jonathan Quebemann, RTI International

**Project year:** 4

**Year-end ARL:** 6

**Project description:** This project is a collaboration among RTI International, the Colorado Basin River Forecast Center (CBRFC), Colorado State University (CSU), and Utah State University (USU) to couple advanced data assimilation techniques with distributed hydrologic modeling to provide improved water supply forecasts for the Colorado River basin. In addition, the project team is working with Denver Water and the Dolores Water Conservancy District to demonstrate how the probabilistic ensemble forecast information can be used to improve water management decision making.

**End users/Partners:** Colorado Basin River Forecasting Center (CBRFC), Denver Water, Dolores Water Conservancy District

**Data sources, models, technology:** NASA MODIS MODSCAG, MODDRFS, GPM, IMERG, NLDAS, Utah Energy Balance Snow Model, NWS Research Distributed Hydrologic Model, Community Hydrologic Prediction System, NASA Earth Exchange

**Major accomplishments in CY 2019:**

- The forecast system has been deployed and tested within the Colorado Basin River Forecast Center (CBRFC); all data and systems have been conveyed to CBRFC; continued support is being provided by RTI to assist CBRFC in their testing of the forecast system.

- The use of RTI-ROSE to process the forecast ensembles in support of reservoir operational decision-making has been demonstrated within Denver Water with a positive response

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**Project Title**: California's Groundwater Future: Relating Subsidence and Consumption in the Central Valley

**Principal Investigator:** John T. Reager, NASA Jet Propulsion Lab

**Project year:** 1

**Year-end ARL:** 4

**Project description:** The aim of this project is to develop a groundwater numerical model using groundwater depletion from GRACE, land subsidence from InSAR, and in situ hydrologic data from U.S. Geological Survey (USGS) and California Department Water Resources (CA-DWR). The model, calibrated to GRACE groundwater anomalies and InSAR-measured patterns of surface deformation, will be able to better simulate the spatial and temporal dynamics of land subsidence induced from groundwater depletion within the Central Valley of California. The project is being conducted in close partnership with USGS and CA-DWR and the final calibrated model will be able to assist CA-DWR in sustainable groundwater management across the Central Valley in compliance with California's Sustainable Groundwater Management Act (2014).

**End user/Partners:** U.S. Geological Survey (USGS), California Department of Water Resources (CA-DWR)

**Data sources, models, technology:** NASA GRACE and GRACE-FO, European Space Agency Sentinel 1 Interferometric Synthetic-Aperture Radar (InSAR), USGS Central Valley Hydrologic Model (CVHM) 1 and 2.

**Major accomplishments in CY 2019:**

- InSAR data up to 2015 have been processed for use in the calibration of the groundwater model CVHM-2. We are working with Co-Is to further extend model-ready InSAR data to 2019 and decide on the optimal format and time period for model calibration.
- CVHM-2 has been extended from its previous version, CVHM-1, to include more recent hydrologic data (2003-2015). Calibration of the model to hydrologic (well and streamflow variables) and geologic parameters (subsidence) has been underway with USGS, starting with regions of high subsidence rates. Model outputs have been adjusted to better showcase subsidence patterns within the aquifer layers over time. Various

model simulations in the Central Valley have been initiated using base case parameters from USGS.

- GRACE-measured groundwater anomalies and volume change will be temporally correlated to InSAR-measured subsidence rates and inferred aquifer volume change, respectively, to distinguish elastic vs. inelastic subsidence across the Central Valley.
- Recent presentations on the project include:
    - Reager, J, California's groundwater future: Relating subsidence and consumption in the Central Valley, NASA ASP WR Meeting, July 17, 2019, JPL.
    - Reager, J.; K. Kim; T. Farr; C. Faunt, California's groundwater future: Relating subsidence and consumption in the Central Valley for SGMA, poster, Oct. 21-24, 2019, Valencia, Spain.

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**Project Title**: Optimizing the Indus Basin Irrigation System and Reservoir Operations Using Remotely Sensed Snow Surface Properties in the ParBal Model

**Principal investigator:** Karl Rittger, Institute of Arctic and Alpine Research, University of Boulder, Colorado

**Project year:** 2

**Year-end ARL:** 4

**Project description:** This project uses sophisticated research algorithms to create essential water variables (EWVs) for snow and glacier ice. The EWVs are analyzed as indicators to long-term trends in the Indus River basin. In addition, we use the Parallel Energy Balance model (ParBal) along with satellite-based EWVs to estimate maximum seasonal SWE and hourly snow and ice melt in mountainous terrain without the use of in situ observations. We combine historical ParBal estimates of SWE with a new high-resolution passive-microwave data set and physiographic variables using an innovative neural network to create near-real-time estimates of snow and ice melt. These melt estimates serve as input into the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) Model. The estimates in turn will provide reservoir inflow hydrographs to the HEC-ResSim Model reservoir simulation, which is specifically designed to duplicate and improve the existing water management system comprising the Tarbela and Mangla Reservoirs. We build on a current government-to-government effort between the United States Agency for International Development (USAID), USACE, and the Government of Pakistan (GoP) to provide actionable information for water resource planning.

**End users/partners:** U.S. Army Corps of Engineers, State Department-Embassy Islamabad, Pakistan Meteorological Department, Indus River System Authority, Pakistan Water Power Development Authority, Pakistan Ministry of Climate Change

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**Project Title:** Integrating GRACE and GRACE Follow-On Data into Flood and Drought Forecasts for the Continental U.S.

**Principal Investigator:** Matthew Rodell, NASA Goddard Space Flight Center

**Project Year:** 4+

**Year End ARL:** 8

**Project Description:** This project developed, refined, and is now routinely generating 1-3 month soil moisture and groundwater wetness/drought forecast maps for the contiguous U.S. Our unique approach integrates data from GRACE, GRACE-FO, and other observations within a land surface model that is subsequently forced into the future by downscaled seasonal climate predictions. The products are now being widely disseminated by the National Drought Mitigation Center through their public facing website. The value of our wetness/drought products for streamflow prediction was demonstrated by our partners at NOAA's North Central River Forecast Center, who continue to work on ways to integrate the products into their operations.

**End Users / Partners:** National Drought Mitigation Center; NOAA North Central River Forecast Center

**Data sources, model, technologies:** GRACE, GRACE-FO, NASA's Land Information System driving the Catchment Land Surface Model, GEOS-5

**Major Accomplishments in 2019:**

- UT began to deliver terrestrial water storage anomaly data from GRACE-FO.
- GSFC began to assimilate GRACE-FO data into the model and thus incorporate them into the forecast wetness/drought products.
- JHU finished refining the GEOS-5 forecast downscaling routine.
- GSFC began to generate and deliver 1-, 2-, and 3-month drought wetness forecasts to NDMC on a monthly basis.
- UNL developed a map template and new NDMC webpage for distributing the drought forecast products.
- NOAA/NCRFC used historical GRACE DA groundwater and SWE, in addition to soil moisture, in experimental retrospective forecasts and demonstrated value added.
- RFF continued to assess Value of Information resulting from our project.
- Getirana, A., M. Rodell, S. Kumar, H.K. Beaudoing, K. Arsenault, B. Zaitchik, H. Save, and S. Bettadpur (2020): GRACE improves seasonal groundwater forecast initialization over the U.S., *J. Hydrometeor.*, 21 (1), 59-71, doi:10.1175/JHM-D-19-0096.1.

**Relevant project websites / links**
https://drought.unl.edu/droughtmonitoring/Tools.aspx

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**Project Title**: Cyanobacteria Assessment Network

**Principal investigator:** Blake Schaeffer, Environmental Protection Agency

**Project year:** 4

**Year-end ARL:** N/A

**Project description:** The Cyanobacteria Assessment Network (CyAN) is a multi-agency project (involving the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, U.S. Environmental Protection Agency, and U.S. Geological Survey) to develop an early warning indicator system for algal bloom detection in U.S. freshwater systems. This research will utilize historical and current satellite data and supports federal, state, and local partners in their monitoring efforts to assess water quality to protect aquatic and human health.

**End users/partners:** USEPA Regional Offices (10 in total), U.S. Army Corps of Engineers, Environment Canada, state water/environmental management agencies, EPA Office of Water, state EPA agencies

**Data sources, models, technology:** Landsat, Sentinel-2 and Sentinel-3

**Major accomplishments in CY 2019**:

- Changes in water quality can be challenging to detect, even in communities where routine monitoring occurs. Observing changes across multiple places and during various times can be difficult, resulting in missed events such as the sudden development of cyanobacterial harmful algal blooms that may pose environmental, animal, and human health issues. The Cyanobacteria Assessment Network (CyAN) is a multi-agency project (involving the EPA, NASA, NOAA, and the USGS) to develop an early warning indicator system using historical and current satellite data to detect algal blooms in U.S. freshwater systems. It puts the power of satellite technology in the hands of communities so they can detect changes in cyanobacterial harmful algal blooms. The research supports federal, state, and local partners in their monitoring efforts to assess water quality to protect aquatic and human health.
- CyAN made daily, weekly, and true-color satellite data from the European Commission's Copernicus Program Sentinel-3A Ocean and Land Color Instrument (OLCI) accessible to

32 state departments of health or environment with webinar trainings and technical assistance as requested in 2019.

- Methods for quantifying the cyanoHAB annual magnitude, temporal frequency, spatial extent, and lake occurrence have been developed and published. In 2019, CyAN made the satellite imagery available to the public through a mobile application with 1000+ downloads and a four-star rating in less than six months on Google Play. As a result, data from this project is connected to the Oregon Cyanotoxin Drinking Water Rule, as well as Utah, Idaho, Colorado, and Wyoming health advisories.
- Information provided by CyAN allows communities to make decisions that may reduce the societal costs linked to decreased water quality such as illness, missed days of work, or possible drinking water contamination.

**Plans for 2020:** The project will complete national validation of the ability to derive chlorophyll relevant to trophic status reporting, satellite cyanoHAB detection against state issued health advisories and reported toxin concentrations, and the mobile application will be mirrored on a web-based platform to reach more end-users.

**Relevant project websites/links:**
https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan

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**Project Title**: Analysis of Agricultural Water Supply-Demand Imbalance During the Unprecedented California Drought Using NASA Satellite Data

**Principal investigator:** Noah Molotch, University of Colorado, Boulder

**Project year:** 3

**Year-end ARL:** 6

**Description:** It is critical to accurately model the timing and magnitude of snow melt in the Colorado River Basin, where melt of the seasonal mountain snowpack dominates regional hydrology, populations are increasing, and snow melt patterns are shifting. This project addresses the limitations of temperature index modeling in the Colorado River Basin by developing the capacity at the Colorado River Basin Forecast Center (CBRFC) to run a spatially distributed snow energy balance model to support operational decision making. The ability to run any physically based model over snow-dominated headwaters is currently limited by the lack of energy balance information from in situ observation networks. We are addressing the data limitation by assimilating remote sensing imagery to inform net radiation and an atmospheric model to inform meteorological variables. The project, a joint effort between the CBRFC, USDA ARS Northwest Watershed Research Center, and University of Utah Snow

Hydrology Group, will produce realistic maps of snow-covered area, snow water equivalent, and streamflow.

**End-users/Partners:** Colorado River Basin Forecast Center, USDA-ARS Northwest Watershed Research Center

**Data Sources/Models:** MODIS/VIIRS, GOES, Airborne Snow Observatory, High Resolution Rapid Refresh (HRRR) model, Automated Water Supply Model (AWSM)/Spatial Modeling for Resources Framework (SMRF)

**Major Accomplishments in CY19:**

- The AWSM model, which has the snow energy balance model iSnobal at its core, was set up and tested in Senator Beck Basin, Colorado, which has 15 years of in situ snow energy/mass balance data for model forcing and validation. The model outputs match observations of snow melt magnitude and timing only when snow albedo is updated/assimilated. The standard time since snowfall (age based) albedo curve misses the snow depletion date by up to three weeks and has lower peak runoff, showing the value of accounting for snow albedo and net radiation.
- Automated HRRR downloads were set up, and for a shorter subset of the record (Wyoming 2017/2018), the model was tested with HRRR meteorology. HRRR generally captures atmospheric patterns over the SBB domain and outputs compare well to observations and baseline runs.
- Following successful testing of the model in SBB, we have set up and are running the model over a larger watershed, the Upper Gunnison, in the UCRB; outputs will be compared to CBRFC forecast points.
- PI Skiles presented invited talk at the 2019 AGU annual meeting (San Francisco, CA): *Advancing remote sensing methods to constrain physical understanding of accelerated mountain snowmelt*.
- Two graduate students were hired onto the project; in total the project will fund three students (1 PhD, 2 masters). Science team meetings (PI Skiles, NWRC Team) were held in Boise, Idaho and again in San Francisco at the AGU. A full team meeting was held in Salt Lake City at the CBRFC office.

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**Project Title**: Developing a Dynamic SPARROW Water Quality Decision Support System Using NASA Remotely-Sensed Products

**Principal investigator:** Richard Smith, USGS

**Project year:** 3

**Year-end ARL:** 4

**Project description:** The goal of this project is to develop a dynamic decision support system for coastal managers in the Southeastern United States through use of remotely sensed data and other NASA Land Information System (LIS) products within the US Geological Survey SPARROW water quality model. SPARROW is widely used throughout the United States for long term, steady state water quality analysis. However, users increasingly have been asking for a dynamic version of the model that can provide seasonal estimates of nutrients and suspended sediment to receiving waters. Time varying SPARROW outputs would aid water managers in decision making regarding allocation of resources in protecting aquatic habitats, planning for harmful algal blooms, and restoration of degraded habitats, stream segments, or lakes. The spatial and temporal scale of satellite remote sensing products and LIS modeling data make these sources ideal for the purposes of development and operation of the dynamic SPARROW model. Project Activities:

1. Acquire remotely-sensed Earth observation products potentially associated with nutrient and sediment sources and transport to coastal waters in the study area.
2. Aggregate the remotely-sensed data products into catchment (i.e. sub-watershed) values.
3. Test the data products produced in Activity 2 in the existing S.E. regional steady-state SPARROW model to ascertain their significance in relation to the water quality observations in the study area streams.
4. Compile seasonal values of the remotely-sensed indices that are found to be significant in Activity 3 for the period 2001 - 2015.
5. Using those data, in-stream water quality observations, and other ancillary data, develop dynamic (seasonal) SPARROW models for the study areas at their respective spatial scales.
6. Modify the existing Decision Support System (DSS) to include an R-based user interface, an automated algorithm to extract the necessary remotely-sensed and LIS data.
7. Provide training, demonstrations and support to transition the model to end users for sustainable use in the post project period.

**End users/partners:** (1) the Mobile Bay National Estuary Program, (2) the Tampa Bay Estuary Program, (3) the Sarasota Bay Estuary Program, (4) the Weeks Bay National Estuarine Research Reserve, (5) the North Inlet – Winyah Bay National Estuarine Research Reserve, and (6) the Southwest Florida Water Management District

**Data sources, models, technology:** MODIS, VIIRS, OMI, LIS, Landsat, Sentinel, SMAP, GRACE, NLCD

**Major Accomplishments in 2019:**

- Remotely sensed datasets were used to improve previous calibrations (Activity 5) of TN, TP, and suspended sediment models for watersheds feeding the end-user estuaries.
- A 100-year historical and future (1940-2040) land cover data file was developed, and then used to develop total nitrogen source estimates for the same period. These data are needed to account for legacy groundwater inputs to streams in the study area in future years.

- SPARROW water quality models previously developed in the SAS language (Activity 5) were successfully run in the current beta-version of the R-language SPARROW model.
- Seasonal temperature and precipitation forecasts were successfully accessed from the North American Multi-Model Ensemble (NMME), and then successfully used in running a preliminary dynamic SPARROW water quality model. This procedure will be used to make short-term seasonal water quality forecasts within the SPARROW Decision Support System under construction (Activity 6).
- For long-term water quality forecasts, temperature and precipitation projections for a period centered on 2040 (2030-2050) were compiled for several climate change scenarios from the Coupled Model Inter-comparison Project Phase 5 (CMIP-5). These were then used to run preliminary SPARROW water quality models for long-term seasonal projections for 2040 based on the "RCP 4.5: Intermediate Emissions and Moderate Mitigations" scenario (Activity 6).
- Project members made presentations of project work at the National Water Quality Monitoring Council's 11th National Water Monitoring Conference (March, Denver), the NASA ASP Water Resources Team Meeting (June, Boulder), Alabama Water Resources Conference (September, Orange Beach, AL.), and two presentations at the American Geophysical Union Meeting (December, San Francisco).

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**Project Title**: Averting Drought Shortages in the Colorado River*:* Transitioning Long-Range, Data-Infused Scenario Modeling to Operations of the Central Arizona Project

**Principal Investigator:** Enrique R. Vivoni, Arizona State University

**Project Year:** 1

**Year-End ARL:** 3

**Project Description:** An ongoing drought in the Colorado River Basin has reduced levels in Lake Mead to the extent of triggering a reduction in Arizona's Colorado River supply allocation under the Drought Contingency Plan agreement. Arizona State University and the Central Arizona Project have partnered to transition an operational hydrologic model to assess the climate and land use change risks to long-range water supply security in the basin. The hydrologic model will be parameterized and tested with NASA observations to build confidence in its performance at sub-basins scales. Stakeholder-informed scenarios of climate and land cover change will be used to generate simulations out to 2100 to capture range of uncertainties.

**End Users/Partners:** Central Arizona Project and its network of Colorado River Basin partners (11 in total from seven states and the federal government).

**Data Sources, Models, Technology:** NASA MODIS products (NDVI, LST, Snow cover, LAI, Albedo), SMAP products (SM), NLDAS-2 reanalysis products, LOCA downscaled climate products, EPA ICLUS land cover change products, Variable Infiltration Capacity (VIC) model, statistical characterization tools.

**Major Accomplishments in 2019:** Stakeholder engagement process underway with 12 partners through project kickoff meeting, project webinar, participant survey, and establishment of a Research Advisory Council and Collaborative Modeling groups. Second generation of LOCA-forced VIC simulations completed, with analysis underway for journal publication (Whitney et al., to be submitted to Water Resources Research). Collection and processing of MODIS LST and Snow Cover completed. VIC comparisons to MODIS LST over central Arizona completed, with analysis underway for journal publication (Wang et al. to be submitted to Water Resources Research).

**Plans and Expectations for 2020:** Confidence-building activities for VIC model over Colorado River Basin with comparisons to MODIS LST and Snow Cover. Application of advanced statistical characterization techniques for model-data comparisons. Identification of model development efforts necessary in project, including physical representation of channel transmission losses. Determination of climate and land cover change scenarios to be utilized in third-generation of LOCA- and ICLUS-forced VIC simulations. Involvement of stakeholder groups in project development and decision making. Project presentations at western water modeling and management conferences. Two publications in Water Resources Research, with work commenced on three additional manuscripts.

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**Project Title**: Decision Support System to Enhance Water Quality Modeling and Monitoring using Remote Sensing Data

**Principal investigator:** Josh Weiss, Hazen and Sawyer

**Project year:** Completed

**Year-end ARL:** 6

**Project description:** Our research team is investigating correlations between satellite-based observations of watershed conditions (e.g., vegetation and land cover indices) and subsequent in situ measurements of water quality. Results have indicated strong correlations for many watersheds for total organic carbon, total suspended solids, and nutrients. Correlations are improved with combined, regional-scale models that leverage multiple in situ monitoring sites. A statistical approach based on a generalized linear mixed effect (GLME) algorithm with explicit treatment of spatial and temporal variability has been developed to build models that can be applied in a predictive manner to support seasonal decision-making. The data processing,

analysis, and visualization tools are being integrated into a decision support system that can be used for data analysis and predictive modeling for other watersheds.

**End Users/partners:** NYC Department of Environmental Protection (NYC DEP); Raleigh Public Utilities; Northern Colorado Water Conservancy; Lower Colorado River Authority; University of Maryland Baltimore County; RTI International

**Data sources, models, technology:** MODIS NDVI, EVI, GPP, LAI, Fpar, TRMM, MATLAB (Mathworks, Natick, Mass.), utility data sets from project participants

**Relevant project websites/links:** https://www.hazenandsawyer.com/work/projects/using-satellites-to-enhance-source-water-quality-monitoring/

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**Project Title**: Integrating NASA Satellite Soil Moisture and Precipitation Products to Augment Operational Hydrologic Prediction Capabilities of River Authorities in the State of Texas

**Principal investigator: Yu** Zhang, University of Texas at Arlington

**Project year:** 1

**Year-end ARL:** 4

**Project description:** Summary: Improve reservoir inflow forecasts by Texas river authorities and the Army Corps of Engineers by integrating NASA satellite precipitation estimates and soil moisture products. The goal is to improve precipitation estimates in areas NEXRAD coverage is poor and develop more reliable, real-time loss factors for operational HEC-HMS.

**End Users/partners:** Texas river authorities and the Army Corps of Engineers

**Data sources, models, technology:** SMAP soil moisture observations, SMOS soil moisture observations (since October 2011), Global Precipitation Mission (GPM) precipitation observations, and MODIS NDVI, GOES lightning data

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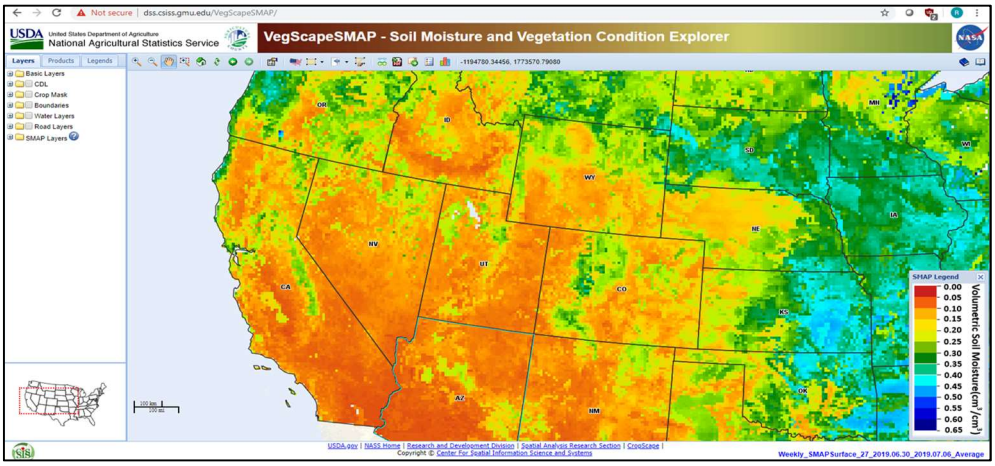
## WWAO Projects

In 2019, WWAO continued to fund six Water Projects in implementation phase. These projects reported significant technical achievements and end-user interactions, highlighted below. WWAO's Water Projects address core issues facing the western U.S. now and in the future –

water availability, water consumption, drought, and water forecasting. Project partners include farmers; local and tribal communities; and water managers, decision makers, and agencies at the federal, state and local levels.

### *i) High-Resolution Soil Moisture*




***Goal:*** Harness soil-moisture data from satellites to improve measures of soil moisture at both ground-level and in the root zone for agricultural and other partners.
***Lead:*** Rajat Bindlish, NASA Goddard Space Flight Center
***Partners:*** U.S. Department of Agriculture's National Agriculture Statistics Service (USDA NASS); University of Virginia.
***Capability:*** Mapping surface soil-moisture at 1-km spatial resolution
***Applications:*** Crop-yield forecasting**;** Drought monitoring and impact assessment.
***Achievements & Highlights:***

- A thermal-inertia-based algorithm was developed to disaggregate SMAP soil moisture using land surface temperature and vegetation data to a scale of 1 km. An operational platform was built to host the new high-resolution data, and implemented in a NASA high-performance computing system. The soil moisture outputs were validated using in situ measurements from the USDA's Agricultural Research Service's SMAP core validation sites. A paper describing the approach has been submitted to a peer-reviewed journal.
- Data gaps result from the thermal-inertia approach due to cloud cover in the MODIS data employed. To bridge these gaps, a new approach based on soil texture distribution was developed. A second technical paper describing this approach is being prepared.
- A fruitful meeting was held with the USDA NASS western region office in Sacramento; this office is linked to almond, pistachio and farming groups in California. As a result, the USDA regional directors wish to use the data next growing season.
- High-resolution soil moisture products from April 2015 to December 2019 were delivered to the USDA NASS for the purpose of evaluating soil condition during planting season and identifying areas that could prevent successful harvesting next season.

- USDA NASS has ingested the high-resolution soil moisture into its online VegScape system. A beta version of the system is now available at http://dss.csiss.gmu.edu/VegScapeSMAP/.

In late 2019, the project team had a fruitful meeting with USDA regional directors to demonstrate the value of integrating their improved soil moisture product into the NASS VegScape system.

***ii) Satellite-Based Drought Reporting on the Navajo Nation***

***Goal:*** Use satellite data to improve the way the Navajo Nation reports and manages drought, specifically through the Navajo Nation Department of Water Resources Drought Report, which is presented to emergency managers and used to allocate drought-relief dollars to each chapter in the Navajo Nation.

***How:*** Build a Drought Severity Evaluation Tool (DSET) that combines satellite Earth observations and in situ data in a user-friendly web application. The app is run through Climate Engine, which uses Google's Earth Engine to do on-demand processing of satellite and climate data through a web browser.

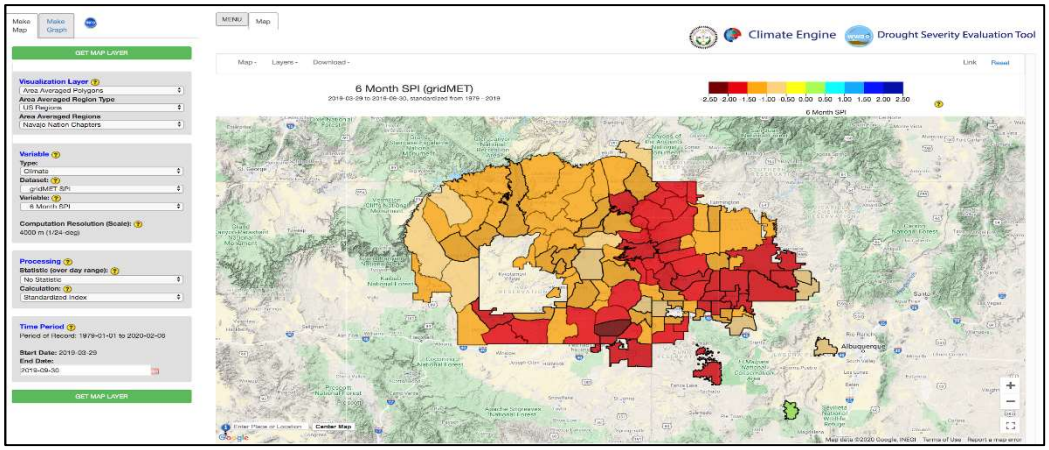
***Lead****:* Amber Jean McCullum, Bay Area Environmental Research Institute/NASA Ames Research Center

***Supporting Investigators****:* Britta Daudert and Justin Huntington (Desert Research Institute); Henrietta Marks (Navajo Nation Department of Water Resources).

***Partner****:* Carlee McClellan (Senior Hydrologist, Navajo Nation Department of Water Resources (NN DWR), Water Management Branch)

***Capability:*** Mapping drought indicators

***Applications:*** Quantification of drought severity at local scales; Allocation of drought emergency funds/resources for drought mitigation.




Map from WWAO's Drought Severity Evaluation Tool displaying area-averaged 6-month Standardized Precipitation Index values for Navajo Nation Chapters.

***Achievements & Highlights:***

- Technical advances:
  - A beta version of the DSET beta was completed: https://app.climateengine.org/dset.
  - NN DWR rain-gauge data were incorporated into the DSET. This step, the first achieved within the Climate Engine computing interface, allows the user to view all 85 rain-gauge locations and historical data across the Navajo Nation to compare alongside NASA data in map- and time-series formats.
  - The team developed the capability to generate area-averaged geocomputing of 3-, 6-, 9- and 12-month drought indices for Navajo administrative boundaries on-the-fly in map- and time-series format.

Navajo Nation Natural Resource Management at a Remote Sensing and Climate Engine Training, April 2019, Flagstaff, Arizona.

- Stakeholder Engagement and Tool Transition:
  - In April 2019, an in-person technical workshop and feedback session for tool improvement was held in Flagstaff, Arizona, with 14 participants from Navajo Natural Resource Management agencies and regional partners. The training was held in collaboration with the Desert Research Institute and NASA's Indigenous Peoples Capacity Building Initiative (IPI). It focused on an introduction to remote sensing, DSET beta testing, and feedback discussions.

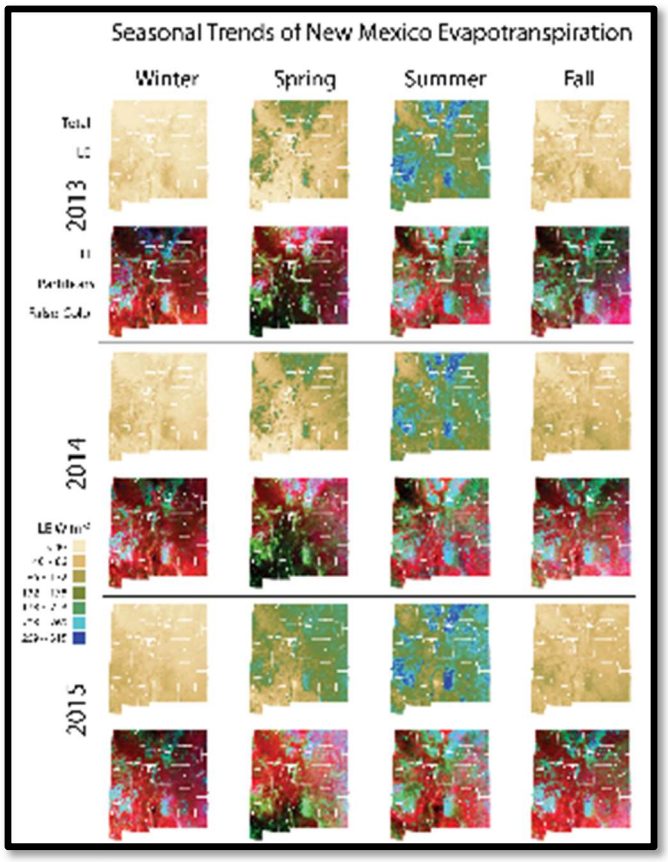
- Another in-person capacity-building workshop, held in December 2019 in Window Rock, Arizona, was led by the project's Navajo Nation DWR intern and partner, with 16 participants from the Navajo Nation Department of Agriculture and students from Dine College.
- An NNDWR intern joined the team to help with tool testing and transition to the partner agency.

➢ Community Outreach: A feature story highlighting the project was published in collaboration with WWAO; a training highlight was published in collaboration with NOAA's National Integrated Drought Information System (NIDIS), an article was published on the Space for U.S. website, a presentation on the work was featured at the Tribal Leaders Summit in collaboration with NASA's IPI, and the project was highlighted in three talks at the 2019 American Geophysical Union Fall Meeting, including at the Google booth.


Left: WWAO feature story on Navajo Nation project. Right: Project partner Carlee McClellan (left) and P.I. Amber McCullum (right) attending the American Geophysical Union Fall Meeting in 2019.

### *iii) Evapotranspiration Mapping in New Mexico*

*Figure at left: Seasonal ET trends, which were provided by the project for inclusion in New Mexico's State Water plan.*




***Goal:*** Develop operational evapotranspiration (ET) data for New Mexico so it can better monitor drought conditions, process water-rights applications, and refine its water-budget modeling.

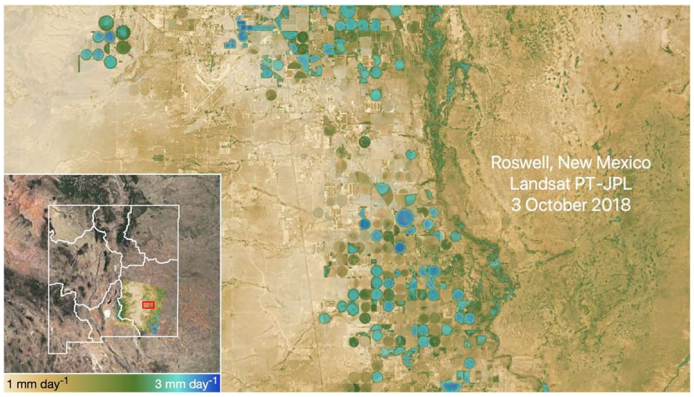
***How:*** Operationalize production of NASA Earth-Observing-System-based drought monitoring data for New Mexico water management**.** Develop access to and a dissemination mechanism for the drought product suite.

***Lead:*** Josh Fisher, NASA Jet Propulsion Laboratory

***Partner:*** New Mexico State Engineer's Office; Interstate Stream Commission.

***Capability:*** Field-scale mapping of ET

***Applications:*** Administration of water rights**;** Wildfire risk assessment; River basin studies.

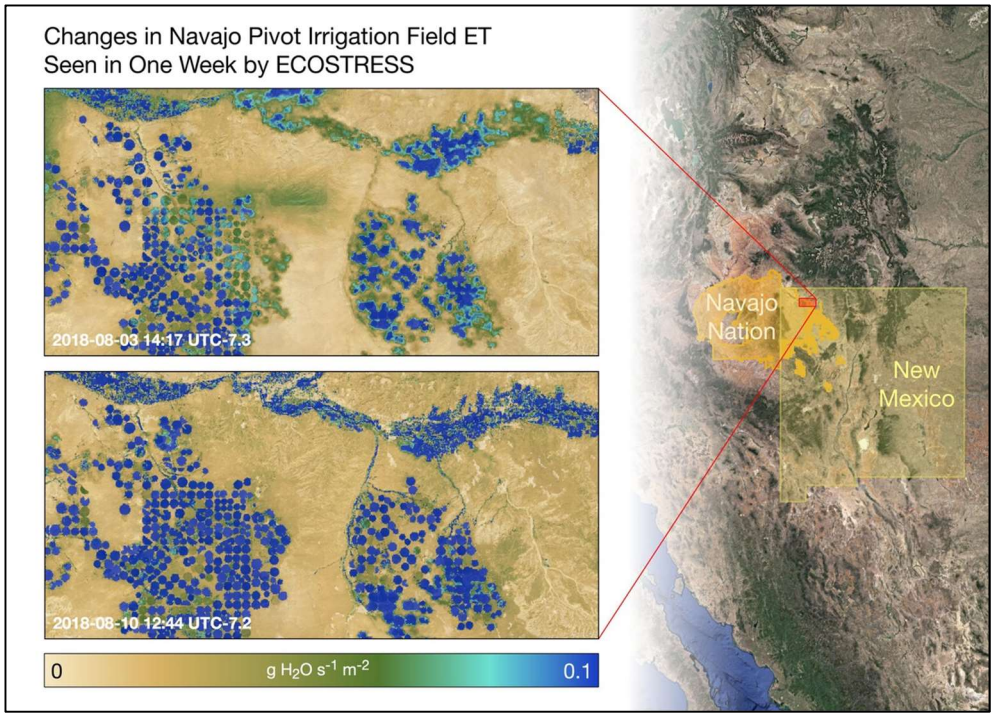



***Achievements & Highlights:***

- The team demonstrated the ability to process the Landsat Analysis Ready Data record to meet the requirements of water rights and forestry use cases in New Mexico. Successful delivery of daily PT-JPL ET data for use in water management has been achieved.
- Notably, the project has shown it can offer a significant advance in water-rights management, by offering the ability to provide water managers with actionable evidence – historical, multi-decadal, satellite-based records of field-scale ET and beneficial use at the field scale.


Numerous in-person meetings, teleconferences, and interactions were held with state and local representatives.

- Seasonal ET trend figures were delivered to New Mexico for inclusion in its state water plan.
- Development began on a data browser to help end-users access the ET data, and cloud storage and cloud services have been identified as a data delivery mechanism and a potential element of a transition plan.
- Testimonials from partners in the New Mexico Office of the State Engineer have been enthusiastic. “I am extremely interested in the data and can’t wait to see the [maps],” said Jerri Pohl, Statewide Projects Supervisor. Frank Scott, Statewide Projects Lead, said, “I am really proud to be a part of this project.”
- Discussions were held with Jake Collison of the University of New Mexico about his floating evaporation pans, which are able to provide an accurate accounting of the evaporative losses within a water system. This discussion inspired a flurry of development at NASA and interactions with partners about the development of water-surface evaporation capabilities to remotely sense changes in reservoir water height.



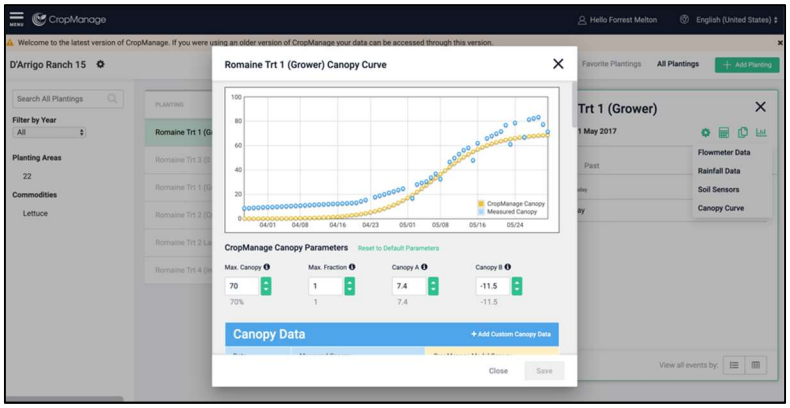

***iv) Satellite-Based Irrigation for Better Crop Management***

***Goal:*** Help farmers in California and beyond grow food in more sustainable ways, with less water and fertilizer, using NASA satellite data inputs.
***How:*** 1) Enhance NASA's Satellite Irrigation Management Support (SIMS) system to reliably provide real-time data for the CropManage decision-support system within 48 hours of satellite overpass, 2) Upgrade CropManage to improve model skill and strengthen satellite data incorporation, and 3) Fully build out a beta version of the CropManage-SIMS application programming interface (API).
***Lead:*** Alberto Guzman, NASA Ames Research Center
***Partner:*** University of California Cooperative Extension

*The team has been meeting with growers in the field to discuss expansion of the CropManage-SIMS application to additional high-value crops.*

***Achievements & Highlights:***

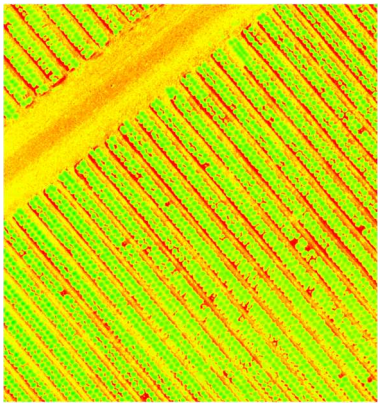
- NASA's SIMS system and the CropManage-SIMS API were integrated into Google Earth Engine.




SIMS data are now integrated with the new version of CropManage via the SIMS API, and are being used by growers to evaluate crop-canopy development and irrigation recommendations.

- Fractional cover data were analyzed for the period 2016-2018 to identify any crops that may require crop-specific relationships.
- UAVs are being flown to collect high-resolution aerial imagery that will be combined with satellite data to develop crop-specific data.
- The commercial sector was engaged and an ongoing collaboration is being pursued with Ceres Imaging to evaluate SIMS fractional cover for almonds, walnuts, and vineyards. Ceres was given access to the SIMS API for the purposes of site evaluation and review of aerial remote-sensing data.

- Rapid atmospheric correction routines were implemented to further reduce data latency from the time of satellite overpass to data being available in CropManage.



- The project held two CropManage training workshops in May and June 2019, as well as various meetings with growers in the field to discuss expansion of the CropManage-SIMS application to additional high-value crops and to plan demonstration projects. In March 2019, an invited presentation was given at the Salinas Valley AgTech Summit to hundreds of growers and agriculture technology companies.
- Scheid Vineyards approached the team in April 2019 to partner on expanding the CropManage-SIMS framework to support vineyards, building on the extensive data network Scheid has already developed. The Almond Board of California invited the team to provide input into their Strategic Plan.

Deployment and maintenance of flux towers at validation sites for vineyards and celery fields.

- NASA Administrator Jim Bridenstine made note of CropManage-SIMS in his February address (https://blogs.nasa.gov/bridenstine/2019/02/19/nasa-is-everywhere-talking-to-the-farm-community/).

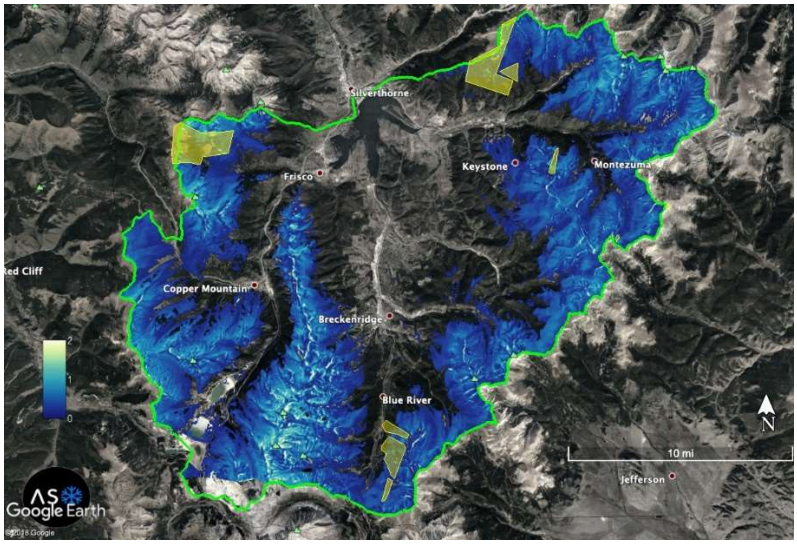
- Towards the end of 2019, the project team met with over 40 staff from the California DWR to discuss a transition plan for the project. A two-day workshop organized jointly with the California DWR is being planned to determine a technology transition strategy.

### *v) NASA's Airborne Snow Observatory and Automated Water Supply Model*

***Goal:*** Incorporate data from NASA's Airborne Snow Observatory (ASO) into precipitation runoff models to improve forecasts of runoff in California's Sierra Nevada and Colorado's Rocky Mountain ranges. Such predictions help reservoir managers make informed decisions about water allocation and reservoir operation, balancing often conflicting needs for drought planning, ecological flows, groundwater recharge, and flood prevention.
***Lead:*** Tom Painter, University of California Los Angeles
***End Users / Decision Makers****:* California Department of Water Resources; USDA Agricultural Research Service; San Francisco Public Utilities Commission; Irrigation districts.
***Achievements:***

- 2018 saw the automated integration of ASO's snow-depth data products into the USDA Agricultural Research Service's Automated Water Supply Model (AWSM), which forecasts the supply of many water basins.
- In February 2019, WWAO participated in the first California DWR ASO Steering Committee meeting. The purpose was to discuss status and priorities for ASO activities during the 2019 snow season, as well as to shape planning for the 2020 snow season. The committee was set up to help ensure that a concept of operations is developed for 2020 that facilitates the successful transition of ASO to an operational snow-survey capability outside NASA that can forecast snow water equivalent (SWE).

- In June 2019, ASO passed a milestone for transitioning its SWE forecasting service to the private sector. Using data collected by a commercial lidar airborne services provider, several SWE forecasts were delivered to the Colorado Water Conservation Board, offering a crucial demonstration of the feasibility of ASO SWE forecasts. The flights were operated by Quantum Spatial Inc. and data processing was funded in part by WWAO.



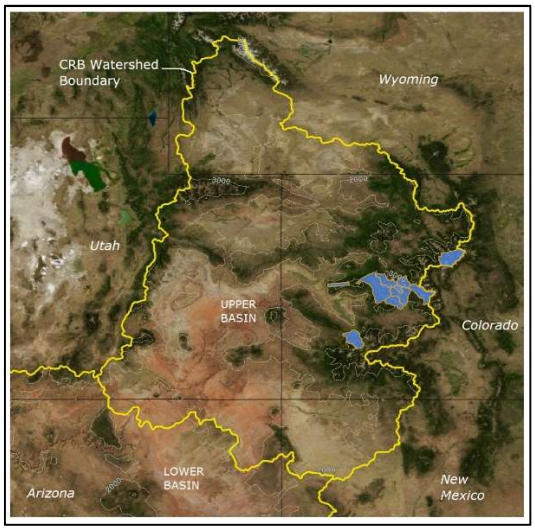

*Computer rendering of ASO flight data collected in June 2019 showing snowfields above Dillon Reservoir in Summit County, Colorado. Credit: NASA ASO.*

- Denver Water Tap published a story highlighting this milestone, explaining that the use of ASO data has helped Denver Water take its first major step forward in snow information gathering since the 1980s. *"The analysis of the flight data indicated there was nearly 19 inches worth of SWE still on the ground in the basin between 12,000 and 13,000 feet on June 24. That was more than double the 9.5 inches of SWE the computer modeling indicated might be in place at that elevation that day."*

### *vi) Using NASA's Airborne Snow Observatory to Improve Runoff Forecasts Provided by the U.S. River Forecast Centers*

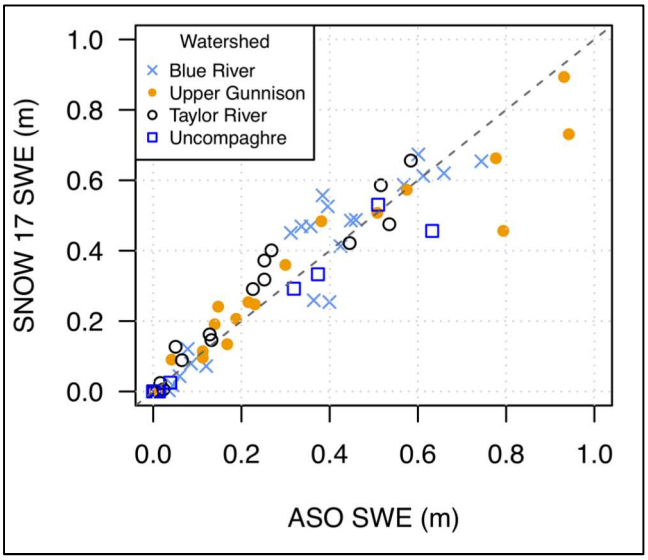
***Goal:*** Derive tangible pathways for the quantitative use of NASA's ASO SWE products to improve runoff forecasting using existing operational tools at the Colorado Basin River Forecast Center (CBRFC) and California Nevada River Forecast Center.
***Lead:*** Kat Bormann, NASA Jet Propulsion Laboratory
***Partners:*** NOAA Colorado Basin River Forecast Center, Southern Nevada Water Authority, University of Colorado Boulder.
***Motivation:*** Streamflow across the western U.S. is predominantly snowmelt-driven. As such, SWE representation in models is a major source of uncertainty in current runoff forecasts. Sparse point-measurement networks have been recently supplemented with spatially-complete snow depth measurements and SWE estimates from NASA's ASO. ASO data represent the state-of-the-

art for instantaneous SWE mapping in mountainous regions and are specifically designed to improve runoff estimates. However, there are logistical barriers to inserting these new ASO data into operational streamflow forecasts that are provided by the River Forecast Centers of the National Weather Service (such as the Colorado Basin River Forecast Center [CBRFC]). This project directly compares zonally-averaged SWE from ASO with areal estimates of SWE from the River Forecast Centers' Snow Accumulation and Ablation Model (SNOW-17 model).




***Achievements & Highlights:***

- This project began in earnest in 2019 and will come to a close in 2020. Data from around 30 ASO snow surveys conducted between 2013 and 2019 are being used for the analysis; 75% of the ASO data being employed have been processed, with 25% still to be processed.
- Initial results suggest that the zonal SWE values from SNOW-17 are highly correlated with those from ASO.
- SNOW-17 performance in Colorado varies greatly with month, with smaller errors at near-peak SWE (April) and larger errors during late season (May). SNOW-17 performance in California varies greatly by sub-basin.




Comparison of zonal SWE obtained from ASO data and the SNOW-17 model in Colorado.

- The CBRFC has begun hindcasting work to evaluate if runoff forecasts improve when SWE data are updated in near-real-time.
- A report will be completed in 2020 summarizing the findings and recommending next steps and tangible actions for using ASO data to improve water operations.

***New Water Projects***


*Credit: Carlee McClellan, Navajo Nation Department of Water Resources/Kim Locke, NASA Harvest.*

At the heart of WWAO's Project Formulation process, we continue to ask four questions:

- What is the current way of solving the issue?
- What does the partner specifically need?

- How can NASA data contribute to improving the issue?
- How will a tool be used after the project has ended?

In 2019, WWAO formulated two new water projects. To ensure solutions that reflected the consensus needs of the water decision-making community, WWAO's starting point was the water needs that had been identified at its Colorado River Basin Needs Assessment Workshop. WWAO then:

- **Prioritized the Water Needs and identified three top needs.** These top needs were Streamflow, Consumptive Use and Drought Monitoring.
- **Surveyed NASA capabilities related to the top needs.** NASA water capabilities were matched to the top needs using: 1) WWAO's Capabilities Catalog, and 2) by identifying researchers who were able to devise new projects with partners and were interested in doing so. Emphasis was placed on the *impacts* that a new capability will have on decision making and the ability to *transition* the NASA research to sustained use by the stakeholders.
- **Formed project teams.** External project partners were identified and teamed up with NASA researchers.
- **Asked the project teams to develop project concepts.** Two concepts were sent out to WWAO's Capability and Stakeholder Engagement Working Groups for review. Both concepts passed their review criteria and moved to a formulation phase, which was fully-funded for up to 12 weeks, and during which project ideas were fully fleshed out.
- **Selected projects to move to implementation phase.** Project awards for these two new efforts are expected in the spring of 2020. Attention will be paid to whether projects can be addressed in the short-term, medium-term or long-term.

# X. APPEDIX B: ABBREVIATIONS AND ACRONYMS

AGU: American Geophysical Union
ALEXI: Atmosphere Land Exchange Inverse
AMIS: Agricultural Market Information System
AMSR-E: Advanced Microwave Scanning Radiometer - Earth Observing System
ARC: Ames Research Center
ARL: Application Readiness Level
ASCAT: Advanced SCATterometer
CADRE: Crop Condition Data Retrieval and Evaluation
CBRFC: Colorado Basin River Forecast Center
CDWR: California Department of Water Resources
CFS: Climate Forecast System
CY: Calendar Year
DSS: Decision Support System
DSSAT: Decision Support System for Agrotechnology Transfer
Envisat: Environmental Satellite
EPA: U.S. Environmental Protection Agency
EROS: Earth Resources Observation and Science
ESA: European Space Agency
ESD: Earth Science Division
ESI: Evaporative Stress Index
ESP: Ensemble Streamflow Prediction
ET: Evapotranspiration
ETM+: Enhanced Thematic Mapper Plus
FAS: Foreign Agricultural Service
FEWS NET: Famine Early Warning System Network
G-REALM: Global Reservoir and Lake Monitor
G20: Group of 20
GDAS: Global Data Assimilation System
GEO: Group on Earth Observations
GEOGLAM: GEO Global Agricultural Monitoring
GEOGLOWS: GEO Global Water Sustainability
GEOS: Goddard Earth Observing System Model
GEOSS: Global Earth Observation System of Systems
GLDAS: Global Land Data Assimilation System
GOES: Geostationary Operational Environmental Satellite
GPM: Global Precipitation Measurement Mission

GRACE: Gravity Recovery and Climate Experiment
GSFC: Goddard Space Flight Center
IMERG: Integrated Multi-satelliE Retrievals for GPM
JPL: Jet Propulsion Laboratory
LIS: Land Information System
MERIS: MEdium Resolution Imaging Spectrometer
METRIC: Mapping Evapotranspiration at high Resolution with Internalized Calibration
MODDRFS: MODIS Dust Radiative Forcing in Snow
MODIS: Moderate Resolution Imaging Spectroradiometer
MODSCAG: MODIS Snow Covered Area and Grain size
NASA: National Aeronautics and Space Administration
NASS: National Agricultural Statistics Service
NCRFC: North Central River Forecast Center
NDMC: National Drought Mitigation Center
NDVI: Normalized Difference Vegetation Index
NGO: Non-Governmental Organization
NLDAS: North American Land Data Assimilation System
NOAA: National Oceanic and Atmospheric Administration
NRL: U.S. Naval Research Laboratory
NRT: Near Real-time
OLI: Operational Land Imager
PEER: Partnerships for Enhanced Engagement in Research
PI: Project Investigator
Sac-SMA: Sacramento Soil Moisture Accounting
SeaDAS: Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Data Analysis System
SIMS: Satellite Irrigation Management Support
SMAP: Soil Moisture Active Passive
SMOS: Soil Moisture and Ocean Salinity
SNODAS: Snow Data Assimilation System
SPoRT: Short-term Prediction Research and Transition
SSM/I: Special Sensor Microwave Imager
SWAT: Soil and Water Assessment Tool
SWE: Snow-Water Equivalent
TIR: Thermal Infrared
TM: Thematic Mapper
TMPA: TRMM Multi-satellite Precipitation Analysis
TOPEX: Topography Experiment
TRMM: Tropical Rainfall Measuring Mission
UN: United Nations
USACE: United States Army Corps of Engineers
USAID: United States Agency for International Development
USDA: United States Department of Agriculture
USGS: United States Geological Survey

VIC:  Variable Infiltration Capacity
VIIRS: Visible Infrared Imaging Radiometer Suite
WWAO: Western Water Applications Office