National Aeronautics
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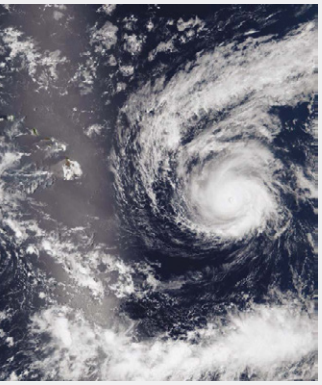

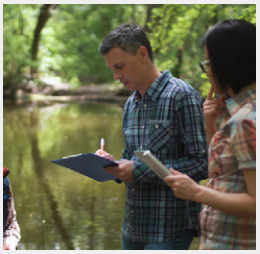

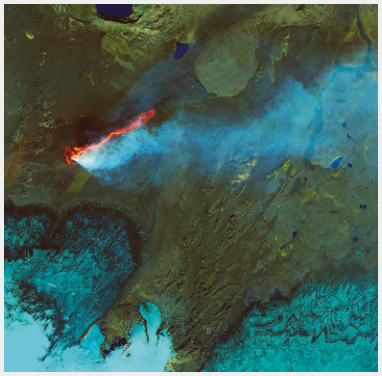

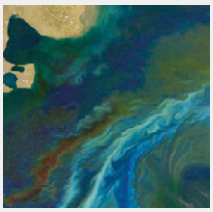

2018
Annual Summary

NASA Earth Science
Applied Sciences Program

Water Resources

Water Resources: 2018 Annual Summary

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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. The projects are carried out in partnership with public- and private-sector organizations to achieve sustained use and sustained benefits from the Earth observations.

The Applied Sciences Program's applications themes are currently focused on four of the nine Societal Benefit Areas (SBAs) of the interagency Group on Earth Observations: Health (including Air Quality), Disasters, Ecological Forecasting, and Water Resources.[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 supports the integration of NASA Earth observations and technologies into management tools for the water resources management community. The Water Resources Applications area currently supports a diverse range of projects in its portfolio, 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.

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 they 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

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

States and internationally to ensure cost-effective and beneficial solutions are provided to water resources managers.

II. OVERVIEW OF 2018

The Water Resources Applications Area, team, and community continued to make strides in addressing critical water resources challenges in the U.S. and globally. In addition to supporting a portfolio of 17 ROSES projects spanning topics such as drought, climate impacts on water resources, water quality and streamflow forecasting/flood monitoring, the Water Resources Applications Area integrated the Western Water Applications Office (WWAO) into its program of activities. 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. The Water Resources Applications Area also was very active in engaging the water resources community in the U.S. (Western States Water Council, National Drought Resilience Partnership, National Integrated Drought Information System, Transboundary Water ad-hoc team) and internationally (GEOGLOWS International Workshop, World Water Forum). In addition, we provided leadership in the establishment of the Group on Earth Observations GLObal Water Sustainability (GEOGLOWS) Initiative for interagency coordination on water security activities, the Committee on Earth Observation Satellites Ad-hoc Working Group, and a USAID Partnerships for Enhanced Engagement in Research (PEER).

III. ASSESSMENT

Calendar year 2018 was very productive, including the completion of six projects, and the selection of eight new projects (bringing the total portfolio to 17 at the end of 2017) from the A37 solicitation. The new projects funded under the A37 solicitation are focused on the development of applications with operational partners to address management challenges related to water quality and agriculture water use. In addition, three impact assessments continued work to quantify the impacts of projects on stakeholder decisions.

The Water Resources team was highly active in engaging with the operational, policy, and practitioner communities as well as Earth-science communities, attending more than 20 meetings and conferences (multiple practitioner meetings such as National Council on Science and the Environment Conference, National Water Quality Monitoring Conference, NOAA National Water Center-PI meeting, USGS-NASA Coordination meeting, Western States Water Council Annual Meeting, U.S. Water Global Water Security Summit, American Society of Engineers World Environmental and Water Resources Congress, Water and Long Term Value Conference, National Academy of Science Arab American Frontiers Symposium, and the Water Funders Initiative, among others).

IV. PROJECT PORTFOLIO

The portfolio currently has 17 active projects, excluding the Western Water Applications Office (WWAO) projects. Nine projects were selected from the A.45 solicitation to develop improved forecasts of water supply anomalies in the mid-term (30–180-day outlooks), and eight projects were selected from the ROSES 2016 A.37 solicitation focused on water quality and agricultural water use and awarded in 2017. Descriptions of these projects are included in the Appendix.

The table below summarizes the distribution of Application Readiness Levels (ARLs) of the 24 projects that were active at the end of the 2017 calendar year, and the final ARLs achieved by the projects completed during 2017. Approximately one-third of projects were selected in 2017 and one-third of the projects closed in 2017. This is reflected in the distribution of project ARLs evenly in the full ARL range shown in the graph below. During 2017, 15 projects advanced one or more ARL.

ARL Levels of all 17 Water Resources Projects in 2018

ARL	# of active projects at the end of 2018	# of projects that closed in 2018
9	0	1
8	1	0
7	2	0
6	1	0
5	8	0
4	2	0
3	2	0
2	0	0
1	0	0
TOTAL	**16**	**1**

V. FOOD SECURITY PROGRAM

In November 2017, the Applied Sciences Program selected the Harvest Consortium, led by the University of Maryland, to receive a total of $14.5 million over a five-year period through its Research Opportunities in Space and Earth Science (ROSES) grant program. Simultaneously, a Food Security Office was established at NASA Goddard Space Flight Center to develop NASA's capabilities in partnership with Harvest (see below). 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. 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.

Harvest

Through a multidisciplinary Consortium of partners, NASA Harvest is advancing the use of satellite data in decision-making related to agriculture in the U.S. and on food security issues around the globe working with other agencies and aid organizations. In 2018, the program's first year of operation, NASA Harvest grew to 30 funded projects and developed more than 40 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 trainings 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. 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.

Food Security Office

During 2018, the Food Security Office at Goddard Space Flight Center began regular meeting with Harvest and convened a nationwide team of NASA scientists with expertise in food and water systems. The team draws on the ingenuity of NASA—with its unique technological and scientific capabilities—to apply NASA's long-term investments for the NASA Harvest consortium. The team recently conducted a survey of current NASA assets relevant to food security and documented them in a peer-reviewed science manuscript and a series of fact sheets, *Food Security from Space: Water availability, vegetation, water quality, and air quality impact on crops*.

More information:

NASA Food Security: science.gsfc.nasa.gov/610/applied-sciences/food.html
NASA Harvest: nasaharvest.org

VI. WESTERN WATER APPLICATIONS OFFICE

Major Accomplishments

The 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 today. To do this, WWAO delivers NASA's capabilities—remote-sensing data, expertise and tools—directly to water 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/.

Calendar-year 2018 (CY18) was a productive year in which WWAO expanded and matured its activities in various ways:

Project Portfolio

In 2018, five water projects continued in implementation phase and a new project was launched toward the latter part of the year. These projects address core issues facing the Western United States, now and in the future—water availability, water consumption, drought, and water forecasting. Project partners include farmers, local and tribal communities, water managers, decision makers, and agencies at the federal, state, and local levels. The six projects are listed below and are summarized in more detail starting on page 12.

- ***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: Help farmers in California and beyond grow food in more sustainable ways—with less water and fertilizer—using NASA satellite data inputs.

- ***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 forecast skill by refining how snowpack is represented in the CBRFC's snow model.

Project water partners have been enthusiastic to harness NASA's capabilities. According to Molly Magnuson, of the New Mexico Office of the State Engineer, WWAO's New Mexico water project, "*will improve water management decisions throughout New Mexico.*" Carlee McClellan, Senior Hydrologist of the Navajo Nation Water Management Branch, presented WWAO's Navajo Nation project at the Native Waters on Arid Lands Summit in Reno, Nevada, which covers climate change, water resources, traditional knowledge, livestock and ranching, and conservation practices. McClellan said that the Navajo Nation Drought Severity Tool being developed by WWAO, "*will…aid the Navajo Nation in its drought decision-making processes for many, many years to come.*"

In 2018, WWAO's Higher-Resolution Soil Moisture Project delivered a prototype close to operational implementation. An interagency agreement between NASA's Goddard Space Flight Center and its project partner—the U.S. Department of Agriculture's (USDA's) National Agricultural Statistics Service (NASS)—was established to enable the use of high-resolution soil moisture in the NASS system. Zhengwei Yang of the NASS Research & Development Division reflected that, *"the project could be a game changer when both top soil moisture and root-zone soil moisture data are available, since it enables near-field-level soil moisture assessment.*"

The year 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. Meanwhile, for the Crop Management project, NASA's Satellite Irrigation Management Support (SIMS) system and a SIMS application programming interface (API) were implemented on Google Earth Engine, while integration and near real-time processing of data from the *Sentinel-2A* Earth-observing mission were completed.

Prioritizing Western Water Needs

As part of its push to identify the most important water issues in the Western U.S., WWAO held a Colorado River Basin Needs Assessment Workshop at Caltech in Pasadena, California, in April 2018. This followed on from the characterization study of the Colorado River Basin that WWAO commissioned in 2017, and from a rapid assessment of water needs conducted in 2016.

WWAO's Colorado River Basin Needs Workshop was attended by a select group of water managers interested in working with NASA. Attendees included 15 non-NASA stakeholders

from five states in the Colorado River Basin; they represented irrigation districts, agriculture, state and municipal water-resource departments, regional wholesale water suppliers, non-governmental organizations, and academia. Paul Brierley, one of the attendees and Executive Director of the Yuma Center of Excellence for Desert Agriculture in Arizona, commented that, *"NASA was eager to hear what capabilities we could put to use. I'm excited for them to develop capabilities based on the needs of Ag [agricultural] producers!"* Peter Gill, River Basin Planning Project Manager of Wyoming's Water Development Office, felt that, *"the workshop informed our agency's move toward better informed, science-based decision making."*

At the end of the two-day meeting, eight key water themes impacting the Colorado River Basin were identified, along with around 80 water needs. Within those eight categories, 13 needs were identified as high-priority and expanded upon in detail. The outcome: a set of three high-priority water needs for those working within the Colorado River Basin, which were summarized in a WWAO report in 2018. These themes are: 1) water-supply forecasting; 2) evapotranspiration over land and water; and, 3) the prediction and impacts of extreme events. They are driving the formulation of the next round of WWAO's water projects to be funded in fiscal-year 2019 (FY19).

As an additional outcome of the workshop, WWAO was invited to participate in the Colorado River Climate and Hydrology Working Group, an interagency collaboration encompassing private, academic, interagency, and state representatives from all the Colorado Basin states. That working group has identified 44 priority needs related to streamflow forecast modeling in the basin; three of those water needs were added to the shortlist of Colorado River Basin needs identified by WWAO as warranting further exploration.

Reach and Impact

WWAO's goal is to develop game-changing water applications. To do this, it requires detailed insight from water managers and decision makers on what they need to make more informed water-management decisions. To gain that insight, WWAO builds strategic partnerships at federal, state, and local levels. This is done through joint studies and projects, topical workshops, formal agreements, participation in interagency working groups, and other collaborations. Highlights of WWAO's partnership activities in 2018 include:

- *Water Studies.* Working with the Western States Water Council, WWAO conducted an in-depth study on the use of cloud-computing technology and information systems by Western-state water-resource agencies, publishing a report in late 2018.

- *Strategic Working Groups.* In 2018, WWAO participated in a number of interagency working groups that are crafting water priorities in the west. These include the National Oceanic and Atmospheric Administration's (NOAA's) National Integrated Drought Information System (NIDIS) Observations and Monitoring Working Group, and the NIDIS Southwest Drought Early Warning System Working Group—both of which focus on drought monitoring; the West Wide Climate Risk Assessment Working Group; the

Southwest Oklahoma Action Plan effort; and the Colorado River Climate and Hydrology Working Group. In July, WWAO (through its Program Scientist, Forrest Melton) was invited by the California Department of Water Resources to serve on the Technical Working Group for the California AB1755 Open Water Information Architecture (OWIA). OWIA is being designed to comply with AB1755 and to improve access to water data in California. In late 2018, WWAO was invited to join the Hydrology and Forecast Technical Advisory Subcommittee for Flood Managed Aquifer Recharge, which is run by the state of California. WWAO is submitting information on NASA's tools and data, and this engagement is an ongoing effort that may bear fruit in terms of new water-project concepts further down the line.

- *Topical Workshops and Conferences*. In collaboration with the Western States Water Council, WWAO hosted a Water Information Management System Workshop at NASA's Jet Propulsion Laboratory in January. A key outcome was the above-mentioned technical report on the use of cloud-computing technology in the water domain. In June 2018, WWAO's Crop Management project gave a presentation on its capabilities to around 100 growers at the Salinas Valley AgTech Summit. During the NASA ASO Annual Meeting in September, WWAO and NASA's ASO conducted an AWSM user workshop with more than 20 users, while in October, approximately 25 growers were trained to use the SIMS/CropManage application. Also in October 2018, WWAO was invited to talk at the Texas Water Conservation Association Fall meeting about how satellite data can be used to improve water management. The audience included river authorities, floodwater drainage and irrigation districts, municipalities, utilities and those interested in groundwater. At the American Water Resources Association meeting in November, WWAO co-hosted a session on Water Quality. And in December 2018, WWAO co-hosted a Winter Outlook on Water Workshop with the California Department of Water Resources, the Water Education Foundation and the Center for Western Weather and Water Extremes. As 2018 came to a close, WWAO convened sessions at the Fall American Geophysical Union Meeting on Science to Action and Food Security (the latter in partnership with the NASA Harvest program), which proved fruitful.

- *Other Collaborations*. In 2018, WWAO held discussions with the Metropolitan Water District of Southern California to establish a Memorandum of Understanding supporting multiple water-management efforts. 2018 also saw the Western States Water Council/WestFAST continue to be a key partner. WWAO explored possible areas of collaboration (such as impact assessment and project coordination) with NASA's SERVIR activity and the Short-Term Prediction Research and Transition Center (SPoRT) at NASA's Marshall Space Flight Center. As a result, Dan Irwin, SERVIR Director, and Ashutosh Limaye, SERVIR Project Scientist, are now part of the WWAO working group. And in September 2018, WWAO met with the USDA's Natural Resources Conservation Service (NRCS) in Oregon to discuss remote-sensing for hydrology and climatology, modeling and water forecasting tools, and the NRCS' products and services. Possibilities for collaboration are being explored.

WWAO Impact Assessment
In 2018, WWAO completed the process of formalizing its impact assessment strategy. Impact assessment helps projects maximize their potential benefits to society. WWAO has adopted a "theory of change" methodology that will be integrated into all WWAO water projects launched in FY19 and beyond. First, the potential benefits of each project to the decision-making community are identified and articulated at the initial stage of project formulation. Next, project deliverables are designed that directly connect to those identified long-term, desired impacts.

WWAO will use its impact assessment process not only to increase the program's long-term impact, but also to determine whether or not to transition individual projects to stakeholders for operational use. Impact assessment will also help to increase awareness of the value of WWAO's work and may strengthen and boost support for NASA's broader Applied Sciences Program research.

NASA Water Capabilities Catalog
While identifying water-management needs is one key thrust of WWAO's work, identifying and disseminating NASA capabilities that can meet those needs is another crucially important effort—as has been emphasized by water partners. In 2018, WWAO launched a new effort to catalog NASA's technical capabilities in water science and technology. Its Capabilities Catalog will offer a collection of useful NASA water-capability summaries to water managers, decision-makers, and the NASA community. A template was developed based on input from WWAO's Water Partner Engagement Team and work started on a series of two-page briefs outlining key water projects funded by WWAO and NASA's Applied Science Program. In 2019, the catalog will become available online and in-print for distribution to water partners and at events.

Western Water Alliance
Calendar year 2018 saw WWAO initiate efforts to create a Western Water Alliance. The Alliance is a group of public organizations and private sector companies involved in western-water management and infrastructure that can partner with WWAO to 1) forge innovative collaborations and 2) help transition WWAO's water projects out of NASA to sustainable, long-term states. In 2018, a strategic charter and communications plan were drawn up. Around 800 organizations were vetted to assess potential areas of synergy with WWAO, and a shortlist was identified. In 2019, organizations will be engaged in dialog leading to recruitment to the Alliance so that collaborations may begin.

Looking Ahead
WWAO will strengthen its efforts on a number of fronts in the coming year:

- **New Water Projects.** In 2019, WWAO will focus on devising water projects by explicitly starting from water-partner needs rather than from a hybrid of needs and NASA capabilities. This strategy will ensure that WWAO's water projects reflect the consensus needs of the water decision-making community and that those needs drive the process

from the outset. To this end, in late 2018, WWAO sent out a Solicitation of Interest to the NASA technical community to request project ideas that could potentially satisfy the Colorado River Basin needs identified. In 2019, WWAO will fund two or three projects that satisfy these criteria. Water partners will be an integral part of the process from project conception on. Impact assessment and project transition efforts will also be built into project development from day one.

- **Water Needs Catalog.** One of WWAO's key goals is to develop a Water Needs Catalog comprised of Use Cases that can drive the formulation of WWAO projects. Such a catalog will inform the NASA Applied Sciences community of water-resource needs and also provide applications guidance to future NASA missions. A Western Water Needs Catalog will be constructed in two ways: 1) through focused engagement with high-priority water partners; and, 2) by building additional relationships with partners and overall public awareness of WWAO.

  In 2018, a Water Needs Assessment was performed for the Colorado River Basin. In 2019 the process will be extended to the Columbia River Basin. First, a study will be conducted to characterize the Columbia River Basin in terms of physical characteristics and the socioeconomic and water-management factors at play, as well as to identify key stakeholders in the basin. In mid-2019, WWAO will host a Columbia River Basin Needs Assessment Workshop with key water partners/decision makers to identify the most important needs in the Columbia Basin. Finally, further needs analysis will be performed by the WWAO team in late 2019 to identify the top-priority needs for the region on which WWAO could potentially focus. These water needs will drive WWAO's FY20 round of water projects.

- **Water Partnerships.** A top 2019 priority for WWAO is to continue building and maintaining relationships with Western water partners. Focused engagement with the right decision makers enables WWAO to understand what water-resource gaps exist, which gaps can be filled, and, critically, the context surrounding how water decisions are made. In 2019, WWAO will continue to collaborate with the Western States Water Council/WestFAST, the USDA, NOAA, the U.S. Army Corp of Engineers, the Colorado River Hydrology & Climate Working Group, the U.S. Bureau of Reclamation, the California Department of Water Resources, the California State Water Resources Control Board, and the Metropolitan Water District of Southern California. WWAO will also explore new partnerships in the Pacific Northwest (with the NRCS), in the Columbia River Basin, and in states such as Texas and Utah.

- **Water Operations Study.** WWAO will conduct at least one study in 2019 to dig deeper into the decision-making context —specifically operations and workflow—of a selected western water decision-making agency. Work has already begun to assess the operational models and workflows being employed by CBRFC and the U.S. Bureau of Reclamation.

- **WWAO Applications Transition Workshop.** By invitation from the Western States Water Council, WWAO will co-host a workshop on how to transfer the technology it develops in its projects from NASA to operational and/or sustaining partners. This will happen around the middle of 2019. Tech transfer will become a more important thrust as WWAO's projects mature.

- **Visiting Committee.** In 2019, WWAO will establish a committee of experts who can help NASA identify key water challenges and partnerships as well as strategic opportunities and gaps. The committee will consist of people from academia, water agencies (local, state and federal), non-governmental organizations, foundations, and possibly commercial entities with a range of expertise (snow, groundwater, irrigation and urban water management, flood response, water quality, water policy, and meteorology/forecasting). Committee members will ideally serve as advocates for WWAO's mission to the broader water-management community and may help review project proposals and plans as needed.

WWAO 2018 Water Project Summaries

Project: Operational Evapotranspiration for the State of New Mexico

Project lead: Joshua Fisher, NASA Jet Propulsion Laboratory

Project description: New Mexico is among the most arid states in the U.S., and consistently suffers from drought conditions that make agriculture, ranching, grazing, fire response, and other water-related activities difficult to manage. This project is working to deliver to the New Mexico Office of the State Engineer remote-sensing-based information that it can use to assess agricultural water-use and drought conditions across the state, as well as improve water planning, particularly during droughts.

End users/partners: New Mexico Office of the State Engineer, U.S. Bureau of Reclamation, New Mexico State Forestry, New Mexico Department of Agriculture, New Mexico Fish and Game, U.S. Geological Survey.

Data sources, models, technology: Evapotranspiration, potential evapotranspiration, Evaporative Stress Index (ESI), normalized difference vegetation index, albedo, land-surface temperature, MODIS.

***

Project: Satellite-Based Irrigation for Better Crop Management

Project lead: Alberto Guzman, NASA Ames Research Center Cooperative Agreement for Research in Earth Science and Technology

Project description: The goal of this project to help growers and water managers in the Western U.S. make more informed and efficient decisions about the amount of water and fertilizer to apply to crops. By combining two existing online tools (NASA's Satellite Irrigation Management system (SIMS) and CropManage), satellite, weather, and soil data can be used to help growers tailor irrigation times and nutrient application to the specific needs of crops like lettuce, strawberries, broccoli, and cabbage. NASA SIMS provides detailed maps and trends of crop canopy conditions and irrigation demand, while CropManage is an application that helps growers and water managers make water and nitrogen-fertilizer decisions at the field level. Results from the project suggest that water use can be significantly reduced with no loss of crop yield or quality. The combined system is also expected to lower the cost of planning, water budgeting, and reporting for compliance with California's Sustainable Groundwater Management Act.

End users/partners: Commercial growers/shippers, agricultural water managers—including farmers primarily on the California Central Coast, crop consultants, irrigation districts, groundwater sustainability agencies, state agencies. Initial focus is on California with potential expansion to stakeholders in the greater Western U.S.

Data sources, models, technology: *Landsat*, MODIS, *Sentinel-2*, SIMS, CropManage app, remote-sensing-based vegetation indices, green fractional-crop cover, basal crop coefficients.

***

Project: Satellite-Based Drought Reports for the Navajo Nation

Project lead: Amber McCullum, NASA Ames Research Center

Project description: The Navajo Nation is the largest federally-recognized Native American tribe in the United States in terms of land area, covering over 70,000 km^2 and occupying parts of northeastern Arizona, southeastern Utah, and northwestern New Mexico. With a population of more than 200,000, the Navajo Nation is prone to frequent and pervasive droughts, and suffers from poor water-supply reliability. More than 40 percent of homes do not have direct access to potable water and must rely on water haulers. The goal of this project is to help improve the Navajo Nation Department of Water Resources Drought Report, which is presented to emergency managers and used to allocate drought-relief dollars throughout the community. Drought-relief funds, which are around $25 million, are currently disseminated throughout the

Navajo Nation evenly among all agencies. A more informed Drought Report would help funds to be allocated in proportion to drought severity and needs.

End users/partners: Navajo Nation Department of Water Resources, Navajo Nation Department of Emergency Management.

Data sources, models, technology: Navajo Nation rain-gauge data, multi-satellite precipitation product from *TRMM* and *GPM*, Integrated Multi-satellite Retrievals for *GPM* (IMERG), Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (a quasi-global rainfall dataset), Drought Severity Evaluation Tool.

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Project: High-Resolution Soil-Moisture Data for Monitoring Crop Conditions

Project lead: Rajat Bindlish, NASA Goddard Space Flight Center

Project description: Operational agencies like the U.S. Department of Agriculture's National Agriculture Statistics Service (NASS) provide agricultural forecasts and assessments that rely on best estimates of soil moisture. Currently these are created using ground input from farmers or field offices, which is an expensive approach that offers only sparse observations across different counties. For better forecasts, they need estimates that track changes in soil moisture with fine resolution over both space and time. This WWAO-funded project is working to explore the feasibility of using soil-moisture data from satellites to improve measures of soil moisture at both ground-level and in the root-zone for NASS, and to satisfy its operational data needs. The information will be helpful for the NASS Crop Weather report, crop grower associations, and other agricultural groups.

End users/partners: U.S. Department of Agriculture's National Agriculture Statistics Service (NASS) (Pacific and Northern Plains Regions), crop grower associations—such as the Almond Board, agricultural extension groups, and university contacts.

Data sources, models, technology: *SMAP*, *SMOS*, *SMAP-Sentinel* products.

***

Project: Operational Analysis and Modeling with NASA's Airborne Snow Observatory

Project lead: Tom Painter, NASA Jet Propulsion Laboratory/UCLA

Project description: The Airborne Snow Observatory (ASO) is a NASA airborne mission that provides water managers with the first-ever estimates of basin-wide snow water equivalent, snow depth, and snow albedo. ASO began in 2012 as a cooperative effort between the

California Department of Water Resources and NASA Terrestrial Hydrology, with flights over the Sierra Nevada and Colorado Rocky Mountains starting in 2013 and continuing to the present. The objective of this project is to incorporate ASO data into precipitation-runoff models to improve predictions of runoff through the Sierra Nevada. Decision makers will potentially use the information to inform decisions about water allocation and reservoir operation, including hydroelectric generation and flood management.

End users/partners: California Department of Water Resources, U.S. Department of Agriculture Agricultural Research Service, San Francisco Public Utilities Commission, irrigation districts.

Data sources, models, technology: NASA ASO measurements of snow depth, snow water equivalent and albedo.

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Project: Improving Snowpack Representation in the Colorado Basin River Forecast Center's Snow Model Using NASA's Airborne Snow Observatory (ASO) Data

Project lead: Kat Bormann, NASA Jet Propulsion Laboratory

Project description: The Colorado Basin River Forecast Center (CBRFC) relies on a lumped snow model (SNOW-17) and point observations to estimate snow water equivalent (SWE); that is, how much water is contained as snow, to guide streamflow forecasts. Streamflow in the Colorado River Basin is driven predominately by snowmelt and the magnitude and spatial distribution of the snowpack in the CBRFC's model is currently poorly constrained with sparse observations. NASA's ASO provides spatially complete measurements of snow depth and SWE estimates at basin-scale resolution. These measurements will allow the CBRFC to markedly improve its understanding of the snowpack, and in turn, improve daily-to-seasonal streamflow forecasts. This project leverages existing ASO data collected within the Colorado River Basin and compares it to historic snow realizations from the CBRFC's snow model. The work explores how to use this refined understanding to improve snow representation in the SNOW-17 model and, in turn, skill in forecasting runoff.

End users/partners: Colorado Basin River Forecast Center

Data sources, models, technology: NASA ASO data

VII. PROGRAM MANAGEMENT

The Water Resources Applications Area program activities focused on integrating WWAO into the overall program management team, expanding the stakeholder framework for the applications area, and assessing gaps in the portfolio.

Global Water Strategy

The Water Resources Program contributed to the US Global Water Strategy. The Global Water Strategy is a plan mandated by the Senator Paul Simon Water for the World Act of 2014, and required vetting and approval by the NASA administrator, the USAID administrator, and Secretary of State. More than 17 U.S. government agencies and departments contributed to the development of this Strategy, which will be coordinated in Washington, D.C., through the Department of State Interagency Water Working Group, and in the host countries through U.S. Missions. It was transmitted to Congress and high priority posts and environmental hubs on November 13, 2017.

2018 Water Resources Team Meeting

The annual NASA Water Resources team meeting was held at the University of Colorado-Boulder, on June 26-28, 2018, with more than 65 participants. The overarching purpose of the meeting was to provide a forum for the NASA-supported water resources community of principal investigators (PIs), water resources partners and stakeholders to exchange information, share updates and collaborate on remote-sensing applications for water resources management.

The meeting also brought together NASA partners and stakeholders from the U.S. western states in an effort to leverage activities across the newly launched NASA Western Water Applications Office, led by the NASA Jet Propulsion Lab in Pasadena, California, with team members located at other NASA Centers, such as Ames Research Center and Goddard Space Flight Center. As a result, the meeting included project overviews that focused on progress related to development of remote-sensing applications, partner engagement and transition to operations, as well as panel discussions that highlighted the importance of impact assessment, stakeholder communications, lessons learned and emerging topics and priorities for the water resources management community.

NASA Water Resources Program Manager Dr. Brad Doorn opened the meeting with an introduction that highlighted the vision and strategic direction of the program, which was then followed by a series of PI presentations from the NASA Applied Sciences Water Resources portfolio on addressing water resource issues across the U.S. These presentations included 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 and mapping of harmful algal blooms and modeling of nutrient loading.

VIII. COMMUNITY LEADERSHIP

Western States Water Council (WSWC) and Western Water Applications Office (WWAO) Water Information Management Systems (WIMS) Workshop, January 16–18, 2018

The Western States Water Council initiated a Water Information Management System workshop, hosted by the Western Water Applications Office and held at NASA JPL in Pasadena, Calif. Held on January 16–18, 2018, the WIMS workshop provided a collaborative forum to discuss a range of data-management topics with representatives from state water-resource agencies. There were 36 presenters—many of whom were representatives from state agencies—and more than 75 attendees, both on-site and attending remotely via webinar. During the workshop, participants also reviewed results from the WSWC survey of Western State Water Resource Agency Use of Cloud Computing Technology and Platforms. The results from the survey included responses from water management agencies in all 18 WSWC member-states and resulted in a joint report from the WSWC and WWAO published in October 2018. The report summarized current state policies and approaches to the use of cloud-computing resources in water-data management and identified both opportunities and challenges in expanding use of cloud-computing resources. The information provided in the report is valuable in informing approaches to technology transfer from NASA to state agency partners in the western United States.

GRAPEX Annual Meeting and Cover of the Bulletin of the American Meteorological Society (BAMS), March 6–8, 2018

The GRAPEX project annual meeting brought together remote-sensing scientists, growers, viticulturalists, ranch managers, and irrigators to develop new applications to leverage satellite data to advance agricultural water management for vineyards. The workshop was held at E&J Gallo to review results from field validation studies and to discuss development of the ET Toolkit for wine-grape growers. A summary of work to date under the GRAPEX project was also published in BAMS and served as the cover story for the September 2018 issue.

GEOGLOWS Annual Meeting, May 9–11, 2018, the European Centre for Medium and Long-range Weather Forecasting, Reading, United Kingdom

The second-annual Group on Earth Observations Global Water Sustainability (GEOGLOWS) meeting was convened at the European Centre for Medium and Long-range Weather Forecasting on May 9 at 1:30 pm. Attendance at the meeting reached 43 people, with participants coming from 10 countries. This meeting included highlights from the four NASA GEOGLOWS projects. The result of this meeting was the incorporation of the Essential Water Variables as a key task, as well as the commitment by key stakeholders to provide support for project sustainability and program support.

2018 Fall Meeting of the American Geophysical Union

The NASA Applied Sciences Water Resources team co-convened four sessions at the 2018 Fall American Geophysical Union (AGU) Meeting in Washington, D.C., on the topic of Remote Sensing Applications for Water Resources Management, Including Droughts, Floods, and other

associated Water Cycle Extremes. In total, 56 abstracts were submitted to this session which were then assigned two oral sessions and one poster session. The sessions covered both national and international applications of remote sensing for monitoring and management of precipitation, irrigation, drought, flooding, groundwater, soil moisture, evapotranspiration, runoff, and water quality. These sessions provided an opportunity for the NASA Applied Sciences Water Resources community to interact, share ideas, and foster new collaborations across science teams. Associate Program Manager John Bolten also gave an Ignite Talk and Christine Lee gave a Hyperwall talk at the NASA Exhibit Booth. Program Brad Doorn and John Bolten gave interviews for the AGU Narratives series.

IX. MAJOR ACCOMPLISHMENTS

ROSES 2018 A.36 Water Resources Selections

The Water Resources Program implemented 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.

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.

NASA reviewed 109 Step-1 proposals resulting in 46 Step-2 proposals in response to this solicitation—NASA selected 13 for awards, totaling approximately $9 million over three years. 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.

Navajo Drought Severity Tool Implementation (WWAO)

In 2018, the Western Water Applications Office funded a project to advance and deploy the "Drought Severity Evaluation Tool" (DSET) for operational use by the Navajo Department of Water Resources. The task built on work from a recent NASA DEVELOP project. In order to determine how best to deploy drought relief resources, the Navajo Nation requested support from NASA to develop satellite-based tools and data to augment sparse rain-gauge data. DSET combines precipitation data from NASA satellites, drought indices, and on-the-ground rain measurements within a user-friendly web interface. It can enable water managers to quickly calculate precipitation on the Navajo Nation for all chapters, agencies, grazing districts, watersheds, or ecoregions, over any historical time-period in recent decades, in near-real-time, to support decision making about allocation of drought emergency funds to impacted regions.

It could also be extended to other regions in partnership with tribal governments. The WWAO project will further develop the tool and implement it onto Google Earth Engine to calculate and visualize 6-month Standardized Precipitation Index (SPI) estimates. Operational deployment is expected in 2020.

***Soil Moisture Active Passive (SMAP)* Satellite Data Delivered in Google Earth Engine**

The operational global *SMAP*-based soil moisture products developed for the USDA-FAS drought monitoring and crop forecasting was successfully transitioned to Google Earth Engine (GEE). The products are the first model-enhanced global soil moisture dataset available on Google Earth Engine. In addition, customized GEE web-based analytical tools were developed to enable the assessment of global soil moisture variability as a function of land-cover change and to easily estimate drought characteristics such as drought duration and intensity using soil-moisture anomalies, as well as to inter-compare them against alternative drought indicators. Combining the web-based tools with the operational *SMAP*-based global soil-moisture data into the GEE catalog will enable a vast diversity of users to quickly and easily access a suite of products and assess the impact of drought conditions and improve planning related to drought risk assessment and early warning. User statistics provided by Google indicate an average of more than 200 weekly unique users of the *SMAP*-based data products.

X. INTERNATIONAL ACTIVITIES

GEO Global Water Sustainability (GEOGLOWS) Update.

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 those who need information to make better decisions together 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-Danial 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

XI. LOOKING AHEAD

The Water Resources Applications area looks to 2019 as a year of growth, expansion, and strengthening of impact analysis across the program—with a plan to implement impact-analysis

activities and plan for the growth of the Western Water Applications Office, in addition to supporting the 16 high-impact projects plus the new selections from ROSES 2018 solicitation in the portfolio.

XII. APPENDIX

A. Water Resources Project Highlights from 2018

Project: 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: 4

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.

Major accomplishments in CY 2018: A publication in the Proceedings of the National Academy of Science about the effect of a warming climate on snow water equivalent availability in California. The key question was: What is the snow water equivalent (SWE) response to a 1-to-2-degrees C increase in the average winter temperature across the Sierra Nevada? Warmer winters reduce the April 1st SWE volume (Figure 1a) and force its centroid, zc, (Figure 1b) to higher elevations. For 1985–2016, a 1-or-2 degrees C increase in the average winter temperature about the mean leads to ~20 to 40 percent increase in the likelihood of below average SWE (Figure 1a,c) and ~60 to 90 percent increase in the likelihood of a higher-than-average elevation of the April 1st SWE centroid (zc) (Figure 1b,d), respectively.

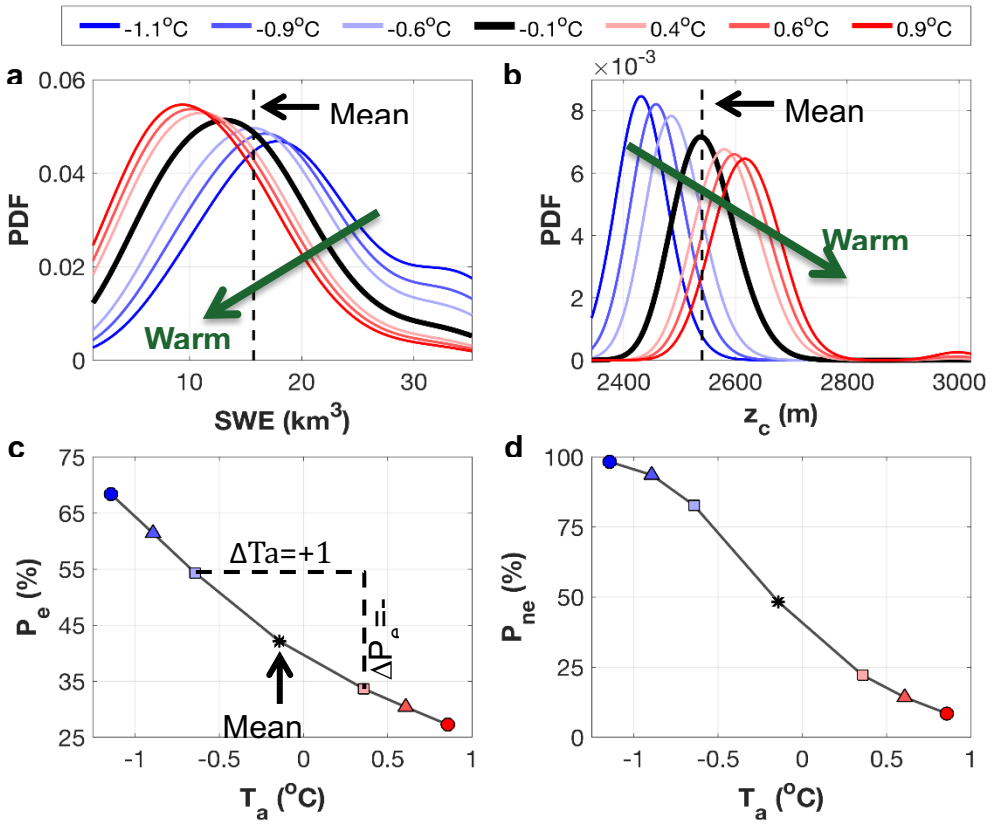

Figure 1: Impact of 1.0, 1.5, and 2.0°C of warming about the long-term mean winter temperature in the Sierra Nevada. a-b) Probability density functions (PDFs) for the Sierra-wide 1 April SWE volume (a) and centroid, z_c, (b) given select average winter temperatures. Limits of x-axes are set to the data limits. c) The exceedance probability, P_e, or likelihood that the SWE volume is larger than the long-term average SWE at different temperatures. d) The non-exceedance probability, P_{ne}, or the likelihood that z_c is lower than its long-term average value given the same temperatures.

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

Principal investigator: Gerald Day, RTI International

Project year: 3

Year-end ARL: 5

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 2018:

- CSU has constructed the Colorado River Basin Goddard Profiling Algorithm (CRB-GPROF), a satellite precipitation retrieval algorithm specific for the Colorado River Basin. Code was developed to produce bias corrected precipitation rates every time there is a new orbit available. This code has been transferred to NASA's Precipitation Processing System to run operationally, and RTI is working to transfer a satellite-gage merging component to CBRFC.
- RTI has calibrated the distributed Snow-17/Sacramento model for the pilot basins, delivered the parametric files to CBRFC, and provided support to CBRFC in setting up the model. CBRFC is running the model operationally in a near-real-time mode.
- RTI has developed an Ensemble Kalman filter framework for the distributed hydrologic model that uses error perturbed forcing to propagate an ensemble of distributed snow model states and updates the states with SNOTEL observations and MODSCAG snow cover. The framework is being applied in a reforecast mode to allow performance comparisons with CBRFC current forecast methods and to support development and validation of the Decision Support System (DSS) component with Denver Water and the Dolores Water Conservancy District.
- USU has configured the Utah Energy Balance (UEB) snow model in an Ensemble Kalman filter and incorporated it as a component of the Research Distributed Hydrologic Model. UEB has been modified to utilize the MODDRFS product to estimate snow albedo during the observed period.
- As part of an Internal Research and Development effort, RTI has developed a generalized optimization framework for ensemble streamflow forecasts using Sampling Stochastic Dynamic Programming. The framework was used as the basis for a DSS to aid Dolores Water Conservancy District in their use of ensemble forecasts. The framework will be used in the development of a decision model for Denver Water next quarter.
- We are working with CBRFC to transfer the technologies to their environment in a way that will allow them to run the new methods in parallel with their existing forecasting method. Reforecasts are being used to provide an objective assessment of the potential improvement in forecast skill over CBRFC's current forecast approach.

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Project: 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: 2

Year-end ARL: 5

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: 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, 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 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

Major accomplishments in CY 2018:

- The project delivered SWE estimates on a bi-monthly basis and arranged monthly conference calls to all project partners and stakeholders beginning in the winter of 2017–18, through early summer 2018.
- The datasets assisted water managers in monitoring conditions in the Sierra Nevada as California was faced with a return to drought with intermittent flooding concerns in 2018.

- Data products are qualitatively being integrated into the CDWR statistical models and CDWR has hired staff to work on quantitative integration. Stakeholders are taking the lead on product ingest and/or contracting the private sector to assist with product generation/ingest.
- The project team met with and interviewed project stakeholders to review initial data products and discuss requirements for delivery of new data products being developed which can improve the water supply analysis.
- Cutting edge paper in the prestigious journal Nature Climate Change by Mountain Hydrology Group member Keith Musselman and others at The National Center for Atmospheric Research (NCAR) about rain-on-snow flooding was published amid many press releases on August 6, 2018.

* * *

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: 1

Year End ARL: 3

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

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 and *GRACE* satellite data.

Major Accomplishments in 2018:

- GEO Plenary: In November of 2018, project Co-I's Norm Jones and Jim Nelson traveled to Kyoto, Japan, to attend the 2018 Group on Earth Observations (GEO) Plenary to deliver presentations related to global streamflow forecasting, web applications for groundwater sustainability, and our GEOGLOWS App Warehouse.
- Collaboration – Brazil: We have coupled the COSMO weather prediction model with the RAPID river routing model to generate 174-hour streamflow forecasts for each reach in La Plata area twice per day. We have created a prototype app for our partners to use to view and download these forecasts.

- 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 which 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 with this development, focusing on automated app install to simplify acquisition and use of apps by our partners in Latin America.

Relevant project websites/links: http://worldwater.byu.edu/

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Project: 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 among 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), US 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 2018:

- Weekly *Sentinel-3* Ocean and Land Color Imager (OLCI) data products were provided to CyAN collaborators

- Assessment metrics for quantifying cyanohabs (extent, frequency, magnitude) were developed and tested for reporting at individual water body levels and states
- Three trainings were conducted on project software, including ArcGIS with RSTools, CyAN mobile applications, and SeaDAS
- Examples of end users featuring satellite products / imagery as a result of CyAN engagement:
    - Utah used the satellite imagery for support on Utah Lake (https://deq.utah.gov/health-advisory-panel/harmful-algal-blooms-habs/utah-lake-jordan-river-canals-algal-bloom-monitoring-2018) and Panguitch Lake (https://deq.utah.gov/water-quality/panguitch-lake-algal-bloom-monitoring-2018).
    - Wyoming used imagery in Lake Viva Naughton and Kemmerer City Reservoir (https://wgfd.wyo.gov/Regional-Offices/Green-River-Region/Regional-Fish-Information/Recreational-use-adivsory-issued-for-Kemmerer-City)
    - Wyoming's exploration with satellite imagery is also noted in Harmful Algal Bloom Action Plan for publicly accessible lakes and reservoirs of Wyoming (http://deq.wyoming.gov/media/attachments/Water%20Quality/Nutrient%20Pollution/Harmful%20Algal%20Blooms/2018-0606_Wyoming_HAB_Action-Plan.pdf).

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

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

Principal investigator: Josh Weiss, Hazen and Sawyer

Project year: 4

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

Major accomplishments in CY 2018:

- Successfully implemented generalized linear mixed effect model algorithm with alternative, non-normal distributions
- Revised prototype software and began scoping dashboard for data visualizations
- Conducted additional modeling and analysis for water quality parameters for the Northern Water and NYC DEP watersheds
- Began preparation of a manuscript for submission in a peer-reviewed technical journal (*Environmental Science & Technology* or similar)
- Presented 4 papers at three industry and technical conferences (American Water Resources Association Annual Meeting, Water Quality Technology Conference, and American Geophysical Union Annual Meeting)
- Discussed potential additional end user applications with five utility and water agency stakeholders

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

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Project: 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: 2

Year-end ARL: 5

Project description: We propose to develop a global agricultural monitoring tool, with a focus on providing early warning of developing vegetation stress for agricultural decision-makers and stakeholders at relatively high spatial resolution (5-km). This tool is based on remotely sensed estimates of evapotranspiration, retrieved via energy balance principals 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 provides operational production and retrospective analyses back to 1979.

Major accomplishments in CY 2018:

- Global ESI based on only MODIS-TIR LST has been running in near-real-time at NASA SPoRT since the beginning of 2018. Near real-time (NRT) ESI products have been made available to project stakeholders and additional stakeholders who became interested in

evaluating the products after the start of the project. Made changes to the color curves used to display ESI to accommodate those with color blindness (Figure 1).

- NRT Global ESI (TIR-only) products have been made available to NASA SERVIR and are currently hosted on their Amazon Web Services cloud platform (http://catalogue.servirglobal.net/Product?product_id=198) and within their ClimateSERV display portal. This has allowed ESI products to be made available to all NASA SERVIR hubs and to the broader scientific community for use and evaluation, especially through seamless integration with GIS-based platforms.
- Integration of IMERG Ka-band observations—will streamline processing of microwave land surface temperature (MW-LST) for MW-ESI product—working on downscaling MW product to produce 0.05 MW-LST data to be consistent with TIR-LST—NRT processing system to ingest, map and generate MW-LST is currently being transitioned into the global ESI system at NASA SPoRT). NRT MW-ESI products are planned to become available in spring of 2019.

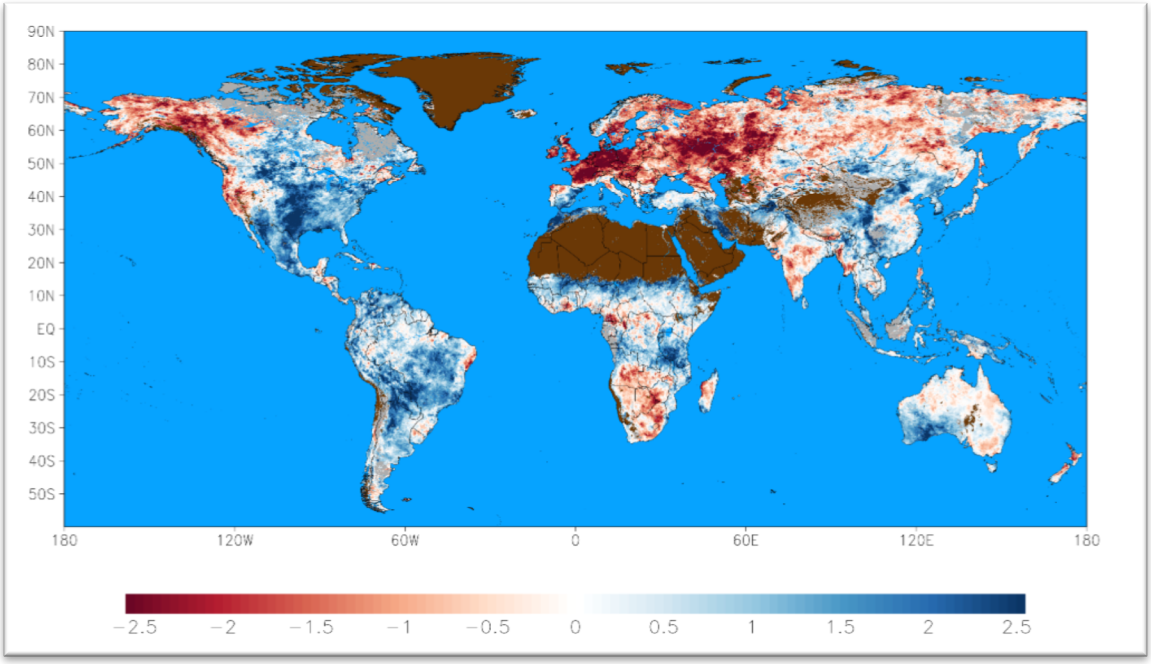

Figure 1. Global ESI for December 1, 2018 using the new color curve.

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

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

Principal investigator: Richard Smith

Project year: 2

Year-end ARL: 4

Project description: The goal of the proposed project is to enhance the USGS SPARROW (Spatially Referenced Regression on Watershed Attributes) water quality Decision Support System (DSS) with a remote sensing-driven seasonal dynamic SPARROW models to aid environmental managers to more effectively manage the waters, habitats and resources under their responsibility. This DSS will provide end users with an on-line tool with which they can make management decisions regarding distribution of resources, mitigation activities, land use restrictions, and water quality alerts.

End users/partners: Mobile Bay National Estuary Program, Tampa Bay National Estuary Program, Sarasota Bay National Estuary Program, Weeks Bay National Estuarine Research Reserve, North Inlet-Winyah Bay National Estuarine Research Reserve

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

Major accomplishments in CY 2018:

- Finished building a preliminary dynamic SPARROW data1 file and a working control file for the entire study region (Southeastern U.S.) 2000-2014. This file is sufficient for construction of preliminary models for all five project (end-user) watersheds. Several preliminary models have been calibrated.
- Completed steady-state version of MODFLOW groundwater model to be integrated with SPARROW models of total nitrogen.
- Progress was made in refining the R-SPARROW and R-Shiny software packages that will be used in web-based visualization of SPARROW models and predictions.
- Approximately 80 percent of the planned remote sensing data sets have been acquired and processed, and 75 percent have been incorporated into the SPARROW data1 file (1st bullet).
- Project participants presented a total of five project-related papers and/or posters at the Fall American Geophysical Union Meeting, the Alabama Water Resources Meeting, and the NASA Water Resources Program Meeting.

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Project: 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: 2

Year-end ARL: 4

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 decision 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 best water management 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 US. Irrigation consulting and management companies in the US and New Zealand.

Data sources, models, technology: APEX and SWAT models; satellite data from MODIS, *Landsat*, *GPM*, *Sentinel*, ECOSTRESS; meteorological data from NCEP and NASA, ground-based measurements from project partners.

Major accomplishments in CY 2018:

- Refinement of retrieval algorithms used to derive crop biophysical parameters (e.g., vegetation density, phenology) from remote sensing data;
- Calibration of the crop model at farm scale using remote sensing information;
- Preliminary validation of the system over Iowa using USDA yield information at county scale;
- Ongoing adaptation of the system for near real time applications (based on near real time MODIS, VIIRS and *Landsat* products);
- Ongoing development of protocols for testing the value of our products in stakeholder operations. The use of near real time products is tested in Canterbury, New Zealand for irrigation management;
- Ongoing development of the project website (http://agwater.umd.edu) to provide stakeholders with direct and near real time access to project outcomes.

Relevant project websites/links: http://agwater.umd.edu

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Project: Enhancing the USDA Global Crop Production Decision Support System with NASA *Soil Moisture Active Passive* (*SMAP*) Satellite Observations

Principal investigator: John Bolten, NASA Goddard Space Flight Center

Project year: 4

Year-end ARL: 8

Project description: The primary goal of this project is to provide NASA products, tools, and information to the USDA Foreign Agricultural Service to advance agricultural productivity forecasting ability of the CADRE crop forecasting system.

End users/partners: USDA Foreign Agricultural Service (USDA-FAS)

Data sources, models, technology: *SMAP*, ASCAT, *GPM*, *SMOS*, Palmer Soil Moisture Model

Major accomplishments in CY 2018:

- Tested *SMAP* system rescaling algorithm and new climatology analysis of *SMAP* surface soil moisture with updated *SMAP* Version 5 algorithm
- Continued vetting and refining of soil moisture products and *SMAP*- based system by stakeholders
- Thorough end-of-season yield analysis was completed using the integrated soil moisture product and other model- and satellite-based products
- Several cases demonstrating impact of *SMAP*-based system and thorough assessment of new data assimilation statistics were completed

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

Principal investigator: Matt Rodell, NASA-GSFC

Project year: 4

Year-end ARL: 6

Project description: The project is generating and refining 1–3-month soil-moisture and groundwater wetness/drought forecast maps for the continental U.S. through the integration of *GRACE*, *GRACE-FO*, and other observations within a land surface model that is forced into the future by downscaled seasonal climate predictions. The products will be distributed to multiple end users by the National Drought Mitigation Center, and their value for streamflow prediction and reservoir management are being tested by our partners at NOAA's North Central River Forecast Center and the Army Corps of Engineers.

End users/partners: National Drought Mitigation Center; NOAA North Central River Forecast Center; U.S. Army Corps of Engineers

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

Major Accomplishments in CY 2018:

- Resources for the Future developed a framework for assessing the Value of Information resulting from our project, which was presented during the Impact Assessment meeting/telecon on March 13th.
- NASA-GSFC completed hindcasts with both unaltered and downscaled GEOS-5 forcing.
- Johns Hopkins University tested routing of the hindcast model output runoff with the HyMAP runoff routing scheme.
- NASA-GSFC developed the capability to assimilate University of Texas at Austin's low latency (quick look) *GRACE/GRACE-FO* product. The approach will be optimized after *GRACE-FO* data become available.
- Resources for the Future presented its framework for assessing the Value of Information of our wetness/drought indicator and forecast products for reservoir operations to our USACE partners on June 22, 2018, which resulted in those plans being refined and specific events/locations being selected for study.
- NASA-GSFC delivered historical wetness/drought assimilated outputs and forecasts to NDMC and NOAA's North Central River Forecast Center (NCRFC).
- Johns Hopkins University continues to refine and compare multiple forecast downscaling approaches.
- NOAA/NCRFC developed a forecast model version to run retrospective simulations that incorporate *GRACE* data assimilation-based soil wetness conditions, in order to quantify the added value they provide.
- Early results from NOAA/NCRFC's testbed show that the *GRACE*-based soil moisture indicators provide valuable information beyond their baseline soil moisture information, resulting in an improved flood forecast for 2011.
- NOAA/NCRFC is investigating ways to incorporate historical *GRACE* data-assimilation groundwater and SWE, in addition to soil moisture, into their runoff/flood forecasts.
- University of Nebraska-Lincoln is reviewing sample (historical) drought forecasts and developing a map template and new NDMC webpage for distributing the drought forecast products.
- USACE is working with NOAA/NCRFC to evaluate *GRACE* data-assimilation-enhanced streamflow forecasts for reservoir operations, focusing on the spring of 2011.
- NASA-GSFC demonstrated that *GRACE*-data assimilation results in 30–90-day groundwater forecasts that are better than those resulting from the open loop (no data assimilation), using historical groundwater data and drought maps for evaluation.

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

Principal investigator: Hyongki Lee, University of Houston

Project year: 1

Year-end ARL: 4

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

End users/partners: National Center for Water Resources Planning and Investigation (NAWAPI) of Vietnam, National Hydro-Meteorological Service (NHMS) of Vietnam

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

Major accomplishments in CY 2018:

- The project team carried out a training workshop at NAWAPI's Headquarters in Hanoi, Vietnam during March 6–7, 2018 for about 30 participants from Vietnam's and Cambodia's stakeholder agencies. The team also chaired a session "Earth Observations for Water Management" with Dr. Pham Nga from Vietnam National Satellite Center during Vietnam Water Week (VACI) 2018.
- The project team tested and confirmed feasibility of forecasting inundation extents from *Jason-3* altimetry from Empirical Orthogonal Function (EOF) analysis of *Sentinel-1* images over lower Mekong.
- The project team has developed an ensemble linear-regression method for estimating river discharges using altimetry-derived river level changes (Kim et al., RSE, 2019) and confirmed feasibility of applying the method to the decommissioned gauges in lower Mekong.
- HYPE (Hydrological Predictions for the Environment) model has been set up over the entire Indochina regions and been initially calibrated using available in-situ river discharges.

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

Principal investigator: Venkat Lakshmi

Project year: 1

Year-end ARL: 5

End users/partners: Karnataka Department of Water Resources

Project description: The Ganga basin is one of the largest river basins in the world, with a total area nearly about 1 million km^2. The main purpose of this research is to compare performance of different precipitation inputs in correctly representing the hydrology of the selected basin. For the preliminary analysis, we have selected the Sone basin for modelling the hydrology using the Soil and Water Assessment Tool (SWAT), considering the availability of discharge data. The majority of the datasets used in the study are publicly available online to ensure that the work can be easily reproduced for further studies. SRTM (Shuttle Radar Topography Mission) 90-m DEM, GIAM (Global Irrigated Area Mapping) IWMI land-use map coupled with irrigated area, FAO (Food and Agricultural Organization) soil maps, precipitation inputs from IMD (Indian Meteorological Department), *TRMM (Tropical Rainfall Measuring Mission*) and *GPM (Global Precipitation Measurement),* discharge data provided by a flood observatory lab at University of Colorado and climatology from the SWAT database were provided as input to the SWAT model for Sone basin.

Three different models were simulated; first with IMD precipitation inputs calibrated for 2000-2008 and validated for 2009–2015, second with *TRMM* inputs calibrated for 2000–2008 and validated for 2009–2017 and third with *GPM* inputs with *TRMM* calibrated model for 2015–2017. Results show that model with *GPM* inputs (R2=0.78) performed much better than the model with *TRMM* (R2=0.58) and IMD (R2=0.52) inputs. One reason that *GPM* inputs performed better than others is due to its finer resolution at 0.1° compared to 0.25° of *TRMM* and IMD, allowing it to capture the rainfall pattern in greater detail. Current study was performed at monthly timescale and so further work includes running the simulation at daily and annual timescales. We further plan on to include the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) precipitation dataset in the study and extend the similar analysis for two more sub-basins of the Ganga River basin

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

Major Accomplishments in CY 2018:

- Presentation at AGU Fall Meeting:
  Mondal, A., V Lakshmi, S Jain and P Kansara, Snow Cover Distribution and Variation using MODIS in the Himalayas of India, American Geophysical Union Fall Meeting, December 11-15, 2017, New Orleans, LA
  Kansara, P. and V Lakshmi, Water quality and quantity assessment using SWAT in the Ganga- Brahmaputra River Basin, American Geophysical Union Fall Meeting, December 10-14, 2018, Washington DC

- Publications in progress: *Evolution of groundwater resources in response to changes in rainfall and vegetation cover across major river basins in India,* to be submitted to Journal of Hydrology.

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

Principal investigator: Christine Lee

Project year: 2

Year-end ARL: 4

Project description: This project will advance the capability of multiple stakeholders of California' water resources to routinely access and utilize Earth observations-based water-quality products to support operational or institutional decision making related to water-management practices. The State Water Project, managed by the California Department of Water Resources, conveys water through the San Francisco Estuary and Delta from northern California/western Sierras to the Central Valley and Southern California. One of the key considerations in the conveyance of this water supply are water-quality issues, as they are used to understand degraded habitat conditions for endangered species, such as the Delta smelt. As such, there has been significant investment decisions made to better understand the linkages between water quality, Delta smelt, and water operations, towards minimizing any further impacts on their ecosystem and survivability due to water-management decisions. Other key water-quality issues that impact other water resources decisions include managing flows for water temperature, promoting beneficial phytoplantkon blooms, and controlling for harmful algal blooms. This project will deliver water temperature, turbidity and chlorophyll products, and work with partners to integrate these products into their efforts to address these water-quality/water-resource issues.

End users: Metropolitan Water District, California Department of Water Resources

Data sources, models, technology: *Landsat 8*, *Sentinel-2A/B*, AVIRIS

Major accomplishments in CY 2018:

- Fully processed all *Sentinel-2* data and *Landsat 8* to turbidity, chlorophyll and delivered to 34N baydeltalive.com
- Significant progress on airborne (AV-NG) derived turbidity-product evaluation
- Established and completed workflows and pipeline for comparison of *Sentinel-2*-derived turbidity to in-situ station data
- Developed application prototype for visualizing satellite and in-situ data

- Eight cruises conducted in total: three in San Francisco Bay Delta (SFBD), one at Oroville and two at SLR
- Beginning to evaluate *Landsat 8* and ECOSTRESS water surface temperature products in the SFBD

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

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Project: 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: 2

Year-end ARL: 5

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, *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.

End users/partners: E&J Gallo Winery, National Grape & Wine Initiative, Almond Board of California

Data sources, models, technology: We are combining Earth observations from NOAA-*GOES*, VIIRS, MODIS and *Landsat* 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 CY 2018:

- The data fusion/ET toolkit with some refinements reliably estimated daily ET over the three Grape Remote-sensing Atmospheric Profile and Evapotranspiration eXperiment

(GRAPEX) vineyard experimental sites, having a significant north-south climate gradient and containing different vine varieties.

- There were 13 manuscripts submitted for the GRAPEX Special Issue in *Irrigation Science*. All except one have been accepted for publication with several currently available as on-line publications. A GRAPEX Special issue volume containing all the publications is planned in 2019.

- Weekly ET estimates have been used to schedule irrigation at Ripperdan 720 VRDI (variable rate drip irrigation) vineyard during the 2018 growing season using different irrigation scheduling protocols and comparing to the "business-as-usual" ET/irrigation scheduling system used by E&J Gallo. Initial results indicate there is a potential for significant water savings using the data fusion/ET toolkit. Impacts on grape yield and quality are now being analyzed.

Publications

- Kustas WP, Anderson MC, Alfieri JG, Knipper KR et. al. (2018a) The Grape Remote sensing Atmospheric Profile and Evapotranspiration eXperiment(GRAPEX). *Bull. Am. Meteorol. Soc.* 99(9):1791–1812. https ://doi.org/10.1175/BAMS-D-16-0244.1
- Knipper, KR, Kustas, WP, Anderson, MC et.al. (2018) Evapotranspiration estimates derived using thermal-based satellite remote sensing and data fusion for irrigation management in California vineyards. *Irrig. Sci.,* 2018, https ://doi: 10.1007/s00271-018-0591-y
- Kustas WP, Alfieri JG, Nieto H, Gao F, Anderson MC, Prueger JH, Wilson TG (2018b) Utility of the two-source energy balance model TSEB in vine and inter-row flux partitioning over the growing season. *Irrig Sci.* https ://doi.org/10.1007/s0027 1-018-0586-8
- Nieto H, Kustas WP, Torres-Rúa A et. al. (2018) Evaluation of TSEB turbulent fluxes using different methods for the retrieval of soil and canopy component temperatures from UAV thermal and multispectral imagery. *Irrig Sci.* https ://doi.org/10.1007/s0027 1-018-0585-9

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

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Project: 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: 2

Year-end ARL: 6

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*, VIIRS, METRIC and SIMS, Google Earth Engine, Web visualization and data dissemination, open-source code repository

Major accomplishments in CY 2018:

- Desert Research Institute (DRI), California State Monterey Bay, University of Idaho, and NASA project investigators successfully held their second end-user *Remote Sensing of Evapotranspiration* workshop at DRI from June 26-29, 2018 (www.dri.edu/et-workshop-2018)
- Finalized the development and implementation of standalone Python model versions of METRIC and SIMS (pyMETRIC and pySIMS) so that state water agencies can run models on local computers
- Developed geodatabase of field-level results for each study area.
- Shared all software on the open GitHub repository - https://github.com/DRI-WSWUP; https://github.com/orgs/Open-ET. All water agency partners have downloaded, tested, and implemented pyMETRIC, pySIMS, and pyQAQC weather software programs
- Developed draft user interface to provide monthly and seasonal raster data and field averages for different years of interest.
- Collaborated with NASA, non-profit, and various university and government partners to leverage this work and create the OpenET project - www.etdata.org

Relevant project websites/links: www.etdata.org; www.dri.edu/et-workshop-2018; 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: 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: 4

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 8 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

Major accomplishments in CY 2018:

- Ensemble seasonal, sub-seasonal and short-range forecasting completed for the Omo-Gibe basin.
- Noah-MP hydrologic model setup and calibrated using GLEAM ET completed. Seasonal reservoir inflow forecast using NMME completed.
- HIDROTERM optimization-model development and application for the reservoir cascade completed.
- All technology transfer workshops planned in Ethiopia have been completed successfully.
- Reservoir inflow forecast and optimization of reservoirs at sub-seasonal and short-range time scales planned.

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

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

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

Project year: 4

Year-end ARL: 9

Project description: The objective of this work is to develop a seasonal water deficit forecasting system that is relevant for the U.S. Agency for International Development (USAID) and U.S. Army Corps of Engineers (USACE)in the Middle East and Africa. These activities are based on existing/mature NASA and NOAA Earth-science capabilities. The primary work has two goals: 1) align and improve the USAID's Famine Early Warning Systems Network (FEWS NET); and, 2) describe water supply and water supply anomalies in the region of interest through a suite of indicators.

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

Data sources, models, technology: GEOS-S2S, CFS seasonal forecasts, LIS, Catchment Land Surface Model (CLSM), Noah-MP land surface model, ASCAT, *SMAP*, *GRACE*, MERRA2, CHIRPS

Major accomplishments in CY 2018:

- Routine seasonal forecasts, including both GEOS-S2S and ensemble streamflow prediction (ESP) forecast methods, were set up to generate close to near real-time hydrological forecasts for end-user partners in USAID's FEWS NET community. These routine runs have been used to generate live forecast products of agricultural drought indicators, such as soil moisture percentiles, provided via a project-based public website developed for our end-users: https://lis.gsfc.nasa.gov/projects/fame

- Seasonal hindcasts of multi-model simulations have been generated and evaluated for different regions of Africa and for the whole continent as well. More than 30 years of GEOS-S2S hindcasts have been generated for the entire African continent and the Middle East region for the different models. The hindcasts are used in helping generate the forecasted drought indicators.

- FEWS NET regional scientists in Africa began using the routine products in August of 2018 in their regional forecast assessments and monthly feedback to USAID food security analysts. Tutorials have been provided to the FEWS NET regional scientists on how to use the Forecasting for Africa and Middle East (FAME) forecast products and FLDAS monitoring products. Project team members have received feedback from the

regional scientists to enhance existing products and provide additional forecast products to support their decision-making processes.

- The NASA-based FAME hydrological forecast system has now been demonstrated, fully documented and presented to the end-users. In July of 2018, a two-day tutorial was provided to all end-users on the project, including ICBA and USACE, to present the project background, describe different aspects of the system, summarize lessons learned, and address user questions.

- The full system has been automated end-to-end, from the bias-correction and downscaling of the seasonal dynamical forecast inputs to the postprocessing of the combined multi-model hydrological variables and agricultural drought indicators.

- The full end-to-end FAME forecasting system has been implemented and used by the FEWS NET team to provide the final forecasted products to the monthly FEWS NET forecast technical review meetings. This effort has secured continued funding from USAID to maintain the system and products for FEWS NET applications.

- The seasonal forecasts have been benchmarked against the baseline ESP climatological forecasts and evaluated with observations, including streamflow gages, satellite-based products (e.g., MODIS-based NDVI, *SMAP* soil moisture), and end-user-based food and water security maps, e.g., FEWS NET's food security classification maps.

- 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.

Relevant project websites/links:
https://lis.gsfc.nasa.gov/projects/fame
https://appliedsciences.nasa.gov/content/13-water13-0010
https://lis.gsfc.nasa.gov/blog/fame-project-research-applications-ongoing-success-story

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

Principal investigator: Jennifer Jacobs, University of New Hampshire (UNH)

Project year: 4

Year-end ARL: 7

Project 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 North Central River Forecast Center's (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/partners: North Central River Forecast Center

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

Major accomplishments in CY 2018:

- Provided prototype satellite snow water equivalent (SWE) maps and times series distributed to NCRFC on a weekly basis during winter of 2017–18 for use during forecasting. Results from a strictly physically-based SWE algorithm were distributed to NCRFC on a daily basis during the winter of 2017–18 for use during operational forecasting. Postdoctoral researcher R. Schroeder visited the RFC during the 2018 snowmelt season to assist RFC senior forecaster B. Connelly with the application of the UNH satellite SWE products in the Community Hydrologic Prediction System decision-making system.
- Transitioned the prototype application system into the partner's decision-making system. Development of the UNH satellite product workflow was completed in October 2018. The workflow was then thoroughly tested at UNH and upon completion disseminated for use at the RFC. Postdoctoral scientist R. Schroeder has completed on-site visits at the NCRFC to present the workflow and satellite products developed.
- The UNH team and the NCRFC forecasters are working to have the NCRFC lead the use of the system and the interpretation of products during the 2018/2019 snowmelt forecast period. Enhancements being made to the satellite SWE products are daily QA/QC flags for wet-snow detection and updating to a NetCDF format for automatic ingesting into the decision-making environment. Results from winter season 2017 compiled and shared with NCRFC.
- Developed strategy to compare snow observations from traditional airborne gamma, USACE snow surveys, and ground sites to satellite observations.
- The system's ability and improved results have been presented to many of our end-user partners, is currently being documented for papers, and presented at regional and national conferences.

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Project: 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: 1

Year-end ARL: 2

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 US Army Corps of Engineers (USACE) Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) Model. These 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: US 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

Major accomplishments in CY 2018:

- Created EWVs for the Indus River basin for 2001 to 2017 at a 500-m scale including snow-cover fraction, snow-grain size, dust-radiative forcing, snow albedo, SWE, and melt from snow on ice, exposed glacier ice, and snow on land.
- Validated gap filled (i.e., under clouds) fractional snow-cover with distributed ground-data showing a root-mean-square error (RSME) of 7 percent to 11 percent in the melt season, with a bias of 3 percent.
- Validated our albedo product with three in-situ stations. Our remotely sensed albedos have a 5 percent RMSE with no bias.
- Analyzed snow cover days in the Indus River from 2001 to 2017 basin and found a decreasing trend, but one that was not statistically significant over this time period.
- Demonstrated our SWE reconstruction methods combined with machine learning can be used to estimate near-real-time SWE and melt in a publication.

- Engaged USACE and Pakistani partners regarding integration into High-End Computing (HEC) modeling framework

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Project: The Global Reservoir and Lake Monitor (G-REALM): Sustained water level monitoring for Agriculture, Regional Security, and Inland Fisheries

Principal investigator: Charon Birkett, University of Maryland

Project year: 2

Year-end ARL: 9 (*Jason-3* data set); 3 (*Sentinel-3A* data set)

Project description: The objective of this project is to provide lake-level products in a near real-time framework. In addition, it aims to expand the current time line of merged products via integration of historical and future multi-platform data sets. These include the historical ESA/ISRO/CNES ERS, *Envisat* and SARAL datasets, and the future ESA/*Sentinel-3A* and NASA/CNES *Jason-3* data set

End users/partners: USDA Foreign Agricultural Service (FAS), US Army Corps of Engineers (USACE/ERDC)

Data sources, models, technology: Satellite radar altimetry data sets including the NASA/CNES *TOPEX/Poseidon*, *Jason-1, Jason-2, Jason-3* series and the ESA/ISRO/CNES ERS, *Envisat*, SARAL, and *Sentinel-3A* series

Major accomplishments in CY 2018:

- Operationally extended the *TOPEX/Jason* series of surface water-level products with data from the *Jason-3* mission. Also, the historically extended time series (back to 1992 where data is available) was also upgraded via an extensive validation exercise. This exercise placed great weight on achieving the highest quality multi-decadal multi-platform series—the 25-year record acting as a new climatic index. Due to the revised on-board tracking logic and improved global DEM, and the enhanced ground data processing, monitoring of the lakes by the latest *Jason* instruments is proving exceptional.
- Created new and preliminary *Jason-2/Jason-3* surface water-level products for a subset of the proposed wetland regions.
- Developed the software and associated satellite track/coastline intersection information necessary for the production of new operational products from the *Sentinel-3A* satellite mission. These will be provided at a new, 27-day resolution and be extended back in time using the historical 35-day ESA data sets. Combined these will form a new (roughly) monthly resolution series.

- Created a new website which will function in 2019 as a secondary source for the lake/reservoir products and be a primary source for the new wetland products.

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Project: Towards Operational Water Resources Management in South Asia Exploiting Satellite Geodetic and Remote Sensing Technologies

Principal investigator: Faisal Hossain, University of Washington

Project year: 5 (final year)

Year-end ARL: >7 (3 applications are ARL9, 1 is ARL7, 1 is ARL5/6)

Project description: To empower water-management agencies of Pakistan, Bangladesh, Nepal, and Bhutan at 30–180 day horizons using geodetic and remote-sensing technologies and models through the following objectives:

1) Satellite Precipitation and GCM-based forecasting (up to 180 days) of anomalies of ***water availability*** using hydrologic model for Ganges-Brahmaputra (GB) and Indus basins water-management stakeholder agencies.

2) *GRACE* and altimetry data (*JASON-2/-3*, *AltiKa*, *Cryosat-2*, *Sentinel-3 satellites*, and *ICESat-2*), ERA-Interim/MODIS based monitoring/projection of **glacier *mass balance***, ***elevation change*** for selected glaciers, and ***snow extent/depth change*** for Indus, Nepal/Bhutan water management stakeholder agencies.

3) Satellite altimetry (*JASON-2/-3*, *AltiKa*, *Cryosat-2*, *Sentinel-3*) based monthly-to-3-monthly monitoring/projection of storage anomalies of ***surface-water*** artificial reservoirs for Indus water management agency.

4) *GRACE*-based monthly-to-seasonal monitoring/projection of ***ground-water storage*** anomalies with sub-monthly frequency of updating for Indus and GB basin stakeholders

5) Satellite altimetry-based ***river-level*** forecasting in the Ganges, Brahmaputra, and Indus basins in near real-time made available at common web geo-portal.

End users/partners: Pakistan Council of Research in Water Resources, Pakistan Agricultural Research Council, Bangladesh Water Board, Department of Hydrology and Meteorology-Nepal, Water Resources Planning and Investigation (NAWAPI), Ministry of Natural Resources and Environment in Vietnam, Bangladesh Flood Forecasting and Warning Centre, and others.

Data sources, models, technology: NMME (GCM) forecast forcings (seasonal), GFS weather forcings (10-15 days), *GRACE*, *GPM* precipitation data, *JASON-2/3*, *AltiKa*, Variable Infiltration Capacity (VIC) Hydrologic Model; Smart phone apps

Major accomplishments in CY 2018:

- Scaling up process for smart irrigation tools for food-water security at 30–180-day timescales to South and Southeast Asia with NASA and NOAA observations.
- Implemented the NOAA GFS based surface water forecast at 10–15-day timescales, useful for flood forecasting.
- Implementing reservoir monitoring tool for multiple agencies in Pakistan, Nepal, and Bangladesh.

Publications

- Hossain, F., M. Bonnema, N. Biswas, S. Ahmad, B. Duong, and N. D. Luong (2019), When floods cross borders, satellite data can help, *Eos*, 100, https://doi.org/10.1029/2019EO115775
- Bonnema*, M. and F. Hossain (2019) Assessing the Potential of the Surface Water and Ocean Topography Mission for Reservoir Monitoring in the Mekong River Basin, *Water Resources Research* (DOI:10.1029/2018WR023743) https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018WR023743
- Sikder*, S. and F. Hossain (2018) Improving Operational Flood Forecasting in Monsoon Climates with Bias-corrected Quantitative Forecasting of Precipitation, *International Journal of River Basin Management*, https://doi.org/10.1080/15715124.2018.1476368
- Biswas*, N., F. Hossain, M. Bonnema*, H. Lee and M.A. Okeowo (2018) A River Morphology based Altimeter Height Extraction Technique for Dynamically Changing Rivers of South and South-East Asia, Remote Sensing of the Environment, vol. 221, pp. 24-37 (https://doi.org/10.1016/j.rse.2018.10.033)

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B. Abbreviations & 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