Applying Earth Observations to Water Resources Challenges

Christine M. Lee, Aleix Serrat-Capdevila, Naveed Iqbal, Muhammad Ashraf, Benjamin Zaitchik, John Bolten, Forrest Melton and Bradley Doorn

Abstract Since 2007, significant strides have been made to build the applied research and Earth observations (EO) capacity building community and develop pathways for NASA and Earth observations to help address challenges in water resources. Water is both a critical research topic (e.g. understanding the global water cycle) as well as a critical resource for civilization. As a result, there is a consensus that information about water availability could be valuable for improved management and for water security. The biggest challenge in developing useful applications is finding a way to translate research products, intended to address research questions, to applications that can yield a societal benefit. This chapter addresses the current challenges and future prospects of earth observing systems in the field of water resources.

C.M. Lee (✉)
NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
e-mail: christine.m.lee@jpl.nasa.gov

A. Serrat-Capdevila
University of Arizona, Tuscon, AZ, USA

N. Iqbal · M. Ashraf
Pakistan Council of Research in Water Resources, Islamabad, Pakistan

B. Zaitchik
Johns Hopkins University, Baltimore, USA

J. Bolten
NASA Goddard Space Flight Center, Greenbelt, USA

F. Melton
Cooperative for Research in Earth Science and Technology,
NASA Ames Research Center, Moffett Field, USA

B. Doorn
NASA Headquarters, Washington, DC, USA

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1 Overview and Current Status

Scientists from remote sensing and capacity building communities have made significant progress in applying satellite data and hydrologic models to address a range of water resource management challenges. Much of this progress occurred following the release of the Earth Science and Applications from Space ("the Decadal Survey") in 2007, which identified priority areas for Earth Science, among which were Earth observations for water-related missions (NRC 2007). The Decadal Survey also underscored the importance of societal benefit and applications (NRC 2007). The convergence of this movement towards building capabilities to understand the global hydrologic cycle and the increasing awareness and understanding of water security issues (United Nations 2015) uniquely position the Earth observations and remote sensing communities to, through applications, provide direct support to addressing water resources challenges. However, while there is consensus that water availability information could be valuable for improved management and for water security (GEOSS 2014), the process for doing so is fraught with numerous challenges. For example, finding an appropriate way to translate data, originally intended to address research questions, to applications that can yield direct societal benefits, is among the most difficult challenges faced by the research-to-operations community. Barriers to this translation are often related not just to technical capacity, but also institutional, organizational, and resource (such as access to infrastructure) capacity and the need to build a common language among team members around a partnership or project.

Currently, there are 18 NASA Earth observing missions that enable scientific insights into the water cycle and also provide useful information to those facing water-related challenges. One prime example of this is in the United States: the U.S. Drought Monitor (USDM) has been an important activity that integrates various datasets to reflect drought conditions. USDM also utilizes and references satellite data to communicate and illustrate the onset and extent of drought events, including the flash drought in the central U.S. in 2012, and the ongoing multi-year drought in California and Western U.S. (National Drought Mitigation Center et al.).

The following case studies represent science applications development that look to address critical water security issues in East Africa (Mara Basin, Nile River Basin), South Asia, and with a global lens. These case studies prioritize partnership development and capacity building, citing such efforts as essential to enabling improved access to and use of Earth observations-based information for their respective decision contexts.

The two key challenges in working in the water resources domain include the following:

1. Water basins cross political boundaries—that is, where water is contained and available is different from how water is managed and treated. Hydrologic boundaries, which can also vary based on whether one is considering water supply on land surfaces or subsurface, are not the same as management boundaries. This issue exists in the U.S., where water is transported across state boundaries to support cities/populations that are hundreds of miles away from its

watershed of origin. This is also an issue in transboundary water basins in, for example, the Nile River in East Africa or the Mekong in Southeast Asia, which span multiple countries. Critically, management decisions, such as the construction of dams, can impact neighboring countries sharing that basin.

2. Water security is dependent on how much water is available, and water availability is dependent on hydrology (what is physically present and accessible) and demands—i.e., who is using water and for what purpose (drinking, sanitation, agriculture, municipal, and industrial), which is also closely tied to infrastructure and development. Security as it relates to freshwater availability is also extremely vulnerable to weather and climate conditions, including changes in precipitation seasonality and inter-annual variability (Feng et al. 2013), precipitation type/phase (rain vs snow) (Barnett et al. 2005), and extremes such as floods and droughts.

Other critical challenges for this community include

3. Understanding how and what water-related information is useful;
4. Bridging the research to operations gap; and
5. Resources to fund activities on the partner or user end can be difficult to obtain

The following case studies examine how applied scientists and researchers have facilitated the use of Earth observations to develop improved data products and support water management practices.

2 Case Study 1. East Africa Mara Basin (2011-present)

Aleix Serrat-Capdevila

The *SERVIR Water Africa—Arizona Team* Project in the Mara Basin

Summary of Project. As part of the NASA-U.S. Agency for International Development (USAID) SERVIR (Sistema Regional de Visualización y Monitoreo) Program and its Applied Sciences Team (AST), the University of Arizona has been working with government agencies and stakeholders from three basins in Africa to better inform water and environmental management decisions. The project supports basin-level water management by developing monitoring and forecasting tools using Earth observations and meteorological forecasts with rainfall-runoff hydrologic models. Since different satellite rainfall products and models have different strengths and weaknesses, a multi-product and multi-model approach was adopted, with the aim of identifying the most suitable approach to supporting decisions.

The three basins that this project focused on are in Africa: the Tekeze River in Ethiopia and Eritrea, the Upper Zambezi in Zambia and Angola, and the Mara River in Kenya and Tanzania. These basins vary by size, topography, latitudes, and management challenges. In this case study, we focus on the Mara River Basin. The project has a three-pronged approach to provide operational capabilities for hydrologic monitoring and forecasting (Fig. 1), which are as follows:

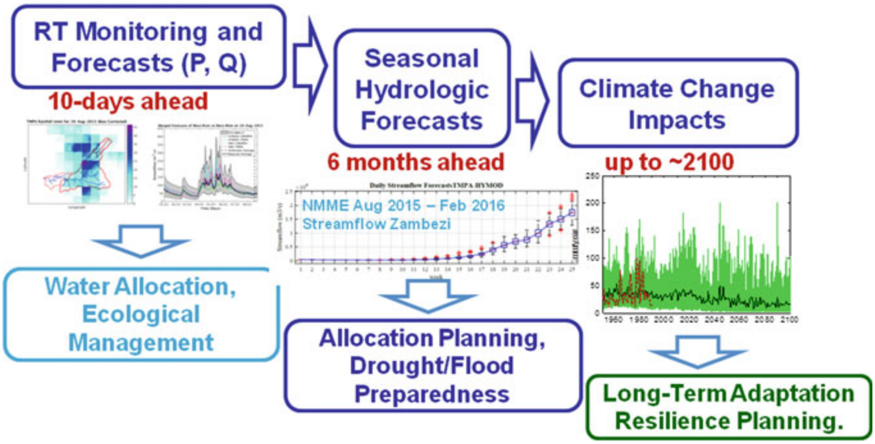

Fig. 1 The three-pronged approach to develop operational monitoring and forecasting capabilities to support water and environmental management activities at different time horizons, ranging from short-term water allocation and ecological management, to seasonal allocation and drought/flood preparedness, and long-term adaptation and resilience planning

(1) Real-time monitoring and short-term forecasting of rainfall and streamflow: use of real-time satellite estimates of precipitation, 7-day meteorological forecasts, and rainfall-runoff models to provide 7–10 day streamflow forecasts.
(2) Medium-term seasonal forecasting: use of downscaled and bias-corrected 6-month ahead seasonal forecasts from sister AST project to run our hydrologic models.
(3) Long-term projections of future climate change impacts on regional water resources, using bias-corrected multimodel projections of rainfall and temperature to drive our hydrologic models.

Description of Target Region. The Mara Basin is located in Kenya and Tanzania between the equator and 2° S, draining into Lake Victoria. Most of its water comes from the highlands of the Mau plateau, where the Mau Forest and tea plantations are, and flows down the Mau escarpment via two main tributaries, the Nyangores and the Amala, which unite to form the Mara River upstream of the grasslands and savannas of the Massai Mara (Kenya) and Serengeti (Tanzania) national parks (McClain et al. 2014). As many other basins in Kenya, the sustainability challenges in the Mara Basin are related to population growth, land-use change, and increased water abstractions, leading to the decrease of ecosystem services and functions. The Mau forest is a natural regulating system that buffers floods, enhances infiltration, and maintains base flows downstream in the game reserves during the dry seasons.

Management Challenges in Agriculture. Human encroachment for wood extraction and expansion of agricultural land (Fig. 2) affect these functions as well as increases the volume of abstracted water upstream in the basin. In addition,

Fig. 2 Land use change in the Mara Basin: the expansion of small-scale agricultural fields (*left*) is a significant pressure on the Mau Forest Reserve (*right*). Tea plantations can be seen, used here as buffer to prevent human encroachment (Image source: Google)

current development plans in the basin include the construction of dams and the expansion of agriculture, a vision that is shared across Africa (UN Water/Africa 2015). As permitted, abstractions have increased in Kenyan basins, and the number of days with very low downstream flows during the dry seasons has progressively increased as well. Poor monitoring and forecasting capabilities are considerable obstacles to the sustainable management of water resources, the long-term viability of agricultural development, and the conservation of natural ecosystems that generate important tourism revenues.

2.1 Understanding User Requirements for Decision Makings

The process for developing useful monitoring and forecasting applications for decision-making starts by understanding the decision-making challenges and context in which these will be used; an important element for success for an applications project is continued engagement with and participation from end users whose decisions could potentially benefit from the application being developed.

To develop an understanding and working partnership with our users (and ultimately understand their management context, challenges, and opportunities to benefit existing decision practices), we approached partnership development through several avenues including

(1) we worked with an in-region partner, who was a hub and bridge to country ministries who were our end users. That partner is the Regional Center for Mapping of Resources for Development (RCMRD—Nairobi SERVIR Hub);
(2) we established regular communications with our end users through meetings and informal discussions;

(3) we supported and participated in a workshop organized by RCMRD, with regional end users, as well as other workshops.

2.2 Workshops with RCMRD and Other Stakeholders

The RCMRD workshop was critical to understanding decision challenges and cultivating relationships/partnerships with regional end users. Workshop participants were officers from water-related government agencies such as the Water Resources Management Authority (WRMA), Water Resources Department (WRD) of the Ministry of Environment, Water and Natural Resources, Kenya Meteorological Department (KMD), and other institutions and collaborators (UNESCO Regional Hydrologist, USAID officers, International Center for Tropical Agriculture, Jomo Kenyatta University, and others). During the workshop, participants provided written responses for the following four questions:

1. What management decisions are you confronted within your workplace?
2. What accuracy/precision is required in the information for each one of these decisions?
3. What information are you using currently for those management and planning decisions?
4. What improvements in the information you are using would make the greatest difference?

We also participated in a multi-day workshop in Bomet, within the Mara basin, with numerous local agency and stakeholders representatives, where we presented and sought feedback for monitoring and forecasting applications that were under development.

This workshop enabled our understanding of critical contextual information related to water abstractions in this region:

- There is a need to better understand hydrologic processes, water resources availability, and the functioning of the system in the basin.
- The basin currently does not have reservoirs and is not regulated
- The decision that can be informed by tools and applications is the issuing of permits for water abstractions
- Livelihood, land-use changes, water quality, and ecosystem services were also raised as important issues
- Data products that were graphically or visually represented were essential to communicating understanding of water resources

Participants were faced with the challenge: if the river is over-abstracted, how can new permits and existing abstractions be coordinated? This is a difficult situation, particularly in times of water scarcity that is also subject to changing seasonal and inter-annual variability. With a better understanding and ability to monitor water resources, abstractions could potentially be better regulated, or "optimized," with a balance be found between much-needed environmental flows during the dry season, which support the Masai Mara and Serengeti ecosystems, and other uses.

Bringing together stakeholders and sectors to build awareness and familiarity with remote sensing information and applications was very valuable for this project. Furthermore, we were able to begin providing a basis for a common language and an expanded understanding of the basin system (from the scientists' perspectives and from the partners' perspectives). These interactions also facilitated the identification of future opportunities to collaborate and evolve the partnership and project. Other decision and planning contexts that this project could provide value to includes the planning and constructions of future reservoirs, preparing for drought and floods, and ecocystems protections (particularly during dry season).

In response to learning these additional priorities and feedback, we were able to adapt our model development efforts and translated our calibration approach to give equal importance to simulating low flows as well as high flows. We also took into account stakeholder feedback about data latency challenges and automated our operational online broadcasting platform to update rainfall estimates in as products become available.

In addition to learning about areas of needs, our partnership also allowed us to communicate regularly about how to effectively use the application outputs—e.g. under what conditions and in what scenarios. For example, our rainfall-runoff applications did not always appear to be well-suited for flood alerts, as the relative errors in satellite estimates can accumulate during flood events, impacting magnitude and timing-of-event characteristics. We also emphasized the importance of using knowledge of uncertainty as a way to understand how precise simulated products are over a given timeframe. As generate practice, we shared guidance for how to use knowledge of uncertainty in conjunction with deterministic models.

Currently, the project provides bias-corrected and downscaled rainfall monitoring displays over its pilot basins, including in the Mara (Fig. 3); multimodel/product simulations and bias-corrected streamflows, with a good uncertainty characterization in model runs; and a merged forecast, probabilistically assimilating the individual model–product combination forecasts and their uncertainty (Roy et al. 2016). The streamflow monitoring and 7–10 day forecasts are operational in the Mara basin and the Zambezi, and they are being implemented in the Tekeze basin. The seasonal forecasting system is operational in the Upper Zambezi. The monitoring displays and forecasts can be found for the three pilot basins at the project site www.swaat.arizona.edu with interactive visualizations for the streamflow forecasts (Fig. 4), for improved access and communication with agencies and stakeholders.

Conclusions. The project is entering its fourth year as of the end of 2015, during which these tools will be fully transferred to RCMRD (the SERVIR Hub in Nairobi) and interested agencies, while we also continue to run and broadcast the forecasts online.

The face-to-face interactions were essential to build trust, strengthen connections with key individuals, and build a foundation for future work, new data acquisition, results sharing, and implementation. The continued dialog with users and stakeholders enables the project to incorporate feedback on an on-going basis and understand how useful a technical will be and how it will be used after its delivery. As such, tracking the trajectory of communications can, in itself, be a

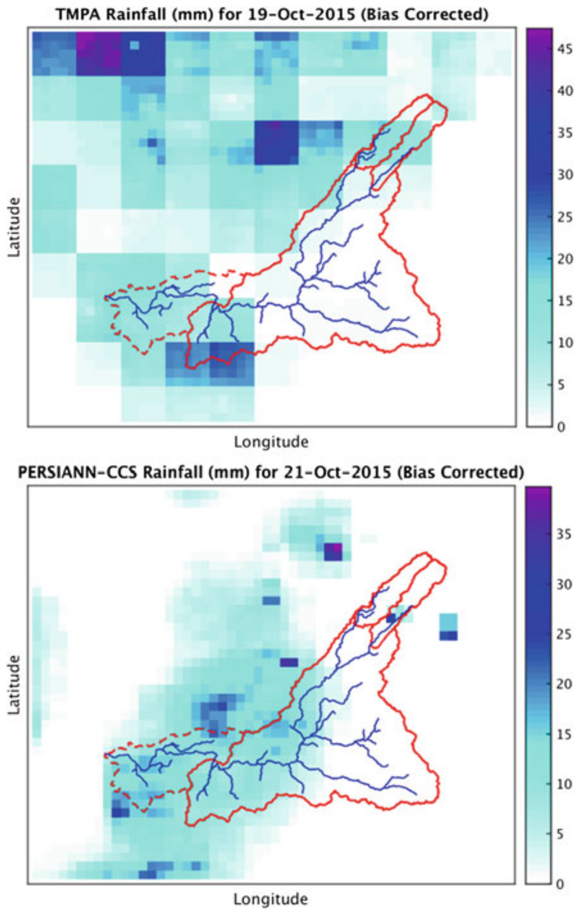

Fig. 3 Real-time bias-corrected satellite estimates over the Mara Basin. In the case of TMPA (*left*) and CMORPH (not shown), estimates at 0.25° were bias-corrected and downscaled using the CHIRPS reference dataset at 0.05°. In the case of PERSIANN-CCS, estimates were bias-corrected and re-gridded from their original 0.04°–0.05° to obtain a consistent input to rainfall-runoff models. *Figure rendered by T. Roy*

reflection of how valuable the tool is to the stakeholders. Ideally, such tools can be evolving applications that are fine-tuned as new remote sensing products become available and management needs evolve.

3 Case Study 2. Africa Nile River Basin (2009–2014)

Benjamin Zaitchik

NASA's Project Nile—Distributed hydrological information for water management in the Nile Basin

Summary of Project. This work aimed to apply NASA tools in support of scientifically informed water management in nations that share the Nile basin (Fig. 5). Over the course of the project (2009–2014), U.S. scientists at Johns Hopkins

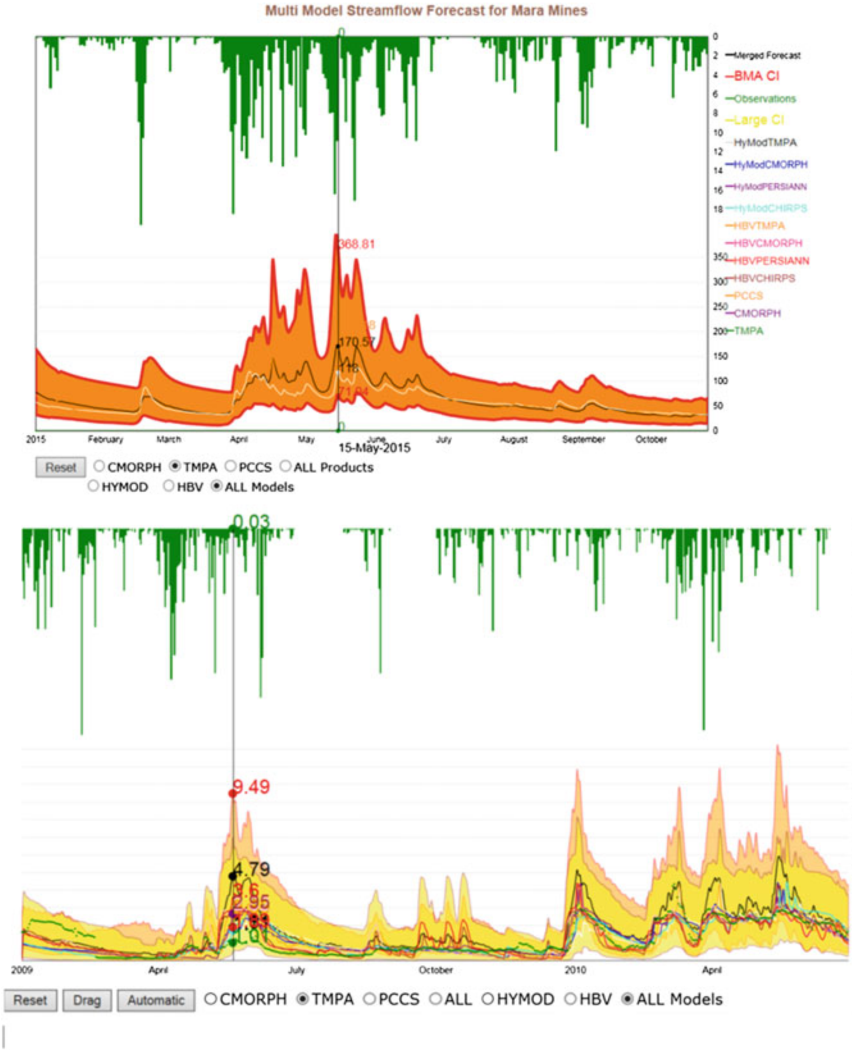

Fig. 4 Experimental interactive displays of streamflow simulations, with 95 % confidence intervals and a merged forecast from Bayesian model averaging. Aggregated basin precipitation is shown in the upper part of the visualization. Note that the user can select the model and product combinations to be shown. *Visualizations by M. Durcik and simulation work by T. Roy, A. Serrat-Capdevila, J. Valdes and H. Gupta*

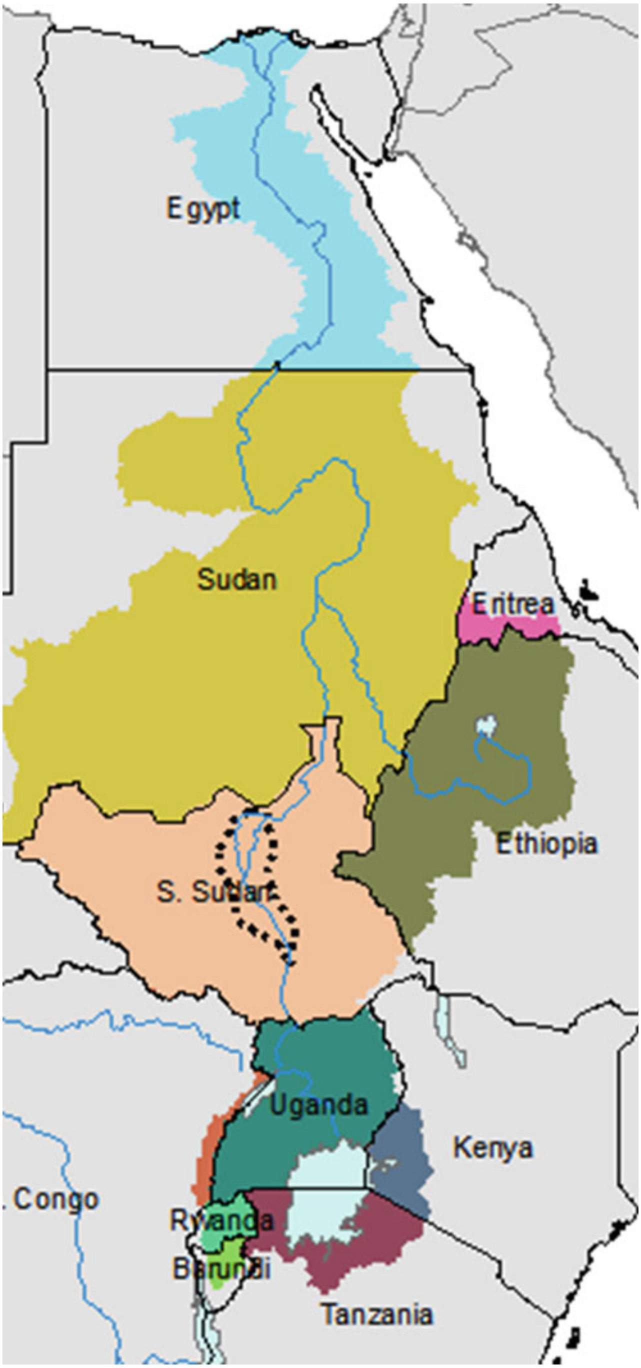

Fig. 5 The Nile basin, which spans eleven countries. The *Project Nile* domain included the entire basin, and at partner request the project's LDAS and ALEXI products were extended to include the full territory of all of these countries except for the Democratic Republic of Congo

University, NASA, U.S. Department of Agriculture (USDA), and the University of Wisconsin worked with partners at USAID, the Nile Basin Office Eastern Nile Regional Technical Office (NBI-ENTRO), the Ethiopian National Meteorological Agency and Environmental Protection Agency, and Addis Ababa University. The team developed satellite-based land cover maps, produced satellite-derived evapotranspiration estimates using a new Meteosat implementation of the USDA Atmosphere Land Exchange Inverse model (ALEXI), and implemented a Land Data Assimilation System (LDAS) customized to match identified information needs.

The work led to improved water balance estimates across the Nile Basin, enhancements to NASA modeling tools, and ongoing collaborations of flood and drought response and climate change adaptation in the Nile and surrounding regions. The research accomplishments of the project are represented in a number of peer-reviewed publications (Anderson et al. 2012a, b; Berhane et al. 2014; Foltz et al. 2013; Satti et al. 2015; Shortridge, et al. 2015; Simane et al. 2013; Wilusz et al. in review; Yilmaz et al. 2014; Zaitchik et al. 2012). Water resource applications addressed in these publications include drought monitoring (Anderson et al. 2012a, b), wetland mapping (Wilusz et al. in review), estimates of irrigated water use (Yilmaz et al. 2014), climate vulnerability analysis (Foltz et al. 2013), agricultural land classification (Simane et al. 2013), and hydroeconomic optimization (Satti et al. 2015).

NASA Data and Transboundary Water Challenges. *Project Nile* exemplified the potential that NASA products have to inform decision making in a contentious transboundary basin. In 2011, LDAS and ALEXI outputs were featured in the Nile Basin Initiative Donors Meeting in Copenhagen and the Ethiopian National Adaptation Plan of Action (NAPA) was submitted to the United Nations Framework Convention on Climate Change to the Nile Basin Initiative's Atlas of the Nile Basin. In each case, the objectivity, trans-national consistency, and non-political nature of NASA-based analysis facilitated open discussion of hydrology of the basin. Demonstrations of decision support were also performed with the Ethiopian Ministry of Water, Irrigation and Energy, in which *Project Nile* LDAS was used to drive a Water Evaluation and Planning (WEAP) system model for the Lake Tana basin. Data were also provided to decision makers at Egyptian Ministry of Water Resources and Irrigation, with a similar analysis in mind. There were discussions of making the *Project Nile* LDAS available as a near real-time data product distributed through NASA data servers, but given geographic overlap with other NASA projects it was decided that LDAS innovations accomplished in *Project Nile* could be fed into other LDAS systems that cover East Africa, including FEWSNET LDAS (FLDAS), which is now distributing a similar analysis through NASA data portals.

Additional Benefits of ***Project Nile***. *Project Nile* has been leveraged for numerous follow-on collaborations across East Africa and, in the case of ALEXI, all of Africa. From a capacity building perspective it has yielded lasting relationships with project partners in Ethiopia, Sudan, Egypt, Kenya, and Uganda, who continue to engage to learn about new NASA products and to improve their modeling skills. We have held workshops for government scientists and academics from Ethiopia, Sudan, Kenya, Rwanda, and Uganda on satellite-based land cover mapping, the theory and use of ALEXI, and the application of *Project Nile* LDAS to water resource analysis.

Challenges: **Contention Around Water in the Nile Basin**. This project also encountered significant challenges that were not rooted in technical or scientific elements of the work but instead were the product of changing geopolitical landscapes. At the time the proposal was written, the Nile Basin Initiative (NBI) was working toward a comprehensive water-sharing framework that would include all member States. During the life of the project, however, the Ethiopian government began construction on the largest hydropower dam in Africa over intense Egyptian objections, resulting in Egypt and Sudan abandoning NBI negotiations for several years, which was then compounded by several transitions in government in Egypt, the founding of South Sudan and its subsequent political turmoil. These events, among others, complicated relationships within NBI. NBI-ENTRO experienced nearly 100 % staff turnover and several changes in strategic vision, while NBI political leadership embraced, then rejected, and subsequently re-embraced the principle of collaborating with NASA for water resource analysis. We worked around these complications by broadening our base of partners at national government agencies, international organizations, and universities in the region, allowing the project to continue providing value to the region project's accomplishments.

Partnerships Lessons Learned. There is no question that the stated capacity building goals of the project suffered due to these institutional difficulties: while *Project Nile* has contributed to the technical understanding of the Nile water balance and its end products have been utilized by decision makers, political barriers and staff turnover within the NBI made it not feasible to achieve operational hand-off to NBI-ENTRO in the timeframe that we were working.

Given this experience, *Project Nile* has shares a few important considerations for other applied sciences projects that may have a focus in transboundary basins where political instability can be a huge facet of the project landscape:

(1) Considerations for partnering with regional organizations (with members states) or working directly with country ministries. In the case of working in transboundary water basins, this consideration is well illustrated by comparing options for partnering organizations: for example, international river commissions in the developing world, with multiple member states, are generally thought to hold the most promise for advancing collaborative water management, as opposed to unilateral development by each member country. However, these organizations are not always fully empowered (both technically and politically) to make substantive progress in these areas relative to member countries. We encountered this tension between regional river commissions and member countries when considering whether to work with the relatively high capacity water ministries in one or more Nile basin countries or to attempt to partner with NBI despite their relative political (and hence technical) fragility. Insomuch as the success of an Applied Sciences project is defined in terms of successful transition of an advanced NASA product, modeling or observation system, in our case, there was an advantage to working with single countries. If the goal is to apply NASA analysis in

partnership to advance scientifically informed water sharing; however, then working with basin commissions may be the more appropriate partner. Indeed, providing a NASA analytical backbone for these organizations has the potential to empower them in the eyes of their member States.

(2) Considerations for partnering with an operational agency or a research entity. Partnering with an academic or research institute may have allowed *Project Nile* to sidestep some of the challenges related to political circumstances that then impeded development of capacity for project hand-off. It is possible that *Project Nile* would have been able to transit an improved model or product to another research group or university with greater institutional and staff stability. This may be because many countries' operational water resource agencies not have the political and financial flexibility to be fully engaged partners: data are proprietary, decision support systems can be resistant to change, and staff and IT time may not be available.

While development and provision of a mature analysis tool has the potential to motivate cost-sharing investments from the end user, our experience with *Project Nile* would suggest an alternate strategy for projects that are higher risk or require preliminary demonstration to win buy-in. For that subset of projects, it can be more valuable and productive to partner with an academic organization or an independent research center, where there is the flexibility and mandate to work on transformative analysis. Such projects are unquestionably "applied" in their objectives, but they fall on the low end of the Applications Readiness Level (ARL) scale and might need partnership from a research group even more than they need immediate access to decision makers. Furthermore, many lower capacity countries turn to universities and research centers for their technical and scientific expertise and in that way these entities can serve as a conduit to an operational partner. Capacity building, thus, that is focused on non-political research institutions would likely have additional benefits for member states. We have found that these secondary partnerships with non-politicized, in-region academic and research centers provided the best data sharing relationships and strongest capacity building legacy for *Project Nile*.

4 Case Study 3 Pakistan: Role of Earth Observation for Operational Groundwater Resource Management in Pakistan: A Capacity Building Perspective from Pakistan (2014-)

Naveed Iqbal

Challenge Summary. Sustainable groundwater resource management is essential to ensure food security and sustainable socioeconomic development of an agrarian country like Pakistan. Surface water availability is scarce and subject to limited storage, increasing population, variable climate conditions, and the occurrence of extreme events (floods and droughts). Together, these factors pose a challenge to managing groundwater sustainably in Pakistan. Other emerging and increasingly complex stressors on Pakistan's water resources are water table depletion, groundwater mining, saline water intrusion, and groundwater quality deterioration.

This situation is further aggravated by limitations in in situ data availability, both spatially and temporally. Furthermore, data collected by various water management agencies in Pakistan are not easily accessible or shared with the research community and policy makers. Currently, different geophysical, isotopic, and groundwater modeling approaches are used for the detailed assessment, analysis, as well as understanding of long-term changes in groundwater dynamics. These tools are used to formulate appropriate strategies under varying climate conditions. These techniques are very detailed but laborious, time-consuming, and costly, as they also involve field surveys. The accuracy of numerical groundwater models is also hampered at large-scale coverage such as in Indus Basin due to paucity of input data.

Remote sensing data can be used as part of a cost-effective approach for conducting hydrologic analyses at various spatial and temporal scales. Its large-scale coverage (regional-to-global), high temporal (days-to-months), spatial resolutions (meters-to-kilometers), and availability of make remote sensing data particularly amenable and valuable for use in data-constrained areas. However, in situ or cal/val activities are required to help ensure remote sensing products are well calibrated and can be used with confidence. Currently, many hydrologists are able to effectively use Earth observations technology for improved water resource management.

Role of Earth Observations. Earth observations have wide applicability in hydrology. Many sensors on-board various satellite platforms are providing useful information pertaining to precipitation, soil moisture, topography, water level measurement in rivers and lakes, terrestrial water storage information, among other variables. These datasets are often freely available at high spatial and temporal scales for regions all over the world. Remote sensing has enabled researchers and managers to conduct more holistic, basin-scale analysis which was not yet possible using traditional approaches based on field surveys and hydrological modeling.

The Gravity Recovery and Climate Experiment (GRACE) satellite observes monthly gravity anomalies at resolutions of 10 micron changes over 200 km, which can be useful for extracting variations in terrestrial water storage (TWS). GRACE is a unique twin gravity satellite that is a joint German Aerospace Center (DLR)-NASA mission that was launched in 2002 (Rodell et al. 2009). GRACE can be used to better understand Total Water Storage (TWS) and calculate groundwater storage (GWS), which is calculated using soil moisture information and GRACE-TWS (Rodell et al. 2009). Monthly groundwater storage changes are useful for the analysis of long-term groundwater system behavior and understanding of groundwater dynamics under climatic implications.

Project Summary. Under a capacity building effort of National Aeronautics and Space Administration (NASA), through University of Washington (UW-Seattle) for Pakistan Council of Research in water Resources (PCRWR), a 6-month professional training on satellite gravimetry (GRACE) application for groundwater

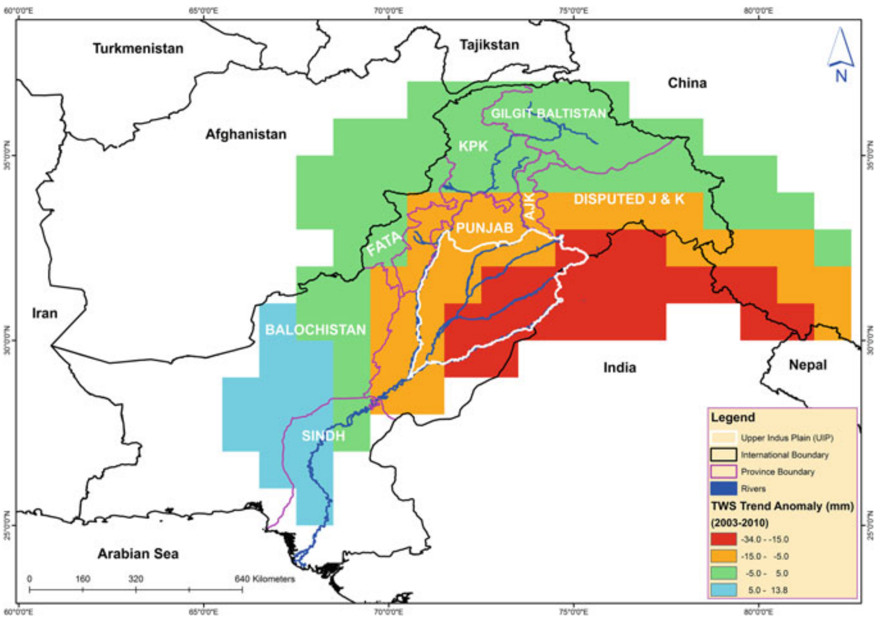

Fig. 6 Variations in terrestrial water storage anomalies over Indus Basin from 2003 to 2010

resource management is conducted at University of Washington (UW). During this specialized training, the effectiveness of GRACE satellite for the groundwater resource management at operational scales is evaluated. The Variable Infiltration Capacity (VIC) hydrological model is applied on Indus Basin for the simulation of monthly soil moisture and surface runoff information at a spatial scale of $0.1° \times 0.1°$ from 2003 to 2010. The GWS changes are inferred from GRACE-TWS using VIC model-generated soil moisture and runoff data.

Variations in TWS range from −34 to −5 mm over Punjab Province from 2003 to 2010 (Fig. 6), potentially due to groundwater use for anthropogenic applications in Punjab Province. Agriculture is the largest user of groundwater and the area is famous as the main food basket of the country due to fertile agriculture land. Punjab Province consists of four riverine flood plains locally known as Thal, Chaj, Rechna, and Bari doabs (area between the two rivers). These doabs are bound by River Indus and its four major tributaries (Jhelum, Chenab, Ravi, and Sutlej). Our analysis utilizes GRACE data and indicates that groundwater storage is being depleted at an average rate of about 12.96 mm/year and 6.78 mm/year in Bari and Rechna doabs and, 7.34 mm/year and 3.54 mm/year km^3/year in Thal and Chaj doabs over the period 2003–2010 (Fig. 7). In Bari and Rechna doabs, the depletion trend is found to be more persistent than in Thal and Chaj doabs due to their intermixed trends of recharge and depletion. Massive flooding in late July 2010 has played a role in significantly decreasing the groundwater depletion rate. It has been observed that GRACE is more sensitive to the significant changes in the groundwater storage variations caused by

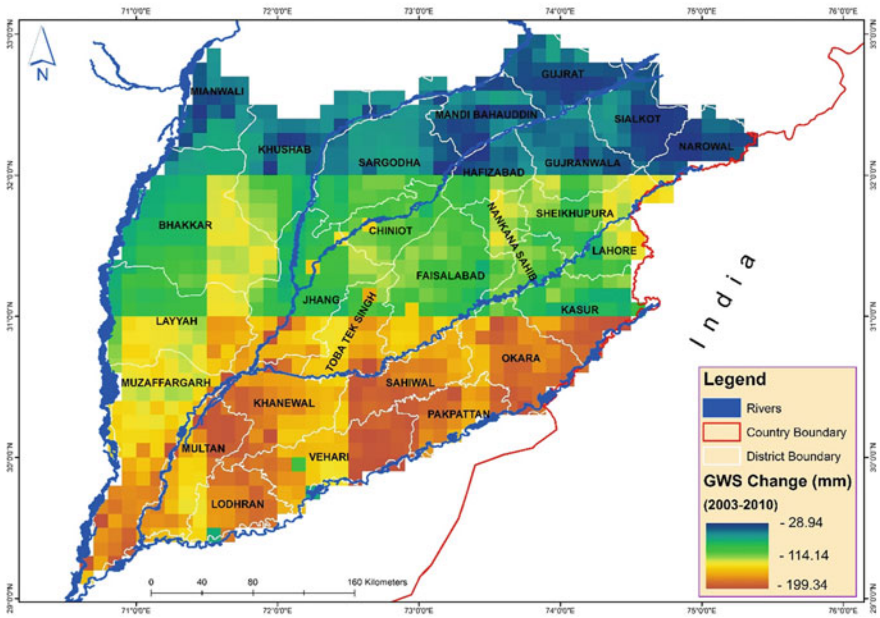

Fig. 7 Changes in groundwater storage anomalies over Upper Indus Basin from 2003 to 2010

depletion or recharge at appropriate scales. Furthermore, its effectiveness increases with large-scale and persistent groundwater storage trends over long periods.

The groundwater storage information is a key parameter for improving groundwater resource management (Jin and Feng 2013). The month-to-yearly spatial and temporal changes in groundwater storage are useful for formulating appropriate groundwater management strategies. It is envisaged that a GRACE-based application is a cost-effective tool for the understanding basin-scale hydrology and monitoring groundwater behavior at operational level. This application will help provide scientific information in a cost-effective way for decision-making and for policy recommendations.

Earth observations are widely available and has been shown to be applicable and useful for natural resources management. An opportunity is presented here, in that the community can now work to maximize the benefit of freely available Earth observations information through applications. Building capacity within the end user community (researchers and managers, for example) is a very important component for translating knowledge to the benefit of mankind. It is an integral link between the data providers and end-user community.

Challenges in Capacity Building for Earth Observations Use. Two major challenges in building capacity to use Earth observations in Pakistan are infrastructure development (hardware and software) and trained personnel. Finding support to establish a properly equipped geospatial lab can also be a challenge, but there have been recent investments at the government and private sector level to help. Many universities have started various satellite remote sensing (SRS) and geographic information science (GIS) programs and are producing skilled technical personnel. The high computation power that is required to run the latest versions of related software and specialized skillsets in the field of Earth observations remain a barrier to being able to fully realize the potential of Earth observations for operational use.

Examples of Capacity Building Activities. Conferences and workshops (with trainings) are a useful approach for generating and expanding awareness of satellite data but a more integrated program, such as a technical exchange or permanent appointment within a trained research team, fully equipped with necessary tools, would enable continued progress in capacity building. Another challenge is retention of skilled personnel, many of whom transition to other positions, creating a gap for a much-needed skillset within the institution.

Capacity building is a continuous process that may require extensive effort in an iterative manner. Furthermore, capacity building is only effective if it is two-way street, where all parties are contributing and gaining equally. A personnel exchange is a type of collaboration that can be extremely effective, more so than a short training course or participation in a conference is. Through these types of concrete, collaborative projects, experts can share their knowledge of applications and help devise solutions for ongoing challenges at the institutional level.

We have observed that the efficacy of capacity building efforts led by researchers at the University of Washington, and supported by NASA, with PCRWR, is very much dependent on ongoing and continued collaborations. The Memorandum of Understanding (MoU) between UW and PCRWR (signed on Nov 2, 2015) will further strengthen the relationships between these two organizations. The future joint activities will also help ensure the sustainability of the current effort. This approach will help PCRWR become more independent by improving its research infrastructure and building a team of specialized professionals.

The operational adoption of GRACE as a tool for groundwater monitoring and resource management and the continuity of GRACE satellite mission in the form of GRACE Follow-on (GRACE-FO) are linked and very important. The expertise on VIC hydrological model for the simulation of soil moisture and surface runoff datasets, assistance for high computation, and relevant softwares are also key requirements for PCRWR. The collaboration between NASA and PCRWR will also help address real-world issues in the field of sustainable water resource management in Pakistan. It will also enable the application of Earth observations as a scientific tool for the social benefit.

Being a federal research and development organization, PCRWR is helping both the groundwater managers and farmers address water resources concerns as well as informing policy recommendations for decision-makers. Different capacity building training programs are being offered by PCRWR on the various water conservation and management techniques for effective water resource management. In this way, capacity building of PCRWR will ultimately help to benefit the operational managers and farmers to achieve the goal of sustainable water resource management.

PCRWR would like to see future joint activities include the use of Earth observations and physical modeling-based tools development for the early warning of floods and droughts, addressing transboundary water issues, real-time soil moisture, and evapotranspiration estimations. Applications that utilize Earth observations for the water cycle budgeting in general could also be of great value in the context of disasters mitigation and sustainable water resource management.

5 Case Study 4: Enhancing Global Crop Assessment of the USDA Foreign Agriculture Service with NASA Soil Moisture Products (2014-)

John Bolten

Project Summary. One example of the operational application of global satellite-based observations for improved decision-making is the NASA-USDA Global Soil Moisture Product employed by the Foreign Agricultural Service (FAS). The development of this global product was envisioned to improve the USDA FAS global crop assessment decision support system via the integration of NASA soil moisture data products. USDA FAS crop yield forecasts affect decisions made by farmers, businesses, and governments by predicting fundamental conditions in global commodity markets. Regional and national crop yield forecasts are made by crop analysts based on the Crop Condition Data Retrieval and Evaluation (CADRE) Data Base Management System (DBMS). Soil moisture availability is a major factor impacting these forecasts and the CADRE DBMS system predominantly estimates soil moisture from a simple water balance model (the Palmer model) based on precipitation and temperature datasets operationally obtained from the World Meteorological Organization and U.S. Air Force Weather Agency.

To improve understanding and prediction of agricultural growth in varying climate regimes, land cover, crop type, and management strategies, it is necessary to recognize the important role that soil moisture plays in the carbon, water, and energy cycles, as well as in regulating crop growth and health. Near-surface soil moisture (i.e., the amount of water in the first few inches of soil) is a critical component of all of these cycles. The volume of water in the first few inches of soil controls infiltration and has a direct influence on the amount of water that reaches lower layers of the soil column. It also constrains land surface temperature by affecting the fraction of latent and sensible heat of the land surface. As a result, observations of near-surface soil moisture are used to help monitor and predict regional flood and drought events (Dai et al. 2004; Komma et al. 2008; Norbiato et al. 2008). In addition, regional variations in soil moisture availability can provide a leading signal for subsequent anomalies in vegetative health and productivity (Adegoke and Carleton 2002; Ji and Peters 2003). Thus, soil moisture has increasingly become a key input to crop forecasting and basin management strategic strategies, as well as many large-scale flood, drought, and agricultural monitoring systems (Mo et al. 2011).

However, very few networks exist due to their high cost of installation and maintenance. In addition, the heterogeneous nature of soil moisture causes in situ methods to be locally restrictive and they do not accurately capture the basin-scale soil-moisture changes that are often needed for water resources management applications (Engman and Gurney 1991). To this end, ground-based observational soil moisture data alone are not sufficient to provide accurate water budget information, and can be greatly improved through the addition of satellite-based regional observations of near-surface soil moisture.

Targeting Decision Making of the USDA Foreign Agriculture Service. The USDA FAS attempts to anticipate the impact of drought on regional agricultural productivity by monitoring soil moisture conditions using a quasi-global soil water balance model (Bolten et al. 2002). However, the accuracy of such models is dependent on the quality of their required meteorological inputs and is thus questionable over data-poor regions of the globe and can be improved through the integration of satellite-based soil moisture observations. In this case, the Palmer soil moisture model implemented by the FAS is driven by daily precipitation and near-surface air temperature observations (Palmer 1965). However, over much of the globe, particularly food insecure areas that are of interest to the FAS, these observations are sparse or do not exist. For example, agricultural areas in South Africa and Brazil are significantly lacking in reliable networks of gage-based precipitation and temperature observations. As a result, the modeled soil moisture over these areas has a high uncertainty, which leads to inaccurate estimates of agricultural productivity. A key challenge for the USDA FAS is to provide monthly global estimates of agricultural productivity over areas like these lacking reliable observations of precipitation, temperature, or soil moisture.

The main objective of the project is to enhance the U.S. Department of Agriculture (USDA) Foreign Agricultural Service (FAS) global crop assessment decision support system via the integration of NASA soil moisture products through the implementation of data assimilation tools. The baseline soil moisture estimates used by USDA FAS are developed using the two-layer Palmer model, which is a physically based hydrologic model forced by daily precipitation and minimum and maximum temperature measurements acquired from the U.S. Air Force Weather Agency. Integration of the satellite observations is done using a 1-D Ensemble Kalman Filter (EnKF) technique set to run with 30-ensemble member (Bolten et al. 2010).

The Palmer model estimates of surface and root-zone soil moisture are derived from the two-layer Palmer water balance model currently used operationally by USDA FAS. The two-layer Palmer model is based on a bucket-type modeling approach as described in *Palmer* (Palmer 1965). It estimates the available water capacity (AWC) of the top model layer, assumed to be 2.54 cm at field capacity, and the AWC of the second layer (i.e., root-zone layer) is calculated using soil texture, depth to bedrock, and soil type derived from the Food and Agriculture Organization (FAO) Digital Soil Map of the World available from the FAO at http://www.fao.org/ag/agl/lwdms.stm#cd1. In this fashion, water-holding capacity for both layers (incorporating near-surface soil moisture and groundwater) ranges between 2.54 and 30 cm according to soil texture and soil depth. Evapotranspiration is calculated from the modified FAO Penman-Monteith method and observations of daily min/max temperature. Further modeling details are available in (Bolten et al. 2010). Required daily rainfall accumulation and air temperature datasets are obtained from the U.S. Air Force Weather Agency (AFWA) Agriculture Meteorological (AGRMET) system which derives a daily rainfall accumulation product based on microwave sensors on various polar-orbiting satellites, infrared sensors on geostationary satellites, a model-based cloud analysis, and World Meteorological Organization (WMO) surface gage observations (Bolten et al. 2010).

The NASA-USDA Global Soil Moisture Product was initially developed using soil moisture observations from the EOS Advanced Microwave Scanning Radiometer (AMSR-E), which provided quasi-global soil moisture observations from 2002 to 2011. The product has transitioned to other satellites as they have become available, including the onset of data availability from the ESA Soil Moisture and Ocean Salinity (SMOS) in 2009 and NASA Soil Moisture Active and Passive (SMAP) in 2015 (Entekhabi et al. 2010; Kerr and Levine 2008). As a result, the system is envisaged to provide over 15-year heritage of global soil moisture which should result in a significant expansion in our ability to study the impact of retrieving surface soil moisture using satellite remote sensing for many agricultural and hydrological applications.

AMSR-E stopped producing reliable observations in October of 2011. The current operational system ingests soil moisture observations acquired from the Soil Moisture Ocean Salinity (SMOS) mission and it is in preparation for switching to data provided by the NASA's Soil Moisture Active Passive (SMAP) mission. Due to the failure of the SMAP active instrument soon after launch, the system is being modified to incorporate soil moisture observations from the Advanced Scatterometer ASCAT instrument onboard the EUMETSAT METOP satellite.

The soil moisture product is based on the implementation of an Ensemble Kalman Filter (EnKF). The EnKF is a nonlinear extension of the standard Kalman filter and has been successfully applied to a number of land surface data assimilation problems (e.g., Reichle 2005). The current system has been found to function adequately using a 30-member Monte Carlo ensemble size (Bolten and Crow 2012) and is being modified to dually assimilate both SMAP and ASCAT soil moisture observations.

The soil moisture products generated by this system have been operationally delivered to USDA FAS since 2013 and have been fully incorporated into the USDA FAS Crop Explorer decision support system since April of 2014 (Fig. 8). Products include surface and subsurface soil moisture, total soil profile soil moisture, and soil moisture anomalies for the surface and subsurface layer. The products have become an invaluable part of the USDA FAS CADRE (Crop Assessment Data Retrieval and Evaluation) and are routinely used by USDA FAS crop analysts and experts to assess and improve their global yield predictions that are included in the

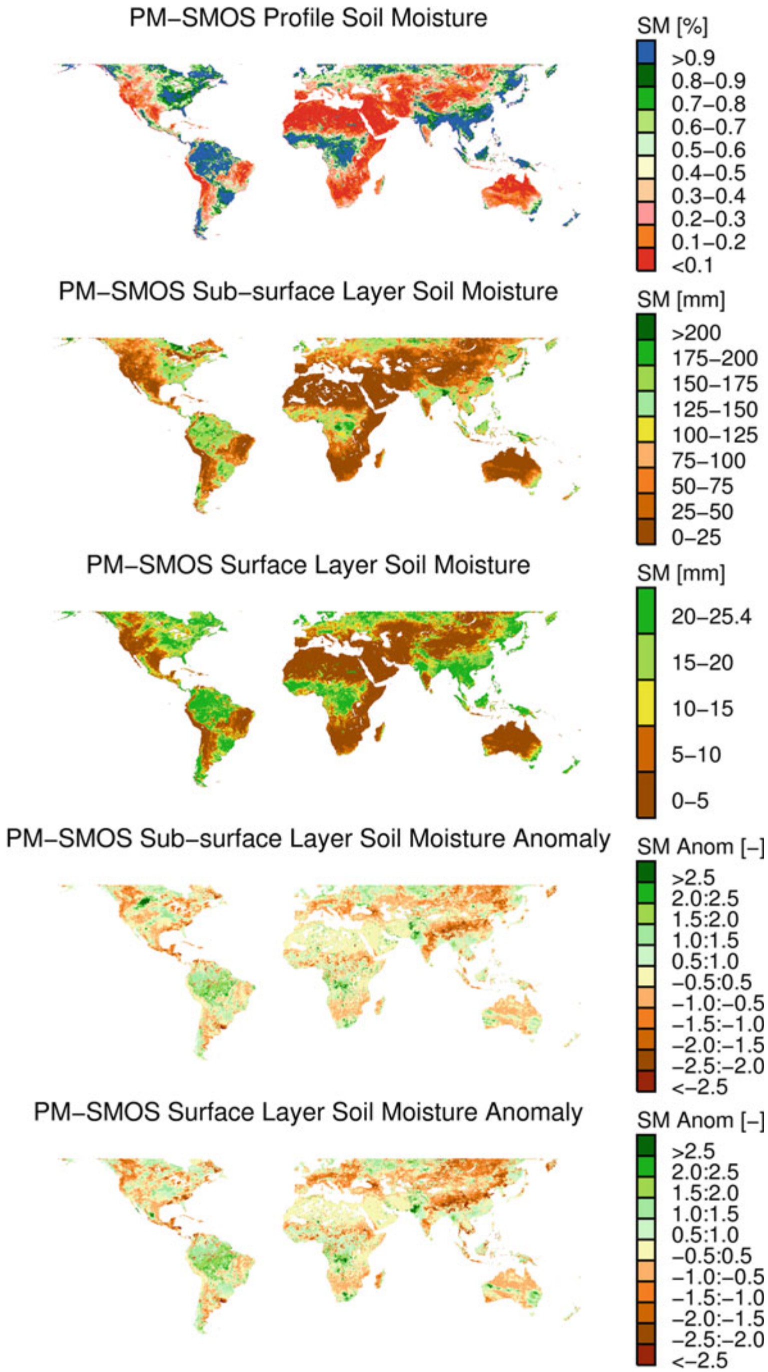

Fig. 8 Examples of the global soil moisture products being operationally delivered to

monthly USDA World Agricultural Supply and Demand Estimate (WASDE) report. Furthermore, since its public release, several additional agencies have expressed interest in utilizing the data including USDA National Agricultural Statistics Service (NASS), which is responsible for assessing the nation's crop conditions and developing yield estimates for the WASDE report as well.

Lessons Learned. One of the keys to success of this project is that it is leveraging off of an existing partnership between NASA and USDA within a user decision context. By addressing specific elements of a partner's existing process for assessing crop productivity, this project is able to provide a quantifiable benefit with its primary focus on enabling improved yield forecasting products, capacity building activities, and a more extensive process to define which decision to target and understand user requirements and constraints.

6 Conclusion

The case studies in this chapter represent a diversity of application activities working to bridge the gap between Earth observations for research and water resource applications needs on an international landscape. They each present different perspectives and approaches with respect to geography, barriers-faced, partnerships, capacity building, and the application targets themselves. Summarized below are the common threads and lessons learned from the case studies.

- **Partnerships are the key to addressing water resource issues, particularly in transboundary water basins**. Most of the projects found success when a common understanding was achieved between the NASA funded investigators and end users. However, as Zaitchik indicated, one key element of success is understanding what types of partners are the best match for the maturity of the application (e.g., research institutions versus a regional coordinating body). Zaitchik also notes that identifying a partner with high potential for being able to sustain the use of a transitioned product is also important, and that this must be weighed against what may appear to be a broader impact (e.g., targeting multiple states through a multilateral organization versus working with specific country ministries.)
- **Capacity building is essential and needs to be a continuous process.** In the case of Serrat-Capdevila's work, and Iqbal's case study, we observe that continuous engagements with partners are critical, and that single, one-off activities such as workshops can have limited impact. In some cases, as pointed out by Iqbal, the next level in capacity building is to develop joint activities that allow members of respective partner organizations to be rooted within each other's teams. Hosting members of the partners' teams within home institutions can help team members develop a good understanding of constraints (both technically and otherwise) and allow continuity in training and access to technical materials and expertise.

- **Potential is huge for Earth observations to benefit end users and to address global or regional water challenges.** In Bolten's work, NASA soil moisture products can greatly benefit USDA FAS, which is employing a global scale model for crop assessment. By targeting an existing element (soil moisture) of an existing process, partner buy-in becomes less of a hurdle since the partner's decision making framework is not being overhauled by a new tool. The potential for Earth observations to provide value to water resources stakeholders, such as research entities or organizations or operational agencies, has also been demonstrated in Serrat-Capdevila, Zaitchik, and Iqbal's work, and targeting various hydrologic variables, such as precipitation, streamflow, evapotranspiration, and groundwater.

Finally, it is also very important to effectively assess and communicate the benefits of this work, and connect those benefits back to the use of Earth observations. Continuing to evaluate and articulate benefits of Earth observations is a vital challenge that is being addressed by the case studies outlined in this chapter and an ongoing focus of the Earth science applications community.

References

Adegoke, J. O., & Carleton, A. M. (2002). Relations between soil moisture and satellite vegetation indices in the U.S. Corn Belt. *Journal of Hydrometeorology*, *3*(4), 395–405. http://doi.org/10.1175/1525-7541(2002)003<0395:RBSMAS>2.0.CO;2.

Anderson, M. C., Allen, R. G., Morse, A., & Kustas, W. P. (2012). Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. *Remote Sensing of Environment*, *122*, 50–65. http://doi.org/10.1016/j.rse.2011.08.025.

Anderson, W. B., Zaitchik, B. F., Hain, C. R., Anderson, M. C., Yilmaz, M. T., Mecikalski, J., & Schultz, L. (2012). Towards an integrated soil moisture drought monitor for East Africa. *Hydrology and Earth System Sciences*, *16*(8), 2893–2913. http://doi.org/10.5194/hess-16-2893-2012.

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–9. http://doi.org/10.1038/nature04141.

Berhane, F., Zaitchik, B., & Dezfuli, A. (2014). Subseasonal analysis of precipitation variability in the Blue Nile River Basin. *Journal of Climate*, *27*(1), 325–344. http://doi.org/10.1175/JCLI-D-13-00094.1.

Bolten, J. D., & Crow, W. T. (2012). Improved prediction of quasi-global vegetation conditions using remotely-sensed surface soil moisture. *Geophysical Research Letters*, *39*(19), n/a–n/a. http://doi.org/10.1029/2012GL053470.

Bolten, J. D., Crow, W. T., Zhan, X., Jackson, T. J., & Reynolds, C. A. (2010). Evaluating the utility of remotely sensed soil moisture retrievals for operational agricultural drought monitoring. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *3*(1), 57–66. http://doi.org/10.1109/JSTARS.2009.2037163.

Bolten, J. D., Crow, W. T., Zhan, X., Reynolds, C. A., & Jackson, T. J. (2002). Assimilation of a satellite-based soilmoisture product into a two-layer water balance model for a global crop production decision support system. In S. K. Park & L. Xu (Eds.), *Data assimilation for atmospheric, oceanic and hydrologic applications* (pp. 449–463). Berlin, Heidelberg: Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-540-71056-1.

Chen, J., Famigliett, J. S., Scanlon, B. R., & Rodell, M. (2015). Groundwater storage changes: Present status from GRACE observations. *Surveys in Geophysics*. http://doi.org/10.1007/s10712-015-9332-4.

Dai, A., Trenberth, K. E., & Qian, T. (2004). A global dataset of palmer drought severity index for 1870–2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, *5*(6), 1117–1130. http://doi.org/10.1175/JHM-386.1.

Engman, E. T., & Gurney, R. J. (1991). *Remote sensing in hydrology*. Chapman and Hall. Retrieved from http://www.springer.com/us/book/9789401066709.

Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., Van Zyl, J. (2010). The Soil Moisture Active Passive (SMAP) Mission. *Proceedings of the IEEE*, *98*(5), 704–716. http://doi.org/10.1109/JPROC.2010.2043918.

Feng, X., Porporato, A., & Rodriguez-Iturbe, I. (2013). Changes in rainfall seasonality in the tropics. *Nature Climate Change*, *3*(9), 811–815. http://doi.org/10.1038/nclimate1907.

Foltz, J., Gars, J., Özdoğan, M., Simane, B., & Zaitchik, B. (2013). Weather and welfare in Ethiopia. *Agricultural and Applied Economics Association*.

GEOSS. (2014). GEOSS water strategy: From observations to decisions. Retrieved April 7, 2015, from http://ceos.org/document_management/Ad_Hoc_Teams/WSIST/WSIST_GEOSS-Water-Strategy-Full-Report_Jan2014.pdf.

Ji, L., & Peters, A. J. (2003). Assessing vegetation response to drought in the Northern great plains using vegetation and drought indices. *Remote Sensing of Environment*, *87*(1), 85–98. http://doi.org/10.1016/S0034-4257(03)00174-3.

Jin, S., & Feng, G. (2013). Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002–2012. *Global and Planetary Change*, *106*, 20–30. http://doi.org/10.1016/j.gloplacha.2013.02.008.

Kerr, Y. H., & Levine, D. (2008). Foreword to the Special Issue on the Soil Moisture and Ocean Salinity (SMOS) Mission. *IEEE Transactions on Geoscience and Remote Sensing*, *46*(3), 583–585. http://doi.org/10.1109/TGRS.2008.917807.

Komma, J., Blöschl, G., & Reszler, C. (2008). Soil moisture updating by Ensemble Kalman Filtering in real-time flood forecasting. *Journal of Hydrology*, *357*(3–4), 228–242. http://doi.org/10.1016/j.jhydrol.2008.05.020.

McClain, M. E., Subalusky, A. L., Anderson, E. P., Dessu, S. B., Melesse, A. M., Ndomba, P. M., Mligo, C. (2014). Comparing flow regime, channel hydraulics, and biological communities to infer flow–ecology relationships in the Mara River of Kenya and Tanzania. *Hydrological Sciences Journal*, *59*(3–4), 801–819. http://doi.org/10.1080/02626667.2013.853121.

Mo, K. C., Long, L. N., Xia, Y., Yang, S. K., Schemm, J. E., & Ek, M. (2011). Drought indices based on the climate forecast system reanalysis and ensemble NLDAS. *Journal of Hydrometeorology*, *12*(2), 181–205. http://doi.org/10.1175/2010JHM1310.1.

National Research Council. (2007). *Earth science and applications from space: National imperatives for the next decade and beyond*. doi:10.17226/11820

National Drought Mitigation Center, US Department of Agriculture, US Department of Commerce, & National Oceanic and Atmospheric Administration. (n.d.). *United States Drought Monitor*. Retrieved from http://droughtmonitor.unl.edu/.

Norbiato, D., Borga, M., Degli Esposti, S., Gaume, E., & Anquetin, S. (2008). Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins. *Journal of Hydrology*, *362*(3–4), 274–290. http://doi.org/10.1016/j.jhydrol.2008.08.023.

Palmer, W. C. (1965). Meteorological Drought. *U.S. Weather Bureau Research Paper 45*.

Parker, D. D., & Zilberman, D. (1996). The use of information services: The case of CIMIS. *Agribusiness*, *12*(3), 209–218. http://doi.org/10.1002/(SICI)1520-6297(199605/06)12:3<209::AID-AGR2>3.0.CO;2-4.

Reichle, R. H. (2005). Global assimilation of satellite surface soil moisture retrievals into the NASA Catchment land surface model. *Geophysical Research Letters*, *32*(2), L02404. http://doi.org/10.1029/2004GL021700.

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, *460*(7258), 999–1002. http://doi.org/10.1038/nature08238.

Roy, T., Serrat-Capdevila, A., Gupta, H., & Valdes, J. (2016). A platform for probabilistic multi-model and multi-product streamflow forecasting. Submitted to Water Resources Research.

Satti, S., Zaitchik, B., & Siddiqui, S. (2015). The question of Sudan: A hydro-economic optimization model for the Sudanese Blue Nile. *Hydrology and Earth System Sciences*, *19*(5), 2275–2293. http://doi.org/10.5194/hess-19-2275-2015.

Shortridge, J. E., Guikema, S. D., & Zaitchik, B. F. (2015). Empirical streamflow simulation for water resource management in data-scarce seasonal watersheds. *Hydrology and Earth System Sciences Discussions*, *12*(10), 11083–11127. http://doi.org/10.5194/hessd-12-11083-2015.

Simane, B., Zaitchik, B., & Ozdogan, M. (2013). Agroecosystem analysis of the choke mountain watersheds, Ethiopia. *Sustainability*, *5*(2), 592–616. http://doi.org/10.3390/su5020592.

UN Water/Africa. (2015). The Africa Water Vision for 2025: Equitable and Sustainable Use of Water for Socioeconomic Development.

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development (SDG#6: Clean Water and Sanitation)*.

Wilusz, D., Zaitchik, B., Anderson, M., Hain, C., Yilmaz, M., & Mladenova, I. (n.d.). Monthly monitoring of flooded area in the sudd wetland using low resolution SAR imagery from 2007–2011. *In Review*.

Yilmaz, M. T., Anderson, M. C., Zaitchik, B., Hain, C. R., Crow, W. T., Ozdogan, M., Evans, J. (2014). Comparison of prognostic and diagnostic surface flux modeling approaches over the Nile River Basin. *Water Resources Research*, *50*(1), 386–408. http://doi.org/10.1002/2013WR014194.

Zaitchik, B. F., Simane, B., Habib, S., Anderson, M. C., Ozdogan, M., & Foltz, J. D. (2012). Building climate resilience in the Blue Nile/Abay Highlands: A role for Earth system sciences. *International Journal of Environmental Research and Public Health*, *9*(2), 435–61. http://doi.org/10.3390/ijerph9020435.