HYDROLOGICAL MODELING AND CAPACITY BUILDING IN THE REPUBLIC OF NAMIBIA

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A hydrological modeling framework suitable for multiscale flood forecasting is introduced and used to build capacity in the Republic of Namibia and around the world.

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Ituated along Africa’s southwest coast, Namibia is a country renowned for its ancient deserts. The most arid country in sub-Saharan Africa, Namibia contains the majority of the Namib Desert, the oldest in the world, and a large portion of the dry Kalahari savannah and semidesert region (Barnard et al. 1998). However, 15% of the nation’s population lives in the northeastern regions (Caprivi and Kavango), abutting Namibia’s borders with Angola and Zambia, and an additional 46% of the population—over 800,000 people—resides in north-central Namibia (Oshikoto, Ohangwena, Oshana, and Omusati; National Planning Commission 2012). This densely populated region represents less than 15% of the total land area (Rukandema et al. 2009) and experiences variable, sometimes flooding, rain with an annual median value of 420–480 mm in the Namibian portion of the Okavango River basin in the nation’s northeast (Newsham and Thomas 2011). The north-central and northeast parts of the country have experienced severe flooding multiple times in the last decade; these floods have affected more than 100,000 people on multiple occasions (Rukandema et al. 2009; Smith 2011). With much of the population dependent on agriculture, accurately monitoring water movement and storage at the surface and in the soils is critical for many Namibians. Flooding affects the nation’s economy, society, security, and public health (Anthonj et al. 2015).

Since the end of the Namibian War of Independence against apartheid-era South Africa in 1990, Namibia has conducted free and open multiparty elections.
These stable politics have allowed a competent and technocratic bureaucracy to grow in the government, which has in turn created a milieu well suited to capacity-building and technology-transfer activities. Capacity building and technology transfer are evolutionary processes of give and take. Like many aspects of life, success in this sort of endeavor requires attention to personal relationships and the will to complete the project on the part of all involved parties. Capacity building is complex and multifaceted: it includes teaching, training, brainstorming, stakeholder meetings, side-by-side implementation, follow-up, review, and frequent conversations (e.g., Hossain et al. 2014; Sheffield et al. 2014; Lampetey et al. 2009).

Over the last 20 years, the number of spaceborne instruments collecting data available to Earth scientists has grown (e.g., Ungar et al. 2003; Friedl et al. 2002; Tapley et al. 2004). It is now feasible, even routine, to access estimates of precipitation, potential evapotranspiration, land use, land cover, topography, soil moisture, and other variables collected from space in a timely fashion. Moreover, these datasets are often available for free regardless of geopolitical boundaries. Multiple studies have described the various remotely sensed datasets on offer, and vast increases in computing power over the same time period have made processing large remote sensing datasets a workable proposition (Li et al. 2015). This same increase in computing power has transformed hydrology from a science using the traditional, one-dimensional, basin-by-basin, lumped parameter paradigm to one using high-resolution, coupled, distributed hydrological models (Wood et al. 2011).

The Ensemble Framework for Flash Flood Forecasting (EF5) is a software package developed at the University of Oklahoma (OU) that encompasses multiple hydrological model cores and additional related software modules. EF5 grew out of and now includes the Coupled Routing and Excess Storage (CREST) hydrological model developed by OU and the National Aeronautics and Space Administration (NASA; Wang et al. 2011). Developed with an emphasis on usability and flexibility, EF5 is well suited to technology transfer activities throughout the developing world. EF5’s modular architecture also enables frequent updates to the software and allows the modeling framework to incorporate new scientific advances as necessary.

This article begins by tracing the history of the joint OU–NASA capacity-building efforts in the Republic of Namibia and other developing regions. Then, we describe the datasets needed to fulfill the modeling goals and the various methods used to produce output for the Namibia Flood Dashboard, which is how the results of the project reach a broad audience. We briefly discuss the quality of the results from EF5 in Namibia. Finally, we present the lessons learned over the course of the project, tips for other groups working in capacity building, and future plans for EF5 and its place in global hydrological modeling.

**THE ORIGINS OF EF5 AND CREST.**

SERVIR–Africa. The development of the CREST family of hydrological models began with CREST version 1.6 (v1.6) in 2010 (Wang et al. 2011). CREST is a distributed hydrological model; runoff generation, evapotranspiration, infiltration, and surface and subsurface routing are computed at each grid cell in the model domain. Infiltration and runoff are partitioned via the variable infiltration curve concept (Liang et al. 1994; Zhao et al. 1980), while surface and subsurface water were routed in this version of CREST using the linear reservoir equations (Nash 1958). CREST was originally designed to enable the rapid production of streamflow and soil moisture estimates at global scales as part of the Global Hydrologic Prediction System (Zhang et al. 2015). To this end, the model accepts precipitation forcing from the NASA Tropical Rainfall Measurement Mission 3B42V7 real-time (TRMM RT; Huffman et al. 2007, 2010) and research products. More generally, gridded precipitation in the Environmental Systems Research Institute (ESRI) American Standard Code for Information Exchange (ASCII) or binary equivalent grid formats is also accepted.

Later, CREST was used to forecast streamflow and soil moisture on smaller scales, starting in the Nzoia River basin along the border between Uganda and Kenya (Wang et al. 2011). As part of this project, the CREST development team created a brief training course, primarily to demonstrate the results of various simulations on the Nzoia. This training course was delivered to the East Africa node of NASA and the U.S. Agency for International Development’s (USAID) SERVIR project: the Regional Centre for Mapping of Resources for Development (RCMRD) in Nairobi, Kenya. RCMRD personnel, with OU’s assistance in model setup and calibration, began running CREST v1.6 in 2011 over a domain covering Kenya, Tanzania, Uganda, and the surrounding areas (Macharia et al. 2010). CREST and EF5 capacity-building activities have since taken place at many locations across the African continent (see Fig. 1). The key characteristics of CREST in a capacity-building context include the following: the ability to run simulations on obsolete or otherwise underpowered computer hardware, the fact that the model is constrained by relatively few model parameters, and the model’s scalability, evidenced by...
Fig. 1. Map of Africa identifying locations where CREST and/or EF5 training and/or implementation has been completed and (inset) the regions of Namibia.
its use for both global and local simulations, depending on user needs.

In 2012, a series of improvements to the original CREST model physics, parameters, and software were released as CREST version 2.0 (v2.0; Xue et al. 2013; Zhang et al. 2015). CREST version 2.0 includes the shuffled complex evolution parameter optimization method (Duan et al. 1992) and enables the use of gridded model parameters in regions where estimation of these values from remote sensing data are possible. The release of CREST v2.0 spawned a corresponding new training course, initially designed, again, for SERVIR-Africa at RCMRD, though at its debut in 2012 hydrologists from 13 additional African and Asian countries attended. This course, more structured than its forebear, focuses on the Wang Chu River basin in Bhutan (Xue et al. 2013) where the majority of CREST v2.0 development work took place. The course consists of nine lessons, focused on CREST data requirements, CREST implementations, using GIS to preprocess data for the model, calibration, and visualization of results. As a result of this training workshop, RCMRD upgraded their implementation to CREST v2.0. SERVIR-Africa personnel have also been trained to conduct CREST training workshops with their partners across Africa. To date, several additional workshops have been held around Africa: some with direct involvement of the CREST developers and others completely independently run by RCMRD.

Namibia. In 2009, 2010, and 2011, devastating floods struck the northern portion of Namibia. In the aftermath of the 2009 flood, the Namibian Hydrological Services (NHS) partnered with NASA and other organizations to launch the Namibia Flood SensorWeb project (Mandl et al. 2013). A SensorWeb incorporates multiple sensors (spaceborne, ground based, and others) into a single framework that can generate useful decision-making products. In Namibia, sensors capable of detecting floods and their impacts, particularly via remote sensing, are of particular interest. As the project progressed, the CREST model became a natural addition for several reasons: its ability to efficiently monitor flood threats, its history of successful implementation elsewhere in Africa, its existing training materials, and its ability to use other sensors in the Namibia Flood SensorWeb project. NHS had sent officials to the 2012 CREST workshop at RCMRD and saw firsthand the potential benefits a CREST implementation in Namibia could offer. As a result, OU was invited to participate in the Flood Dashboard Workshop with the NHS in 2012.

The purpose of this workshop was to identify how output from the CREST model would fit into the larger Namibia Flood Dashboard. To answer this question, NHS described their forecast needs and their data gathering capabilities. The Namibian government operates several stream gauges across the country, most of them equipped with telemetry. This enables CREST calibration on certain river basins and allows for event-to-event determination of the model’s skill. On the other hand, rain gauge networks in the country, though extant, are often operated by other government agencies or outside entities, and obtaining reliable access to rain gauge measurements remains an unsolved problem. One of the rivers heavily subject to flooding, the Okavango, is particularly difficult for NHS to deal with because the vast majority of the catchment area is in Angola, immediately to Namibia’s north, and rain gauging networks there are essentially nonexistent (Pombo and de Oliveira 2015). This of course illustrates the utility of using a hydrological model forced by remotely sensed rainfall not constrained by political borders. Despite enthusiasm for the project on all sides, capacity building is usually an iterative and deliberative process, so the 2012 activities were primarily restricted to high-level exploration of needs and capabilities but did result in an opportunity for an NHS hydrologist, McCloud Katjizeu, to visit OU for a 6-week internship. Time and again we observe that capacity building is a two-way street: Katjizeu taught the CREST developers a great deal about Namibian geography, local forecasting practices, and local forecasting needs during his internship. For example, from Katjizeu’s internship we learned that NHS customers are generally more skilled in the interpretation of estimates of extent and depth of water rather than discharge volumes.

Therefore, in 2013, NASA and OU teams visited the Okavango River in northern Namibia to collect geolocated measurements of the river’s extent; these were ingested into the Namibia Flood Dashboard, the user-facing front end of the Namibia Flood SensorWeb project. (Tragically, the longtime head of the NHS passed away in 2013, but although this loss of institutional knowledge and passion could have had a detrimental effect on NHS and upon the NASA and OU group’s work with the agency, the project continued because of healthy interpersonal relationships with multiple other NHS personnel.) These data can be used by NHS and others to identify areas of the Okavango basin most threatened by flooding impacts. Another team conducted an aerial photo survey of portions of the Okavango from helicopter, which can be used to improve the accuracy of satellite-based estimates of inundation. For the hydrological model, these surveys help to guide the model calibration strategy and help
to elucidate potential roadblocks in the model setup process. Inundation modeling is particularly difficult in the Okavango region because the terrain is exceptionally flat, so any small vertical errors in a digital elevation model (DEM) have a drastic effect on the spatial accuracy of an inundated extent forecast.

The delta portion of the Okavango River basin has been extensively studied in a variety of contexts over the past four decades. Milzow et al. (2009) provide a detailed description of the characteristics of the Okavango delta, along with a summary of hydrological modeling efforts in the region up to that date. However, as Milzow et al. (2011) note, the Okavango River itself has been relatively less studied than the river delta. Their attempt at setting up a hydrological model on the Okavango River in Namibia and Angola was hampered by the accuracy of the remotely sensed precipitation data available. Farther east, in the Limpopo River basin over South Africa, Botswana, Zimbabwe, and Mozambique, Wetterhall et al. (2015) describe efforts to predict seasonal dry spells with the ECMWF’s seasonal forecasting system product (SYS-4). Mwangi et al. (2014), using the same SYS-4 system but in East Africa, found it had good performance at forecasting precipitation in the region and noted that applying the standardized precipitation index (SPI), a drought index, to the precipitation forecasts could be used to improve the prediction of droughts and their associated impacts. In the Zambezi River of southern Africa, Meier et al. (2011) demonstrate that hydrological models based only upon satellite estimates of precipitation and soil moisture can produce viable real-time forecasts of streamflow at a point. The Flood and Drought Risk Management Workshop was held in Namibia’s capital, Windhoek, in February 2014. Toward the end of the workshop, participants were given the opportunity to complete the CREST v2.0 training course. Officials from NHS, the South African National Space Agency (SANSA), RCMRD, and other partner groups did so. As a result, SANSA and SERVIR-Africa have since partnered to host joint CREST v2.0 training workshops in South Africa. Faculty from the University of Namibia and the Polytechnic of Namibia also attended and made plans to incorporate CREST v2.0 training into the curricula of their respective institutions. In capacity-building activities, almost every contact is a potential opportunity to spread an idea or a technology. At the conclusion of the training, NHS, NASA, and OU personnel conducted fieldwork in the Kuiseb River basin of the Khomas Plateau of central Namibia. The team geolocated river gauging stations in the basin to improve NASA satellite products and saw firsthand the challenges of streamflow monitoring in remote desert gauging stations (Fig. 2) as well as the importance of collecting measurements in unusual, nearly unique, terrain (Eckardt et al. 2013).

**APPLYING LESSONS LEARNED. New techniques in capacity building.** By 2014, the CREST v2.0 training course had been completed by around 200 hydrologists, geologists, meteorologists, and others from across Africa, South Asia, and Southeast Asia. However, the training materials had not been updated since 2012, and in the process of teaching several iterations of the course over 2 years, certain flaws in the instructional strategy and course organization became apparent. The course tended toward an illogical progression of topics: it started with applications and implementations of CREST around the world, then had participants run the CREST model, and then at the end taught them how to preprocess topographical

![Fig. 2. Example of typical remoteness of NHS stream gauges in the Kuiseb River basin in the Namib Desert.](a) Sign pointing to the NHS gauge downstream of the Gobabeb Research and Training Centre, southeast of Walvis Bay, Namibia, by 120 km and (b) the Gobabeb gauge.
EF5: Ensemble Framework for Flash Flood Forecasting

Fig. 3. (a) Flowchart outlining current and future capabilities of EF5, where green boxes represent input data structures, blue boxes represent modeling structures, and the orange box represents model output, and (b) the structure of CREST-like model physics as implemented in EF5 with kinematic wave routing in use.

data for the model. The course was also designed to use proprietary and expensive GIS software not available in some countries and situations. Additionally, the course was missing some key components that would have enabled trainees to obtain all necessary data, preprocess them, run and calibrate the model, and then interpret and use the output independently. Simultaneously, another project at OU resulted in the development of new hydrological modeling software: EF5. EF5 is a framework encompassing multiple...
hydrological model cores, including but not limited to the grid cell–based water balance component of CREST, linear reservoir routing as implemented in CREST, routing using the kinematic wave assumption (Chow et al. 1988), and the Sacramento family of water balance models (Burnash et al. 1973). EF5 accepts the same input file formats as the CREST model and adds support for GeoTIFF (tagged image file format) rasters, the binary Multi-Radar/Multi-Sensor precipitation file format (Zhang et al. 2016), and the NASA Global Precipitation Measurement (GPM) Integrated Multi-Satellite Retrievals for GPM (IMERG) product (Huffman et al. 2014). EF5 possesses informative error handling and includes the Differential Evolution Adaptive Metropolis (Vrugt et al. 2008) scheme for automatic calibration of model parameters. EF5 enables ensemble forecasts of flooding by allowing users to run simulations—with the same input data—using multiple hydrological model cores (see Fig. 3 for more information on the organization of EF5 components). Most importantly, perhaps, ensemble forecasts provide an envelope of potential solutions applicable to a specific forecasting problem and can be used to get at the underlying uncertainty characteristic of a particular forecast scenario. In 2016, EF5 became operational across the U.S. National Weather Service (NWS) for flash flood forecasting by local Weather Forecast Offices (Gourley et al. 2017).

The above developments prompted the authors to develop a new hydrological model training course after the conclusion of the 2014 NASA and OU activities in Namibia (see Table 1). The overarching purpose of this course is to enable someone—hydrologist or not—to understand the basic concepts of hydrological modeling and to set up, run, calibrate, and use the model independently using free or open-source software tools and using freely available input and forcing data. To achieve that end, one should complete the entire course, which requires one to remain engaged throughout the course. The easiest way to achieve this is to make the course as hands-on as possible, so covered skills in the course are never taught by just explaining or showing but always by doing. The course also places the necessary skill objectives in logical order, so one begins by learning general modeling concepts, then by preprocessing the necessary data, then by running and calibrating the model, and then by learning how to interpret and use the modeling output. Skills also build upon one another throughout the course, so that complex concepts and competencies come after simpler ones, whenever possible. Finally, the aphorism “practice makes perfect” means that completing the entire process of running a model example just once will not result in the desired outcome, so multiple examples are included in the training, and as one progresses from example to example, the student does more and more work within each example independently. This structure inspires confidence in the participant, which is typically among the most critical traits to engender in the capacity-building process. To maintain continuity and familiarity between the CREST v2.0 and EF5 training courses, especially for longtime users at SERVIR-Africa, the EF5 training course maintains old modeling examples on the Wang Chu River basin and the Nzoia River basin where the CREST model physics were first tested and refined. Common difficulties in capacity building include a lack of continuity in participants from workshop to workshop and mismatches between workshop participants and the collaborators that will eventually do the work. However, we contend that our intense focus on hands-on examples in the training courses has resulted in more year-to-year continuity of participants, as participants expect each time to grow their capabilities and learn new skills. Additionally, because the EF5 training course requires the full attention of participants (again due to the hands-on character of the course), managerial staff tend to self-select themselves out of participating in the course.

The EF5 training course is also modular, and since it follows a logical progression of increasing complexity and difficulty with time, when less time is available

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<th>Table 1. Outline of EF5 model training course.</th>
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<td><strong>Day 2</strong></td>
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<td>2.2 Manual calibration</td>
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<td>2.3 Automatic calibration</td>
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<td>2.4 Interpreting and using model output</td>
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<td><strong>Day 4</strong></td>
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<td>4.1 Connecticut River example</td>
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<td>4.2 Bogota River example</td>
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<td>4.3 Create your own example</td>
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<td>4.4 Conclusions and wrap-up</td>
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for a particular training implementation, the modules at the end of the course can simply be removed or self-taught later at the participant’s leisure. The full version of the course is designed to be completed in 4 or 5 days, but shorter versions have been successfully conducted in multiple instances, and these can take between 1.5 and 3 days to complete. Although originally developed for Namibia, the course contains examples from the around the world, which makes it equally applicable to Southeast Asia, South Asia, Latin America, the United States, or Africa. One difficulty in capacity building that the team is currently working to overcome is distance; it would be most desirable, for example, to conduct training multiple times a year in Namibia, but this is uneconomical and time consuming. Therefore, we have produced videoed versions of the EF5 course for free distribution across the Internet (http://ef5.ou.edu/videos/). We hope that these materials will encourage those who have completed the in-person course to continue their work with the model as well as attract new users to the modeling framework over time.

**Fig. 4.** Example of products available from EF5 as implemented in Namibia: (a) streamflow (m$^3$ s$^{-1}$) in the Okavango River basin, (b) soil moisture (% of CREST soil saturation) in the Okavango River basin, (c) 30-day standardized precipitation index over southwestern Africa, and (d) 87-h GFS rainfall forecast (mm h$^{-1}$) over southwestern Africa, valid 0300 UTC 18 Oct 2015.
The course debuts in Namibia. In 2015, the course described in the preceding section debuted at NHS. Every participant present for the first lesson was still present at the last lesson, which was, according to NHS, a first for them in any capacity-building exercise with any group, an excellent sign that participants remained engaged with the instructional materials throughout. We also were able to present the results of calibrating EF5 for the Okavango River upstream of Rundu, Namibia, and the output from a real-time demonstration system (Fig. 4). This demonstration system includes products focusing on precipitation deficits and meteorological drought as well as streamflow and soil saturation. At the end of the 2015 training, feedback from NHS was overwhelmingly positive, with the director of the agency indicating it was “the best training course we have received from any group” (Fig. 5).

THE REAL-TIME SYSTEM IN NAMIBIA. Forcing. Precipitation forcing to EF5 in Namibia is provided by the NASA TRMM RT product. This estimated precipitation is available every 3 h at approximately 6 h after the valid time of the estimate. The horizontal resolution of this precipitation estimate is 0.25° latitude by 0.25° longitude. Historical daily rainfall from TRMM RT is also used to generate daily updates of the 30-, 90-, and 180-day SPI, a measure of meteorological drought (Zarch et al. 2015). SPI was added to the suite at the request of NHS for years when drought is a larger concern than flooding.

Forecast precipitation is provided to the model by the Global Forecast System (GFS) numerical weather prediction model (NCEP 2003). The GFS precipitation is available from a new model run every 6 h starting about 3 h after the analysis time of each run; the model runs with a 3-h time step. GFS precipitation is also available at a horizontal resolution of 0.25° latitude by 0.25° longitude. EF5 uses the first 99 h (4 days and 3 h) of forecast precipitation from each model run.

Potential evapotranspiration (PET) forcing is from the USAID’s Famine Early Warning System Network.
(FEWS NET), where PET estimates are generated using the Shuttleworth formulation of the Penman–Monteith equations (Shuttleworth 1993). In Namibia, EF5 is forced with monthly mean gridded PET estimates at a horizontal resolution of 0.25° latitude by 0.25° longitude. These monthly mean estimates are the same as those used in the EF5 training course because the higher temporal resolution of daily PET estimates does not significantly improve model accuracy for peak flood flows. Additionally, the monthly mean estimates result in less-complex training materials, since any EF5 example can be run using these global monthly mean estimates. This reduces data requirements and the total file size of the training package, both of which are desirable outcomes in capacity-building activities.

Topographical data. The Namibian implementation of EF5 runs at a horizontal resolution of 0.125° latitude by 0.125° longitude, with a DEM derived from Shuttle Radar Topography Mission (SRTM) data (Smith and Sandwell 2003). SRTM data have been hydrologically corrected and conditioned as part of the Hydrological Data and Maps Based on Shuttle Elevation Derivatives at Multiple Scales (HydrosHEDS) project (Lehner et al. 2008). Using GIS tools, the original HydrosHEDS DEMs, available

Fig. 6. (a) Calibration and (b) validation hydrographs for the Okavango River at Rundu, Namibia. Observed streamflow is measured daily at the Rundu gauging station. Precipitation forcing is from the TRMM 3B42V7 real-time product. The calibration period extends from 1 Jan 2003 to 31 Dec 2006 (NSCE: 0.92, bias: −8.4%, CC: 0.97), and the validation period extends from 1 Jan 2007 to 1 Jan 2011 (NSCE: 0.78, bias: −14%, CC: 0.90).
at 30-arc-s (approximately 1 km at the equator) horizontal resolution, are scaled to the desired 0.125° latitude by 0.125° longitude resolution. Then, the resulting DEM is processed to remove any pits or sinks following the procedure outlined in Jenson and Domingue (1988). Using a vector representation of the Okavango River, it and its largest tributaries are “burned” into the DEM by reducing the elevation values of all the DEM pixels in the river channel. A drainage direction map (DDM) is generated using the eight-direction flow-direction algorithm; this DDM is used to produce a flow accumulation map. While 0.125° (approximately 12 km at the equator) resolution is sufficient for streamflow predictions forced by 0.25°-resolution rainfall estimates, higher-resolution DEMs are needed for inundation mapping.

The recent release of SRTM-II data, available at 30-m resolution, by the government of the United States, enables additional modeling applications like inundation (Buis 2014). However, use of these data in capacity-building activities still generates significant challenges due to large file sizes and lengthy processing times. Although we use some example SRTM-II data in pieces of the EF5 training course, we have so far determined that the computing resources available to many of our capacity-building partners are not yet capable of using STRM-II data for the entire processing and modeling workflow. Therefore, using SRTM-II data only when absolutely necessary or as an illustrative tool during the capacity-building process is advisable.

VALIDATION, RESULTS, AND IMPLEMENTATION. Model performance. Using only commonly available rainfall, PET, and topographical datasets and open-source GIS tools, EF5 simulates the maximum streamflow in the Okavango River at Rundu, Namibia, for each forecast period. EF5 is capable of accurately simulating the peak volume and the peak timing of the annual flooding at Rundu in both dry and wet years. During the calibration period, from 1 June 2003 to 31 December 2006, the Nash–Sutcliffe coefficient of model efficiency (NSCE; Nash and Sutcliffe 1970), the bias of the mean simulation relative to the mean observation, and the Pearson correlation coefficient (CC; Pearson 1895) are 0.92, −8.4%, and 0.97, respectively. For the validation period, from 1 January 2007 to 1 January 2011, these values are 0.78, −14%, and 0.90 (Fig. 6). In general, one should expect a small decrease, as is observed in this case, in various time series comparison metrics when transitioning from a calibration period to an independent validation period. Calibrated streamflow and the other products described in the previous sections are accessible to hydrologists at NHS via the Internet and are produced using the computing infrastructure of the Namibia Flood Dashboard.

The Namibia Flood Dashboard. A joint venture of the Open Cloud Consortium (OCC) and NASA, Project Matsu is a framework that uses cloud computing resources to process satellite imagery into useful Earth science output. Members of the OCC include companies, government agencies, nonprofits, and universities, all of whom are interested in supporting large-scale research projects via a combination of data sharing and pooled computing resources. Among Matsu’s applications is the Namibia Flood Dashboard (http://matsu-namibiaflood.opensciencedatacloud.org/), which is maintained by NASA and ingests the following: data from NASA spaceborne sensors; NHS reports of streamflow and stage height; socioeconomic and infrastructure data from the Namibian government and nongovernmental agencies; results from past in situ surveys conducted by NASA, OU, and other partners; and EF5 simulations of streamflow and soil moisture in the Okavango basin (Fig. 7). The goals of the dashboard are to enable users to make new connections or develop new insights between disparate datasets and to encourage NHS officials to use the available technology to guide their decision-making processes.

Expanding by word of mouth. While sound hydrographs and excellent model statistics are the typical measures of success in hydrology, we must turn to another source of information for measuring success in hydrological capacity building: word of mouth. After the U.S. government’s worldwide release of SRTM-II data in late 2014, several organizations began to plan a series of training and capacity-building workshops at various sites across the world for 2015. In Africa, CREST v2.0 was selected as the demonstration model for workshops in Arusha, Tanzania, and in Pretoria, South Africa, both of which included delegations from multiple African nations. RCMRD personnel, themselves previously trained by OU and NASA scientists, served as trainers for both of these workshops. Meanwhile, in Latin America, the Committee on Earth Observing Satellites and the Secure World Foundation selected OU’s EF5 modeling framework for their Workshop on Higher-Resolution SRTM Data and Flood Modeling in Puebla, Puebla, Mexico, in May 2015, which brought together researchers from 10 countries. On the basis of this workshop, the Mexican Space Agency (Agencia Espacial Mexicana) and the Center for Global Change and Sustainability
RAINFALL

Observe G-WADI, METEOSAT and NASA TRMM satellite rainfall accumulation estimates.

WATER LEVELS

See figures in the table below with readings from our Telemetry Stations, site informants, and the satellite-based SADC Hydrological Cycle Observing System (SADC-HYCO) Data Collection Platforms (DCPs). You can read more about SADC-HYCO here http://sadchyco.srwf.gov.za/about%20us.aspx.

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<td>3.18</td>
<td>3.17</td>
<td>6.04</td>
<td>5.18</td>
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<tr>
<td></td>
<td>Ngoma Gate</td>
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<td>0.27</td>
<td>0.26</td>
<td>3.95</td>
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<tr>
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<td>2.23</td>
<td>2.23</td>
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<tr>
<td>Kwando</td>
<td>Kongola</td>
<td>1.58</td>
<td>1.58</td>
<td>1.58</td>
<td>2.98</td>
<td>2.54</td>
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<tr>
<td></td>
<td>Camp-Kwando (+)</td>
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<td>0.15</td>
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<td>3.55</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Aridara</td>
<td>1.73</td>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

Fig. 7. Example daily flood/hydrological drought bulletin (17 Apr 2015) from the Namibian government, as seen on the Namibia Flood Dashboard (http://matsu-namibiaflood.opensciencedatacloud.org/), showing satellite rainfall products and stream gauge measurements.

in the Southeast (Centro del Cambio Global y la Sustentabilidad en el Sureste) included EF5 training in another workshop on geospatial information processing and usage in Villahermosa, Tabasco, Mexico, in September 2015. These recent activities illustrate how quickly a successful capacity-building project can spread not only from country to country but also from continent to continent.
### Table 2. Sources of a priori EF5 model parameters in global implementation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional impervious area (IM)</td>
<td>Fraction of each grid cell covered by an impervious surface</td>
<td>Elvidge et al. (2007)</td>
</tr>
<tr>
<td>Maximum soil water capacity (WM)</td>
<td>Requires soil textures from the SoilGrids project, which are converted to soil types and then the Green–Ampt effective porosity ( \theta_s ) using a lookup table; ( \theta_s ) values are multiplied by a fixed soil depth (100 cm)</td>
<td>Rawls et al. (1983) for soil type and ( \theta_s ) lookup tables; Hengl et al. (2014) for SoilGrids lookup tables</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity ( K_{sat} )</td>
<td>Soil textures from the SoilGrids project are converted to ( K_{sat} ) using soil type and ( K_{sat} ) lookup tables</td>
<td>Rawls et al. (1983) for soil type and ( K_{sat} ) lookup tables</td>
</tr>
<tr>
<td>Variable infiltration curve exponent ( b )</td>
<td>Soil textures are converted to soil types and then those are converted to a mean ( b ) using lookup tables</td>
<td>Rawls et al. (1983) for soil type lookup table; Cosby et al. (1984) for mean ( b ) lookup table</td>
</tr>
<tr>
<td>Overland alpha ( \alpha_o )</td>
<td>Determined from LULC classifications, which must be converted to Manning’s ( n ) via lookup table</td>
<td>Defourny et al. (2014) for LULC data; Chow (1959) for Manning’s ( n ) lookup table</td>
</tr>
<tr>
<td>Channel alpha ( \alpha ) and beta ( \beta )</td>
<td>Determined via parameter prediction model relating average temperature, rainfall, and DEM data to ( \alpha ) and ( \beta ) values</td>
<td>Vergara et al. (2016) for parameter prediction model; Hijmans et al. (2005) for temperature and rainfall data; Danielson and Gesch (2011) for DEM</td>
</tr>
</tbody>
</table>

**RECOMMENDATIONS AND FUTURE PLANS.** Deploying EF5 globally. To promote CREST and EF5’s continued growth and development across the world, EF5 has also been extended to cover most of Earth’s land surface between 50°N and 50°S. In the global implementation, EF5 rainfall forcing is supplied by the NASA GPM IMERG product. Zhang et al. (2015) present a global modeling case study using CREST v2.0 with uniform global parameters and satellite precipitation forcing. In this implementation, we go a step further and develop gridded a priori model parameters from remote sensing data sources, as described in the subsequent paragraphs (see Table 2). This implementation allows us to demonstrate to the participants in our capacity-building activities that the modeling framework can be used for many different applications, from producing simpler single-point lumped-parameter forecasts to global gridded estimates of streamflow and other model states.

Fractional impervious area (IM), one of the CREST model parameters within EF5, is determined from the gridded data described in Elvidge et al. (2007). Using data from the SoilGrids project (Hengl et al. 2014), the relative fractions of sand, silt, and clay in a given area’s soil are determined. Then the maximum soil water capacity (WM) and the soil saturated hydraulic conductivity \( K_{sat} \), two additional CREST parameters, can be estimated from the Green–Ampt lookup table in Rawls et al. (1983). The value of \( K_{sat} \) comes directly from this lookup table, while WM is defined here as the product of a fixed soil depth (100 cm) and the Green–Ampt effective porosity \( \theta_s \) from this lookup table. Cosby et al. (1984) provides an analogous lookup table that relates the soil type to the exponent of the variable infiltration curve \( b \), another CREST parameter. The two remaining CREST parameters, PET conversion factor and initial value of soil water, are set to uniform values of 1 and 0, respectively.

The procedure for determining global values of the kinematic wave parameters continues along similar lines. The \( \alpha_o \), or overland alpha, parameter is determined from the land-cover/land-use (LULC) data at the European Space Agency’s Climate Change Initiative project (Defourny et al. 2014) and a lookup table in Chow (1959) that relates a given LULC classification to a value of Manning’s \( n \). The other major kinematic wave parameters, channel alpha and channel beta, \( \alpha \) and \( \beta \), respectively, are generated following the procedure in Vergara et al. (2016) with their parameter estimation model extended globally, including ungauged grid points. This parameter estimation model requires average temperature and precipitation, which have been obtained from Hijmans et al. (2005). Additionally, a DEM is required to produce \( \alpha \) and \( \beta \) as well as to run the model; in this implementation, we employ the Global Multi-Resolution Terrain Elevation Data 2010 (GMTED2010) DEM from the U.S. Geological Survey (Danielson and Gesch 2011). The remaining routing parameters in EF5 are set to uniform global values.

All parameter grids and topographical data are resampled to a horizontal resolution of 0.05° × 0.05°.
Fig. 8. (a) Scatterplot of daily maximum streamflow as measured at these gauges in the Global Runoff Data Centre (GRDC) between 1 Jan 2003 and 30 Dec 2014 compared to EF5 forecasts of daily maximum streamflow at the same locations and over the same time period, where gauges north of 50°N have been removed from the analysis because of an absence of precipitation forcing in that region, and (b) global map of stream gauges used to validate results from the EF5 global modeling system.
for this global system. A preliminary evaluation of the simulation is undertaken using observations from a set of 3,763 stream gauges across the world (Global Runoff Data Centre 2016). Gauges south of 50°S and north of 50°N are excluded from the analysis because satellite precipitation forcing is unavailable in those areas. Observed peaks in streamflow between 1 January 2003 and 30 December 2014 are identified by retaining only those values in the highest 10% of all values for each gauge. Then, these observed peaks are compared to simulations from EF5 (Fig. 8). Though preliminary, these results suggest great potential utility for flood forecasting and monitoring with EF5 and remote sensing–derived a priori model parameters. Real-time output from this global implementation of EF5 can be monitored online ([http://floods.global](http://floods.global)), and the EF5 source code is also available online ([https://github.com/HyDROSLab/EF5](https://github.com/HyDROSLab/EF5)).

**Capacity-building best practices.** Capacity building has never been and will never be an easy process. However, there are a few guiding principles that can increase a project’s odds of success. As we learned in the transition from CREST v2.0 to EF5, it is critical to remain responsive to the needs of a particular partner. Although a change in strategy may, at the time, seem unnecessary or difficult, it can result in technical improvements, a wider user base (Fig. 9), and more fruitful collaboration. Successful training efforts require a willingness to “read the room.” If training participants cannot complete a particular training course, it is incumbent upon the course designer to investigate the reasons for it and mitigate them accordingly, as we learned in replacing CREST v1.6 and v2.0 training courses with EF5. As much as possible, any technical training should involve copious amounts of hands-on practice and reduce discussion of theory or one-sided lecturing to minimal levels. Incorporation of locally produced information is a powerful technique for maintaining an engaged partnership, as is done by hosting government hydrology bulletins on the Namibia Flood Dashboard.

As user needs evolve and mature, capacity-building activities must mature as well. An instructive example in this case involves the use and interpretation of ensemble hydrological forecasts. Currently, the EF5 training course invites participants to only partially consider the advantages and uses of ensemble hydrological forecasts because the majority of the course’s targeted audiences are more comfortable with decision-making based upon deterministic forecasts. Cloke and Pappenberger (2009) found that ensemble hydrological predictions can enable national governments to more effectively produce useful flood alerts, while simultaneously identifying several challenges arising from the use of these ensemble systems. Several of these challenges are particularly trenchant in the realm of capacity building, including a lack of computing power in the target regions and optimal strategies for training.

Fig. 9. Map of all past, current, and future EF5 implementations and capacity-building activities.
forecasters or other end users. Ramos et al. (2013) present an interesting example, from a hydrological conference, in which a simple game is used to illustrate how forecast uncertainty can impact decision-making. Activities along these lines could be incorporated into future iterations of the EF5 training course. Bruen et al. (2010) provide several examples of how ensemble hydrological forecasts can be visualized, all of which could be tested in future capacity-building activities and customized as needed for various audiences. Finally, Emerton et al. (2016) review a handful of regional and global flood forecasting systems and outline seven grand challenges: data availability, precipitation forecasting, human influences, demonstrating forecast value, communicating results, and evaluating results. While the capacity-building activities outlined in this study attempt to address certain of these grand challenges, future work on our systems should take place in a framework where all are cognizant of each of these grand challenges.

Perhaps surprisingly, we contend that youth and greenness are actually advantages in capacity building. The first two authors of this paper, both graduate students at the time of this manuscript’s initial submission, are the primary developers of the EF5 training course and the EF5 modeling framework and have been the course instructors for all of the EF5 capacity-building sessions described in the paper. Though some observers could identify this as a distinct disadvantage for reasons including the ability (or lack thereof) to sustain project funding or to identify a “next generation” of project leaders, we contend that these factors are outweighed by the flexibility (and the youthful disregard for the impossible) enjoyed by many graduate students. Things will go wrong from time to time, but those with the willingness to rapidly alter their trajectories reap the benefits. Power cuts, computer failures, illnesses, communication breakdowns, and more will conspire to upend even the most well-designed capacity-building programs. Those who choose to persevere will discover that all parties to the partnership will accrue substantial benefits.

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This monograph pays tribute to one of the leading scientists in meteorology, Dr. David Atlas. In addition to profiling the life and work of the acknowledged “Father of Radar Meteorology,” this collection highlights many of the unique contributions he made to the understanding of the forcing and organization of convective systems, observation and modeling of atmospheric turbulence and waves, and cloud microphysical properties, among many other topics. It is hoped that this text will inspire the next generation of radar meteorologists, provide an excellent resource for scientists and educators, and serve as a historical record of the gathering of scholarly contributions honoring one of the most important meteorologists of our time.