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Project Partners:
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Project Stakeholders:
Ethiopian Water Works Corporation, end-user of the decision support system;
Ethiopian Ministry of Water, Irrigation, and Electricity

Earth Observations, Models and Technologies applied:
Satellite precipitation estimates: NASA TMPA 3B42RT (to be replaced by GPM/IMERG), JAXA GSMaP;
NOAA CPC-WMO GTS gridded raingauge estimates;
The North America Multi-Model Ensemble (NMME) seasonal climate forecasts;
NOAA Climate Forecast System (CFS v2) Sub-seasonal to Seasonal (S2S) ensemble;
US NCEP Global Ensemble Forecasting System and Canadian Meteorological Centre medium-range deterministic and ensemble weather forecasts;
THORPEX Interactive Grand Global Ensemble (TIGGE) ensemble weather forecasts (CMA, CPTEC, ECMWF, MeteoFrance, UKMet, JMA).

A. OVERVIEW

The project's overall goal was "**utilize remote sensing data and seasonal climate forecasts in a Decision Support System (DSS) to optimize reservoir operation for hydropower production**." The case study is the Omo-Gibe River basin in Ethiopia that has a series of hydropower dams (see Fig. 1). The Application Readiness Level (ARL) at the start of the project was 3 (i.e. variability established). The project goal has been successfully met. We have developed a new decision support system (DSS) for stakeholders that provides information useful for decision making on hydropower reservoir planning. In addition, the DSS provides a range of products (from climate forecasting to hydrologic forecasting) that could be of use to a range of stakeholders in the water sector. For transfer and implementation of the DSS, we have developed a Graphical User Interface (GUI), and conducted hands-on workshops in Ethiopia over a period of six months to train key stakeholders. The final ARL has been 8 (application completed and qualified; functionally proven).

In the following section, we describe the key project findings, outcomes, and outputs.

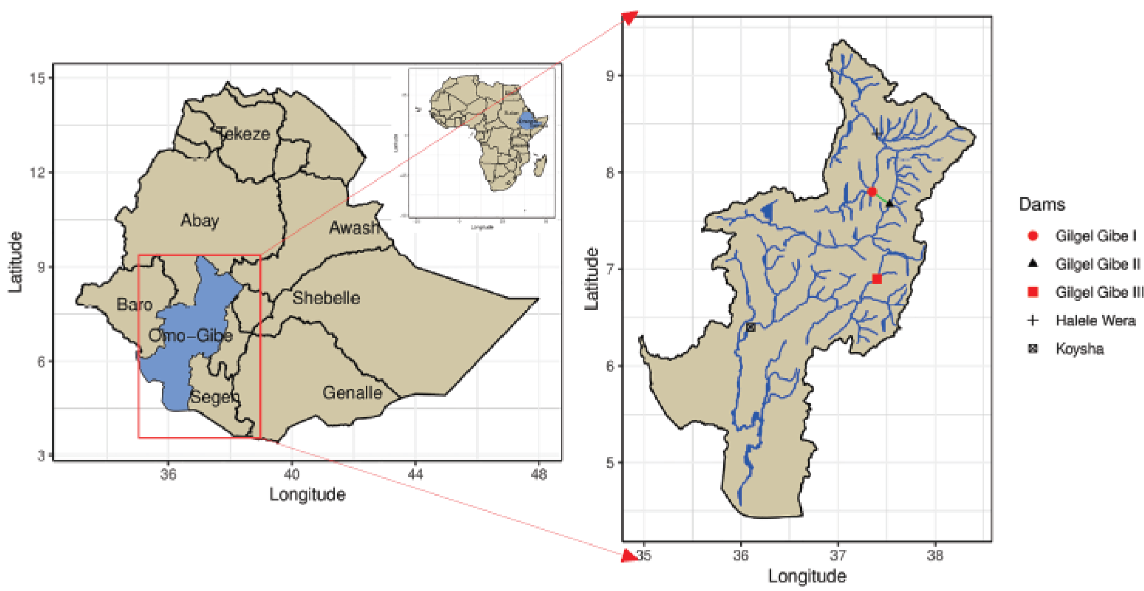

Fig. 1. *The Omo-Gibe River basin consisting of a cascade of five reservoirs, located in Ethiopia. The hydropower reservoirs used in this study (Gilgel Gibe I and Gilgel Gibe III) are highlighted in red. The green line represents a tunnel which connects Gibe I and Gibe II reservoirs.*

B. KEY SCIENTIFIC FINDINGS

We started by developing a new flowchart for seasonal hydropower planning framework (see Fig. 2).

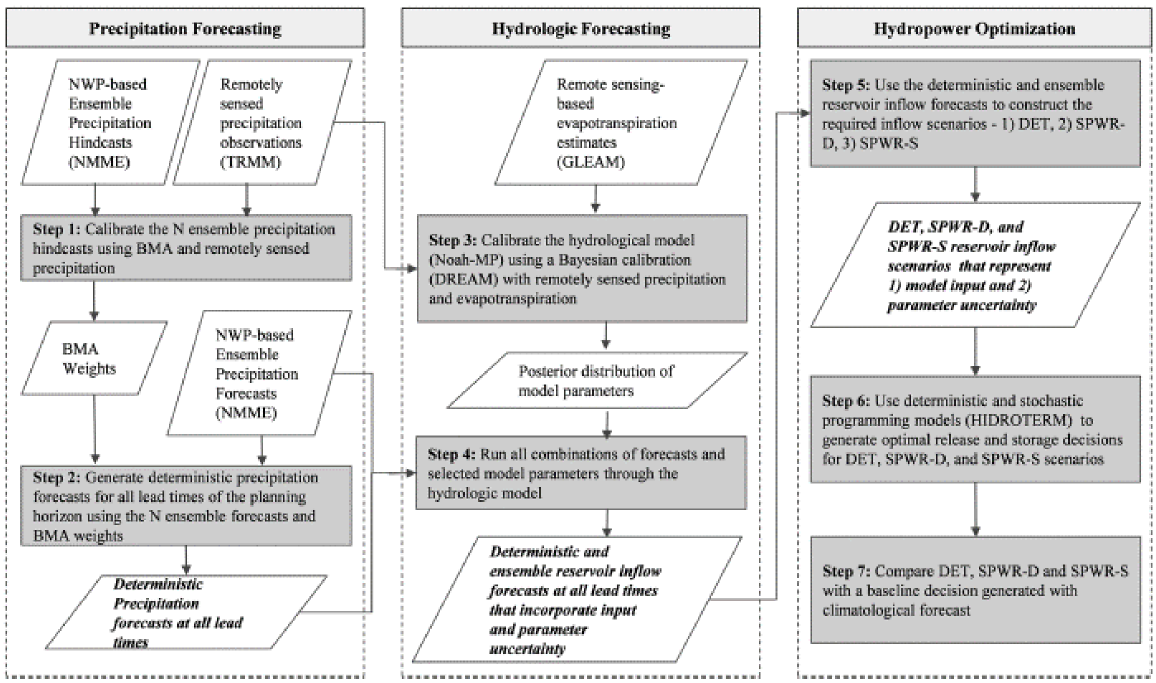

Fig. 2. *Flowchart for seasonal hydropower planning framework developed in this study. The precipitation forecasts, observational datasets, hydrologic model, and optimization algorithm used in this research are mentioned in parenthesis.*

The flowchart has three major components: (1) precipitation forecasting, (2) hydrologic forecasting, and (3) hydropower optimization.

We identified and addressed three major research questions that are key to developing a decision support system for hydropower reservoir planning:

Research Question 1: Can seasonal precipitation forecasts combined with remotely sensed estimates of precipitation and evapotranspiration generate reliable reservoir inflow scenarios in the absence of streamflow observations?

Research Question 2: How do uncertainties in precipitation forecasts and model parameters impact seasonal reservoir inflow forecasts?

Research Question 3: To what extent does incorporation of inflow uncertainty in the first/immediate stage of a stochastic programming with recourse model affect the release policy and hence hydropower production?

B.1 Addressing Research Question 1

Validation of NMME Precipitation Forecasts: We validated the seasonal precipitation hindcasts from one of the Numerical Weather Prediction (NWP) models, the North American Multimodel Ensemble (NMME), using the satellite-based TRMM datasets. We specifically used 30-member seasonal ensemble precipitation forecasts from three NMME models (CanCM3, CanCM4, and GEOS5). Figure 3 presents a time series comparison of different precipitation forecast models with the observed data. The key findings include: (a) the 3-model, 30-member ensemble precipitation forecasts from NMME are accurate at short lead times (1-3 months), and (b) Bayesian Model Averaging (BMA) of the ensemble precipitation forecasts outperforms the ensemble mean as well as the individual models at all lead times.

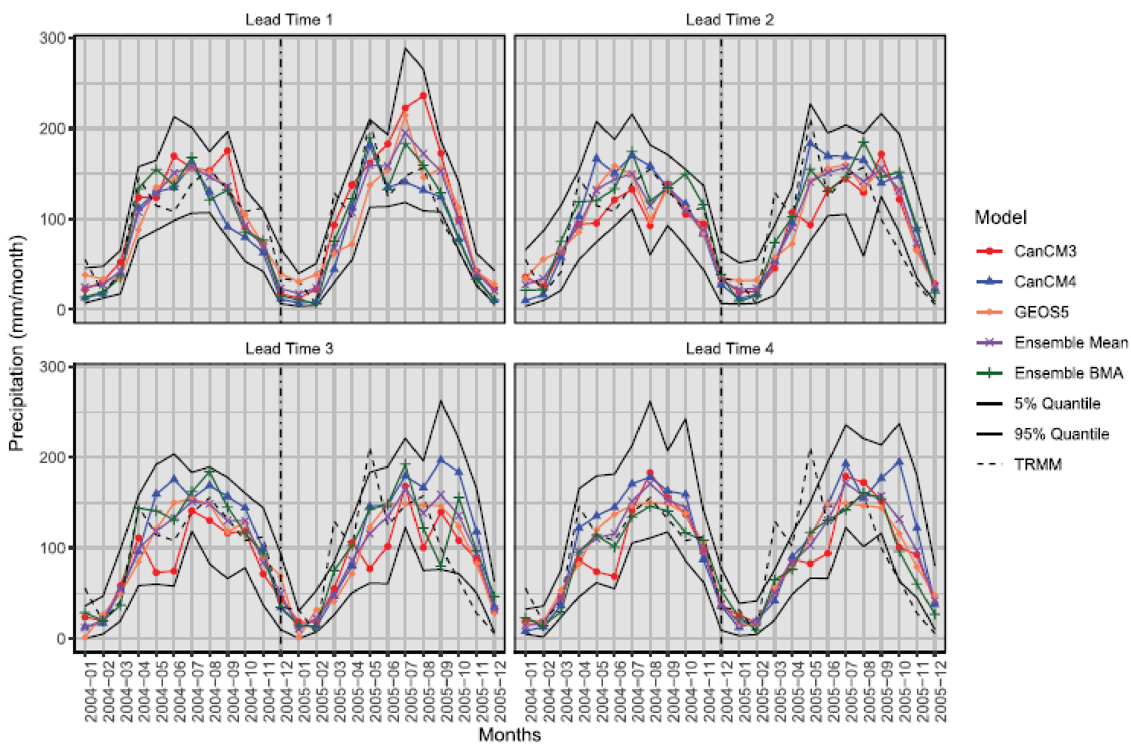

Fig. 3. *Time series comparison of precipitation from different NMME models and observations (TRMM) for different lead times (1-4 months). We present the mean of the 10 members from CanCM3, CanCM$, and GEOS5. 'Ensemble Mean' and 'Ensemble BMA' are the simple mean and Bayesian Model Averaging of all 30 ensemble members. In addition, we present the 5% and 95% quantiles of all 30 ensemble members.*

Another key finding is that the inclusion of large-scale teleconnections as geostatistical predictors along with NWP multi-modeling can greatly enhance the forecasting skill of NWP seasonal and weather forecasts over not only the Omo-Gibe river basin (our primary study region), but also over all the major river basins of Ethiopia. In Figure 4 we show the benefits of utilizing the El Nino-Southern Oscillation as a predictor along with all eight NMME models into a Bayesian-optimized ensemble mean forecast for the Blue Nile river basin, showing that summer season rainfall over the basin can be skillful forecast (correlation coefficient *=0.73*).

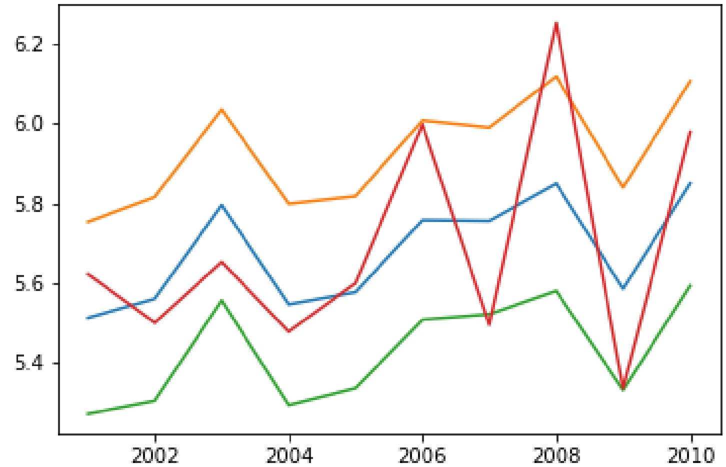

Fig. 4. *Calibrated forecast of Blue Nile summertime precipitation using a weighted average of ENSO plus the 8 NMME models. June 1st forecast of June – October rainfall. The year being forecast is left out when calculating forecast weights and regression coefficients. Red – TRMM, Blue – ensemble mean (R=0.73), Orange - 90th percentile, Green – 10th percentile; y-axis scale is in mm/day.*

Similarly, geostatistical information at weekly-evolving time-scales can also be used to enhance NWP rainfall forecasting skill. In Figure 5 immediately below, we show how the Madden-Julian Oscillation (MJO) impacts rainfall anomalies over Ethiopia based on the phase of the MJO. This information, along with NWP rainfall forecasts from NCEP's CFSv2, can be combined through a quantile regression model, to significantly improve weekly time-scale rainfall forecasts, as shown in Figure 6.

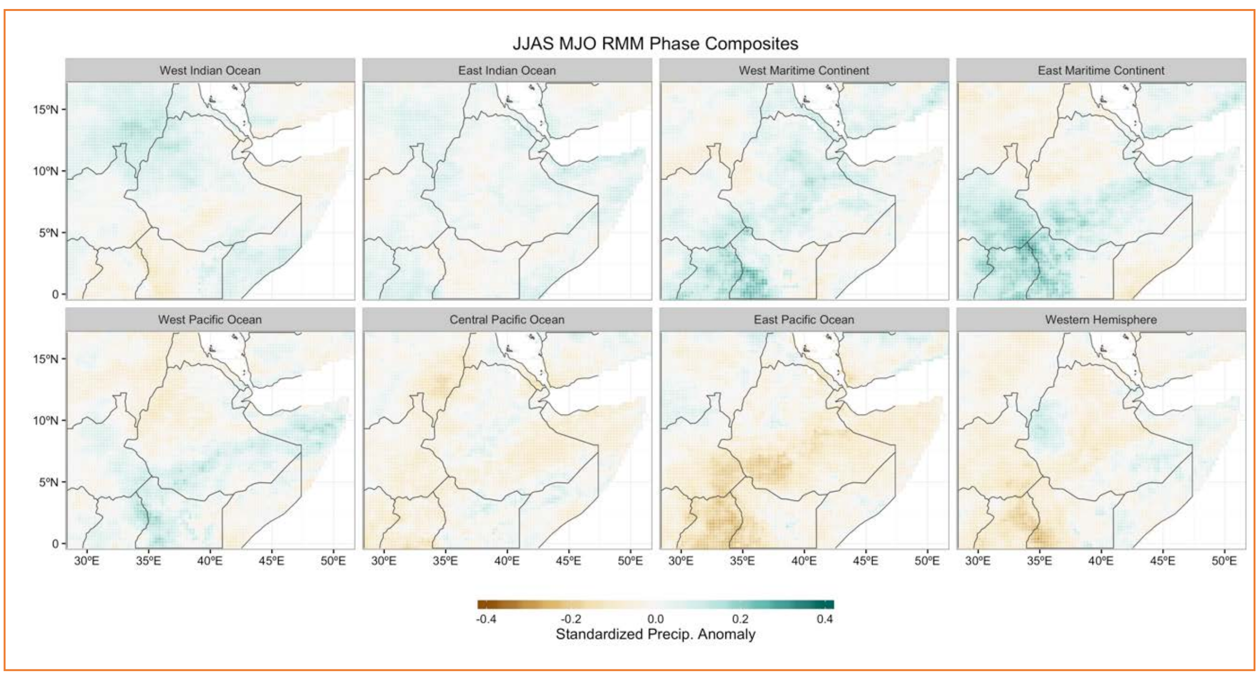

Fig. 5. Composites of June–September average precipitation anomalies corresponding to each phase of the MJO. Periods with no MJO activity are not shown.

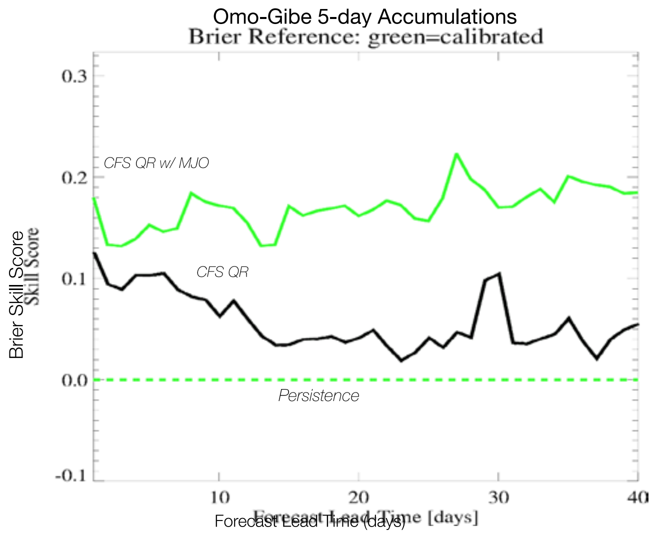

Fig. 6. Brier skill scores for NCEP CFSv2 NWP 5-day accumulated rainfall forecasts over the Omo-Gibe river basin (black line) as a function of lead-time (days), and a combined quantile regression model utilizing MJO phase and anomaly information along with CFSv2 (green line), showing the appreciable improvement in forecasting skill that comes with the inclusion of the MJO at all lead-times.

At daily-to-two-week time-scales, combining NWP ensemble forecasts into a multi-model forecast can provide significant benefits in forecasting skill for extreme events, as shown below in Figure 7 (here, 90^{th} percentile rainfall), where we compare rainfall forecasting skill of four weather centers (Canada – CMC, ECWMF, US – NCEP, UK Met Office) to a combined multi-model over Ethiopia. As shown in the figure through the use of the Brier skill score, the multi-model forecast is equal to or out-performs any individual model for all of the 12 primary Ethiopian river basins shown.

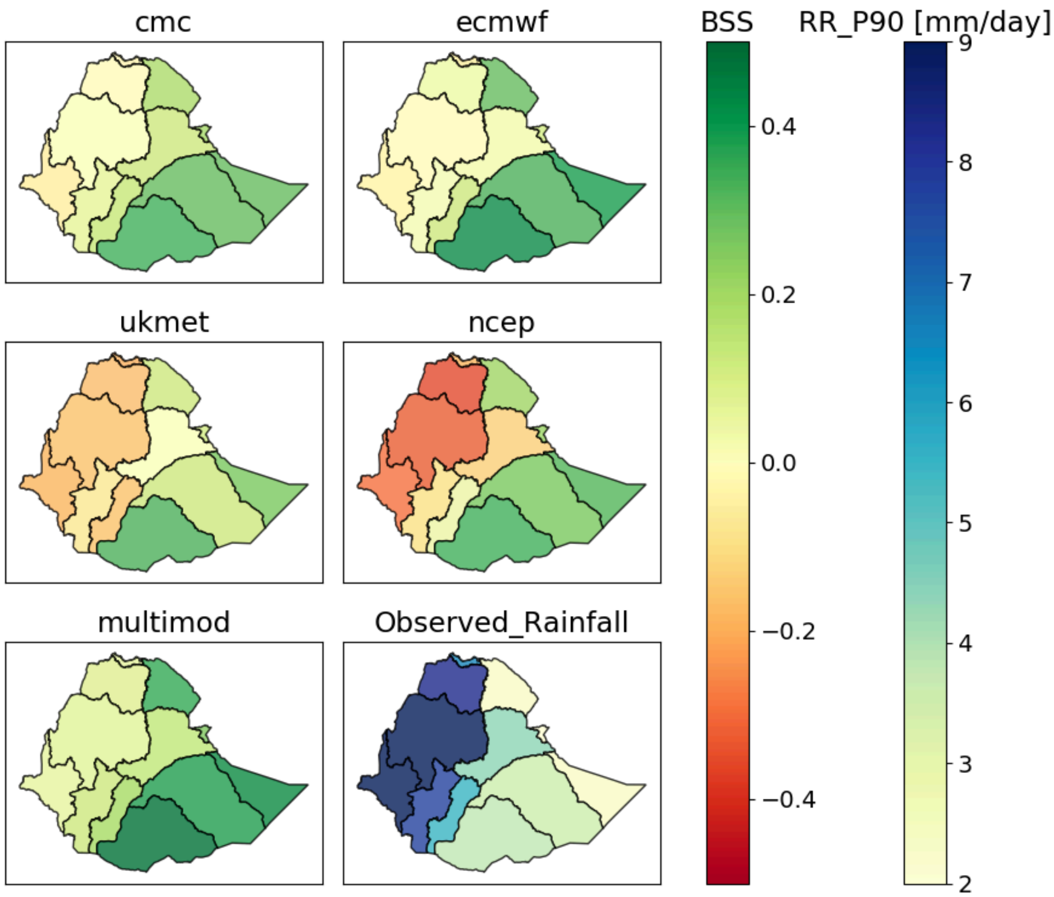

Fig. 7. *Brier skill score for precipitation exceeding the catchment-specific 90th percentile of rain after bias correction, showing how the multi-model forecast is equal to or out-performs any individual model for all of the 12 primary Ethiopian river basins shown. The lower right plot displays the precipitation amount corresponding to the catchment-specific 90th percentile. +24 hr ensemble forecasts were used to create these plots.*

Validation of the Noah-MP Hydrologic Model: To translate the NMME precipitation forecasts into reservoir inflow forecasts, we choose the Noah-MP (Multiparameterization) Land Surface Model, driven through NASA's Land Information System. The Noah-MP model builds on the original Noah Land Surface Model by incorporating a dynamic groundwater model, improved representation of vegetation canopy, and snowpack. In the absence of streamflow measurements for the calibration of the hydrologic model, we explored the possibility of using satellite evapotranspiration as a proxy for calibration. Figure 8 reveals that the Noah-MP hydrologic model calibrated with satellite-based evapotranspiration estimates (GLEAM) perform well in simulating evapotranspiration. We can also conclude that the calibration of the Noah-MP hydrologic model with evapotranspiration estimates results in accurate estimation of streamflow (results are shown in Koppa et al. 2019).

In summary, the combination of numerical weather predication-based ensemble precipitation forecasts and evapotranspiration-calibrated hydrologic model has the potential to generate reliable reservoir inflow forecasts.

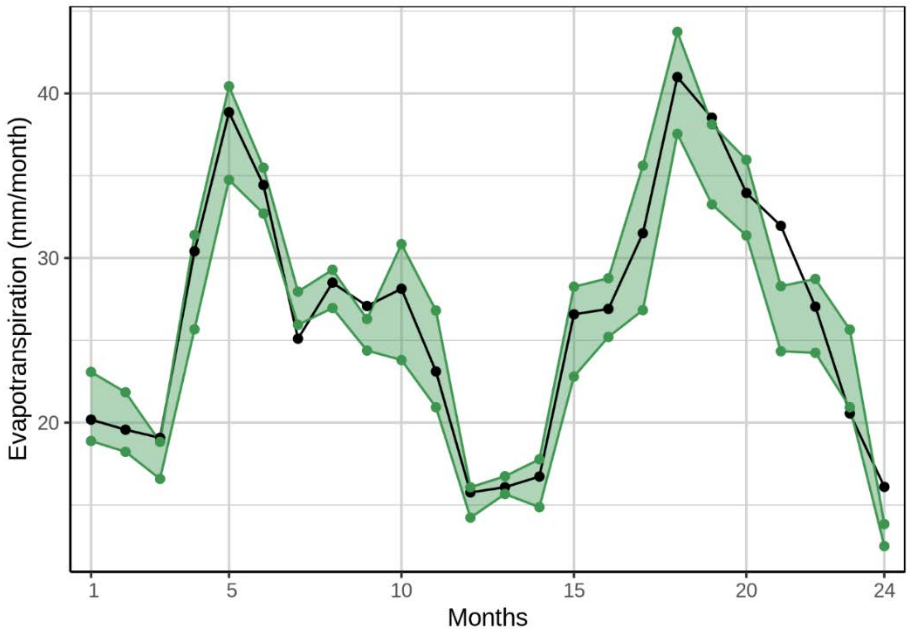

Fig. 8. *Time series comparison of evapotranspiration from evapotranspiration-calibrated Noah-MP model (green) and observed evapotranspiration estimates (black) from GLEAM for the calibration (12 months of 2004) and validation (12 months of 2005) time periods. The 5% and 95% quantiles from the behavioral solutions of Bayesian calibration are used to determine the uncertainty in modeled ET (green band).*

B.2 Addressing Research Question 2

Uncertainty in Reservoir Inflow: The classical formulation of a stochastic programming with recourse model, used for seasonal hydropower planning, considers the first stage to be deterministic and the subsequent stages to be stochastic. In data-scarce catchments, this assumption may not be appropriate. We reformulated the stochastic programming with recourse model for hydropower planning to consider the uncertainty in seasonal reservoir inflow forecasts at the first/immediate stage. As shown in Fig. 9, we considered three different reservoir inflow scenario structures: single deterministic forecast (DET), first stage deterministic and the rest stochastic (SPWR-D), and (c) all stages stochastic (SPWR-S).

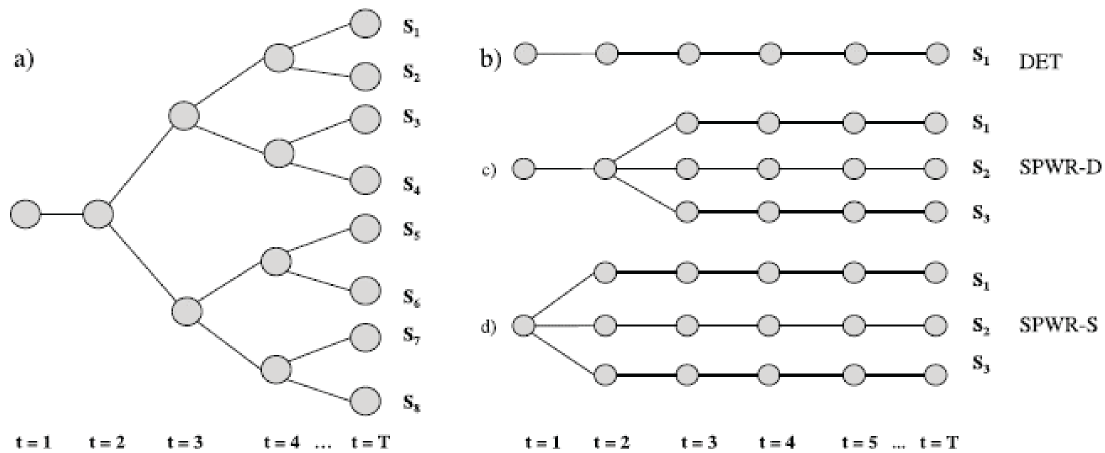

Fig. 9. *A visual representation of different reservoir inflow scenario structures – (a) scenario tree, (b) a single deterministic forecast (DET), (c) first stage deterministic and the rest stochastic (SPWR-D), and (d) all stages stochastic (SPWR-S).*

We compared the differences in reservoir inflows among the three scenarios. Figure 10 presents the deterministic (from BMA) and stochastic (raw forecast ensembles) inflows used to construct the three scenario trees. Our results show that the ensemble seasonal inflow forecasts exhibit considerable uncertainty, with the deterministic inflow values consistently lower than the mean of the raw ensembles. In addition to quantifying uncertainty in reservoir inflows forecasts using stochastic programming, we quantified the impact of model parameter uncertainty on inflow forecasts. As shown in Fig. 11, parameter uncertainty does not have significant impact on the uncertainty of reservoir inflows.

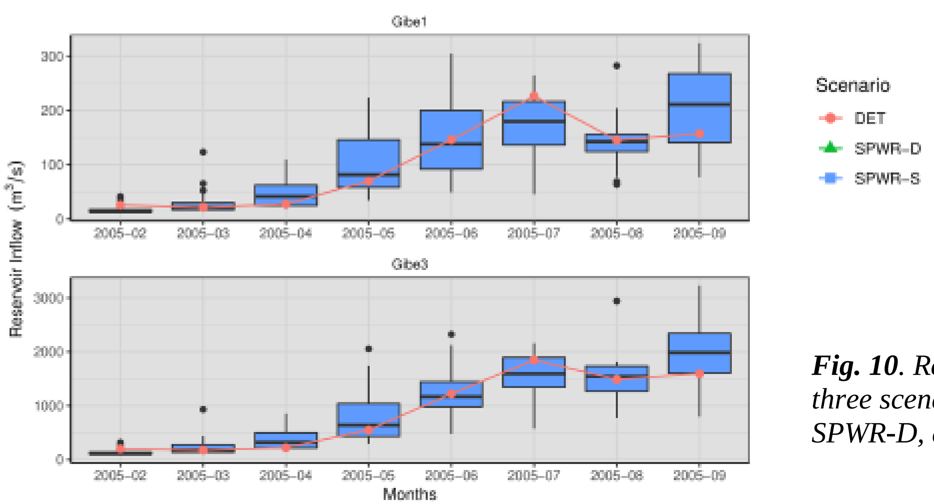

Fig. 10*. Reservoir inflows for three scenario structures (DET, SPWR-D, and SPWR-S).*

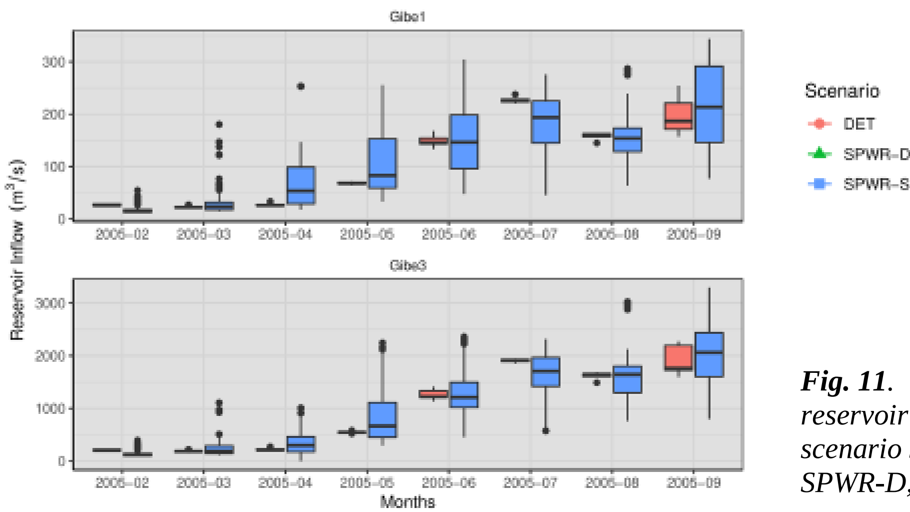

***Fig. 11**. Uncertainty in reservoir inflows for three scenario structures (DET, SPWR-D, and SPWR-S).*

Optimal Release Decision: In our study, the formulation of the hydropower optimization model is based on HIDROTERM, a nonlinear programming optimization model previously developed for planning the operation of the Brazilian hydrothermal system. We modified the model, originally deterministic, to solve the multi-stage stochastic programming with recourse model for our study.

The objective function is represented by

$$min\ \ ZH = \sum_{s}\sum_{t}\left\{p_s \cdot dt_t \cdot \left(D_t - \sum_{i} P_{i,s,t}\right)^2\right\}$$

Where i = hydropower plant/reservoir index; dt_t = time period duration (10^6 s); s = scenario index; t = time period index; p_s= probability associated with each scenario; $P_{i,s,t}$ = power production (MW); D_t = objective demand, usually the total demand minus the fixed generation, though it can be defined arbitrarily by the user (for example, as the maximum installed power capacity MW); and ZH = model objective (10^6 s.MW²). The model minimizes the expected value of the quadratic departures from the demand so that the hydropower production will follow the specified demand variations. The model is subject to a set of constraints.

In Fig. 12, we present the results of the optimized release decisions generated for the three inflow scenario structures. Our results show that the uncertainty in in the inflow forecasts affect the optimized release decisions only in the dry months. The uncertainty in the inflow forecasts does not affect optimized release decision during wet months, as the power releases reach the capacity of the power plants.

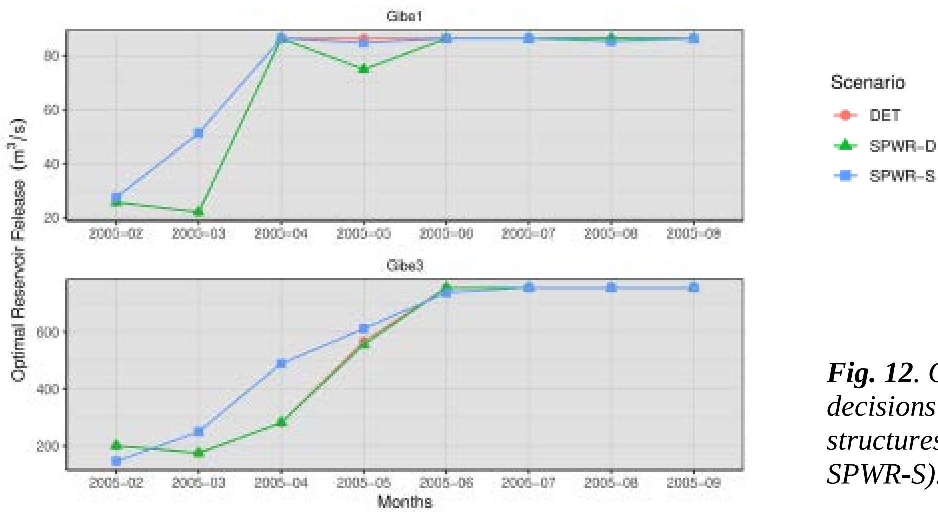

***Fig. 12**. Optimal release decisions for three scenario structures (DET, SPWR-D, and SPWR-S).*

B.3 Addressing Research Question 3

Optimal Power Production and Impact of Uncertainty in Inflow Forecasts

Figure 13 presents the optimized hydropower productions corresponding to the optimized release decisions for each of the three inflow structures. Our results show that in terms of hydropower production (combined Gibe I and Gibe III power production), the inflow scenario fan with SPWR-D leads to the most conservative estimate (2.67×10^6 MWh), followed by the completely deterministic scenario structure (2.69×10^6 MWh) and the SPWR-S (2.86×10^6 MWh). Thus, we see limited differences (5% to 6%) in hydropower production between the different scenarios.

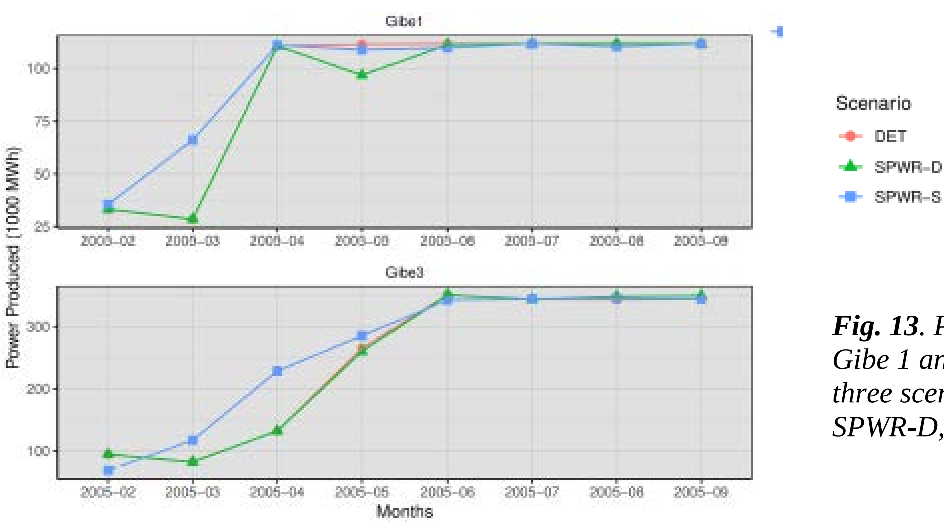

***Fig. 13**. Power produced in Gibe 1 and Gibe 3 reservoirs for three scenario structures (DET, SPWR-D, and SPWR-S).*

Finally, we compare the optimized hydropower values with the actual power produced at the Gibe I reservoir for the months of February–September 2005. The actual power produced in Gibe I for the 8-month study period was 0.53×10^6 MWh (sourced from Ethiopian Electric Power). In comparison, the optimized hydropower generated from the DET, SPWR-D, and SPWR-S scenario structures were 0.73×10^6 MWh, 0.71×10^6 MWh, and 0.76×10^6 MWh, respectively. The power that could be generated from the use of our DSS exceeds the actual power produced by 34% to 43%, indicating that the use of our DSS can significantly increase the power generation efficiency of existing hydropower systems in Africa.

C. **CAPACITY BUILDING AND TECHNOLOGY TRANSFER**

C.1 Decision Support System Transferred to Stakeholders in Ethiopia

A series of workshops to transfer a novel Decision Support System (DSS) were held in Addis Ababa, Ethiopia over the course of six months between December 2017 and May 2018. The transfer of the developed DSS took place in three phases: I) Remote Sensing, II) Climate Forecasting and III) Streamflow Forecasting and Hydropower Optimization. The workshop had participants from the Ethiopian Construction Works Corporation (ECWC), the Ethiopian National Meteorological Agency (NMA), and the Ethiopian Ministry of Water and Energy, amounting to 20 participants. See Figure 14 for a sample photo showing the training participants.

Fig. 14. *Some of the participants of the workshop undergoing hands-on training during the second phase of technology transfer workshop*.

C.2 Software for decision support system

We have developed a GUI interface for the dissemination of real-time and automated climate data. Figure 11 shows a screenshot of the current display and user interface. Features of the system include: (a) 2 spatial scales of catchments with zoom feature, (b) 5 temporal scales (24-hr / 5 dy / 1 mo / 3 mo), (c) Choose between NASA TRMM or JAXA satellite rainfall, (d) Choose between 8 TIGGE forecast models for the 24 hour and 5 day-averaged data along with a multi-model forecast, (e) Choose between 8 NMME forecast models for the 1 month and 3 month data, (f) Data on Hydro 1K catchments for a larger East Africa domain, and upstream of gauging sites for specific basins (Omo-Gibe), (f) Click on catchment to get time series plots and info about the catchment,

(g) Data download option, (h) Forecasts are bias corrected using a quantile-to-quantile mapping, (i) Both ensemble mean and the full range of ensemble members are shown in the graphs / text files.

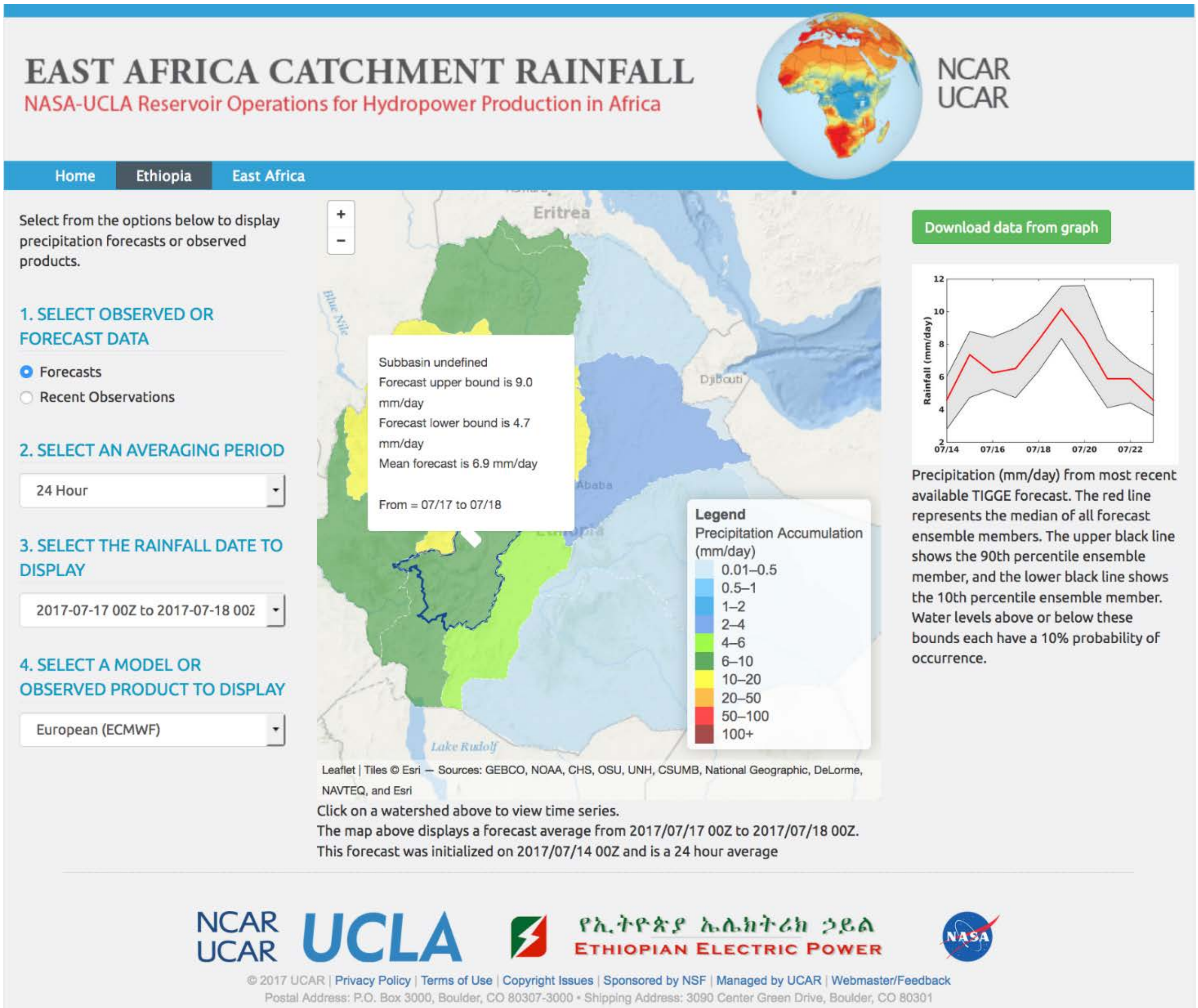

Fig. 15. *GUI for the dissemination of catchment precipitation data to stake holders. Forecasts are available from the NMME seasonal models (monthly and 3-month averages), as well as from the TIGGE models (1-day and 5-day averages) going out 2 weeks. Recent satellite observations are also available at the same time scales. Precipitation data are displayed at two different resolutions which can be accessed by zooming in and out and for both a large East Africa domain, as well as a more focused Ethiopia domain that includes the Blue Nile and Omo-Gibe basins. For the Omo-Gibe basin, the data are available on catchments upstream of local gauging sites. In addition to the map display, users can assess the data in graphical form as well as for download as a text file.*

D. PROJECT OUTPUTS

D.1 Publications in Peer-Reviewed Journals

<u>Published</u>

Koppa, K., M. Gebremichael, R. Zambon, W.W-G Yeh, and T. Hopson, 2019: Seasonal hydropower planning for data scarce regions using multi-model ensemble forecasts, remote sensing data, and stochastic programming, Water Resources Research, 55, 10.1029/2019WR025228

Broman, D., B. Rajagopalan, T.M. Hopson, M. Gebremichael, 2019: Spatial and temporal variability of East African Kiremt season precipitation and large-scale teleconnections, International Journal of Climatology, https://doi.org/10.1002/joc.6268.

Koppa, A., M. Gebremichael, and W.W-G Yeh, 2019: Multivariate calibration of large scale hydrologic models: The necessity and value of a Pareto optimal approach, Advances in Water Resources, 130, 129-146, 10.1016/advwatres.2019.06.005

Koppa, A., and M. Gebremichael, 2017: A framework for validation of remotely sensed precipitation and evapotranspiration based on the Budyko Hypothesis, Water Resources Research, 53(10), 8487-8499, 10.1002/2017WR020593.

<u>Under Review</u>

Stellingwerf, S., E. Riddle, T. Hopson, J. Kneivel, B. Brown, and M. Gebremichael, 2019: Optimizing precipitation forecasts for hydrological catchments in Ethiopia using statistical bias correction and multi-modeling, Earth and Space Science (in review).

Broman, D., B. Rajagopalan, T.M. Hopson, 2019: Spatial and Temporal Variability of Sahelian West African Summer Monsoon Precipitation and Large-scale Teleconnections. Journal of Geophysical Research (in review).

Riddle, E., J. Boehnert, T. Hopson, M. Gebremichael, 2019: Partnering with users in India and eastern Africa to improve hydrological forecasts. EOS, Transactions, American Geophysical Union (in review).

<u>Under Preparation</u>

Koppa, A., et al., 2019: Global patterns of uncertainties and errors in water and energy balance closure from satellite, Water Resources Research (expected submission date: Dec. 31, 2019).

Demissie, Y., et al., 2019. Evaluation of seasonal precipitation forecasts over East Africa, International Journal of Climatology (expected submission date: Dec. 31, 2019).

Boehnert, J., et al., 2019. Communicating water resource and flood risk in East Africa and South Asia. *In Box, Bulletin of the American Meteorological Society* (expected submission date: Dec. 15, 2019).

D.2 Conference Presentations

Riddle, E.E., J. Boehnert, T.M. Hopson, M. Gebremichael, “Improving Access to Multi-model Rainfall and River Stage Forecasts in Eastern Africa and Northern India”, AMS Annual Meeting, Boston, January 2020.

Riddle, E.E., S. Stellingwerf, T.M. Hopson, B. Brown, J. Knievel, M. Gebremichael, “Evaluating TIGGE Rainfall Forecasts for Tropical Eastern Africa”, AMS Annual Meeting, Boston, January 2020.

Yue, H., Gebremichael, and A. Koppa, " Satellite Precipitation for Hydropower Management in Africa", AGU Fall Meeting, San Francisco, December 2019.

Gebremichael, M., A. Koppa, T. Hopson, and WWG Yeh, “Optimizing Reservoir Operations for Hydropower Production in Africa through the Use of Remote Sensing Data and Seasonal Climate Forecasts”, 2019 NASA Applied Sciences Program, WWAO & Water Resources Team Meeting, Portland, Oregon, July 2019. (*Invited Presentation*).

Alam, S., A., Koppa, and M. Gebremichael, “Validation of Global Precipitation and Evapotranspiration Datasets from a Long-Term Water and Energy Balance Perspective”, The 12th International Precipitation Conference, University of California Irvine, California, June 2019.

Koppa, A., R. Zambon, T. Hopson, M. Gebremichael, and WWG. Yeh, "Seasonal Hydropower Planning in Data Scarce Regions: The Role of Ensemble Forecasts and Remote Sensing", European Geophysical Union General Assembly, Vienna, April 2019.

Koppa, A., E. Riddle, T. Hopson, M. Gebremichael, and WWG. Yeh, "A decision support system for seasonal hydropower planning in East Africa using remote sensing and ensemble forecasts", AGU Fall Meeting, Washington D.C., December 2018. (*Oral Presentation*).

Gebremichael, M. and Hopson, T., “Optimizing Reservoir Operations for Hydropower Production in Africa through the Use of Remote Sensing Data and Seasonal Climate Forecasts”, NASA Applied Sciences Program Water Resources Team Meeting, Boulder, June 2018. (*invited presentation*)

Koppa, A., M. Gebremichael, and WWG. Yeh, "Overcoming the cascading issues of data scarcity and uncertainty for seasonal hydropower planning in East Africa", European Geophysical Union General Assembly, Vienna, April 2018.

Gebremichael, M. and Hopson, T., “Optimizing Reservoir Operations for Hydropower Production in Africa through the Use of Remote Sensing Data and Seasonal Climate Forecasts”, NASA Applied Sciences Program Water Resources Team Meeting, Los Angeles, July 2017. (*invited presentation*)

Koppa, A., and M. Gebremichael, "A Framework for Validation of Remotely Sensed Precipitation and Evapotranspiration Without the Use of Ground-Based Measurements", European Geophysical Union General Assembly, Vienna, April 2017.

Koppa, A., M. Gebremichael, and WWG. Yeh, "Moving beyond streamflow observations: Lessons from a multi-objective calibration experiment in the Mississippi basin", AGU Fall Meeting, New Orleans, December 2017. (*Oral Presentation*)

Riddle, E.E., T.M. Hopson, M. Gebremichael, J. Boehnert, D. Broman, K. M. Sampson, D. Rostkier-Edelstein, D. C. Collins, N.R. Hashadeep, “An operational ensemble prediction system for catchment rainfall over eastern Africa spanning multiple temporal and spatial scales", AGU Fall Meeting, New Orleans, December 2017.

Hopson, T.: Keynote speaker, Israeli Meteorological Society Annual Meeting, "Weather Forecasts and their Health and Societal Impact", Tel Aviv, Israel. March 23, 2017.

Broman, D., T.M. Hopson, B. Rajagopalan, E. E. Riddle, M. Gebremichael, S.S. Demissie, "Sub-seasonal evaluation of East African rainfall for improved hydrologic forecasting", AGU Fall Meeting, San Francisco, December 2016.

Koppa, A., and M. Gebremichael, "Development of a validation framework for remotely sensed water and energy balance components in data scarce catchments using the Budyko Hypothesis", AGU Fall Meeting, San Francisco, December 2016.

Riddle, E., Demissie, S., Hopson, T., Boehnert, J., Gebremichael, M.: "Validation of Multi-scale Catchment Rainfall Forecasts for use by Reservoir Managers in Eastern Africa", NOAA's 41st Climate Diagnostics and Prediction Workshop, 3-6 October, 2016.

Gebremichael, M., T. Hopson, E. E. Riddle, and W. W.-G. Yeh, "Towards Optimization of Reservoir Operations for Hydropower Production in East Africa," 2016 NASA Water Resources Team Meeting at the NOAA National Water Center, Tuscaloosa, AL, April 2016, (*invited*).

Gebremichael, M., "Optimizing Reservoir Operations for Hydropower Production in Africa through the Use of Remote Sensing Data and Seasonal Climate Forecasts," WC-12 Capacity Building through Strategic Partnerships: Leveraging Innovative Tools, Applied Research and Big Data, the Food-Energy-Water Nexus, 16th National Conference and Global Forum on Science, Policy and the Environment, January 2016, (*invited*).

Gebremichael, M., "Evaluation of IMERG Satellite Rainfall Estimates in the Blue Nile Basin," American Geophysical union – 2015 Fall Meeting, San Francisco, December 2015.

Mekonnen, Z. T., M. Gebremichael, and S. S. Demissie, "Characterizing Water Resources of the Nile Basin Using Remotely Sensed Data," American Geophysical union – 2015 Fall Meeting, San Francisco, December 2015.

Demissie, S. S., M. Gebremichael, T. M. Hopson, E. E. Riddle, and W. W.-G. Yeh, "Towards Optimization of Reservoir Operations for Hydropower Production in East Africa: Application of Seasonal Climate Forecasts and Remote Sensing Products," American Geophysical union – 2015 Fall Meeting, San Francisco, December 2015.

Gebremichael, M., "Towards Optimization of Reservoir Operations for Hydropower Production in East Africa: Application of Seasonal Climate Forecasts," 10th Alexander von Humboldt Conference 2015, Water-Food-Energy River and Society in the Tropics, European Geosciences Union Topical Conference Series, Addis Ababa, Ethiopia, November 2015, (Leonardo Lecture) (*Invited*).

D.3 Software

We have developed a new web-based online tool that can be used to view, extract, and download weather time-scale and seasonal time-scale forecasts and satellite rainfall observations of precipitation over watersheds of East Africa. The URL of this new tool is: http://nasa-ucla.rap.ucar.edu/.