Developing a Flood Monitoring System From Remotely Sensed Data for the Limpopo Basin

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Kwabena Asante
University of Essex

G. A. Artan
Igad Climate Prediction and Applications Ce…

Developing a Flood Monitoring System From Remotely Sensed Data for the Limpopo Basin

Kwabena O. Asante, Rodrigues D. Macuacua, Guleid A. Artan, Ronald W. Lietzow, and James P. Verdin

***Abstract*—This paper describes the application of remotely sensed precipitation to the monitoring of floods in a region that regularly experiences extreme precipitation and flood events, often associated with cyclonic systems. Precipitation data, which are derived from spaceborne radar aboard the National Aeronautics and Space Administration's Tropical Rainfall Measuring Mission and from National Oceanic and Atmospheric Administration's infrared-based products, are used to monitor areas experiencing extreme precipitation events that are defined as exceedance of a daily mean areal average value of 50 mm over a catchment. The remotely sensed precipitation data are also ingested into a hydrologic model that is parameterized using spatially distributed elevation, soil, and land cover data sets that are available globally from remote sensing and *in situ* sources. The resulting streamflow is classified as an extreme flood event when flow anomalies exceed 1.5 standard deviations above the short-term mean. In an application in the Limpopo basin, it is demonstrated that the use of satellite-derived precipitation allows for the identification of extreme precipitation and flood events, both in terms of relative intensity and spatial extent. The system is used by water authorities in Mozambique to proactively initiate independent flood hazard verification before generating flood warnings. The system also serves as a supplementary information source when *in situ* gauging systems are disrupted. This paper concludes that remotely sensed precipitation and derived products greatly enhance the ability of water managers in the Limpopo basin to monitor extreme flood events and provide at-risk communities with early warning information.**

***Index Terms*—Hydrology, rainfall effects, rivers, time series.**

I. Introduction

In early 2000, the Mozambican coast was bombarded by heavy January rains followed by a series of four tropical cyclones: 1) Astride on January 4; 2) Eline on February 22; 3) Gloria on March 10; and 4) Hudah on April 8. Cyclone Connie also induced heavy regional rainfall, although it failed to make landfall as a named storm. The most severe was Cyclone Eline, which made landfall in the central Mozambican district of Sofala with maximum sustained winds of 120 km/h and gusts of up to 260 km/h [1]. The cyclone dumped large quantities of precipitation that conspired with the wet soils and high reservoir levels from antecedent events to produce the flood of record in the lower reaches of the Limpopo River basin in southern Mozambique. An estimated 700 lives were lost; 45 000 people were rescued from floodwaters; an estimated 500 000 people were displaced from their homes; and more than $400 million of property was damaged by the floodwaters [2]. Vast areas, some up to 20 km away from the normal river channel, were under water for several weeks. Fig. 1 shows images of satellite-derived precipitation associated with four of the cyclonic systems.

Field surveys conducted in the lower Limpopo valley in the aftermath of the floods by the national archive of Mozambique, Arquivo do Patrimonio Cultural [3], indicate that most of the people in the affected areas received warnings issued by the water management agency responsible for the basin, i.e., Administração Regional de Águas do Sul. The warnings gave notices of rising river levels in upstream reaches of the Limpopo River and warned people in low-lying areas to move to higher ground. However, the warnings were qualitative in nature, and they failed to convey the magnitude of the event. While there are several important urban centers within the basin, much of the Limpopo drains through sparsely populated rural areas. Installation and maintenance of *in situ* gauging equipment in such settings is an expensive undertaking. In a developing country like Mozambique, the widespread installation of gauging equipment is constrained by its high cost.

In addition, *in situ* flow and precipitation gauges are often washed away by the very floods they are designed to monitor, and reconstruction of gauges is a common postflood activity around the world [4]. This problem is illustrated by the two graphs in Fig. 2, which show flows at Beit Bridge, an important gauge on the main stem of the Limpopo river basin, and the number of functioning gauges along the same river in South Africa. The figure clearly shows gauges being destroyed or rendered inaccessible by the successive waves of floodwaters. By the time the third and largest flood wave arrived, many key stations including Beit Bridge were already destroyed, leaving Mozambican water authorities with no source of information on the actual magnitude of floodwater. They consequently relied on their knowledge of previous flood events in issuing the flood warnings. The 2000 floods turned out to be far more severe than any previous event in living memory, and many areas previously regarded as safe were inundated.

The Limpopo experience highlights the need for supplementary systems to monitor extreme events. While direct estimation of flow from remote sensing is still not possible in operational settings, remote sensing of precipitation is now a

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K. O. Asante, G. A. Artan, and R. W. Lietzow are with the Science Applications International Corporation, U.S. Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, SD 57198 USA (e-mail: asante@usgs.gov; gartan@usgs.gov; lietzow@usgs.gov).

R. D. Macuacua is with Administração Regional de Águas do Sul, 4033 Maputo, Mozambique (e-mail: arasul@tropical.co.mz).

J. P. Verdin is with the U.S. Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, SD 57198 USA (e-mail: verdin@usgs.gov).

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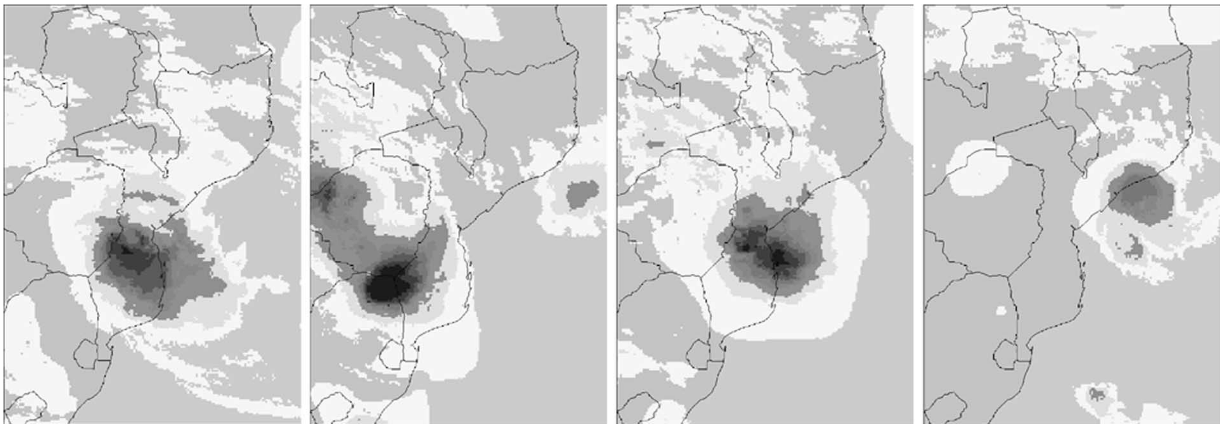

Fig. 1. Satellite-derived precipitation estimates showing rainfall fields associated with four different tropical storms over Mozambique during a two-month period in early 2000. The images show rainfall associated with (a) Cyclone Connie on February 3, (b) Cyclone Eline on February 23, (c) Cyclone Gloria on March 13, and (d) Cyclone Hudah on April 7.

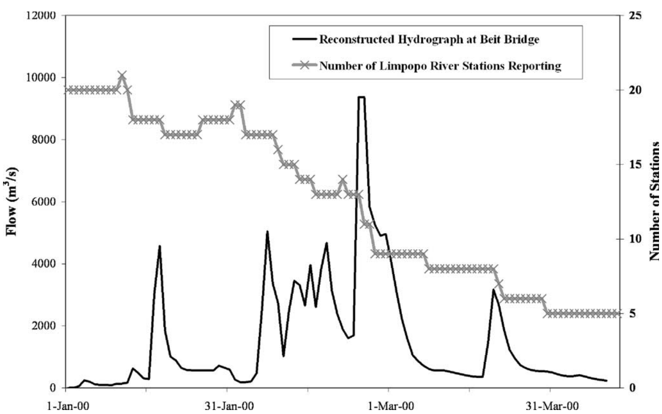

Fig. 2. Graph showing reconstructed Limpopo river flows at Beit Bridge in South Africa on the primary y axis and the number of hydrometric stations reporting daily flows within the basin in South Africa on the secondary y axis. The exact magnitude of the flood peak on February 24–25, 2000, could not be determined accurately because it exceeds the maximum value on the rating curve at the location.

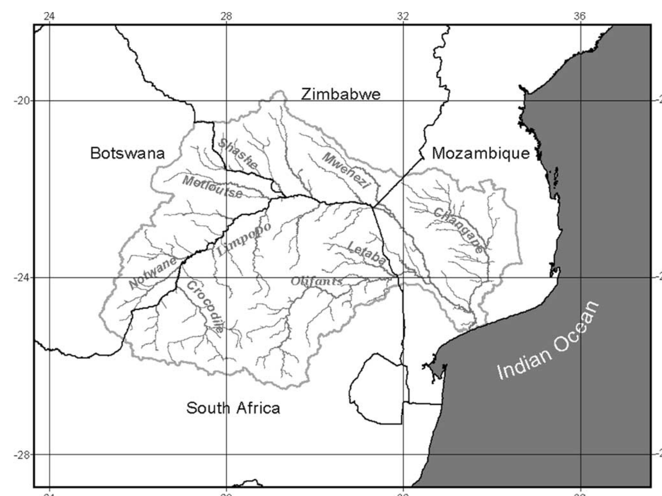

Fig. 3. Map of the Limpopo River Basin in southern Africa with riparian countries and major tributaries.

well-developed field with a number of operational products being generated on a daily basis from a combination of imagery from infrared (IR), microwave, and spaceborne radar sensors. The resulting imagery permits estimation of precipitation along the path of cyclones as they traverse the land surface, and these data sets afford hydrologists the opportunity to model the propagation of floods over the land surface. In this paper, we present a flood monitoring system for the Limpopo basin, which uses remotely sensed data to characterize the severity of flood hazards in terms of relative magnitude and extent. The flood monitoring system supplements *in situ* monitoring infrastructure by providing spatially continuous coverage over the entire drainage basin at regular intervals using data from spaceborne sensors that cannot be destroyed by floodwaters.

II. Background

A. Limpopo Basin

The Limpopo, one of the largest river basins in southern Africa, was the worst affected basin in the 2000 floods [2]. With a drainage area of more than 400 000 km^2, the Limpopo basin spans four countries including Mozambique, South Africa, Zimbabwe, and Botswana, as shown in Fig. 3. From its farthest reaches in the Drakensberg Mountains of South Africa, the Limpopo travels a distance of more than 4000 km to its mouth at Zongoene on the Indian Ocean. The lower Limpopo basin, defined as the Mozambican portion of the basin, bore the brunt of the flooding with inundated areas more than 30 km wide along some river reaches.

Accessing and integrating hydrologic data from the three upstream countries to identify flood hazards is a major challenge for the Mozambican water authorities. They consequently recognized the value of implementing a flood monitoring system using remotely sensed data, which is continuous across national borders. In this application, remotely sensed precipitation data are used to identify extreme precipitation events, while extreme flood events are monitored by ingesting and propagating the precipitation data in a hydrologic model.

B. Hydrologic Model Description

The Geospatial Streamflow Model (GeoSFM) developed at the U.S. Geological Survey Center for Earth Resources

Observation and Science (USGS/EROS) was adopted for hydrologic routing in the Limpopo Flood Monitoring System. GeoSFM is a semidistributed hydrologic model developed as an extension of the ArcView Geographic Information Systems (GIS) software. It consists of GIS-based preprocessing and postprocessing modules and a routing module that uses a dynamically linked library. GeoSFM is created in a mixed-programming environment for time series manipulation and hydrologic computations. The preprocessing module delineates and parameterizes catchments and river reaches from digital terrain data.

In this paper, the Limpopo basin is divided into 303 catchments with an average contributing area of about 1400 km^2 and an associated river reach approximately 45 km long. Remotely sensed vegetation from the Global Land Cover Characteristics database [5] is used to estimate vegetation resistance for overland flow computations. Estimates of required hydrologic parameters, such as the soil water holding capacity, are estimated from the FAO/UNESCO Digital Soil Map of the World [6], [7] data. Other parameters such as flood wave celerity within the river channel are estimated based on values reported in the literature [8], [9].

Potential evapotranspiration (PET) is generated at daily intervals from output fields in National Oceanic and Atmospheric Administration (NOAA)'s Global Data Assimilation System [10] and the Penman–Montieth equation for a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 $s \cdot m^{-1}$, and an albedo of 0.23 [11]. A 100×100 km^2 resolution grid of PET is computed daily at USGS/EROS and placed on a File Transfer Protocol (FTP) site for users to download. The calculation of actual evapotranspiration is then performed dynamically within the GeoSFM model using antecedent moisture conditions and soil water holding capacity.

III. Methodology

A. Monitoring Extreme Precipitation Events

IR satellite images from Meteosat are acquired every half hour (every 15 min under the Meteosat Second Generation program). These images are distributed without charge to national meteorological agencies around the world that have Primary Data User System receivers installed. IR satellite images are good estimators of the spatial distribution of precipitation, but they are poor estimators of magnitude, particularly where precipitation is induced by frontal or orographic processes. To improve the accuracy of precipitation magnitude estimates, data from *in situ* rain gauges are blended with the IR satellite images [12]. Rain gauge data from national meteorological stations are available through the Global Telecommunications System (GTS) operated by the World Meteorological Organization. There are 32 GTS stations within the Limpopo basin, an average of one station per 12 000 km^2. The GTS data are integrated by NOAA's Climate Prediction Center (CPC) with available microwave-derived rainfall rates from two sensors, i.e., the Special Sensor Microwave/Imager and the Advanced Microwave Sensor Units, into a merged precipitation product [13].

Another approach to estimating precipitation from satellite data involves the spaceborne radar launched on National Aeronautics and Space Administration (NASA)'s Tropical Rainfall Measurement Mission (TRMM) in 1998. Three-hourly rainfall rates measured by TRMM's radar have been processed and distributed operationally since 2002, and in October, 2005, the entire climatological archive (1998 to present) was reprocessed and made available to the public. TRMM has made significant contributions to operational monitoring of rainfall rates associated with tropical cyclones, particularly through the work of Lonfat *et al.* [14] at NOAA's Hurricane Research Division. However, TRMM can miss some rapid onset or fast moving storms because of its 3-h sampling period. NASA consequently generates a merged TRMM-based product that also integrates available IR and microwave imagery, thus capturing the best characteristics of each of the satellite image sources.

Many potential end users are located in developing countries and typically do not have the remote sensing skills or software to manipulate the data sets into formats that are readily ingestible into their operational models. To aid such users, the USGS serves as an intermediary and performs postprocessing and distribution of both the NOAA CPC and NASA TRMM merged products. Such postprocessing may include transforming the data sets into GIS formats, projecting the images into the equal-area projections used by local agencies in the respective countries, and reducing the volume of data by clipping to locally appropriate data windows. The reprocessed data sets are posted on an anonymous FTP site at USGS/EROS for access by users in Mozambique and other parts of the world for use in monitoring extreme precipitation and flood events.

An extreme precipitation event is defined in this paper as the exceedance of a threshold of 50 mm/day of mean areal precipitation (MAP) over any catchment. This threshold is subjectively selected. It reflects the authors' perception of the hazard posed by precipitation events in the basin. Subjectivity of threshold selection is a common problem associated with event-based analysis, and the choice of a different threshold could result in slight differences in the distribution of hazards. However, the definition of a threshold permits quick identification of events requiring additional monitoring. It also allows the frequency of extreme precipitation events happening in different parts of a basin to be compared.

B. Monitoring Floods With Remotely Sensed Precipitation

By contrast, extreme riverine flood events are classified in terms of departure from normal. Statistical theory would ordinarily suggest that approximately 30 years of annual streamflow values are required to fit lognormal, log Pearson, and other statistical distributions used for flood frequency analysis. However, the current archive only contains approximately eight years of daily satellite-derived data sets. An alternate 30-year daily precipitation climatology has been created from the reanalysis of existing monthly climatologies from Global Climate Models [15] or available station data. However, the resulting daily precipitation grids have spatial and temporal statistics that are substantially different from those obtained from satellite-derived precipitation estimates. Interpreting anomalies

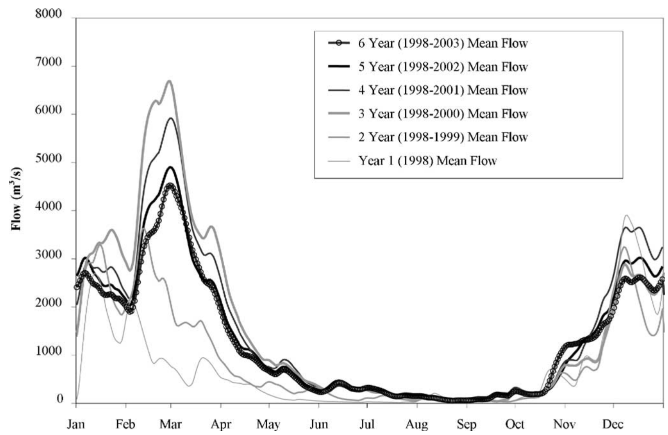

Fig. 4. Evolution of streamflow climatology computed from satellite-derived precipitation at Beit Bridge, South Africa. The climatology begins with simulated streamflow in 1998 and is updated each year until 2003.

computed from the two different data sets consequently presents many challenges.

In this paper, we adopt a climatology computed from satellite-derived precipitation only between 1998 and 2003. The resulting precipitation and streamflow climatology can be updated periodically as new remotely sensed data become available. The expectation is that as the archive of historical data grows, the noise in the daily streamflow climatology will also be reduced with a consequent improvement in the characterization of extreme events. As seen from the sequence of climatologies in Fig. 4, the Limpopo basin climatology becomes reasonably stable after approximately five years. It is worth noting that the occurrence of near record floods and relatively severe drought years within this period contributed significantly to the convergence toward a stable climatological mean in a relatively short time. Longer time series would be required to attain stability in areas of the world with more persistent climatic patterns because a climatology covering a dry or wet portion of the interannual cycle could be heavily biased.

This result highlights the need for hydrologic satellite mission planners to work with operational users to develop strategies for producing and updating a climatology that can be used to interpret extreme events from real-time remote sensing products. In the absence of such a climatology, operational users may not be able to incorporate the data from a new hydrologic mission into their monitoring efforts until the mission is well into its design life. The gradual evolution of climatology beginning in 1998 assumes the absence of prior knowledge of precipitation patterns predating the satellite-derived data. A more representative climatology can be attained faster by beginning with an existing climatology from an alternate data source and updating it with data from the remotely sensed sources using data assimilation techniques developed in the meteorological and oceanic sciences.

In this paper, an extreme streamflow event is defined as the occurrence of a flow anomaly exceeding 1.5 standard deviations above the short-term mean annual flow. The streamflow time series used to identify streamflow statistics is generated by ingesting and routing the satellite-derived precipitation data through the river basin using GeoSFM. In operational use, the model is run everyday to produce three-day forecasts of streamflow and flow anomalies. With average time-to-peak at the basin outlet exceeding two weeks, three-day streamflow forecasts are produced using satellite-derived precipitation estimates without introducing quantitative precipitation forecasts from mesoscale models. Recognizing the potential for errors associated with the model setup and input data, streamflow forecasts generated by the model are used primarily as a trigger to initiate independent verification from field sources of a forecasted extreme event. The system also serves as a backup for areas and periods where there are no *in situ* data sources available.

IV. Results

A. Analysis of Extreme Events

An analysis of extreme precipitation and streamflow events was performed for the period 1998–2003. Items 1 to 4 in Table I show a comparison of the number of extreme precipitation events using the respective NOAA CPC and NASA TRMM merged products. In general, the NASA product identifies approximately 60% more extreme precipitation events than the NOAA product. The analysis shows that residents of the Limpopo basin can expect an average of one or two extreme precipitation events each year. Regions that are most prone to extreme precipitation events such as the Changane and Letaba watersheds can expect between five and nine such events each year, depending on which of the two precipitation products is used. These two watersheds would consequently benefit from the implementation of flash flood warning systems. By comparison, a basin-wide average of between two and four such events was identified in 2000 with the most hazard prone watersheds recording between eight and 15 events.

A similar analysis of daily streamflow simulations is presented in the second part of Table I. It shows that the remotely sensed precipitation from the two sources results in very similar distributions of extreme streamflow events. On average, river reaches in the Limpopo basin exceed the established flood warning levels between 25 and 27 days each year with the most flood prone reaches exceeding the warning level between 39 and 44 days each year. In 2000, most of these reaches were above the warning level 2.5 times more frequently than expected. The anomalously high streamflow is also evident in Fig. 5, which shows the variation of relative streamflow anomaly at Beit Bridge on the main stem of the Limpopo River. The 2000 floods stand out as extremely anomalous events with flow estimates exceeding seven standard deviations above the mean annual flow.

Another perspective on the extreme events is presented by the variation in the number of catchments experiencing above-normal flow as shown in the second graph in Fig. 5. The number of catchments with above-normal streamflow is used as a surrogate for the magnitude of runoff generation because it gives a good indication of the spatial extent of the problem. The Limpopo application demonstrates that the use of satellite-derived precipitation, even with an uncalibrated model, allows for the identification of extreme events both in terms of relative intensity and spatial extent.

TABLE I
DISTRIBUTION OF EXTREME PRECIPITATION AND STREAMFLOW EVENTS IN THE LIMPOPO BASIN BASED ON ANALYSIS OF THE MERGED SATELLITE PRECIPITATION PRODUCTS FROM NASA'S TRMM AND NOAA'S CPC FROM 1998 TO 2003

Description	NASA TRMM Estimate	NOAA CPC Estimate
Average number of extreme rainfall events per watershed per year	1.8	1.1
Average number of extreme rainfall events per watershed in Y2000	4.1	2.8
Highest mean annual extreme rainfall events in a watershed	8.8	5.2
Highest number of extreme rainfall events in a watershed in Y2000	15	8
Average number of extreme streamflow events per watershed per year	26.3	25.9
Average number of extreme streamflow events per watershed in Y2000	63.2	70.3
Highest mean annual extreme streamflow events in a watershed	43.5	39.2
Highest number of extreme streamflow events in a watershed in Y2000	108	137

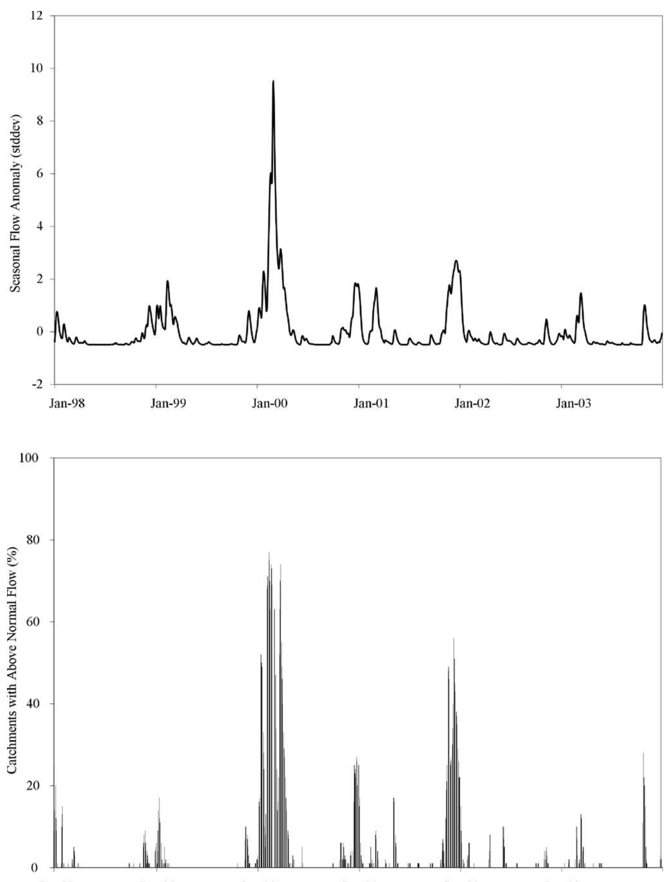

Fig. 5. (a) Variation of streamflow anomaly at Beit Bridge on the main stem of the Limpopo River. The peaks associated with the cyclones in 2000 are clearly visible. (b) Spatial extent of extreme streamflow events as illustrated by the variation in the number of catchments with above-normal flow on each day.

V. CONCLUSION AND RECOMMENDATIONS

The 2000 floods in the Limpopo basin provided important lessons about the dangers of relying solely on *in situ* data for flood monitoring and warning generation. In the aftermath of the storm, a system has been instituted for identifying extreme precipitation events, defined as daily MAP values exceeding 50 mm over any catchment. Extreme streamflow events are also identified by propagating the remotely sensed precipitation in a hydrologic model and comparing the resulting flow forecasts with climatology. The magnitude of the flood event is estimated by the flow anomaly presented in terms of standard deviations above the mean flow within the same river reach. The spatial extent of the extreme event is also tracked by computing the number of catchments with rivers recording above-normal flow.

While the absolute accuracy of extreme events was not assessed in this application because of data limitations, the relative flood characterizations produced by the system provide water authorities with important lead time for initiating event verification actions, such as requesting other riparian countries to provide updates on flow status, and prepositioning field personnel and equipment to intensify *in situ* monitoring efforts. Communities may also be put on notice to pay closer attention to radio broadcasts and other warning dissemination services [16]. These increased preparedness and early warning measures are a major improvement over alternatives such as relying solely on *in situ* gauges, waiting for the timely communication of hazard information from other riparian countries, or, even worse, waiting for flood waves to propagate into vulnerable areas without warning. In summary, remotely sensed precipitation and derived products enhance the ability of water managers in the Limpopo basin to provide rural communities with early warning of extreme flood events.

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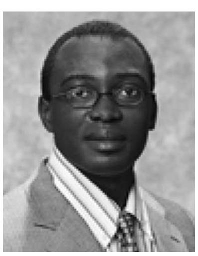

Kwabena O. Asante received the B.S. degree in civil engineering from the University of Nairobi, Nairobi, Kenya, and the M.S. and Ph.D. degrees in civil engineering from the University of Texas at Austin.

He is currently a Senior Scientist of hydrology and geospatial analysis with the Science Applications International Corporation, U.S. Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, SD. His research involves monitoring large-area hydroclimatic hazards with remotely sensed data and developing decision support tools.

Rodrigues D. Macuacua received the Certificate in Hydrometry from the Centro de Formação Profissional de Águas e Saneamento, Maputo, Mozambique, and the Diploma in civil engineering technology from Instituto Industrial do Maputo, Maputo. He is currently working toward the B.S. degree in information technology at the Instituto Superior Politecnico e Universitario, Maputo.

He is a Senior Hydraulic Technician with Administração Regional de Águas do Sul (*Translation: Southern Regional Water Authority*), Maputo, Mozambique. He has more than 20 years of experience in field hydraulic measurements. During the past five years, he has also been responsible for preparing daily streamflow forecasts and flood warnings for the Limpopo basin using a combination of remotely sensed and field data.

Guleid A. Artan received the B.S. degree in civil engineering from Somalia National University, Mogadishu, Somalia, and the M.S. degree in agricultural and irrigation engineering and the Ph.D. degree in civil engineering from Utah State University, Logan.

He is currently a Senior Scientist of hydrology and remote sensing with the Science Applications International Corporation, U.S. Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, SD. He specializes in continental-scale modeling of streamflow and snowmelt processes.

Ronald W. Lietzow received the B.S. degree in aeronautical engineering from the University of Minnesota, Minneapolis, and the M.S. degree in forestry (with specialization in remote sensing) from the University of Idaho, Moscow.

He is currently a Senior Science Analyst with the Science Applications International Corporation, U.S. Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, SD. He has more than 20 years of experience in applications development, research, and training in geographic information systems.

James P. Verdin received the B.S. degree in civil engineering from the University of Wisconsin–Madison, the M.S. degree in civil engineering from Colorado State University, Fort Collins, and the Ph.D. degree in geography from the University of California, Santa Barbara.

He is currently the International Program Manager with the U.S. Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, SD. He has more than 20 years of experience in research and management of remote sensing application.