

A FLOOD EARLY WARNING SYSTEM FOR SOUTHERN AFRICA

Guleid A. Artan, Miguel Restrepo, Kwabena Asante
USGS, Raytheon, EROS Data Center, Sioux Falls, SD, 57198
E-mail:gartan@usgs.gov

James Verdin
USGS, EROS Data Center, Sioux Falls, SD, 57198

ABSTRACT

Sizeable areas of the Southern African Region experienced widespread flooding in 2000. Deployment of hydrologic models can help reduce the human and economic losses in the regions by providing improved monitoring and forecast information to guide relief activities. In this study, we describe a hydrologic model developed for wide-area flood risk monitoring for the Southern African region. The model is forced by daily estimates of rainfall and evapotranspiration derived from remotely sensed data and assimilation fields. Model predictive skills were verified with data observed stream flow data from locations within the Limpopo basin. The model performed well in simulating the timing and magnitude of the stream flow during a recent episode of flooding in Mozambique in 2000.

INTRODUCTION

In February of 2000, the Mozambican coast was hit by a series of tropical storms. The most severe of these was cyclone Eline, which followed on the heels of cyclone Connie. Eline made landfall on February 22, moving over the headwater basins of the Limpopo River and dumping record amounts of rainfall. The historically high rainfall from Eline, coupled with saturated soil conditions due to the passage of Connie, produced a flood wave in the lower reaches of the Limpopo basin estimated to be higher than the two hundred year return period event. During Eline ensuing flood period, over seven hundred lives were lost, close to one million people were displaced from their homes, and millions of dollars of property were damaged by the floodwaters. Satellite images acquired during the event show vast areas under water, some up to 20 km away from the normal river channel. Had wide-area flood hazard monitoring techniques been in place, it would have been possible to better monitor and respond to the event as it unfolded by giving advance warning to the people that lived in the threatened area.

Ideally, wide-area flood hazard monitoring is accomplished with a flood forecast model aided by a dense network of rainfall gauging or radar stations reporting in real time. Most of the Limpopo basin has only sparse rain gauge coverage and data collected are available only after a significant delay. Due to their operational availability and global coverage, satellite data offer effective and economical means for calculating areal rainfall estimates in sparsely gauged regions. However, the quantitative use of satellite rainfall estimates in hydrological applications has until recently been limited.

The U.S. Geological Survey (USGS) Earth Resources Observation Systems (EROS) Data Center, as one aspect of its support of the Famine Early Warning System Network (FEWS NET), has undertaken efforts to enhance flood monitoring and modelling capabilities of the Southern Regional Water Authority of Mozambique (ARA-Sul). ARA-Sul is the agency within Mozambique that has the responsibility of issuing flood warning for the basins in the Southern portion of the country. In this study, we will describe a wide-area flood hazard monitoring stream flow model (SFM) developed by the USGS for this purpose, with applications of the model to the Limpopo River basin. The model simulates the dynamics of the runoff processes using precipitation estimated from remotely sensed data as the primary dynamic forcing variable. The model is currently operational for a large portion of Southern African, with catchment modelling units ranging from 10^2 to 10^3 km² in area, with a mean area of 3500 km².

MODEL AND REMOTELY SENSED DATA OVERVIEW

The SFM simulates the dynamics of runoff processes by utilizing remotely sensed and widely available global geographic data sets. The model is parsimonious: parameter and variable input data requirements are few. The SFM is a physically based catchment scale hydrologic model (semi-distributed hydrologic model). The supply and

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demand (precipitation and evaporation) fluxes of water between the atmosphere and the Earth's surface are the most important inputs to the model. Both rainfall estimates (RFE) and potential evapotranspiration (PET) input to SFM are estimated in part from remotely sensed data. National Oceanic and Atmospheric Administration (NOAA) provides the USGS/EDC with daily RFE accumulations calculated according to the method described by *Herman et al.*, (1997) and *Xie et al.* (1997). The RFE data was calculated with the first method (*Herman et al.*, 1997) from 01/1998 to 12/2000, where from 01/2001 the RFE, is calculated with the second method.

The basic inputs for RFE are geostationary thermal infrared satellite imagery and daily rain gauge reports from the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO). General relationships between cloud top temperatures and precipitation rates are exploited, with refinement from the GTS data (though they are typically sparse). With the method of *Xie et al.* (1997) incorporating also satellite microwave data from two instruments, the Special Sensor Microwave/Imager (SSM/I) of the Defence Meteorological Satellite Program, and the Advanced Microwave Sounding Unit (AMSU) on board the NOAA polar orbiters. Microwave data strengthen the rainfall estimate thanks to the more direct physical relationship between rainfall and the signal at the satellite, compared to the case for thermal infrared data. Microwave data cannot be relied upon exclusively, though, since their frequency of observation is far less than for thermal infrared images from geostationary satellite.

PET, representing the atmospheric demand for water from the Earth's surface as a function of solar radiation, air temperature, wind, humidity, and atmospheric pressure, is an essential element for calculation of the soil water balance. A program that calculates PET on a cell-by-cell basis according to the Penman-Monteith equation (*Shuttleworth*, 1992; *Verdin and Klaver*, 2001) is applied daily on a global scale at EDC. The model uses USGS-developed GIS routines that ingest grids of input variables produced by NOAA's Global Data Assimilation System (GDAS) on a 1-degree mesh.

AN APPLICATION OF SFM TO THE 2000 FLOODS OF MOZAMBIQUE

The first major flood event of the Mozambique 2000 flood took place in the period between February 5 and 10 right after cyclone Connie hit the area. By looking at the RFE product for February 4th (Figure 1) and the soil moisture status map of the area depicted in Figure 2 (the map is an output of SFM), it was possible to estimate with a good predictive skill the unfolding historical flood event that took place on February 5. Cyclone Eline hit the area while still much of the region was still under water due to the unseasonably high rainfall of late January and early February. By the time Eline dumped a record amount of rainfall on the area (see Figure 3), given that a high antecedent soil moisture was observable over the entire basin (see Figure 4), and coupled with the fact that river was running above or close to bankfull stage conditions in most of the lower part of the basin, it was then possible to foresee and issue warning for a historical flood event.

Given the above facts a SFM was implemented in Mozambique as a flood hazard-monitoring tool. Before the use of the SFM for flood hazard monitoring, a preliminary model calibration was carried out, with the model driven by climatologically consistent rainfall data that span from 1994 to 1996. The rainfall use was the Collaborative Historical African Rainfall Model (CHARM) of *Funk* (1999). CHARM consists of a downscaled of global circulation model reanalysis (*NCEP/NCAR*) precipitation fields constrained by monthly gridded station data of *Willmott and Matsuura* (2000). Then, model verification using data from 01/1998 to 12/2001 was executed; RFE and PET images were used as the driving meteorological variables. Simulated stream flows were compared with observed stream flows compiled at several locations along the main stem of Limpopo and tributary streams. The observed stream flow employed in the verification exercise we describe here was supplied by South African Department of Water Affairs and Forestry (DWAF). Note that the SFM system was only available at the end of the flooding event of 2000 and that prevented the use of the system as a flood-hazard monitoring tool.

Table 1 summarizes the results of the comparison between simulated and observed flows at some locations on Olifants River, a major tributary of the Limpopo. Although Mozambique and not South Africa was where the worst flooding was observed nearly all of DWAF gauges were washed away or damaged by the floods of 2000. Therefore the analysis of the data for nearly all of the sites was limited to the years 1998 and 1999. Figure 5a-b shows hydrographs for two key locations, with dashed lines on the graphs indicating the time when the gauges were washed away or obstructed by debris. In general, the model performance in simulating both the timing and magnitude of the stream flow was good with both for large and smaller basins. Some of the disagreement between simulated and observed flow could be due to a tendency of the *Herman et al.* (1997) method to overestimated rainfall. Another major source of the discrepancies between observed and simulated stream flows at various sites could also be due to rating curve errors. For example, the Beit Bridge gauge on the South African side of the

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Limpopo River station was found to have recorded flows 30% lower than a Zimbabwean gauge located only 3 km upstream (*U. Stellenbosch and Ninham Shand Co. Eng, 1999*).

Table 1. Statistical summary of comparison between simulated and observed stream flow at some locations on the Olifants River.

| Gauge Location | Upstream Area (km ²) | Correlation |
|----------------|----------------------------------|-------------|
| Krokodilpoort | 4690 | 0.72 |
| Buffelspoort | 7483 | 0.82 |
| Engelhard | 12938 | 0.99 |
| Mamba | 49826 | 0.87 |

Given the above facts, a SFM implementation in Mozambique as a flood hazard-monitoring tool included provision of context to calculated flows by using the model to produce thirty-six years of continuous historical daily flows. As explained in the introduction, a primary motivation for developing the SFM was the limited availability of conventional hydrometeorological station data to support drought and flood hazard monitoring. This same situation thwarts efforts to calibrate and validate the SFM. To compensate in part for this, an effort was made to provide historical context to model flows. Based on thirty-two years of simulated stream flows, recurrence intervals of different floods were determined and used as warning levels for flood hazard. Users of the SFM output were informed of the rank of current simulated flow estimates relative to historical intra- and inter-annual variations. Comparison of percentile ranking of the current flows relative to the simulated historical flows made possible a better appreciation for current simulated flows than if they were presented alone. In this way, a description of the relative magnitude of current stream flow was provided, making up for uncertainty of stream flow estimates in an absolute sense.

The model is run daily to produce a three day forecast starting from the 2001 rainy season of the Southern African region. For each day, model results are posted on the World Wide Web (http://gisdata.usgs.net/moz_floods/sfm/asmmap.asp).

ACKNOWLEDGMENTS

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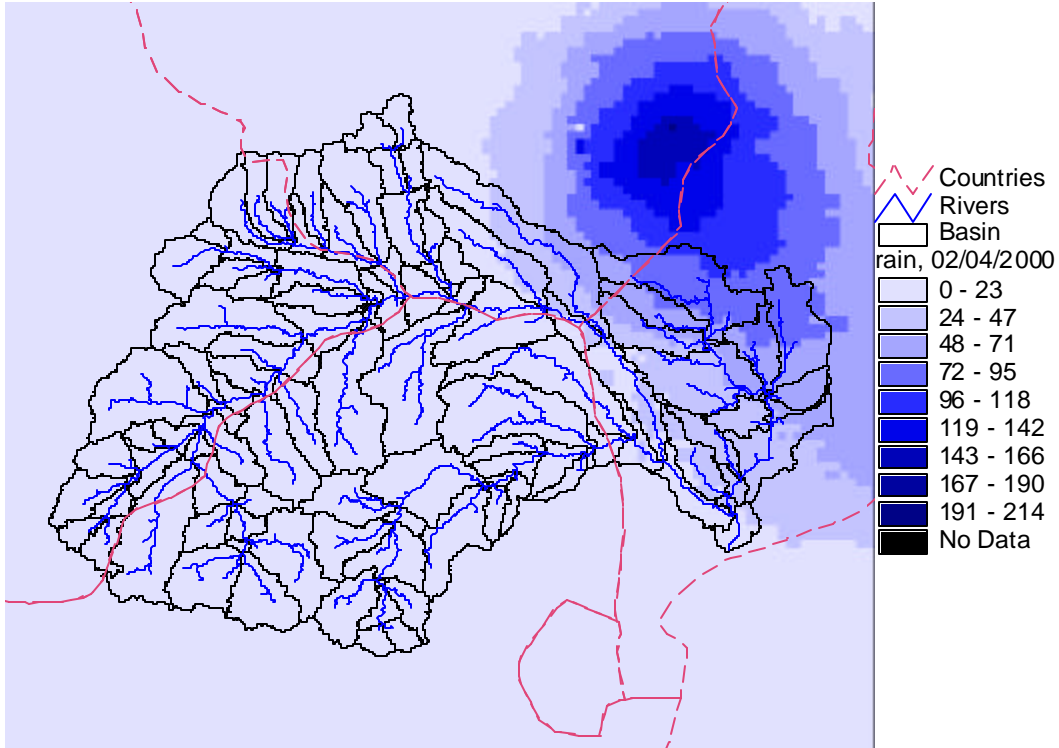


Figure 1. Rainfall distribution over the Limpopo basin as predicted by the RFE (*Herman et al., 1997*) for February 5, 2000.

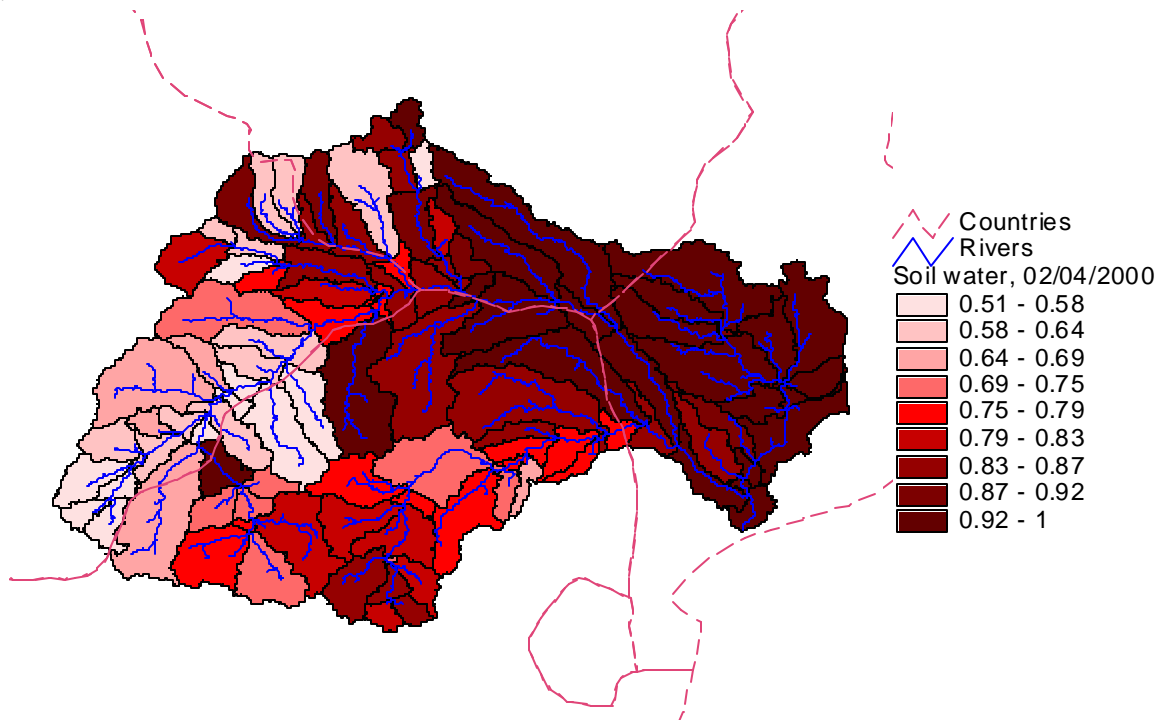


Figure 2. Soil moisture content status of the Limpopo basin estimate for February 5, 2000 by stream flow model.

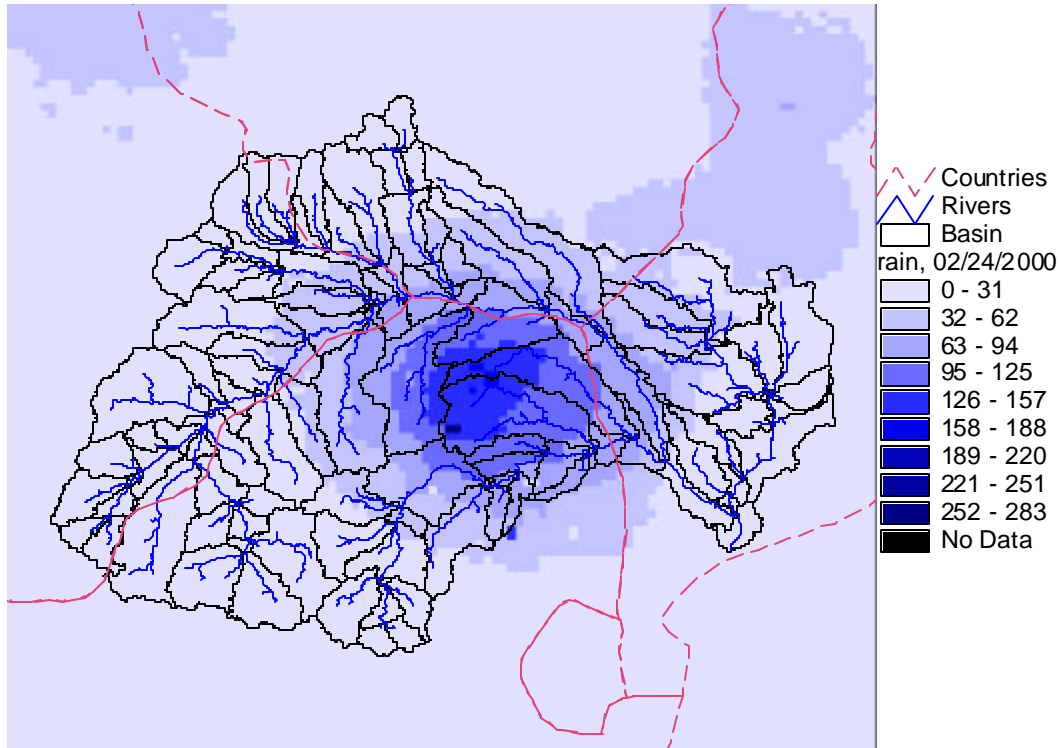


Figure 3. RFE (Herman *et al.*, 1997) of February 24, 2000 during the passage of cyclone Eline over the area.

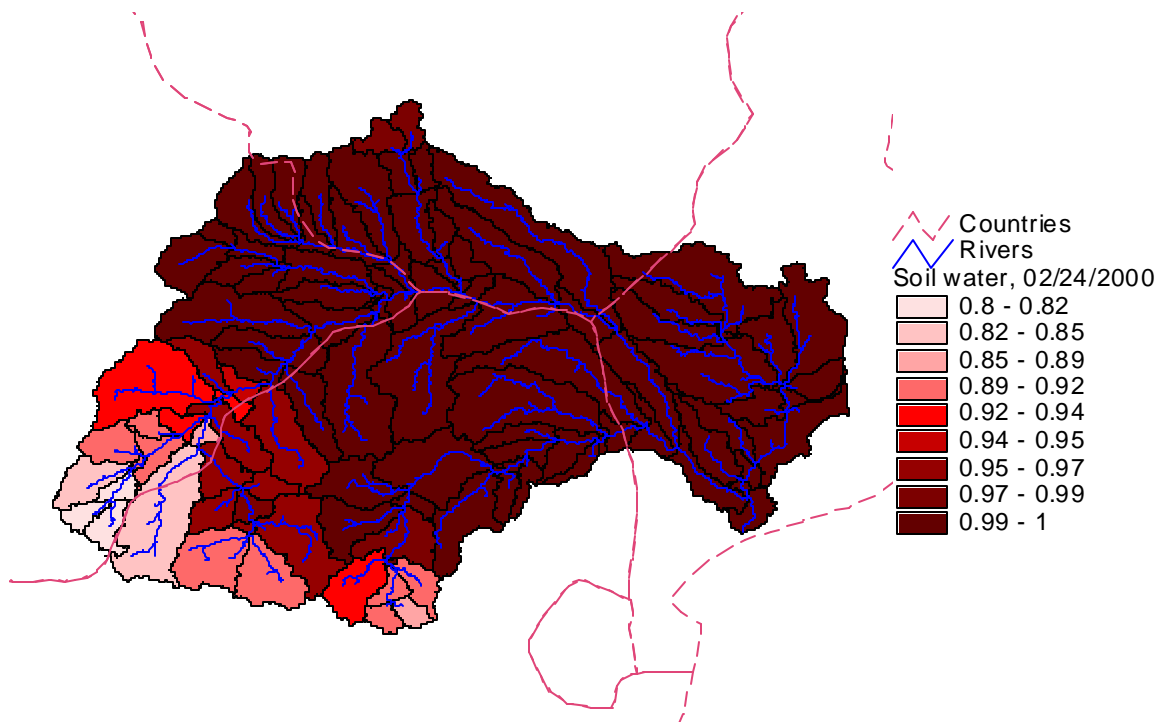


Figure 4. State of the soil water condition on February 5, 2000 of Limpopo basin as calculated by stream flow model.

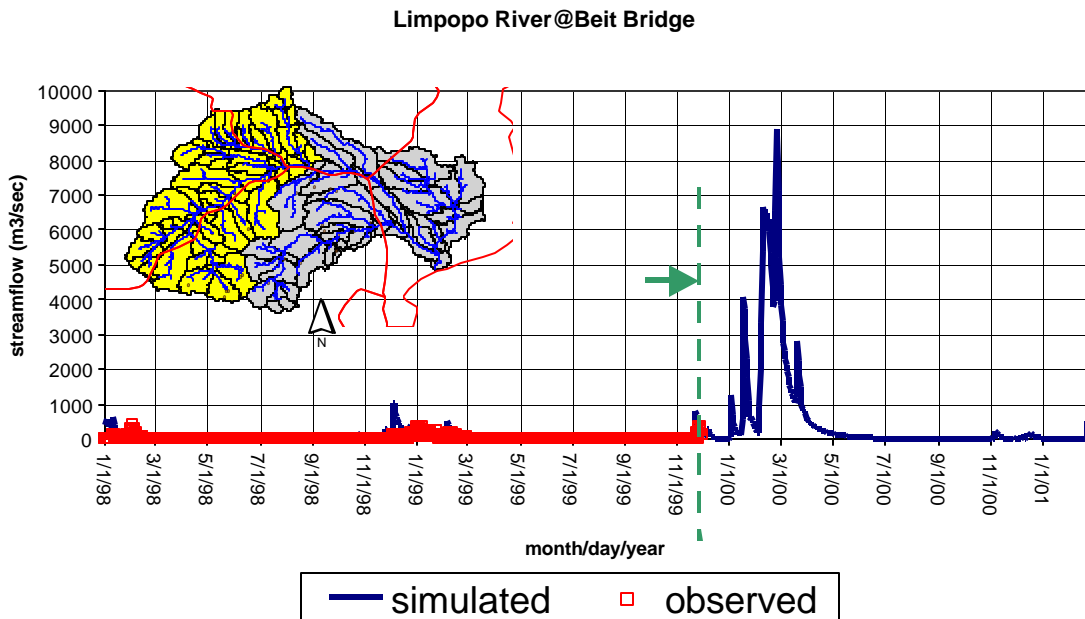


Figure 5a.

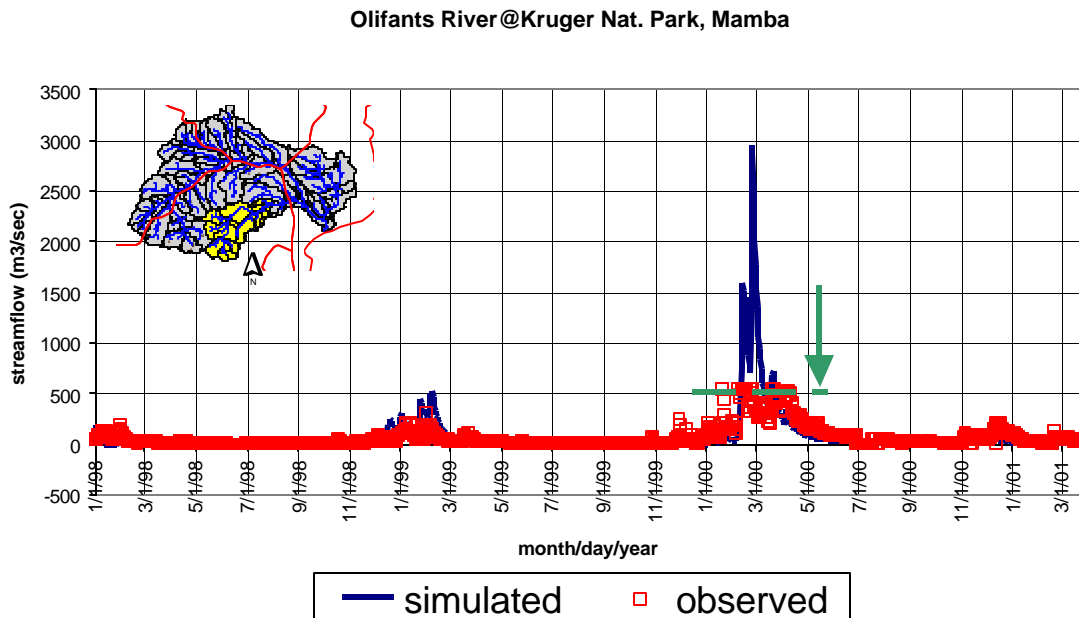


Figure 5b.

Traces of observed and simulated stream flows for the period from January 1998 to May 2001 for the Limpopo and tributary Olifants a dashed line showing when the gauges were washed out or obstructed by debris. Sites represent a variety of spatial scales and ecosystems in the watershed: (a) Beit Bridge, and (b) Mamba.