Management of Olifants Basins Floods: Application of Geospatial Stream Flow Model

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Abstract

The Limpopo River Basin is under threat of floods and adverse impacts have become more pronounced with the occurrence of each event. The capacity of current measures to mitigate the adverse impacts of floods has been significantly exacerbated by limitations in flood monitoring and forecasting as well as predicting the areas that are likely to be inundated. Latest developments and advances in integrated technologies of Geographic Information Systems (GIS), remote sensing and hydrological modeling offer opportunities for improving flood monitoring and forecasting as well as predicting the areas that are likely to be inundated. This study aims to improve on the capabilities of flood forecasting and hence decision making on flood management options. The study was carried out in the Olifants Sub-basin of the Limpopo River Basin. Geophysical properties and time series data were obtained from satellite images and historical records. The spatial and temporal attributes were stored and analysed through GIS, which was linked to a Geo-spatial Stream Flow Model. The geophysical parameters of the sub-basin such as soil properties and topography were used to parameterise the model. The calibrated model performed very well with regressions between observed and forecast stream flows at selected gauging stations ranging between 94% and 98%. A major finding of this research work is that a travel time of two days is predicted as the period it will take for a flood wave to reach Chókwè after leaving the Massingir Dam in the Olifants Sub-basin. It is also shown that the prediction of a flood event at Chókwè can be made between three to five days. This time benefit is of crucial importance in issuing early warning about an impending flood which may affect up to 130,000 people.

Media grab

Combining GIS, remote sensing and hydrological modeling delivers a powerful flood forecasting tool. In the Olifants Sub-basin, this can provide a five-day warning of major floods with two-day travel time to the flood-prone Chókwè District in Mozambique.

Introduction

The recent high profile flooding events including Bangladesh in 1987, 1988 and 1998 (Islam and Sado, 2002), Mississippi River in 1993 (Kunel and Angel, 1994; Kolva, 1993; Walker and Lawrence, 1993), Zambezi and Limpopo Rivers in 2000 (Guleid et al., 2004; ARA-Sul, 2000), have drawn attention to the need for new and improved methods for assessment, management and modelling of large scale flooding events. In the case of the Limpopo River Basin, reviews conducted after the 2000 flood by the Mozambican Water Administration – Southern Region (ARA-Sul, 2000) have identified the need for tools that enable hydrologists to assess and predict daily stream flow and the areas that are likely to be affected by flood.

The Olifants River, one of the tributaries of the Limpopo River Basin, was selected as the study area. The irregularity in seasonal rainfall results in fluctuations in river flow, which results in frequent dry spells and floods. The application of hydrologic models for streamflow forecasting and coordination of flood management can help to reduce the human and economic losses in the region specifically in the Mozambican side which is located downstream. This research attempts to address this problem by investigating the applicability of one of the available models. This will guide decision makers when selecting the most appropriate one in the context of developing countries.

The main objective of this research is to improve the capabilities of stream flow forecasting for flood management in the Limpopo Basin by using tools, which incorporate GIS and Remote Sensing. Three specific objectives were defined, namely: a) collect and validate data applied into flood forecast model for Olifants River Sub-basin; b) calibrate the model and verify the results obtained; and c) map the flood risk area at different water levels in Chókwè and to predict flood flows and travel times.

Methods

This study was conducted mainly through desk studies using short term historical remote sensing rainfall, evaporation data, topography and land cover. These data were obtained from the United States National Oceanic and Atmospheric Administration Climatic Prediction Centre and by United States Geological Survey (http://edcdaac.usgs.gov/sed6s/africa, http://edcdaac.usgs.gov/qtopo30/hydrm, http://edcdaac.usgs.gov/glcc/fc_int.html), river discharge from DWAF (1999-2005), locations of villages, cities, schools and hospitals from the Mozambican population census of 1997, soil characteristics from FAO (ftp://daac.gsfc.nasa.gov/data). To map the flood area and quantify the predicted impacts of flood the methodology recommended by Verdin et al. (2004) was used (see also Geological Survey, 2001).

The Arcinfo GIS software contains a function “Flooded Area Map” to display a map to show areas that could be inundated by flood-waters. The function uses the forecasted flow depths and the Digital Elevation Model (DEM) data to identify the area where flooding may occur. The governing equation in this process is the energy equation in Verdin et al (2004). To quantify the downstream impact a map with villages and public infrastructure (schools and hospitals) was overlain by the flood risk maps. Three levels of floods were selected, defining as the maximum level the 2000 flood level at Chokwe, which was 10.5 m above the reference level. To select the flood map areas the guidelines by ARA-Sul (2004) were followed, adopting the existing flood alert level at Chokwe hydro-stations which is 4.5 m above the scale reference. The accuracy of the flood risk maps was verified firstly comparing the maximum flood level produced by the DEM with a satellite image of March 2000, and secondly through field visits.
Numerical model for flood forecasting in the Olifants

The conceptual representations of the model processes represented refer to logical expressions (e.g. what if), and mathematical expressions (that describe the hydrological processes). The logical expressions involved in this study are related to retrieval, classification, measurement, overlaying, neighbourhood and connectivity operations used to compute terrain analysis for flow routing, basin characteristics, generate rainfall and evaporation files. The mathematical expressions involve the equations and functions applied to calculate the hydrographs (Non-uniform velocity grids and predetermined uniform velocity values were applied in Entenman, 2005), soil water balance (using a single layer soil), stream flows (pure translation routing method in Entenman, 2005; Asante, 2001; USGS, 2001); and to map flood risk areas (by using the energy equation in Verdin et al. (2004)).

Model Simulation

The data analysis methods were mostly performed using Geo-spatial Stream Flow Model (GeoSFM) simulation dynamically interfacing with a GIS model and Microsoft Excel spreadsheets. The GIS provided data to GeoSFM, and after processing the GeoSFM feeds the GIS. The GIS was itself populated with data derived from remotely sensed images, at a daily time step. Remote Sensing (RS) thus formed the source of data required to apply the model. Also a new relation was established between the modelling elements (RS-GIS-Model-GIS). The statistical calculation flows were done using a spreadsheet.

Model calibration and validation

For calibration two methods were tested, namely (a) One Soil Layer Lag Routing and (b) Two Soil Layers Routing. For this paper the One Soil Layer Lag Routing was used because of its superior performance. To adjust the model parameters to closely match the real system, five parameters were chosen: Soil Water Holding Capacity, Soil Depth, Interflow, River Flow Percentage Loss, and Celerity. The model was validated by applying it to another time series. Regression analysis was used to measure the performance. The Root-Mean-Square Error (RMSE) equation in Walford (1994) and $P$-value were evaluated to verify the results produced by the model after calibration process.

Results and Discussion

Modelling test

Figure 1 shows the performance of the model results after calibration at the Olifants River at gauging station B7H015. This station drains an area of 2,649 Km$^2$ where the daily lowest flow occurred between October, November and part of December 1999 (between 0.9 and 5.8 m$^3$.s$^{-1}$). The daily highest peak flow occurred between 23 and 29 May 2000, the maximum flow occurring on 28 February (6,780 m$^3$.s$^{-1}$). For validation the model was applied to another period (2000-2001) using the same parameter values (Figure 2).

The model results show a positive relationship between the forecasted and observed streams flow at Olifants (B7H017) with a regression coefficient of $r^2=0.94$ with $P$-value equal to 0, i.e. the difference between observed and forecast stream flows are not statistically significant. These differences can be explained by factors such as dam discharges upstream of the gauging stations and the initial soil moisture status, which were not well known. The Root-Mean-Square Error at B7H015 is equal to 2.7 m$^3$.s$^{-1}$.

Management alternatives for reducing impacts of floods

Figure 3 below shows different flood levels at Chókwè region in the lower Limpopo downstream of the Olifants river, where Level 1 corresponds with a water stage between 4.5 - 6.5 m above reference level, flood level 2 between 6.5 - 8.5 m and flood level 3 with 8.5 - 10.5 m.
Figure 3. Flooded area in the at Chókwè region in the lower Limpopo (shown in blue), against a digital elevation model at three flood levels (a) 4.5 - 6.5 m; (b) 6.5 - 8.5 m; (c) 8.5 - 10.5 m.

At flood level 1 the following villages are inundated namely: Chiquita, Chilucuane, Conhane and Mabranjane. In total 7,000 people can be affected, seven primary schools, and two hospitals (Figure 3a).

At flood level 2 the following additional villages will also be inundated: Chiguidela, Chiaquelane, Muianga, Malhazene, Sangene, Mabranjane, Mapapa, Chinangue and Muzumia. In total 32,500 people will be affected, as well as 16 primary schools and four hospitals (Figures 3b).

At flood level 3 (Figure 3c), which corresponds with the February 2000 floods, the following additional villages will be affected: Zuza, Nwachicoloane, Massavasse, Chiaquelane, Changulene, Muianga, Malhazene, Chiduanchine, Mabranjane, Bombofo, Tittle, Conhane, Chinangue and Muzumia. Also all the four cities in Chókwè district will be inundated, namely Macarretane, Chókwè, Lionde and Xilembene. In total 130,000 people will be affected, as well as 27 Primary Schools, one Secondary School and seven hospitals.

Figure 4 shows how flood wave passed through the river system during February and early March 2000, as modelled. At Olifants (B7H015) the peak occurred on 25/02/2000 and at Letaba a few hours later that same day. The peak reached Massingir Dam one day later. Downstream of the Massingir Dam, the flood peak was observed on 27/02/2000 and finally at Chókwè on 29/02/2000. It thus took one day for the peak to pass through Massingir dam, and from there it took two days to reach Chókwè.

Conclusions

The 2000 extremely high flood event in the Limpopo basin provided important lessons about the dangers of relying solely on in situ observed water levels and manually calculated flows for flood monitoring as explained in the introduction. The primary motivation for testing the Geospatial Stream Flow Model for the Limpopo River Basin was the limited availability of conventional climatological station data to support drought and flood hazard monitoring. Extreme streamflow events were identified by propagating the remotely sensed precipitation in a hydrologic model and comparing the resulting flow forecasts with observed flows. It was concluded that the model performed reasonably well in simulating the timing of the peak flows but the magnitude was over-estimated. Knowledge of the antecedent soil moisture status is an important factor in improving the magnitude of flood peaks. Also, reservoirs need to be properly represented as well as actual storage levels, otherwise certain flows are not adequately modelled. Adequate information at identified control points during flood events provide crucial information to predict inflows into Massingir Dam, enabling flood warnings to be given within three days before actual flooding would occur. This can potentially save the lives of up to 130,000 people.
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