USE OF SPACE TECHNOLOGY IN THE MANAGEMENT OF WADI WATER RESOURCES

Bashar, K. E. 1, Abdo, G. M. 2 and Gadain, H. M. 3

1 UNESCO Chair in Water Resources, Khartoum, Sudan. (bashar_ke@yahoo.co.uk, basharke@hotmail.com) (Correspondent)
2 Civil Engineering Department, University of Khartoum, Khartoum, Sudan. (gabdo2000@yahoo.com)
3 Regional Hydrologist, U.S. Geological Survey, Famine Early Warning Systems Network, Nairobi, Kenya. (hgadain@fews.net)

Received Nov. 2010, accepted after revision Feb. 2011

ABSTRACT

Wadi hydrology is a bit complicated than river hydrology. It is characterized by flashy floods and their runoff processes are not fully understood. Many regions of the world face annual flooding threats especially from flashy rivers and Wadis. These floods result in destruction of cropland, damage to infrastructure and ultimately the loss of human lives. Through the use of hydrologic modeling techniques it is possible to better predict, prepare for and react to such events.

This paper presents a modeling approach that makes use of remotely sensed data and geospatial tools to forecast flows at the outlets of Wadis. A seasonal stream in Sudan called Gash is under focus in this study due to its flashy flood nature and havoc it creates to residents along its banks. A Geospatial Stream Flow Model (GeoSFM) developed by the U.S. Geological Survey is used to simulate the dynamics of runoff processes by utilizing remote sensing, numerical weather forecast fields, and geographic data sets describing the land surface. The
model is a geospatial wide-area flood hazard monitoring system. Its hydrologic component is physically-based, catchment-scale model. The basic unit of the GeoSFM is the “sub-basin” and it permits a daily water balance calculation. Calculations determine water entering the stream network from each sub-basin through upland headwater basin routing module and channel routing module. The model parameters have physical meaning determined by the spatial distribution of basin characteristics. Using the available spatial data, the Gash catchment is delineated together with its sub-basins and streams network using digital elevation model (DEM) data in Arc View GIS environment. The catchment characteristics such as runoff curve number, Manning coefficient, etc., were derived from vegetation and soils. Using the GeoSFM the runoff from each sub-basin is generated through use of daily satellite rainfall and evapotranspiration estimate, flow routing is then performed to route the flow to the outlet of the catchment. The model is calibrated using part of the observed river flow data (1998 – 2001) and validated using the rest of the data (2002 – 2003).The results of the application are satisfactory giving promising approach for modeling and managing Wadi water resources in areas where observed hydrological data is either limited or unavailable

**Keywords:** Wadi hydrology, rainfall-runoff modeling, Flood management

1. **INTRODUCTION**

Sustainable development and management of Seasonal Wadis requires reliable and properly analyzed data. Long period monitoring of Wadi discharge is essential as well as other information including, meteorological, topographic, structural and soil.

Historical hydrologic data is very limited [1]. The major limitation of the development of Wadi hydrology in arid zones is the lack of high quality observations [2], especially rainfall and evaporation records. Remotely sensed data can be used to supplement the limited available observational data to bridge this gap. Satellite technology provides some real potential for comprehensive rainfall and evapotranspiration monitoring in space and time; however, most of the satellite rainfall estimation techniques are still experimental and require further research, in terms of calibration and validation. The rainfall estimates are produced operationally by the National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA/CPC) from satellite imagery and ground station data. In Africa, NOAA has provided dekadal RFE FEWS NET since 1995 [3]. In 1998, daily accumulations began being provided, and in 2001, a new method based on [4] was adopted.

Acknowledging the vast geospatial data archive available, hydrologic models’ parameters can be derived from remotely sensed data. This fact lead to a shift in paradigm to catchment scale modeling framework using grid or sub-basin based modeling. The shift permits the strike of a balance for a physical realism of the process representation and availability of data to describe the system as well as easier operational real-time use [5].

Gash is a trans-boundary catchment (shared between Sudan, Eritrea and Ethiopia) and experiences considerable socio economic activities, environmental issues, flooding (approximately 1 in 5 years). The river Gash catchment area is almost completely located outside the Sudan boundaries which, makes it difficult to obtain complete records for stream flow and flood forecasting modeling. Change of course and sedimentation are also experienced [6]. It has a catchment area of 31,000 Km², a river length of 200 km and a slope of approximately 200 cm/Km. The mean annual discharge is 680 million cubic meter [7].
The river is considered a source of frequent terror to the inhabitants on both sides of its banks especially in Kassala town (the capital of the Kassala state in Eastern Sudan). Kassala town suffered many attacks by the Gash River most of which were very severe. Some of the records are 1975, 1983, 1988, 1993, 1998 and 2003 [7]. Figure 1 presents the total annual flows together with maximum annual flows for Gash for the past 100 years. It is clear that the maximum annual flow is almost 10 times the minimum one, indicating the high variability of the flows in Gash River.

The upper Gash catchment lies in the Eritrean and Ethiopian highlands, characterized by high altitude and steep slopes (Figure 2) and flat slope when entering Sudan. The Eritrea part of the catchment is also high altitude region, but the slopes become gentler. In Sudan, the terrain becomes flat, and extends for long distances creating a delta and a wide flood plain.

Figure 1: River Gash Total Annual Flow (Mm$^3$) and Maximum Annual Flow (m$^3$/s)

Figure 2: Terrain and Hill shade of Gash Basin
USE OF SPACE TECHNOLOGY IN THE MANAGEMENT OF WADI WATER RESOURCES

The high rainfall in the Ethiopian highlands especially in the months of July to September cause increased discharge in the main Gash River channel downstream, as the terrain becomes flat, there is accumulation of flow in the channel, occasionally causing floods in the adjacent areas.

The river is highly seasonal and considered the main source of water supply to Kassala town during the dry and wet season. The flood plain is the main source of groundwater recharge and agriculture is widely practiced during the wet season.

2. Modeling Approach

This study uses the USGS Geospatial Stream Flow Model (GeoSFM) developed by USGS [5, 8]. The choice of the model stem from the good behavior the model demonstrated during application on real time basis for modeling the Mozambique floods. The model simulates the dynamics of runoff processes by utilizing remotely sensed data and widely available global data sets. It is a physically based catchment scale semi distributed hydrologic model. The model consists of a graphical user interface GUI that run within the Arc View Geographical Information System for input data preparation and visualization of model output and a rainfall runoff simulation component.

The GeoSFM rainfall-runoff component has four main modules; water balance, catchment routing, distributed channel routing, and stream flow forecast updating. In the water balance module the sub-basins are the subject of a daily balance calculation. This calculation determines how much water enters the stream network from each sub-basin. In the water balance module the soil is conceptualized as composed of two zones, an active soil layer where most of soil-vegetation-atmosphere interactions take place and a groundwater zone. The active soil layer itself is divided into an upper thin soil layer where both evaporation and transpiration take place, and a lower soil layer where only transpiration takes place.

The catchment runoff mechanisms considered in the model are excess precipitation runoff, direct runoff from impermeable area of the basin, rapid subsurface flow (interflow), and base flow contribution from groundwater. The runoff produced by the water balance module is routed in two phases. First the catchment runoff is routed at the sub-basin level to its outlet, and then the flow is routed through the main channel network. In the sub-basins, the subsurface runoff is routed using a set of two conceptual linear reservoirs, while the surface runoff routing is carried out using diffusion wave equation modified for use in GIS environment [9]. In the river channel network water is routed using a nonlinear Muskingum-Cunge scheme [10]. The model when applied in real time mode, has a forecast updating module for basins with stream gauge data available. An output error correction approach is used for hydrograph updating.

The model parameters have physical meaning and can be determined from remotely sensed data. The parameterization is accomplished through the use of three data sets describing the earth’s surface namely; topography, land cover, and soils.

3. Input Data

Table 1 below lists the input data and their sources. This data is available as public domain from the relative paths and can be processed within Arc View GIS using the GeoSFM GUI. The model is not restricted to using these datasets rather, other types of data can be processed and used.

The DEM is used to delineate the basin boundaries and stream networks and embeds topological information in digital format of grid cell resolution- one kilometer. Figure 3 shows the elevations as clipped from the African DEM and the delineated catchment boundary and stream network.
Table 1: Input data and their Sources

<table>
<thead>
<tr>
<th>No.</th>
<th>Data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>USGS HYDRO1K database (derivative of the USGS digital elevation database)</td>
<td><a href="http://edcdaac.usgs.gov/gtopo30/hydro">http://edcdaac.usgs.gov/gtopo30/hydro</a></td>
</tr>
<tr>
<td>4</td>
<td>Daily version of the NOAA 10-day rainfall estimate (RFE) images</td>
<td><a href="http://edcintl.cr.usgs.gov/adds/data/data.html">http://edcintl.cr.usgs.gov/adds/data/data.html</a></td>
</tr>
<tr>
<td>5</td>
<td>Daily potential evapotranspiration fields as input to the Penman-Montieth equation</td>
<td>Can be obtained using Global Data Assimilation System (GDAS) climate fields</td>
</tr>
</tbody>
</table>

Figure 3: Digital Elevation Model of Gash River

USGS Global Land Cover Characteristics Database together with the FAO soil data rainfall incident on a basin is portioned to separate surface runoff from water infiltrating into the soil.

The GeoSFM model required soil parameters (i.e., soil water holding capacity, saturated soil hydraulic conductivity, hydrologically active soil layer depth, and soil texture) were extracted from digital soil map of FAO using SCS methods [11]. The FAO Soil Map was used in characterization of the hydraulic properties of the earth's surface. The extracted properties were used by the model to set hydraulic parameters that govern subsurface water movement and changes in soil moisture content. The rate at which subsurface soil layers release water to the stream network also depends on these physical soil attributes.

The rainfall estimates were obtained from NOAA FEWS RFE. These estimates of gross precipitation input to each basin were prepared from METEOSAT thermal images and ground based rainfall stations; 0.1 degree latitude/longitude grid at 1-km resolution [3], the evapotranspiration data is derived from daily accumulations of six hourly data of NOAA Global Data Assimilation System (GDAS) and a Penman-Montieth evaporation method utilizing the USGS Global land cover for plant canopy resistance [12].

4. RESULTS AND DISCUSSIONS

Using the derived parameters form the terrain, land cover and soils data, the model is applied to the 31,000 Km² Gash catchment. The available hydrometeorological data were divided to create a set used for model calibration and a remaining set used for validation. Calibration in GeoSFM is done manually to determine a practical range of the parameter values preserving the hydrograph shape, minimum error in peak discharges and volumes. The whole parameters needed for the runoff generation process were taken into consideration. The runoff curve number, the soil water holding capacity, the active soil depth and the groundwater components had significant influence on the simulated flow discharges. The remaining parameters were adjusted to match the simulated and observed peak flows, volumes, time to peaks and hydrograph shape [13].

Data for the period 1998 to 2001 were used for the calibration exercise, while data from 2002 to 2003 were drawn upon for the validation...
USE OF SPACE TECHNOLOGY IN THE MANAGEMENT OF WADI WATER RESOURCES

mode. Figure 5 shows modeled and observed hydrographs during calibration at a site just near the Eritrean border inside Sudan where the calibration and validation were conducted.

The efficiency criterion ($R^2$), Equation 1, is used to judge the model performance. The estimated $R^2$ value for the calibration period is found to be 0.56 which may be satisfactory to judge on the similarity and consistency between the observed and estimated hydrograph shape [14].

$$R^2 = \frac{\sum(y - \bar{y})^2 - \sum(y - \hat{y})^2}{\sum(y - \bar{y})^2}$$

where:
- $\hat{y}$: Estimated flow discharges by the model,
- $Y$: Observed flow discharges,
- $\bar{y}$: Mean of $y$ in the calibration/validation period.

In comparing the calibration period, the model performed reasonably well in simulating both the timing and the magnitude of the stream flow at this site with exception of the few cases where over estimation and underestimation is evident. The discrepancies observed between the simulated and observed flows can be explained in large part by the lack of rainfall data in the upper sections of the basin highlands for the calibration and validation periods at this site (Figure 5 and 6). The discrepancies can also be attributed to the river course changes due to changing morphology of the river at this site. This can create a serious problem in the rating curve used to derive the stream flows. It is also noticed that, the model produces stream flow during the dry period; this can mainly be attributed to the base flow component of the model, which is not well modeled in the GeoSFM. This leads to longer period recession in the hydrograph and hence the generation of stream flows during the dry period.

It can be pointed out that the model produced relatively reasonable results taking into consideration averaged (time invariant) parameters were used for the whole calibrated period (4 years) and lumped parameters values for the whole area of the watershed. From Figure 5, it can be noticed out that the model succeeded to produce a relatively similar hydrograph shape. The estimated hydrograph mimic closely the rises and falls of the observed one.

As can be seen from Figure 4 it is clear that the model produced relatively over estimated results in some years due to the fact that, in the calibration stage, one set of parameters were applied to the whole period which comprised different levels of flooding cases. Accordingly, the model performance differed from one year to another.

The model constantly over estimated the recession part of the hydrograph. This is due to problems in the base-flow component of the model. The model cannot sharply bring the recession to zero.

Model validation demonstrates the capability of the model to produce accurate predictions for periods outside the calibration period [15]. Model validation for this study was used to determine the effectiveness of the calibrated parameters in predicting the flow discharges at Kassala. The validation period covers low and high flooding year cases. Figure 5 shows the simulated and observed flow discharges for the validation period. It can be noticed that the simulated discharges values are higher than the observed ones especially for the year 2003. The estimated $R^2$ value for the validation period is found to be 0.51 which is relatively small compared to the calibration period. The estimated $R^2$ value for the validation period is found to be 0.51 which is relatively small compared to the calibration period. Similar to the calibration stage, the model produced rather over estimated flows in the case of low flooding year. Again this can mainly be attributed to the input data during this period.
5. CONCLUSION

The simulated stream flow compared fairly well with the observed data with a correlation coefficient of $R^2 = 56\%$, especially in capturing the flow peaks. The trend in rise and fall of the observed and simulated stream flow hydrographs was similar and the timing of the peak is captured very well with the exceptional cases where the simulated flow was slightly higher than the observed. This is due to the fact that only single set of parameters were used for the whole calibration period which include different levels of peak flows. Also given the seasonal nature of the river and the zero flows during the dry period, the model performance was weak.
USE OF SPACE TECHNOLOGY IN THE MANAGEMENT OF WADI WATER RESOURCES

The higher simulated values could be as a result of the model’s lag effect: whereas observed discharge narrowed down to zero at the end of September, the model would take a little longer to recede to zero discharge. This can be attributed to the fact that the base-flow component of the model.

It should also be noted that the resolutions of the input data is very coarse for such studies and that the rainfall estimates were not calibrated for the study. In general the model was able to produce the observed situation with reasonable accuracy and thus be used as a planning tool for Wadi hydrology.

References