FLOOD FORECASTING IN TANZANIAN CATCHMENTS

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ABSTRACT

Floods are still a problem to many countries in the world todate. Floods do cause damages to property and sometimes loss to human life. Flood control measures by structural and non-structural methods are available in the literature. However, structural flood control measures are financially infeasible in most developing countries today. Flood forecasting is a non-structural measure for reducing flood damages. It is a means of providing early flood warnings to flood prone areas. The Linear Perturbation Model has been applied for real time flood forecasting in Tanzanian catchments. The Linear Perturbation Model in an updated mode performed better in five catchments and can be used for real time flood forecasting in such catchments.

1.0 Introduction

Tanzania has an area of 936262 square km and lies between latitude 1^{o} and 11^{o} south and between longitude $29^{o}30'$ and $40^{o}30'$ east. The mean temperature varies from $20^{o}C$ to $25^{o}C$ in the coast and from $14^{o}C$ to $20^{o}C$ in the highland. The mean annual rainfall varies from 500mm in the central part of the country to over 2400mm in southern highlands

(Bogard et al., 1988; CCKK, 1982). The climatic cycle in Tanzania can be divided into four periods and these are: December-February; March-May; June-August; and September-November.

During the period, December to February, the Intertropical Convergence Zone (ITCZ) is out far south of the country and the North-East monsoon winds are relatively dry. Therefore, the Northern part of Tanzania is dry during this period. However, Orographic lifting and convergence with the air stream causes considerable rain in the southern part of the country.

During the period March to May, the ITCZ returns too Tanzania. Heavy rains mostly of convectional type result due to large scale convergence and instability of air masses.

During the period June to August, the prevailing winds are the South-East monsoons and they bring little moisture if any, because the air masses originating from the Indian ocean loose their moisture when passing over the Island of Madagarscar. The ITCZ traverses rather rapidly from North to South during September to November. This sets in the beginning of rains in most parts of the country. In fact the hydrological year starts from November to October.

Floods do occur in Tanzania and the flood prone areas are: lower valley of the Rufiji river, Kilombero river, Ruvu river and Lukuredi river. The definition of a flood are many. From hydrological point of view, a flood is any relatively high water level above an arbitrarily selected flood level. To be more precise Ward (1978) defines a flood as a body of water which rises to overflow land which is not normally submerged. Floods in Tanzania are caused by heavy and/or prolonged rainfall.

Floods do cause damages to property and sometimes loss to human life (Ward, 1978, Tanzania Sunday News, August 20, 1989). Flood control measures such as non-structural and structural are available in the literature. Structural measures by dams are suitable only when the value of property exceeds the construction costs of dams or if human life is at high risk. Non structural flood control measures are employed where structural measures can not be implemented (technically or financially) especially in developing countries, Tanzania being one of them. Non-structural flood control measures are: flood zoning and flood forecasting.

Real time flood forecasting which can be used to reduce flood damages is presented in this paper. This approach can be used to provide sufficient advance information of flood occurrence. This can enable people and their property to move to higher areas.

2. Real Time Flood Forecating

Flood forecasting involves the establishment of a flood magnitude and future time of its occurrence. Thus flood forecasting is the ability to provide flood warning to residents along a river. Flood forecasting has been used in many countries to provide flood warnings in flood prone areas (Hoyt and Lngbein, 1953, Alekhin, 1964). Flood forecasting can be achieved either by correlation, routing and/or by rainfall-runoff models (Chapman and Dunin, 1975). Flood forecasting by use of rainfall-runoff models is the approach which has been demonstrated in Tanzanian catchments and therefore is presented herein.

A model is a conceptualization of a real system which retains the essense of that system for a particular purpose. In real time forecasting, there are three main model requirements and these are: model accuracy; model consistency; and model versatility. The model accuracy is a refection of the extent to which the model satisfies the objective function. Some authors have termed this model requiremnt as the model efficiency (Nash and Sutcliffe, 1970). Model consitency is the persistence of the level of the model accuracy and the estimate of the parameters through different samples of the data. Model versatility is the ability of the model to maintain its level of accuracy and consistency when subjected to adverse applications (WMO, 1975).

There are many rainfall-runoff models in the literature (Eagleson,, 1967; Dooge, 1968; Nash, 1969; Clarke, 1973; Fleming, 1975; Box and Jenkins,1976; Nash and Barsi, 1983; UNESCO, 1985). The Linear Perturbation Model has been found to give satisfactory results on large and humid catchments (Kachroo et al. 1989). Most flood prone areas in Tanzania are found in relatively wet regions. Thus, the Linear Perturbation Model (LPM) has been applied for real time flood forecasting in Tanzanian catchments is explained herein.

2.1 Selection of Catchments

Tanzania is a large country with adverse climate and physiography. Among the climatic factors, rainfall is the most important factor which influences the regime of rivers. Catchment area is a major physiography factor which influences the regime of rivers. Therefore, catchments were categorized according to size and rainfall (table 1). Table 2 presents the selected catchments.

Table 1: Catchment categories

Catchment Category	Area (Sq.km)	Rainfall (mm)
1	<500	1000 - 2000
2	500 - 2000	< 1000
3	2000 - 10,000	< 1000
4	2000 - 10,000	1000 - 2000
5	> 10,000	1000 - 2000

Table 2: The selected catchments

Catchment Name	Area km^2	Annual Rainfall (mm)	Discharge and Rainfall Record
Kimani/Gr.North 1KA9	448	1000	1963-68
Ruvu/Kibungo 1H5	420	1500	1963-68
Sonjo/Sonjo 1KB 23	68	1600	1963-68
Mbarali/Igawa 1KA 11	1600	900	1963-67
Little Ruaha/ Ihimbu 1KA21A	2480	1000	1963-68
Ruvu/Morogoro Road 1H8	15,190	1500	1963-67
Kilombero/Swero 1KB17	33,400	1200	1961-64

2.2 Linear Perturbation Model (LPM)

The linear perturbation model was developed by Nash and Barsi (1983). For a single input series the LPM is expressed as follows:

$$Y_i = \sum_{j=1}^{m} X_{i-j+1} h_j + e_i \quad \text{for } i = 1,2, \ldots, n$$

where, h_j are pulse response ordinates; e_i is white noise; m is the memory length and n is the number of observations. The seasonal component Q_d or R_d is estimated by

$$Q_d = \frac{1}{L} \sum_{r=1}^{L} Y_{d,r}$$

where $Y_{d,r}$ is observed discharge or rainfall on date d in year r and L is the number of years in the calibration period.

The seasonal mean values were smoothed with unconstrained Fourier series representation using four harmonics. Time series of perturbations Y_i and X_i were calculated by subtracting smoothed seasonal mean values from observed rainfall and discharge series for the period of calibration.

$$Y_i = Q_i - Q_d$$
$$X_i = R_i - R_d$$

where, Q_d and R_d are seasonal mean discharge and rainfall values on day d; R_i and Q_i are the observed rainfall and discharge values.

The pulse response function was estimated by the method of ordinary least squares. Estimated outflow perturbations were obtained by convoluting the pulse responses with rainfall pertubations. The addition of the smoothed seasonal mean discharge to estimated perturbations constitute the estimated discharge which is the model estimate $\hat{Q}_i$, which is expressed as

$$\hat{Q}_i = \sum_{j=1}^{m} x_{i-j+1} + Q_d + e_i$$

$$i = 1,2, \ldots n; \; d = 1,2, \ldots, 365$$

The model efficiency, R^2, was computed using the following expression:

$$R^2 = (F_o - F) / F$$

where $F = \sum_{i=1}^{n} (Q_i - \hat{Q}_i)^2$, model variance

$F_o = \sum_{i=1}^{n} (Q_i - \bar{Q})^2$, initial variance

Q_i and $\bar{Q}$ is the observed and mean discharge respectively.

The model was allowed to run at various memory lengths for each catchment. The ratio of observed discharge to estimated discharge was recorded and this is because a good memory length has a ratio of close to unit. Table 3, shows the optimal memory lengths for all catchments and the corresponding model efficiency. From table 3 it can be seen that all catchments have relatively higher values of model efficiency during calibration except Sonjo. The low model efficiency for Sonjo might be due to either failure of the model or poor quality of rainfall and discharge data or both. During the verification period, Mbarali and Sonjo catchment were found to have the lowest model efficiency. Again this could be due to the failure of the model or due to poor quality of data.

Table 3: Summary of the results obtained with the linear perturbation model.

Catchment	Memory length (Days)	Cal. Period (Years)	Ver. Period (Years)	Model Efficiency &	
				Cal.	Ver.
Kimani/Gr.North (1HA9)	30	4	2	61	47
Ruvu/Kibungo (1 H 5)	35	4	2	74	59
Sonjo/Sonjo (1KB 23)	10	4	2	34	-12
Mbarali/Igawa (1KA 11)	20	3	2	52	36
Little Ruaha/ Ihimbu (1KC21C)	30	4	2	71	62
Ruvu/Morogoro (1h8)	40	3	2	65	61
Kilombero/Swero (1KB 17)	50	3	1	72	83

Note: Cal. = Calibration
Ver. = Verification

The series of residuals from the model were examined for persistence (Rumambo, 1990). It was found that the residuals showed evidence of persistance for all the catchments. (e.i. positive autocorrelation coefficients). The presence of persistence suggests that the linear perturbation model can be improved if made to operate in an updating mode. This requires the fitting of an autoregressive model to the residuals and correct the model forecast accordingly. Autoregressive model coefficients were calculated using the Yule-Walker equations (Box, Jenkins, 1976). The results are given in table 4.

Having computed the autoregressive model coefficients or parameters ϕ_i, the correction of the next forecast (U_t) is given by:

$$U_t = \phi_1 U_{t-1} + \phi_2 U_{t-2} + \ldots + \phi_5 U_{t-5}$$

where ϕ_i are the autoregression coefficients presented in table 4, and U_t are the residuals of the Linear Perturbation Model.

The Linear Perturbation Model when fitted with an autoregressive model component is expressed as follows:

$$\overset{*}{Q}_t = \hat{Q}_t + U_t$$

where $\overset{*}{Q}_t$ is the updated forecast

By using the Linear Perturbation model fitted with an autoregressive model component the model efficiencies for all catchments were determined and are presented in table 5. From table 5, it can be seen that the model efficiency has greatly increased when operated in an updated model.

Table 4: Autocorrelation coefficients of the residuals (U_t) of the linear perturbation model.

	Lag in Days				
Catchment	1	2	3	4	5
1. Kimani/GR. North Road (1KA9)	0.78	0.64	0.56	0.49	0.44
2. Ruvu/Kisango 1H5	0.42	0.38	0.36	0.30	0.25
3. Sonjo/Sonjo 1KB23	0.32	0.40	0.26	0.17	0.20
4. Mbarali/Igawa 1KA 11	0.64	0.58	0.58	0.46	0.46
5. Little Ruaha/ Ihimbu 1KA23A	0.93	0.88	0.85	0.81	0.78
6. Ruvu/Morogoro 1H8	0.83	0.62	0.48	0.40	0.35
7. Kilombero/Swero 1KB 17	0.98	0.97	0.97	0.95	0.94

The results are good except for Sonjo and Mbarali catchments. For the calibration period, the model efficiency ranged from 81% (Ruvu at Kibungo) to 99% (kilombero at Swero) while for the verification period ranged from 80% (Kimani) to 99% kilombero at Swero). From the above results, the model performed excellent for three catchments namely little Ruaha, Ruvu (1H8) and Kilombero with model efficiencies 95%, 94% and 99%, respectively.

No correlation was found between model efficiency and catchment area as well as catchment mean annual rainfall. The model can be applied for real time forecasting in the three catchments(Little Ruaha, Ruvu(1H8) and Kilombero) where its performance in an updated model has been found to be excellent.

Table 5: Comparison of results of linear perturbation model with updating and non-updating

Catchment	Model Efficiencies %			
	Non updated mode		Updated mode	
	Cal.	Ver.	Cal.	Ver.
1. Kimani/Gr. North Road (1KA9)	61	47	85	80
2. Ruvu/Kibungo (1H5)	74	59	81	81
3. Sonjo/Sonjo (1KB 23)	34	-12	48	54
4. Mbarali/Igawa (1KA 11)	52	36	84	29
5. Little Ruaha/ Ihimbu (1KA 21A)	71	62	96	95
6. Ruvu/Morogoro Road (1H8)	65	61	89	94
7. Kilombero/Swero (1KB17)	72	83	99	99

Note: Cal. = Calibration

Ver. = Verification

3. Summary

The linear perturbation model was applied to seven catchments in Tanzania. The model performed well in five catchments except for Sonjo and Mbarali. A study of the model residuals indicated the existence of persistence (indicated by positive autocorrelation coefficients). The model was made to operate in an updated mode by fitting it with an autoregressive model component. The Linear Pertubation model (Updated mode) performed better in five catchments except for Sonjo and Mbarali (i.e. model efficiency increased significantly than in the non updated model).

4. Conclusions

The verification model efficiency of the Linear Perturbation model in an updating mode has been found to be significantly high than in the non-updating mode for the five catchments (see table 5). It can therefore, be concluded that, the Linear Perturbation model (updated mode) can be used for real time flood forecasting in the five catchments {Kimani (1KA9); Ruvu (1H5); Little Ruaha (1KA 21A); Ruvu (1H8) and Kilombero (1KB17)}.

REFERENCE

1. Alekhim, I.M. 1964 "Short-range Forecasting of Lowland River Runoff". Jerusalem: Israel Program for Scientific Translation Ltd.
2. Bogardi, J.J. Duckstein, L., and Rumambo, O.H. 1988 "Practical Generation of Synthetic Rainfall-Event Time Series in a Semi-arid Zone". Journal of

Hydrology, 103: 357-373.

3. Box, G.E.P. and Jenkins, G.M. 1976 "Time Series Analysis: Forecasting and Control". Holder-Day Inc.,
4. CCKK, 1982 "Water Master Plans for Iringa, Ruvuma and Mbeya Regions". Carl-Bro- CowiConsult - Kampsax - Kruger.
5. Chapman, T.G. and Dunin, Fox. 1975 "Prediction in Catchment hydrology". South Australia, neley: The Griffin press.
6. Clarke, R.T. 1973 "Mathematical Models in Hydrology". Irrigation and Drainage Paper 19, Rome: UN/FAO.
7. Dooge, J.C.I. 1968 "The Hydrological Cycle as a Closed System". Bull. Int. Ass. Scient. Hydrol. 13(1).
8. Eagleson, P.S. 1967 "Optimal Density of Rainfall Networks". Water Resources Research, 3(4): 1021 - 1033
9. Fleming, G. 1975 "Computer Simulation Techniques in Hydrology". New York, Elsevier.
10. Hoyt, W.G. and Langbein, W.B. 1955 "Floods". Jersey: Princeton U.P.
11. Kachroo R.K. et al 1989 "Application of Linear Techniques in Modelling Rainfall - Runoff Transformation". Galway: Dept. of Hydrology.
12. Nash, J.E. and Barsi, B.I. 1983 "A Hybrid Model for Flow Forecasting on Large Catchments". Journal of Hydrology, 65: 125 - 137.
13. Nash, J.E. and Sutcliffe, J. 1970 "River Flow Forecasting Through Conceptual Models Part I. A Discussion of Principles". Journal of Hydrology.
14. Rumambo, O.H. 1990 "Applications of the Linear Perturbation Model in Real Time Flood Forecasting in Tanzania". Unpublished M.Sc. Dissertation, University

of Dar es Salaam Tanzania.

15. Sunday News, Tanzania August 20, 1989.
16. UNESCO 1985 "Teaching Aids in Hydrology". Technical Paper in Hydrology No 27, Paris.
17. Ward, R.C. 1978 "Flood: A Geographical Perspective". Macmillan Press, London.
18. WMO 1975 "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting". Geneva.