A CONCEPTUAL APPROACH TO WATER RESOURCES MANAGEMENT FOR A CATCHMENT IN TANZANIA.

By

Mwanuzi, F.L.* & Mutabazi, A. A.**
* Department of Civil Engineering.
P.O. Box 35131, DAR ES SALAAM
** Irrigation Division, Ministry of Agriculture.

ABSTRACT

In hydrology/Water resources, normally rainfall data are available for longer periods than runoff data. Many attempts have been made to extend these runoff data by using system approach and conceptual models. The conceptual approach to simulate runoff at the outlet of a catchment is based on the physical processes involved in the transformation of rainfall into runoff (river flow). In this paper a conceptual model, (SEAMOD) has been used. This model has a limited number of parameters to optimize when compared to other models like the sacramental model. Also it requires less input data. The model assumes that the storage is divided into three layers, the surface storage, subsurface storage in the unsaturated zone and subsurface stoppage in the saturated zone. The results showed that the model under estimated the low flows from the catchment, but when the storage were lumped together, it underestimated the high flows (peaks). Graphical comparison of the calculated and observed discharge showed that the model fits the data very well.

INTRODUCTION

In most developing countries the main source of inadequate data system can be attributed to the shortage of manpower, both professional and subprofessional and lack of logistic support and basic understanding of the absence of water resources study from various authorities concerned. For measured data, there are a lot of uncertainties leading to errors e.g. measurement errors, instrumental errors etc. If the mechanism governing the evolution of the causative agent is known then the response can be predicted or calculate within a given degree of precision.

It is known that rainfall data, sometimes called leading indicator[1] are available for longer duration, but the runoff, sometimes called the response usually are available for short duration. For the periods of concurrent data, i.e. periods when the leading indicator and response are available, a joint study is made to establish their relationships. Methods employed include the use of system model[2] and conceptual models.

Ndembera catchment (Fig. 1) data will be used in this paper to study the relationship between rainfall and runoff by applying conceptual modeling approach. A period of concurrent data of rainfall, runoff and evaporation were from 1962 to 1978, though rainfall data were available for a period of 1961 to 1986. Fig. 2 and Fig.3 shows rainfall and runoff respectively of the catchment.

The Ndembera Catchment

The catchment is located in the southern part of Tanzania as shown in (Fig. 1). It consists of hilly terrain consisting of precambrian granite and gneiss rocks. The vegetation in the area is mostly grassland with bands of savannah trees. The whole basin is about 1200 square kilometres and the catchment outlet is at Madibira. The possibilities of irrigation at Madibira for rice were investigated by FAO[3] and the Ministry of Agriculture. This irrigation field has been subjected to an annual flooding from the main river of the catchment (Ndembera river). Subsequently the river changed its course and resulted to a more or less permanent swamp within the proposed irrigation field.

CONCEPTUAL APPROACH

The conceptual approach to simulate runoff at the outlet of a catchment is based on modelling the catchment behaviour through recognition of the physical processes involved in the transformation of rainfall into runoff (stream flow).

Simulation models based on physical and mathematical concepts have been developed since the beginning of 1960's. To mention a few; the Stanford Watershed Model[4] which simulates hourly stream flows/discharges, the SSARR model[5] which simulates hourly stream flows including the effects of reservoirs and diversions in the watershed, the R009 model[6] and its modified

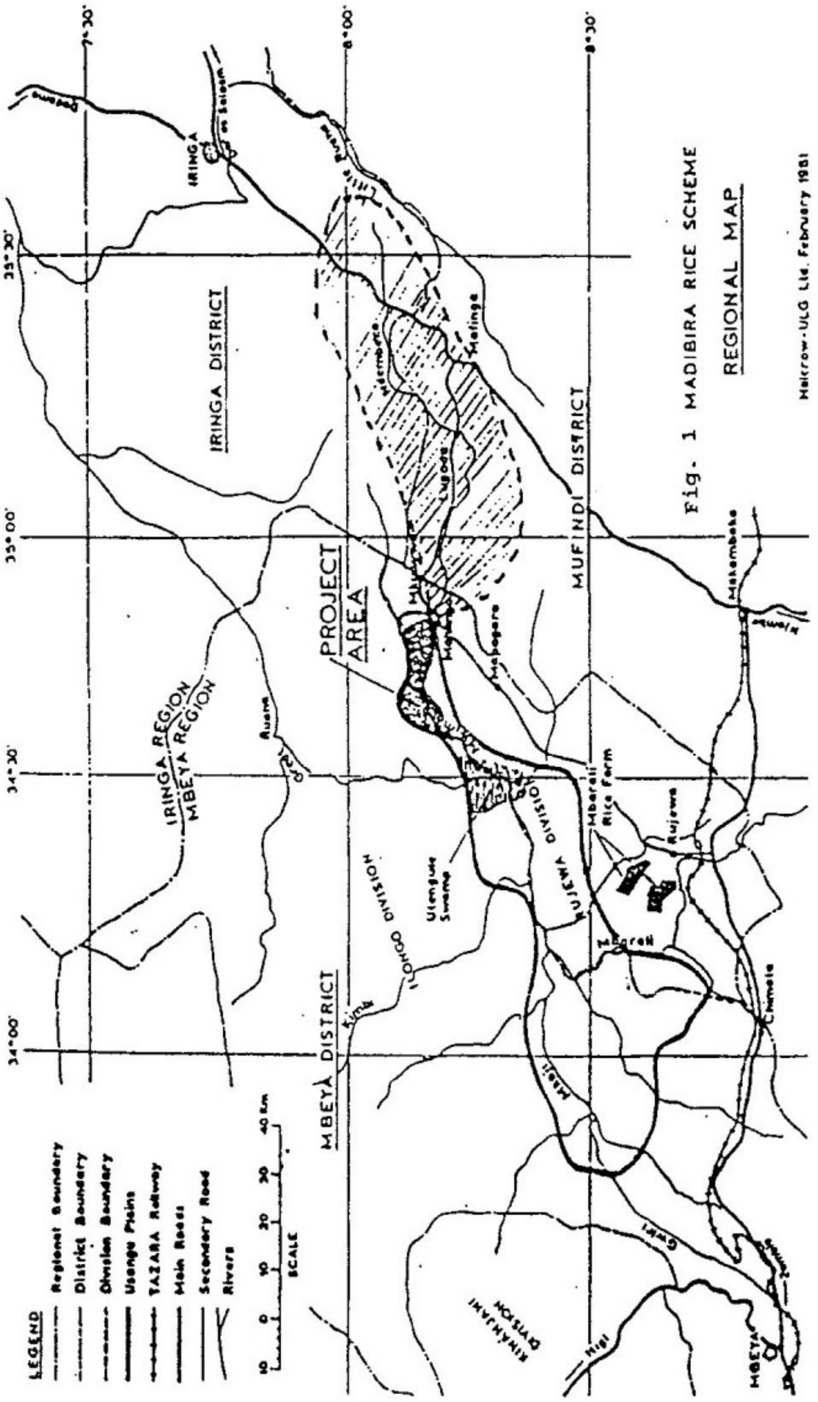

Fig. 1 MADIBIRA RICE SCHEME

REGIONAL MAP

Halcrow-ULG Ltd. February 1981

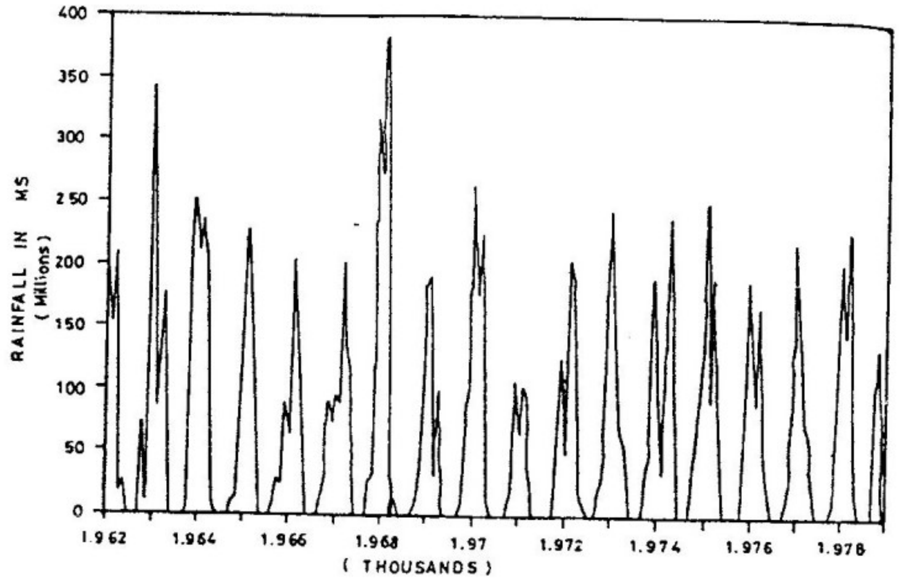

Fig.2 Rainfall - Madibira Basin

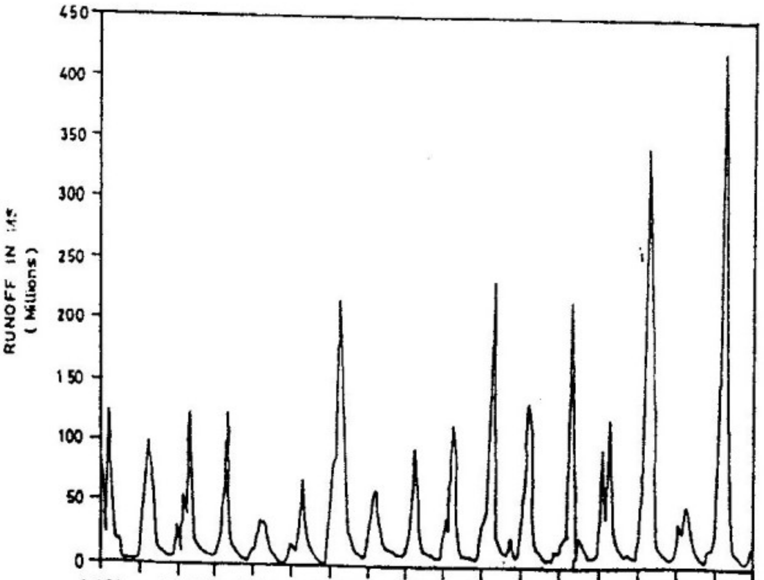

Fig.3 Runoff - Ndembera River in Madibira Basin

version MMO8[7] which simulates daily stream flows, and the USGS model[8] which can simulate both daily and hourly stream flows.

Monthly stream flow model were attempted by Riley[9], later by Amisial and Uzcategui[10]. Progressively Salas and Cardenas[11] developed a seasonal monthly simulation model for watershed (SEAMOD).

The complex behaviour of a catchment can also be simulated by abstract system models formulated mathematically though sometimes it is difficult to formulate a mathematical model that can describe the various sub physical processes taking place in the catchment.

The results obtained so far have not yet proved the superiority of any approach. Indeed, both approaches have their merits and limitations. While a simple model lacks in adequate representation of the complex catchment system, the problem with an elaborate model lies with its too many parameters, none of which can be properly evaluated from the limited information available about the transformation system. With the increased use of weather radar and remote sensing data, and the accumulating experiences on understanding of the physical processes of hydrological systems, more elaborate and physically sound hydrological model might be applied in practice.

However, at present, simple conceptual models are still dominant models used in hydrological simulation and forecasting practice. This paper specifically applies the conceptual approach to water resources management for the Ndembera catchment in Tanzania. The conceptual model, National Weather Service Model called Sacramental Model was overviewed, but because of its input data demand and many parameters to optimise it was disregarded. The Seasonal Model (SEAMOD) was adopted as it required a limited input data and has few parameters to optimise. An attempt to modify the model was made and the results were compared.

The National Weather Service Model (NWS) The NWS is a conceptual model for soil moisture accounting and flow routing[12] adopted from a huge National weather Service River Forecast system (NWSRFS) developed by NWS Sacramental Soil Moisture, California, River, Forecast Centre, thus called the sacramental model (SAC-SMA). The conceptual formulation of the model is shown in Fig. 4.

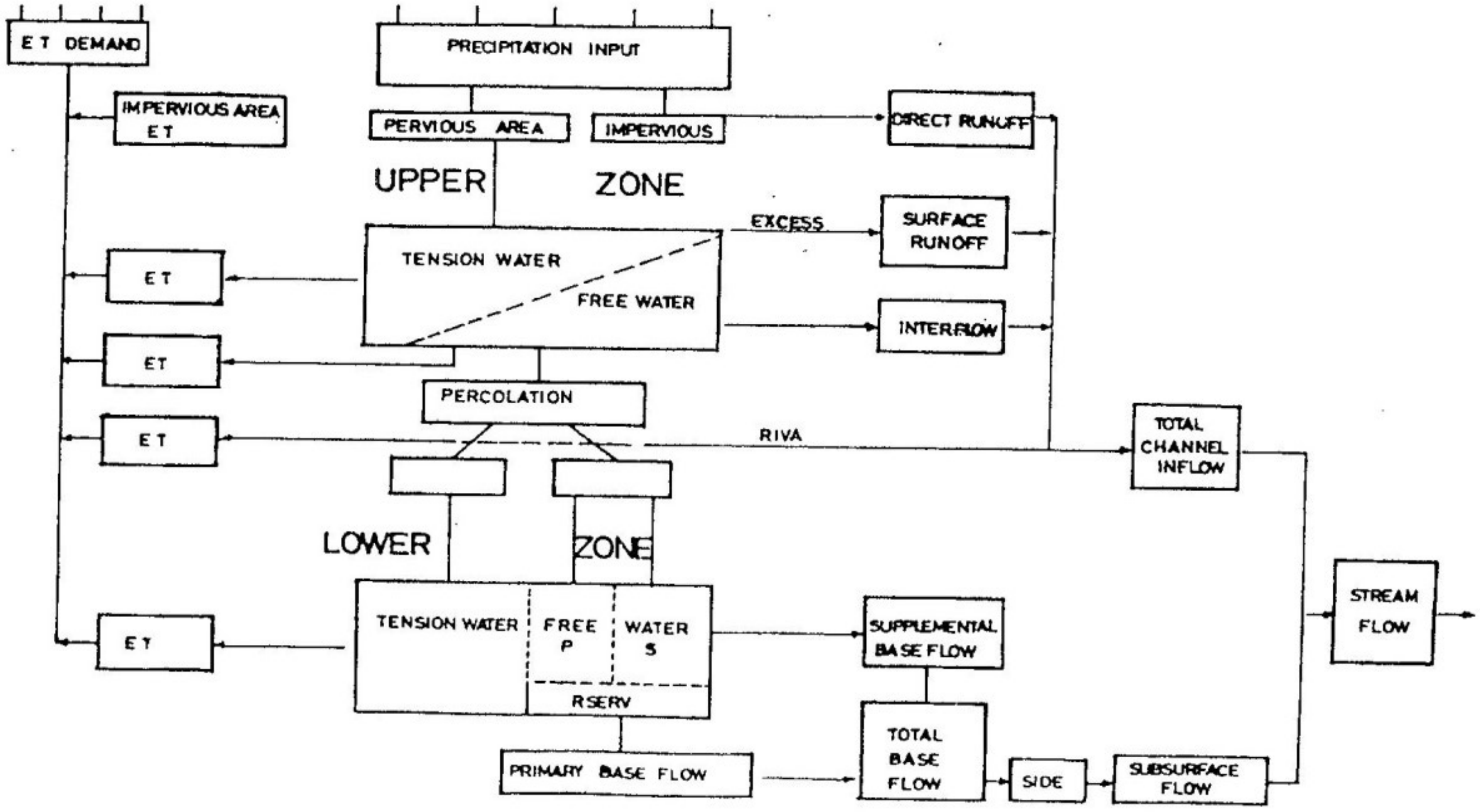

Fig.4 Flow chart of Sacramento Soil - Moisture Accounting Model

The model assumes that;

(a) A catchment consists of two storage, the upper zone and the lower zone.

(b) The catchment is partitioned (Fig. 5) into interconnected segments each segment representing a different portion of the catchment having, relatively uniform properties and where conditions may be characterized by a unique set of processes

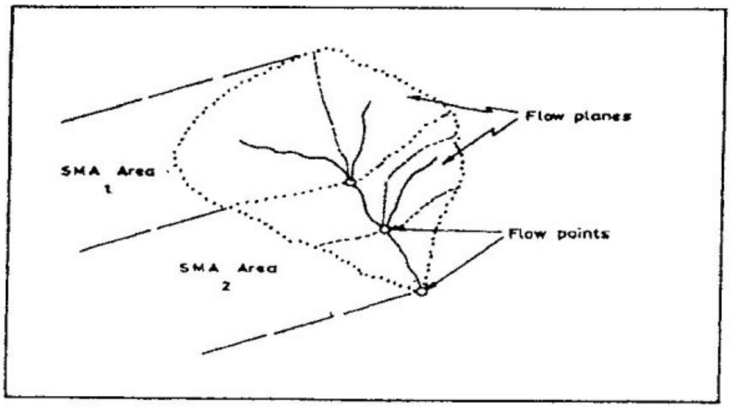

Fig. 5 A schematic of watershed partitioning of the NWS Model

Table 1 gives the parameter and variables of the model. Some of the parameters can be optimised automatically by the model and some can be optimised by trial and error. A maximum of 12 parameters were optimised automatically when the catchment was considered as a single catchment (no subdivision). The model could not give good results since the data were limited. With the available map of scale 1:000 000 it was not possible to establish a proper river cross section, overland flow length and flow plane areas which are demanded by the model. The model was disregarded.

Seasonal Model for Watershed (SEAMOD). This is also a conceptual model to simulate the various hydrological processes occurring in a watershed (catchment) at a seasonal monthly time scale. The model can be schematised as shown in Fig. 6.

Table 1. Summary of NWS-PC model parameters including state variables of SAC-SMA model.

SAC-SMA Model Parameters

PXADJ - precipitation adjustment factor

PEADJ - evapotranspiration demand adjustment factor

PCTIM - fraction of permanent impervious are

ADIMP - fraction of impervious area when all tension storage requirement are met

RIVA - fraction of basin covered by stream, lakes and riparian vegetation

UZK - upper zone free water storage depletion coefficient

LZSK - lower zone supplementary depletion coefficient

LZPK - lower zone primary depletion coefficient

PFREE - fraction of percolated water transmitted directly to the lower zone free water

RSERV - fraction of lower zone free water unavailable for transpiration purposes

ZPERC - proportionality constant in increasing percolation from saturated to dry conditions

REXP - exponent defining curvature in percolation curve with changes in the lower zone soil moisture deficiency

SIDE - portion of baseflow not observed in the channel

UZTWM - upper zone tension water storage capacity
UZFWM - upper zone free water storage capacity

LZTWM - lower zone tension water storage capacity
LZFSM - lower zone supplementary water storage capacity

UZFPM - lower zone primary water storage capacity

SAC-SMA State Variables

UZTWC - upper zone tension water storage content

UZFWC - upper zone free water storage content

LZTWC - lower zone tension water storage content

Table 1 (continuation)

LZFSC - lower zone supplementary water storage content

UZFPC - lower zone primary water storage content

ADIMC - temporary impervious area storage content

Kinematic Wave Model Parameters

TAREA - total flow plane area (second level partitioning)

CHLNG - overland flow length or channel length

SLOPE - overland flow plane or channel slope

RCMAN - roughness coefficient

PAREA - fraction of the area serviced by overland flow plane

SAREA - contributing area to a collector channel

ASHAPE - shape of the channel used

CHWDT - channel width

ZLNG - channel side slope

UBF - subsurface flow hydrograph ordinates

Unitgraph Muskingum Model Parameters

TAREA - total flow plane area

UT - unit hydrograph ordinates

UBF - subsurface flow hydrograph

AMK - Muskingum travel time

AMX - Muskingum storage parameter

NSRC - number of subreaches

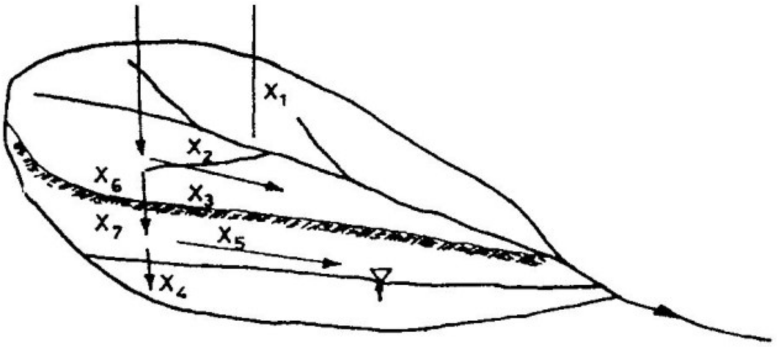

Fig. 6 Schematic representation of SEAMOD

Where; X1 = Evaporation coefficient.
X2 = Wet season runoff coefficient
X3 = Dry season runoff coefficient.
X4 = Groundwater flow coefficient.
X5 = Baseflow coefficient.
X6 = Wet season infiltration coefficient.
X7 = Dry season infiltration coefficient.

Model assumption are;

a) The watershed can be divided into a number of subwater sheds (Fig. 7) which are considered to be homogeneous.

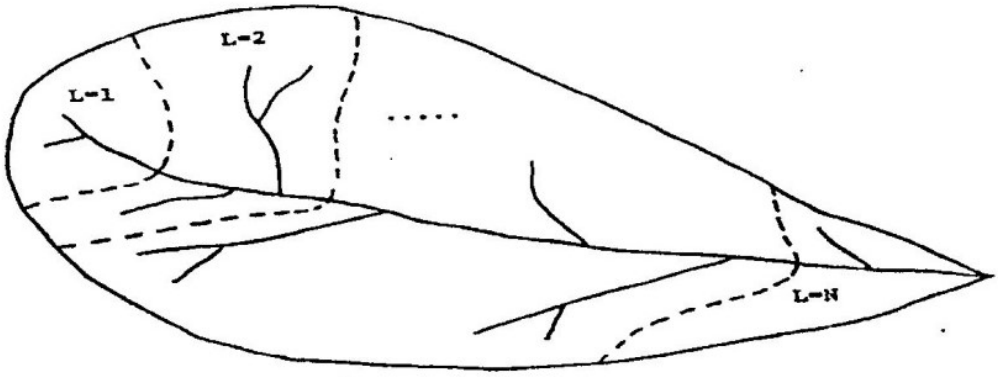

Fig. 7 Example of the division of a watershed into N subwatersheds.

(b) The sub watersheds are composed of three storage, the surface storage, the subsurface storage in the unsaturated zone and the subsurface storage in the saturated zone (Fig. 8).

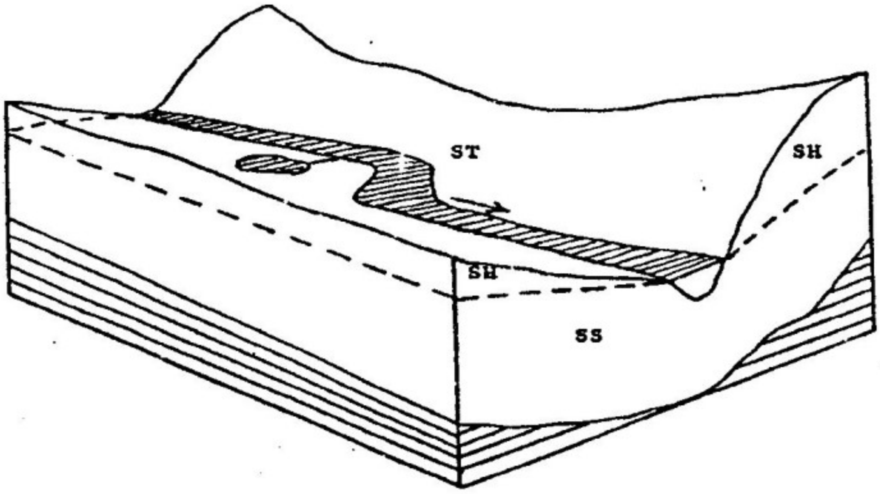

Fig. 8 Storages considered in a subwatershed: ST = surface storage, SH = storage in the unsaturated zone and SS = storage in the aquifer.

(c) Each storage has input and output which can be known
(d) Different storage of each sub watershed are related to each other by given hydrological processes (Fig. 9)

The basic processes considered by the SEAMOD are;

(i) surface runoff
(ii) Infiltration
(iii) evapotranspiration
(iv) base flow and
(v) groundwater flow

Some of the seven (7) parameters as shown in Fig. 6 can be optimised/ calibrated automatically by the model. Other parameters like seasonal infiltration capacity, threshold soil moisture for evapotran-spiration, soil saturated capacity and field capacity are determined by experience and judgement. Table 2 presents some of the physical properties of the soil[13].

During optimisation one of the five objective function can be selected among the following;

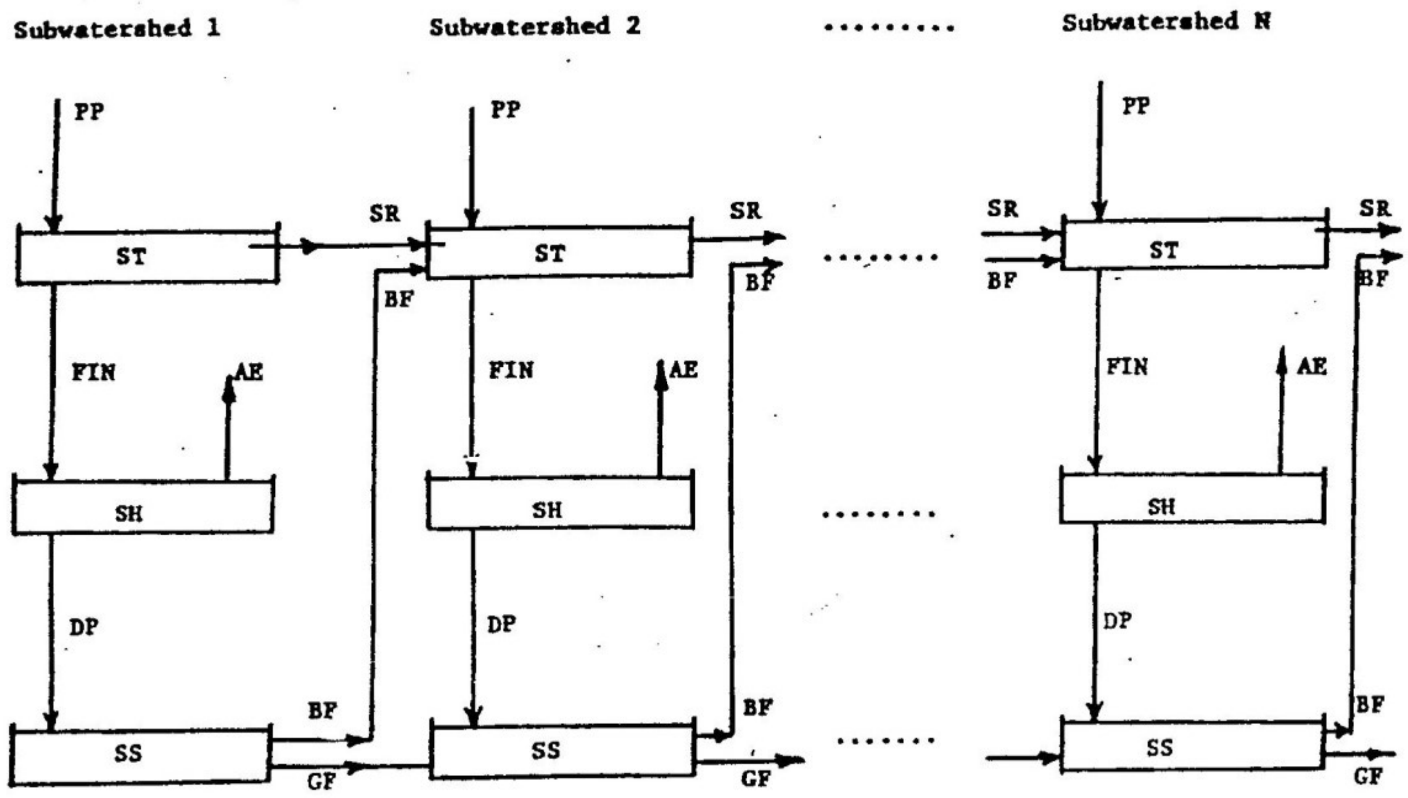

Fig. 9 Schematic representation of a conceptual hydrologic model for watershed simulation.

1. Sum of squared errors
2. Sum of absolute errors
3. Sum of absolute relative errors
4. Sum of absolute logs of errors
5. Min (mix error).

Objective function number one tends to produce relatively large errors during dry seasons. Number two tends to work very well both in wet and dry seasons. Nevertheless, whichever function is used, a graphical output should be observed and visually compared. Different possibilities of the parameters were tried, varying the first month of simulation either in the dry season or in the hot season, varying the objective functions as well as the initial soil storage, the best combination gave a percentage difference of 49% (Historical minus computed divided by historical discharges). A graphical results is given by Fig. 10.

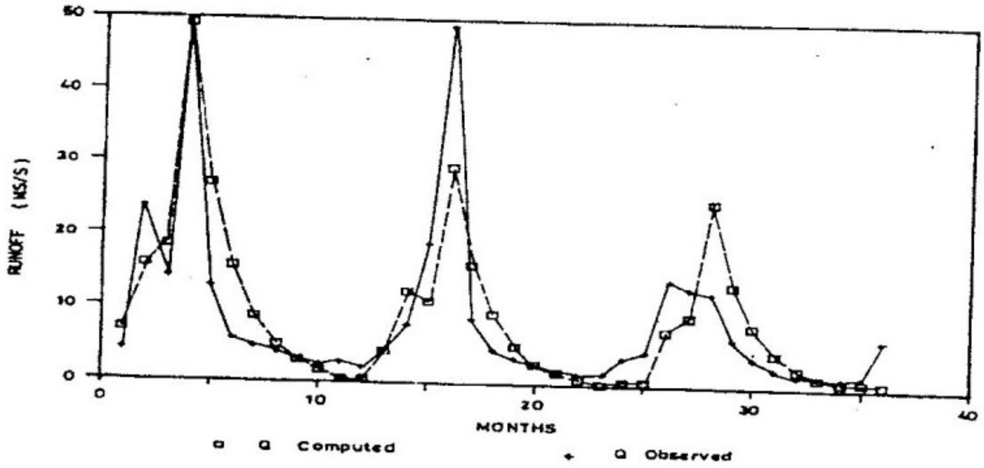

FIG.10 SEAMOD MODEL OUTPUT

Water balance equations were replaced by the conceptual formulation[14] as given by Fig.11

Table 2 **Representative Physical Properties of Soils (Taken from Hansen et al., 1980)**

Soil Texture	Infiltration[a] and Permeability. (cm/hr) I_f	Total Pore Space (%) N	Apparent Specific Gravity A_s	Field Capacity (%) FC	Permanent Wilting (%) PW	Total Available Moisture[b] Dry Weight (%) $P_w = FC - PW$	Volume (%) $P_v = P_w A_s$	cm/m $d = \frac{P_v}{100} A_s D$
Sandy	5 (2.5–25)	38 (32–42)	1.65 (1.55–1.80)	6 (6–12)	4 (2–6)	5 (4–6)	8 (6–10)	8 (7–10)
Sandy loam	2.5 (1.3–7.6)	43 (40–47)	1.50 (1.40–1.60)	14 (10–18)	6 (4–8)	8 (6–10)	12 (9–15)	12 (9–15)
Loam	1.3 (0.8–2.0)	47 (43–49)	1.40 (1.35–1.50)	22 (18–26)	10 (8–12)	12 (10–14)	17 (14–20)	17 (14–19)
Clay loam	0.8 (0.25–1.5)	49 (47–51)	1.35 (1.30–1.40)	27 (23–31)	13 (11–15)	14 (12–16)	19 (16–22)	19 (17–22)
Silty clay	.25 (.03–0.5)	51 (49–53)	1.30 (1.30–1.40)	31 (27–35)	15 (13–17)	16 (14–18)	21 (18–23)	21 (18–23)
Clay	0.5 (.01–0.1)	53 (51–55)	1.25 (1.20–1.30)	35 (31–39)	17 (15–19)	18 (16–20)	23 (20–25)	23 (20–25)

Note: Normal ranges are shown in parentheses.

[a] Intake rates vary greatly with soil structure and structural stability, even beyond the normal ranges shown above.

[b] Readily available moisture is approximately 75% of the total available moisture.

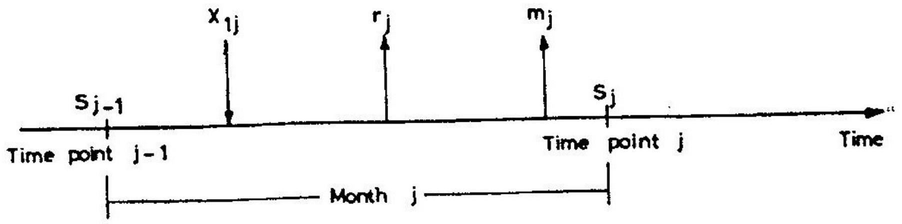

Fig. 11 Schematic representation of the water balance.

from the figure;

$r_j = X2_j\,(1 - e^{-a1Sj})$ (1)

$m_j = a2S_{j-1} + a3\mathrm{Max}\,(X1_j - r_j\,, 0)$ (2)

$S_j = S_{j-1} + X1_j - r_j - m_j$ (3)

where a1, a2, and a3 are unknown parameters;
$a1 > 0$
$0 < a2 < 1$
$0 < a2 < 1$
$0 < a3 < 1$

$X1_j$ = Areal precipitation
$X2_j$ = Potential evapotranspiration
m_j = Expected runoff
r_j = Real evapotranspiration
S_j = storage at the end of month j

The equations above reflects the mechanism in which rainfall and evapotranspiration are transformed to runoff. Equation (1) expresses the real evapotranspiration, r_j as a fraction of potential evapotranspiration, $X2_j$ which increases with the moisture content of the catchment at the beginning of month j. Equation (2) models the expected runoff as m_j being the sum of the delayed runoff $a2S_{j-1}$ (base flow) and the relative quick runoff, either equal to $a3(X1_j - r_j)$ or O whichever is greater. Equation (3) expresses the water balance of the whole catchment. This modification could not improve the results since the new percentage difference is about 56% (Fig. 12). This under stimated the peak discharge very much.

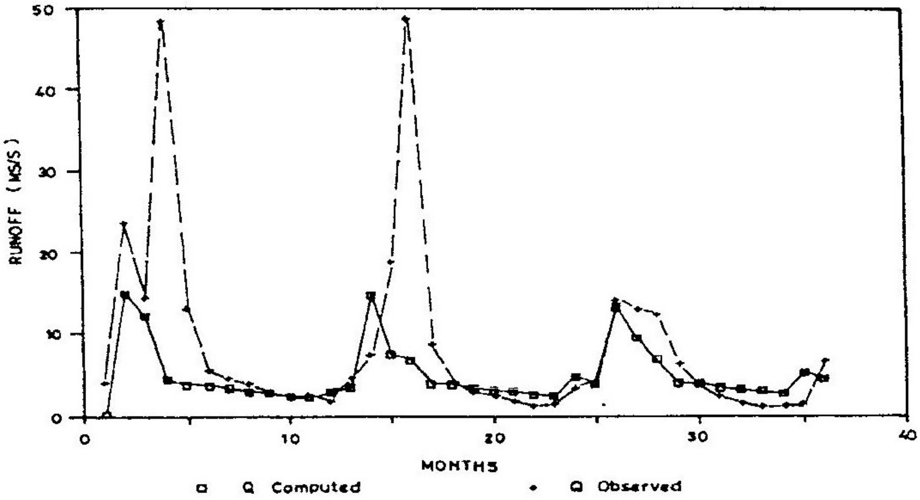

Fig.12 Modified SEAMOD Output

CONCLUSION

From the results, the minimum percentage difference which was obtained is 49%. This is very high, though a graphical comparison shows a reasonable fit. Much difference might be attributed by outliers at some points. Data analysis must be performed to see if there is some outliers. The modified version of SEAMOD gave the worse results which might be due to reasons explained early in addition to the lumped nature of the storage.

Moisture in the soils differs from depth to depth and depending on whether it has rained before or how long it took before the next rain has occurred. The bad results could also be attributed by assumption of an homogeneous catchment which in reality it is not the case.

It is suggested to gather more information/input data so as to try the SACRAMENTAL model as it seems to consider more practical processes taking place in the catchment.

It can be concluded further that, as long as it is difficult to establish the obseved values of soil moisture states, baseflow, deep percolation and infiltration water, conceptual model are still questionable unles these prameters are measurable for comparison/control of simulated results.

REFERENCES

1. Vandewielle, G.C., Some Concepts in Random Processes, CSOOTW/176, Free University Brussels, Belgium, 1992.
2. Liang, G.D., Linear Models for Multiple Inflows - single Outflow Flow Routing in Real Time, *PhD Thesis,* Department of Engineering Hydrology, University College Galway, Ireland, 1989.
3. Halcrow - ULG Ltd, *Report,* Ministry of Agriculture, Dar es Salaam Tanzania, 1981.
4. Crawford N. and Linsley R., Digital simulation in hydrology Stanford Watershed model IV, *Tech. Report No.39.* Department of Civil Engineering, Stanford University, California, 1966.
5. U.S. Corps of Engineers, Program Description and User Manual for SSARR Model, *U.S. Army Engineer Division*, North Pacific, Portland, Oregon, 1972.
6. Mero, F. An Approach to Daily Hydrometeorological Waetr Balance Computations for Surface and Groundwater Basins, *Prceedings IIC-UNESCO Seminar for Integrated River Development,* Delft, Holland, 1969.
7. Mero, F., The MM08 Hydrometeorological Simulation System. Basic Concepts and OPewratior's Guide, *Tahal Consulting Co.* Telaviv, Israel, 1978.
8. Lavesly, G. et al 1987, U.S.G.S., Daily Precipitation Runoff Model, Preliminary User's Manual, Denver, Colorado, U.S.A., 1987.
9. Railey et al, Application of Electronic Analog Computer to Solution of Hydrologic and River Basin Planning Problems. Utah Simulation Models, Rep. PRWG-32-1, Utah Water Research aboratory , College of Engineering, Utah State Unversity, Lagan UTAH, 1966, p129.
10. Amisial, R. Uzcatequi, G. Simulation Model for Alto A Pure Hydrologic System, CIDIAT, Merdia, Venezuela, 1970.
11. Salas, J., Cardenas, A., A Conceptual Model for Predicting Monthly Stream Flows, Special Report, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, 1981.

12. Tobias, et al, National Weather Service Model - PC Version, River Forecasting Centre, California, 1986.
13. Hansen, V.E., Islaelsen, O.W., Stringham O.E., Irrigation Priciples and Practices, John Wiley and Sons, New York, 1980.
14. Mwanuzi, F.L., Implementation of the Model QUAL2E on the Microcomputer and its Application in Water Quality Management, MSc. Thesis, Free University Brussels Belgium, 1986.