An hydraulic based model for simulating monthly runoff and erosion

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Abstract

A number of rainfall-runoff computer models exist for estimating catchment runoff from daily or monthly rainfall records. The majority of these are based on semi-empirical models which therefore lack the ability to be applied to new catchments without calibration. A model based on simplified hydrodynamics equations was therefore compiled in an attempt to reproduce runoff based on the physical laws of nature. The kinematic equations were used so that the model does not account for backwatering or unsteady flow conditions, but otherwise it is designed to include the effects of bed shear and the concentratrion of water from overland, subsurface and stream components.

Monthly rainfall figures, which are more readily available than autographic and even daily records, are required as well as the number of rain days per annum which enables the program to estimate storm durations. This in turn enables runoff rates to be estimated which in turn can be used for calculating rates of soil erosion and transport.

Infiltration into the ground is accounted for by means of a plug-type model and subsurface flow is assumed to comprise two components. A perched water table releases water soon after a storm, thereby creating the recession limb of the hydrograph and infiltration from the perched water table into a subterranean ground-water aquifer recharges the aquifer for providing dry weather base flow into streams.

The model has been tested with a number of catchments in South Africa and has proved reliable with minimal calibration as would be expected from an hydraulic-type model.

Introduction

Hydrologists and water resource planners are frequently confronted with a lack of streamflow records when attempting to size reservoirs and utilise river flows. Not only is the number of stream gauges insufficient but records are often missing in part or inaccurate. On the other hand, rainfall records in South Africa have been kept up to date for much longer periods and the number of rain gauges maintained by the Weather Bureau is sufficient to provide fairly reliable data at least on a monthly and sometimes daily basis for the majority of catchments in the country. The level of sophistication which is justified is often also only at a monthly discretisation level so that the use of monthly rainfall for generating monthly streamflow volumes is desirable.

Unfortunately the rainfall-runoff process is complex and cannot be modelled accurately using average rainfall figures over a month as infiltration is often only for short periods during and after rainstorms and streamflow is made up of components due to surface runoff and subsurface contributions.

There have been a number of models proposed for estimating monthly streamflow and for patching records in South Africa. On an international basis the Stanford watershed model (Crawford and Linsley, 1966) is perhaps the most recognised. Pitman (1973) compiled a similar but more simplistic model for South African conditions and that model is widely used in South Africa. Experience is now such that fairly reliable calibration factors are available and the simplicity of the model is such that it will remain popular.

There are, however, shortcomings in the existing models and these are primarily due to the fact that the models are empirical rather than based on hydrodynamic principles, i.e. although the original Stanford watershed model had simplistic catchment outflow and infiltration models these have been subdued by the necessity to calibrate the models and experience has led to methods of adjusting the relationships to obtain reasonable output. There can, however, be times when such models produce inaccurate answers and such times will include periods of intense rainfall as well as drought periods. High rainfall figures will result in non-linear rainfall-runoff relationships so that flood flows cannot expect to be modelled for extreme storms. Dry weather flow conditions are primarily from ground-water contributions and unless the aquifer characteristics are accounted for the results of simple empirical type models can be misleading and even dangerous where small storage schemes are involved.

The fact that water velocities and shear stresses are not accounted for means that the above type models cannot be used for soil erosion prediction on a monthly basis or any other basis.

The model which Paling et al. (1989) developed is a conceptual deterministic model. It is based on the simplified hydrodynamic equations for overland flow and the simplified Green Ampt (1911) infiltration model for vertical flow into the soil and underlying aquifers. The parameters required by the model are actual physical factors which can be measured or are available in literature. In the case of some factors which are difficult to observe e.g. aquifer characteristics, they can be obtained by calibration. For overland flow, factors such as the roughness, the slope and width and overland flow length of the catchment are required. Since real runoff is not in the form of a perfect sheet flow a factor to account for flow in rills is required. Such factors will be new to the user and guides are given later in this paper. The permeability of the soil is required, but since this is highly influenced by the fact that most soils are semi-saturated, further guides are given for assessing this. Infiltration is assumed to be plug flow and the emergence of the flow or interflow can be included. A number of layers of aquifer are possible although normally 2 or 3 are adequate. The first layer can be fairly shallow and act as an interflow layer with overland flow.

With so-called hydraulic models, many hydraulic parameters are not the same as would be measured in a laboratory. This is particularly so in the case of surface roughness and infiltration

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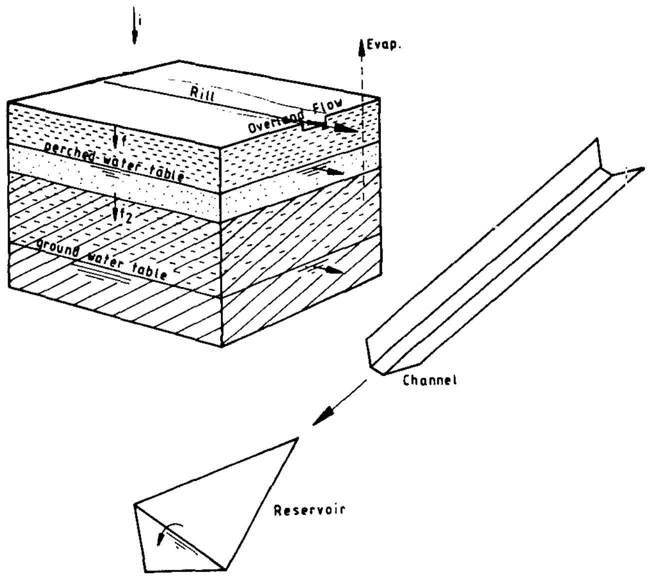


Figure 1
Diagrammatic assembly of models

rate (Stephenson, 1989b). Lumped models (i.e. where model sub-catchments are average conditions over a large area) generally require higher roughness factors than engineers will be accustomed to under laboratory or channel flow conditions. This could be because the depth of overland flow is less, resulting in lower Reynolds numbers or because the relative roughness for shallow flow is greater or because overland flow is not direct but tortuous.

Infiltration rates on a macro scale also appear lower than under laboratory conditions. A prime factor is that the soil is unsaturated in nature. It could also be because the runoff concentrates in rills or rivulets. The soil surface area available for infiltration is therefore less than the total catchment area. The latter flow concentration or canalisation effect results in a deeper and faster flow than for overland flow and more rapid concentration times. Some of these aspects have been addressed in the model described.

Basis of model

The program attempts to reproduce runoff and silt yield on a monthly basis, using basic catchment parameters and monthly rainfall records.

In order to estimate surface runoff rates and soil erosion rates, it is, however, necessary to operate the model using a very much shorter time interval e.g. hourly instead of monthly. An estimate of the distribution of the monthly rain is therefore made, using the average number of rainy days in a year. The number of hours of rain a month is taken to be proportional to the number of rain days per year multiplied by the ratio of months rainfall to average rainfall all to the power of 0,75. The rainfall intensity is therefore increased to the power of 0,25 for precipitation greater than mean. The factor 0,75 was found by experiment on rainfall data from Transkei.

The program is able to accommodate various combinations of three elements or modules (Fig. 1):

- Plain rectangular catchments: with rill factor, cover factor and permeability
- Uniform recatangular channels with erodible or stable beds
- Reservoirs

Data input formats are indicated in Table 1 for the various possible modules. Conceptual models may be subdivided into deterministic and parametric models. In the former case, the mathematical expressions used in the model purport to represent the physics of the actual processes modelled, i.e. the theoretical structure of the model is based on physical laws. Under these circumstances, input parameters to the model will be physically measurable quantities relating to the various processes, such as roughness, slope, flow length and so on. Parametric modelling on the other hand is less rigorous than pure deterministic modelling, although some deterministic components may be included, and the model parameters are not necessarily defined as measureable physical uantities.

In the conceptual models the method of routing of overland flow, and the routing method for water conduits and reservoirs determine largely the degree of realism than can be attained. The continuity principle applied to one-dimensional flow can be written as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_i \qquad (1)$$

where:

Q = volumetric flow rate
x = distance in direction of flow
A = cross-sectional area
t = time
q_i = lateral inflow rate per unit length along the x-axis.

The conservation of momentum for one-dimensional, unsteady, non-uniform flow is given by the following euation:

$$S_f = S_o - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t} \qquad (2)$$

where:

S_f = friction gradient
S_o = bed slope
y = water depth
v = mean water velocity
g = gravitational acceleration
t = time

The equations for the conservation of mass and momentum are known as the St. Venant equations and describe a hydrodynamic wave. Often the change in water velocity over time during the passing of a surge is very gradual. The flow can thus be considered near-steady, under which conditions the acceleration terms will play only a minor role.

If, in addition, the cross-section of the conduit is fairly constant, a uniform flow may be assumed. This will reduce the conservation of momentum equation to:

$$S_f = S_o \qquad (3)$$

which means the equation of motion can be approximated by a uniform flow formula of the general form $Q = ay^b$, where a and b are constants. The combination of the continuity equation and a uniform flow formula describes kinematic flow.

If the flow over land areas as a result of a storm is assumed to

TABLE 1
DATA SHEET; RAFLER - RAIN FLOW (EROSION MODEL; CONVERTS MONTHLY RAINFALLS (IN % MAR) TO RUNOFF)

Max. 30 modules - plains, channels and reservoirs in downstream order.

INPUT - on terminal:

Runtitle
MAP (mm)
(Raindata filename)
(Output filename)
Raindays per annum

Start year of raindata file (years = Oct - Sept the next year)

End year

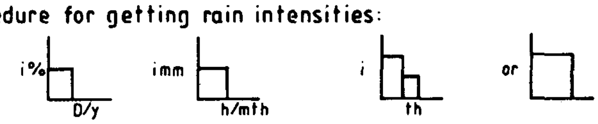
Merge at end of program - lines 1900 onwards up to start year.

Catchment Channel/Reservoir Data:

Module	No.	To. No.	Type	Length m	Width m	√So/n	Rill Ratio	Cover factor	Sat. perm	Soil Suc.m	Sedmt. dmm
Catchment			1								
Channel			2 (4=fixed bed)								
Reservoir			3			Depth m					
Last Line	0										

Cover factor, eg. 0,5 - 1 = Tilled
,7 = bare
,5 = open veg.
,3 = matted
,1 = covered

Procedure for getting rain intensities:



(Rain days/an) → rain hours/month → Two intensities
& mm rain

be evenly distributed, this flow is effectively steady and uniform. Conseuently kinematic theory can be applied. Constantinides and Stephenson (1983) have demonstrated that the kinematic equations can also be applied to closed conduits.

Viesmann et al. (1977) list some twenty programs in use for event, continuous or urban runoff modelling. They describe some of the widely used ones in considerable detail, in particular the Stanford Watershed Model (Crawford and Linsley, 1966), which may be considered to be the first comprehensive, continuous digital model available. Green and Stephenson (1985) describe and compare the performance of a number of event models for application in an urban environment, notably the stormwater management model (Huber et al., 1982), the Illinois urban drainage area stimulator (Terstiep and Stall, 1974), a two-dimensional kinematic model (Constantinides, 1982) and URBCEL (Diskin, 1984). Also included in the performance comparison is a one-dimensional kinematic model, WITWAT (Green, 1984). Pitman (1973) compiled a model on the lines of the Stanford Watershed Model for local conditions, which provided practising engineers in South Africa with a mainstay, particularly in ungauged areas. His model was also applied to patch the gaps in flow gauge records in the popular series *Surface Water Resources of South Africa* (Pitman et al., 1981).

A common limitation of many continuous simulation models is the fact that the catchment runoff is based largely on surface runoff, with the contribution of ground-water flow being handled empirically. Although the antecedent soil moisture is generally taken into account, this only serves to estimate the reduction in surface runoff. In reality part of the infiltrated water will reappear sooner or later and contribute to the runoff. Short delay times are caused by interflow, a process by which alternatingly surface water infiltrates into the topsoil and shallow ground water emerges to surface at terrain irregularities. Part of the infiltrated water will percolate to the deeper ground water table, which in turn will provide a base flow component to the runoff.

The introduction of both interflow and base flow into a rainfall runoff model facilitates a more realistic representation of the actual process. The additional field data requirements related to subsurface conditons constitute a drawback, but this can be overcome by generalisations, depending on the accuracy reuired.

A catchment area under study can be subdivided either by superimposing a grid or by delineating areas with similar characteristics into modules (Stephenson, 1989a). The latter option opens the possibility to introduce a higher degree of flexibility, particularly in lumping together or further subdividing catchment areas. By describing all components of a study area such as catchments, auifers, rivers and reservoirs as interrelated modules a large degree of flexibility is obtained.

Rainfall simulation

The rainfall input reuirements for a continuous monthly simulation model can be less stringent than for event simulation. If rainfall records are available, daily data are generally readily obtainable, but they may pose some economic and practical drawbacks. For a long simulation period and the use of records from several rainfall stations, the computer memory capacity can be overburdened. Furthermore the data input effort could become prohibitively expensive, while daily records are also prone to more errors than monthly ones. Therefore, in this model the historical monthly rainfall reords form the basis for the simulated rainfall intensity and duration.

There is a tendency for rainy days to occur in clusters. Based on historical records, average number of rainy days for each month can be established. The number of hours of rain per month is taken to be proportional to the number of rainy days per month multiplied by the ratio of months rainfall to average rainfall all to the empirical power of 0,75 i.e.

$$TR = AH \times RD(M) \times 12 \times R(K,Y,M) / [MAP (K)]^{0.75} \quad (4)$$

where:

TR	=	number of hours of rain per month
AH	=	constant
RD (M)	=	number of rainy days for month M
R (K,Y,M)	=	monthly rainfall for region K, year Y, and month M (mm)
MAP (K)	=	mean annual precipitation for region K (mm)

The rainfall intensity during a particular month is found from the ratio of monthly rainfall and TR. Instead of distributing the hours of rain over the various rainy days, precipitation is assumed to take place uninterrupted for the first TR hours of the month.

Sediment yield calculation

Silt yield from catchments is calculated using Yalin's theory (1963) which is based on Shield's critical shear slope criterion for erodibility. Total erosion is summated over each month and deposited into the downstream element each time step.

In the case of channels only what comes into the channel from plains is assumed removable for some modules. Accretion of silt will occur if inflow is greater than potential erosion in the channel and the channel will flow clean if erosion potential is greater than silt inflow. For one type of channel module the bed is assumed erodible.

The same technique is used at reservoirs, but a minimum volume is assumed at reservoirs so that invariably there is net accretion. In fact the way to calculate total yield of a catchment is to assume a large reservoir downstream and accumulate the silt load in it.

Model operation

Despite being based on hydraulic principles there are many aspects of the model requiring estimates of field parameters. It is often most economic to calibrate the model against some observed data rather than to do small-scale field tests which reuire averaging on large areas.

The runoff model appears particularly sensitive to infiltration rates. The first factor to adjust in the model calibration for any particular catchment study is the infiltration rate, which can vary from one subcatchment to another. The correct volume of runoff is an indication of correct infiltration rates. The soil suction is not found to be particularly influential on results.

In order of sensitivity, other factors most readily obtained by calibration are:

- Number of rain hours per month (obtained from number of rainy days per year and a conversion factor).
- Rill ratio. This has a direct bearing on infiltration as well.
- Cover factor. This affects erosion rate.

Overland flow

If the surface flow takes place along depressions the cross-sectional area of flow is

$$A = RR \times W \times Y \; (m^2) \quad (5)$$

Due to the shallow nature of the depressions and their spread over the width of the catchment, the wetted perimeter can be approximated by P = W (m). The surface flow euation can thus be written as:

$$Q1 = \frac{\sqrt{s}}{n} \times W \times (RR \times Y)^{5/3} \; (m^3/s) \quad (6)$$

The upper limit of the flow is determined by the availability of water, or:

$$Q2 = Y \times W \times X/DT \; (m^3/s) \quad (7)$$

which may play a role if the time increment DT takes on a high value. The smallest value of Q_1 and Q_2 is selected to represent the actual surface runoff. Subsequently the depth of the water is reduced to account for the runoff. Additional reduction will take place as a result of infiltration.

Infiltration into the unsaturated zone

The infiltration is based on a conceptual model utilising Darcy's law as proposed by Green and Ampt (1911). Darcy's law can be written as:

$$v = \frac{f}{n} = k(Lf + h + Sw) / Lf \; (m/s) \quad (8)$$

where:

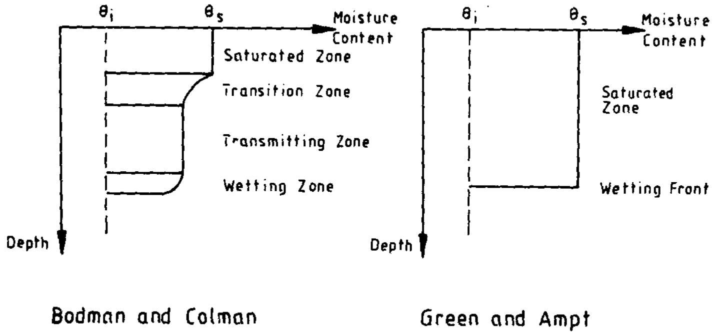


Figure 2
Comparison of Green and Ampt soil moisture profile with Bodman and Coleman profile (after Stephenson and Meadows, 1986)

v = infiltration velocity (m/s)
f = infiltration rate (m/s)
n = porosity
k = permeability = hydraulic conductivity (m/s)
Lf = depth to the wetting front (m)
h = surface ponding depth (m)
Sw = suction at the wetting front (m)

Several assumptions were necessary to write Darcy's law in the form above, namely (Stephenson and Meadows, 1986):

- There exists a distinct and precisely definable wetting front.
- Suction at the wetting front remains essentially constant, regardless of time and depth.
- Above (behind) the wetting front, the soil is uniformly wet and of constant hydraulic conductivity.
- Below (in front of) the wetting front, the soil moisture content is relatively unchanged from its initial moisture content.

The approximate nature of the Green and Ampt (1911) model is illustrated by a comparison with the actual soil moisture profile as given by Bodman and Colman (1943) (Fig. 2). After the surface water film has disappeared the pending saturated zone starts moving downwards.

The capillary suction at the wetting front S_w is the difference of the capillary potential at the soil surface and that at the wetting front. Values for this parameter can vary between 50 mm for sand and 500 mm for clay (Lambourne and Stephenson, 1986).

The hydraulic conductivity of an aquifer under saturated conditions is the combined property of the porous medium and the fluid flowing through it. However, for practical purposes it is essentially a function of the aquifer material alone. The hydraulic conductivity reduces with reducing particle size. An indication of values for the hydraulic conductivity under saturated conditions is given in Table 2. The values may vary slightly from one author to another depending on the definition of particle size limits.

During downward seepage in the unsaturated zone the hydraulic conductivity is reduced due to entrapped air in the soil trying to force its way up through the water.

In an analysis of numerous soil samples Rawls et al. (1982)

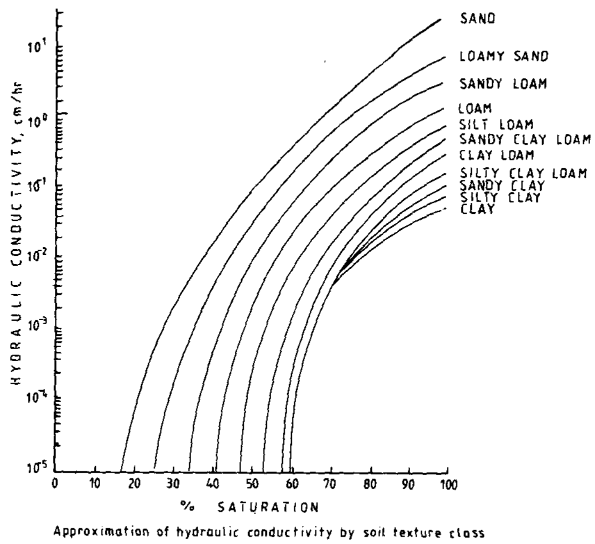


Figure 3
Hydraulic conductivity of soils (After Rawls et al., 1982)

TABLE 2
APPROXIMATE HYDRAULIC CONDUCTIVITY VALUES (SATURATED)

Material	Particle size mm	k (m/s)
Gravel	> 2	10^{-2} - 10^{0}
Sand	2 - 0,02	10^{-5} - 10^{-3}
Silt	0,02 - 0,002	10^{-8} - 10^{-6}
Clay	< 0,002	10^{-12} - 10^{-9}

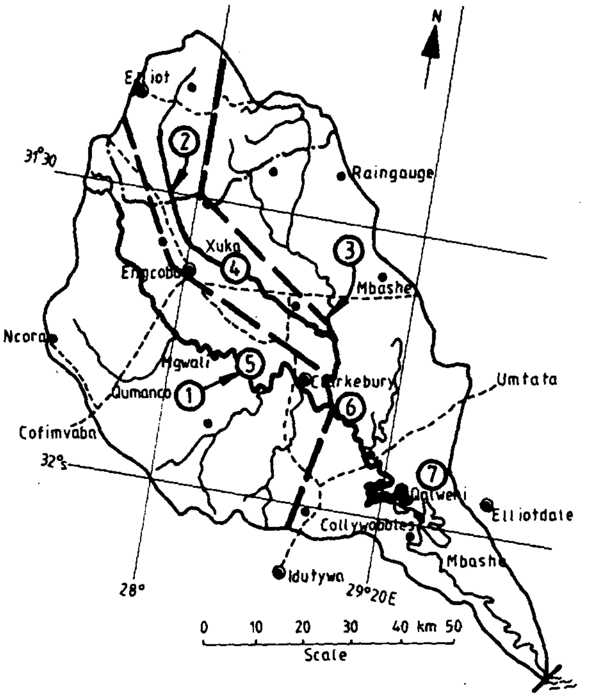


Figure 4
Map of Mbashe catchment with subcatchments and modules for RAFLER

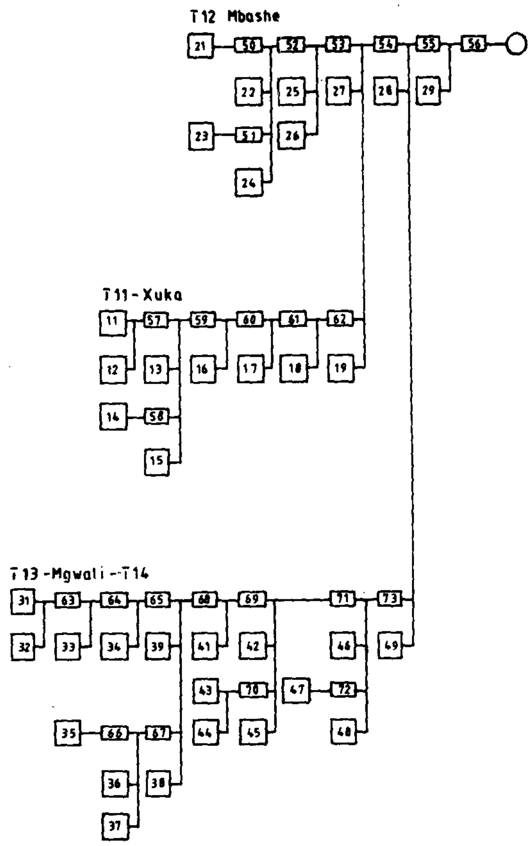


Figure 5
Module data set for Mbashe River

derived a detailed relationship between soil grade, degree of saturation and hydraulic conductivity (Fig. 3).

If the moisture content decreases during a series of simulated dry days, the downward seepage reduces to virtually zero. As a result the infiltration capacity reduces to almost zero and no further increase of the moisture content can take place. Therefore the model was simplified and follows Bouwer's (1966) suggestion that the hydraulic conductivity in the unsaturated zone can be approximated by a value which is 50% of the hydraulic conductivity under saturated conditions.

Application

The use of the rainfall-runoff model is illustrated by an application.

The model was applied to the Mbashe River in Transkei. Its sources lie in the eastern escarpment of the Lesotho highlands and its main tributaries are the Xuka and the Mgwali Rivers (see Fig. 4 and the model in Fig. 5). A flow recorder collected data between July 1956 and June 1967. As a result there is 10 years of information against which the simulation results can be calibrated (Table 3). The total catchment area upstream of the gauging station is 4 800 km^2.

It will be noted that the last item for the catchment auifer modules ranges from 1 to 4. This indicates that 4 separate rainfall data files will be used. The last module in the data set represents the most downstream river section for which the output will be printed as well as stored in an output data file. The data set is concluded by a zero to indicate end of file.

The 4 rainfall data files are derived from *Surface Water Resources of South Africa* (Pitman et al., 1981) supplemented with data from the Weather Bureau. The former also provided average figures for the Pan evaporation in this region. Average number of rainfall days were calculated from data from the Weather Bureau. For calibration purposes an abbreviated version of the rainfall data files was used, starting with October 1955.

The resulting simulated monthly runoff data are plotted in Fig. 6 against the recorded data. In the same plot the rainfall data (averaged for the 4 regions) are given. This last addition can be particularly useful to detect anomalies between rainfall and recorded runoff.

The simulated data seem to correspond reasonably well with the recorded data. The discrepancies between the simulated and recorded data are most noticeable in the peak runoff. The discrepancies may in part be due to the fact that the simulation model invariably assumes the rainfall to precipitate at the beginning of the month while in reality heavy rainfall at the end of one month may be followed by heavy rainfall at the beginning of the next, causing a shift of runoff volume from one month to the next.

The success of the simulation should therefore not only be judged by the degree in which the simulated data follow the recorded data. There are two ways to evaluate the overall result.

- Firstly, the simulated annual figures should be compared with the recorded annual figures.
- Secondly, the simulated data can be plotted against the recorded data in a scatter diagram.

A successful simulation should result in an even narrow distribution of points on both sides of the diagonal line.

The list of control parameters shows that the study area has

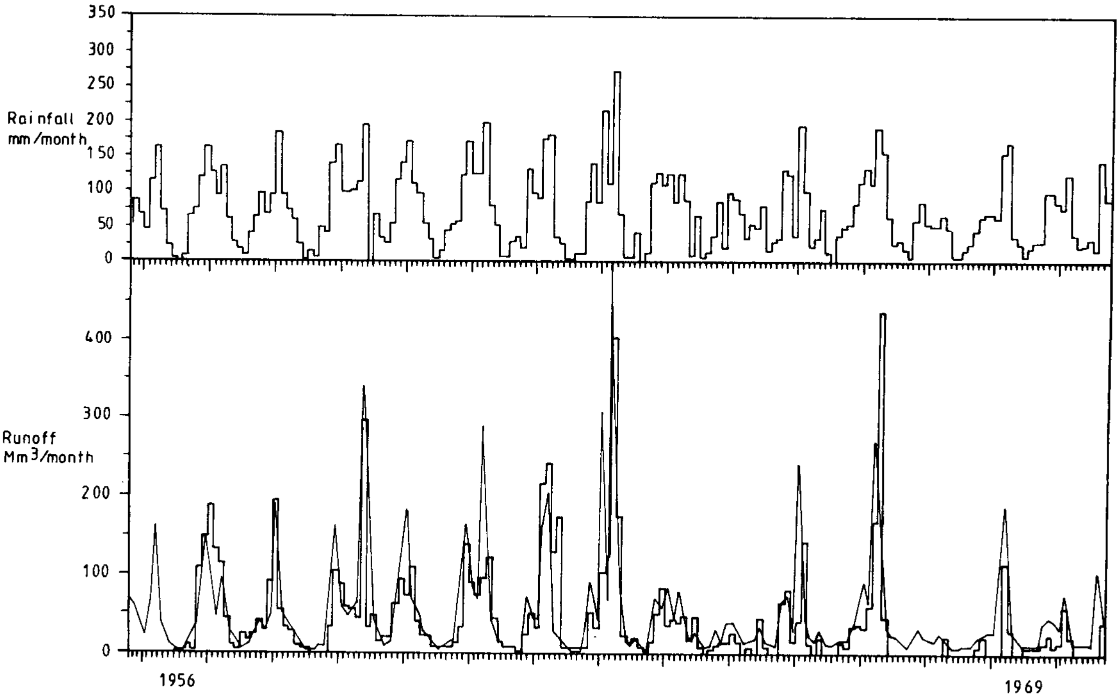


Figure 6
Rainfall for the Mbashe Region, and recorded runoff (block diagram) and simulated runoff (graph) for Mbashe River at TIM04

TABLE 3
FLOW RECORD FOR THE MBASHE RIVER AT MBASHE BRIDGE IN Mm³/MONTH

	O	N	D	J	F	M	A	M	J	J	A	S	Sum
1955									(6,5)	5,6	5,3	12,6	x
1956	4,5	110,9	151,1	189,6	132,7	115,4	44,4	10,5	5,5	24,9	18,0	24,8	832
1957	41,5	27,9	92,5	195,4	53,6	32,5	28,2	10,3	7,2	5,1	1,2	3,9	499
1958	2,9	33,9	105,1	87,5	57,7	54,2	44,0	296,8	30,9	49,1	15,5	20,7	798
1959	19,2	61,9	95,0	72,9	109,9	39,1	21,5	21,7	7,6	7,4	7,0	8,6	472
1960	12,2	32,8	140	88,3	72,4	95,7	122	42,6	13,0	8,1	8,2	7,8	643
1961	2,8	23,0	50,4	31,6	215	241	128	174	5,9	5,2	4,7	4,6	887
1962	5,9	51,0	29,5	103	124	403	173	19,0	13,2	16,6	6,1	2,6	947
1963	13,8	49,9	82,9	32,4	55,5	37,5	45,0	14,8	45,1	6,9	2,1	6,2	392
1964	10,1	13,2	12,0	23,6	13,6	1,0	5,7	0,1	42,2	6,0	1,1	1,5	130
1965	63,0	78,7	14,4	39,2	143	10,3	1,1	18,7	3,9	0,9	0,9	13,9	388
1966	5,5	30,9	33,9	29,0	59,2	167	437	41,8	x	x	x	x	(804)
1967	x	x	x	x	x	x	17,7	3,4	3,1	3,4	3,5	0,4	(31)
1968	5,8	17,4	(3,9)	(3,9)	(13,0)	113	24,8	(4,6)	(2,5)	4,6	5,1	4,2	(202)
1969	9,9	20,1	5,4	11,0	56,2	17,5	(3,6)	x	x	x	(6,5)	36,7	(167)

been generalised to a large degree, by fixing a number of variables. If more detailed information would be available for individual catchment-aquifer modules some or all of the variables could be included in the module data set and the program adjusted to read these variables.

Erosion and sediment transport

The fact that the rainfall-runoff model is based on hydrodynamic principles enables water velocities overland and in streams to be calculated. This in turn facilitates calculation of erosion rates.

A modified version of the rainfall-runoff model was developed to incorporate the calculation of erosion and sediment transport. The erosion and sedimentation processes are simulated for all 3 module types, i.e. catchment, channels and reservoirs, and will be discussed in detail.

The RAFLER (rainfall-flow-erosion) program is supposed to be used after the program has been satisfactorily calibrated for flow. The variable values are then carried forward to be used in RAFLER. For the sediment calibration a number of new variables are introduced. They are allocated a certain value at the beginning of the program.

Sediment transport data for a particular site are more difficult to obtain than runoff data. Extensive field work may be reuired to estimate both the suspended load and bed load of a river under varying flow conditions. The lower limit of the sediment transport capacity can sometimes be derived from the rate of reservoir siltation.

Catchment modules

In the present model rill erosion is not considered; all sediment production and transport is assumed to take place on the catchment surface. The erosivity of the catchment is defined by a cover density CG(I) (CG(I) = 1 for complete cover, i.e. no erosion) and an erosivity factor KS(I). The erosivity factor is the same as used in the universal soil loss equation and generally needs to be determined empirically.

The catchment surface is considered to consist of a layer of loose soil (immediately available for transport) underlain by a layer of erodible, but not loose, soil (available for detachment and thus conversion to loose soil). Depths of loose soil and erodible soil are input to initial values and adjusted for addition and removal at each time step during the simulation. A value for the *in situ* density of the loose soil must also be specified (provisionally 1 500 kg/m^3).

In each time step an amount of erodible soil is converted to loose soil at a prescribed rate (e.g. 0,015 mm/month) to account for sediment production by fragmentation. This is effective only if the depth of erodible soil is positive at that time.

During each time step the depth of loose soil is reduced by the sediment discharge from the catchment (i.e. the sediment discharge rate off the catchment multiplied by the current time increment and divided by the module area and *in situ* soil density). The removed sediment is therefore assumed to be derived uniformly from the catchment area. The depth of loose soil is constrained to be positive.

If the depth of erodible soil is positive then some of it is transferred to loose soil to account for raindrop detachment. The rate of detachment is given by Meyer (1971);

$$D_r = K_D K_S i^2 (1-Z_W/Z_M)(1-C_g) \qquad (9)$$

in which:

D_r is the detachment rate in kg/(m^2·h)
K_D is a detachment coefficient (= 0,0138 N/mm^2 (Foster, 1982))
K_s is the soil erosivity (USLE value) in kg·h/(N·m^2)
i is the effective rainfall intensity in mm/h
Z_w is the combined depth of water and loose soil in m
Z_m is the penetration depth of raindrops $= 3\,(2/23i^{0,187})$ mm (Li, 1979)
C_g is the cover density

The incremental depth of detachment is added to the depth of loose soil and subtracted from the depth of erodible soil.

Because sheet flow depths are small it is assumed that sediment transport on plains occurs as bed load only. The bed load transport capacity rate is computed using the Meyer-Peter and Muller (1948) equation, which can be expressed as:

$$Q_s = 0{,}041\,(\tau_o - \tau_c)^{1,5} \times W \qquad (10)$$

in which Q_s is the boundary shear stress in N/m^2.

$\tau_o = \gamma y s$
γ is the unit weight of water (9 810 N/m^3)
y is the flow depth in m (assumed to be the average of the value at the end of the previous time increment and the current value)
s is the catchment slope
τ_c is the critical shear stress for sediment motion $= 0{,}047\,(S_s - 1)\,D_s$ in the Meyer-Peter and Muller equation
S_s is the relative density of the sediment (assumed = 2,65)
D_s is the size of sediment particles

The potential sediment transport rate is limited to the total amount of loose soil available during the current time interval. The lower value of either the sediment transport capacity or the transport rate limited by availability defines the sediment discharge rate for the time interval.

Channel module

As for catchments the bed of a channel is assumed to comprise a layer of loose soil underlain by a layer of erodible soil. No erosion of the river bed in addition to the sediment supplied from the catchments or specified as initial loose soil is accounted for. All erosion is assumed to occur on the bed and the potentially important contribution from bank erosion has not been considered.

During each time step the depth of loose soil on the channel bed is augmented by the net sediment discharge in the channel. The net sediment discharge is the sediment discharge rate from upstream contributing modules minus the sediment discharge rate from the channel divided by the module area and *in situ* soil density.

In the runoff calculations for the channel module only the flow volume is taken into account. For the erosion and sediment transport evaluation, however, the water depth has to be known. For this reason a routine is included to determine the water depth as well as the average flow velocity and the hydraulic radius.

Sediment transport is assumed to occur by bed load and suspended load. The bed load capacity is computed using the Meyer-Peter and Muller equation, as for the catchment module, except that the hydraulic radius is used to calculate shear stress rather than the flow depth. The suspended load capacity is assumed to be the average flow velocity multiplied by the sediment concentration at mid-flow depth, the flow depth and the channel width. The concentration at mid flow depth is calculated, using the conventional concentration distribution function,

$$C_{y/2} = C_a \left(\frac{2D_s}{y-2D_s}\right)^{W/\kappa U_*} \qquad (11)$$

in which:

$C_{y/2}$ is the mid flow depth concentration in kg/m^3
C_a is the concentration in the bed layer (= $Q_{be}/11{,}6\,U_* 2D_s$) (Einstein, 1950)
Q_{be} is the bed load capacity, kg/s
U_* is the shear velocity, m/s $= \sqrt{\tau_o/\rho}$ (12)
ρ is the density of water (1 000 kg/m^3)
w is the sediment particle fall velocity (m/s)
κ is the von Karman constant (= 0,4)

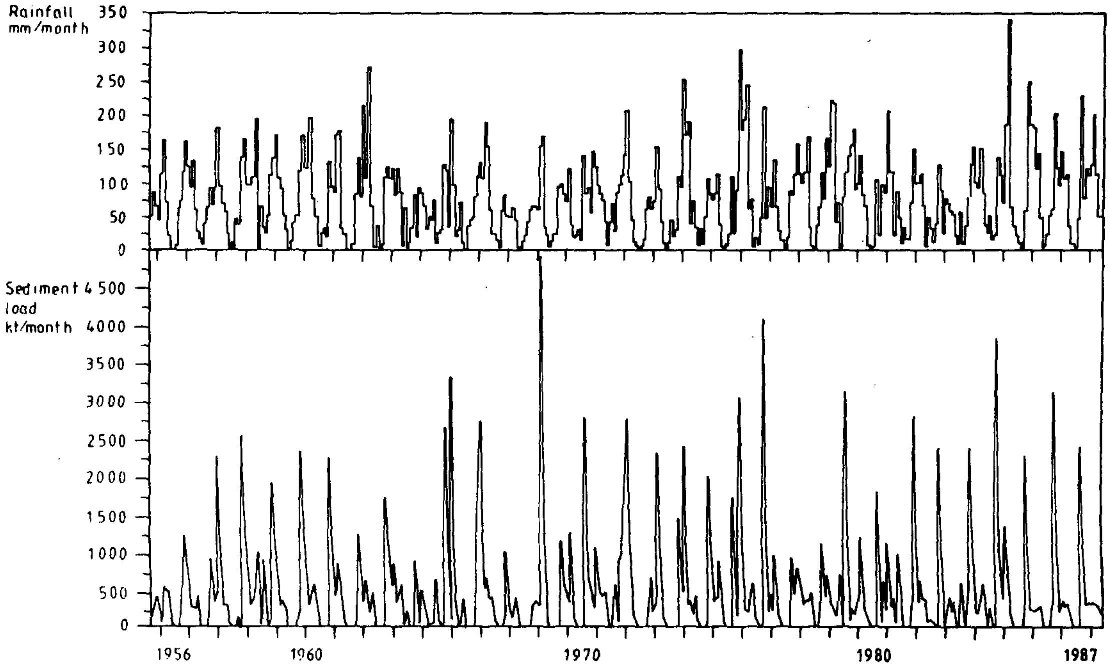


Figure 7
Sediment load at TlM04, Mbashe River

The total load capacity (bed load and suspended load) has to be compared with the amount of sediment available for transport during the current time interval.

Application of RAFLER

The rainfall-runoff-erosion model was applied to the Mbashe River in Transkei. Siltation problems at the Collywobbles hydro-electric scheme have resulted in several studies related to the sediment build-up in the reservoir (e.g. Watermeyer, 1987, and Stewart, Sviridov and Oliver, 1986). Silt surveys indicate that in a period of approximately 4 years, the total reservoir capacity was reduced by 70% and the live storage capacity by 50%.

After a few simulations a reasonable record was obtained with the following values for the erosion and sedimentation control parameters:

- *In situ* density of loose soil for catchment, 1 500 kg/m^3
- Sediment particle size 0,2 mm
- Sediment fall velocity, 0,02 m/s
- Detachment coefficient, 0,0138
- Soil fragmentation rate, 0,03 m/month
- Average catchment cover density, 0,8
- Average catchment erosivity factor, 0,5

The results of the simulation are presented in Fig. 7. If the simulation results for the 1987/8 season are excluded the mean annual sediment runoff is 5 067 kt/a. This exclusion is required as no rainfall data were available for the period from June through September 1988 and thus those sediment load data are incorrect.

By introducing a variable reflecting the average number of rainy days per month, fluctuations in the monthly rainfall are translated into differing rainfall intensities. Occasionally this may give unexpected results in the sediment output. In the case of an unusually wet month during the dry season with an average of one or two rainy days per month, the program will interpret this as a severe storm with a high rainfall intensity. Since the rainfall intensity has a direct bearing on the rate of erosion the sediment output will to some extent be over-estimated. Therefore, high sediment transport values during the dry season should be considered with caution.

References

BODMAN, GB and COLEMAN, EA (1943) Moisture and energy conditions during downward entry of water into soils. *Proc. Soil. Sci. Soc. of America* 7 116-122.

BOUWER, H (1966) Rapid field measurement of air entry value and hydraulic conductivity of soil as significant parameters in flow system analysis. *Water Resour. Res.* 2(4) 729-738.

CONSTANTINIDES, CA (1982) Two-dimensional kinematic modelling of the rainfall-runoff process. Report No. 1/82, Water Systems Research Programme, Univ. of the Witwatersrand, Johannesburg.

CONSTANTINIDES, CA and STEPHENSON, D (1983) Urban hydrology and drainage : Comparison of kinematic and time shift routing of conduits. Report No. 3/83, Water Systems Research Programme, Univ. of the Witwatersrand, Johannesburg.

CRAWFORD, NH and LINSLEY, RK (1966) Digital simulation in hydrology : Stanford watershed model IV. Tech. Report No. 39. Dept. of Civil Engineering, Stanford Univ., California.

DISKIN, MH (1984) CELMOD - A semi-distributed cell model for conversion of rainfall into runoff. First draft of a report submitted to Southwest Rangeland Watershed Research Center, US Dept. of Agriculture, Tuscon, Arizona.

EINSTEIN, H (1950) The bed load function for sediment transport in open channel flow. *Tech. Bull. 1026,* US Dept. of Agric. SCS, Washington DC.

FOSTER, GR (1982) Hydrological modelling of small watersheds. In: Haan, CT, Johnson, HP and Brakensiek, DL (eds.) *ASAE Monograph* 5 297-370.

GREEN, IRA (1984) WITWAT stormwater drainage program version II. Report No. 2/84, Water Systems Research Programme, Univ. of the

Witwatersrand, Johannesburg.
GREEN, IRA and STEPHENSON, D (1985) Urban hydrology and drainage : Comparison of urban drainage odels for use in uth Africa. Report No. 3/85, Water Systems Research programme, Univ. of the Witwatersrand, Johannesburg.
GREEN, WH and AMPT, GA (1911) Studies of soil physics, 1. The flow of air and water through soils. *J. of Agric. Sci.* **4**(1) 1-24.
HUBER, WC, HEANEY, JP, NIX, SJ, DICKENSON, RE and POLMAN, DJ (1982) *Stormwater Management Model, User's Manual.* Dept. of Environmental Engineering Sciences, Univ. of Florida, Gainesville, Florida.
LAMBOURNE, JJ and STEPHENSON, D (1986) Urban hydrology and drainage: Factors affecting storm runoff in South Africa, II: Water losses. Report No. 3/86, Water Systems Research Programme, Univ. of the Witwatersrand, Johannesburg.
LI, RM (1979) Water and sediment routing from watersheds In: Shen, WH (ed.) *Modelling of Rivers.* Wiley Interscience, New York.
MEYER, LD (1971) Soil erosion by water on upland areas. In: Shen, HW (ed.) *River Mechanics* **2** Fort Collins, Colorado.
MEYER-PETER, E and MULLER, R (1948) Formulas for bed-load transport. *Proc. 3rd Conference, Intern. Assoc. of Hydraulic Research.* Stockholm, Sweden. 39-64.
PALING, WAJ, STEPHENSON, D and JAMES, CS (1989) Modular rainfall-runoff and erosion modelling. Water Systems Research Group, Univ. of the Witwatersrand, Johannesburg.
PITMAN, WV (1973) A mathematical model for generating monthly river flows from meteorological data in South Africa. Report No. 2/73, Hydrological Research Unit, Univ. of the Witwatersrand, Johannesburg.
PITMAN, WV, MIDDLETON, BJ and MIDGLEY, DC (1981) *Surface Water Resources of South Africa.* Report No. 9/81, Hydrological Research Unit, Univ.of the Witwatersrand, Johannesburg.
RAWLS, WJ, BRAKENSIEK, DL and MILLER, N (1982) Green-Ampt infiltration from soils data. *ASCE J. Hydraul. Div.* 62-70.
STEPHENSON, D and MEADOWS, ME (1986) *Kinematic Hydrology and Modelling.* Elsevier Science Publ., Amsterdam. 250 pp.
STEPHENSON, D (1989a) A modular model for simulating continuous or event runoff. *Proc. IAHS Conf.* Baltimore, IAHS publ. **181** 83-91.
STEPHENSON, D (1989b) Selection of stormwater model parameters. *ASCE, J. Environ. Eng.* **115**(1) 210-220.
STEWART, SVIRIDOV and OLIVER (1986) Feasibility study on desilting of the Mbashe weir. Sandton.
TERSTIEP, ML and STALL, JB (1974) The Illinois urban drainage area simulator, ILLUDAS, Illinois State Water Survey, Urbana. *Bulletin* **58.**
VIESSMAN, W, KNAPP, JW, LEWIS, GL and HARBAUGH, TE (1977) *Introduction to Hydrology.* Harper and Row Publ., New York.
WATERMEYER, CF (1987) Discussion of: reservoir sedimentation: The stable non-euilibrium state, by G.W. Annandale. *The Civil Engineer in South Africa.* **2** 60-65
YALIN YS (1963) An expression for bed-load transportation. *ASCE J. Hydraul. Div.* **89** (HY3) 221-250.