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WATBAL
A Semi-Distributed, Physically Based Hydrological Modelling System

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A semi-distributed, physically based hydrological modelling system, WATBAL, which accounts for the entire land phase of the hydrological cycle is described. As compared to the two alternative hydrological model types, i.e. the traditional lumped, conceptual rainfall runoff models (STANFORD model type) and the complex, fully distributed, physically based model (SHE model type) WATBAL represents an intermediate approach.

In the model, primary attention is given to the hydrological processes at the root zone level through a distributed, physically based approach whereas the groundwater processes are simulated in less details by use of a lumped, conceptual approach. This approach allows WATBAL to utilize spatially distributed input data to account for the spatial and temporal variability of meteorological conditions, vegetation and soil properties. Thus WATBAL can e.g. utilize digital satellite information as input data.

WATBAL has primarily been designed as a tool for predicting the runoff from ungauged catchments and for assessing the hydrological effects of land use changes. The capability of the model for simulating ungauged catchments is tested using results from a recent feasibility study for medium size dams in Zimbabwe.

Introduction

Most rainfall-runoff models in practical use today are based on a conceptualization of the hydrological cycle in which case the physical basis and spatial variability of individual processes to a large degree is ignored and replaced by lumped, conceptual analogues. As long as the aim is to provide a truthful representation of a rainfall-runoff process for which historical records exist, e.g. for the purpose of extension of runoff time series or real-time forecasting of floods, experience has shown that the lumped, conceptual approach generally can provide for a satisfactory empirical fit to the response of a particular catchment.

Although the parameters of such models bear some relation to the subsystems which they represent, they do not have a direct physical interpretation and cannot be measured in the field. Hence, in certain important water resources investigations involving ungauged catchments or a change of catchment characteristics, the very nature of the conceptual approach will usually preclude a satisfactory application.

To overcome these difficulties the modelling approach must necessarily be changed to include physical and measurable parameters. Furthermore, as a result of the physical basis, a distributed approach must be applied, since it is the spatial variability of individual hydrological processes and their interaction which determines the response of the catchment area. The European Hydrological System (the SHE model) is an example of a fully distributed, physically based model of the entire land phase of the hydrological cycle, Storm (1986). Obviously, a model like the SHE model is very complicated with relatively large requirements with respect to computer facilities and data.

However, considering the overwhelming complexity of any catchment area, comprising inhomogeneities in every soil profile as well as the spatial and temporal variability of other catchment characteristics any application of a deterministic fully distributed and physically based model immediately faces problems with respect to data availability, parameter estimation and computational requirements.

In developing countries in particular, information on catchment characteristics is in general rather sparse. However, by the use of satellite data to supplement commonly available information, a fair representation of the topography, vegetation and soil conditions may usually be obtained. Fortunately, these factors are among the most important ones controlling soil moisture storage which is a key variable in the hydrological cycle, and hence for determining the overall water balance.

The model presented in this paper has been designed so as to make full utilization of the above-mentioned catchment data within reasonable computational requirements to allow large scale applications. This has been achieved by incorporating a physically based, distributed representation of the processes affecting soil moisture storage using well proven relations based on measurable parameters, while subsurface flows, for which very limited information in general will be available, has been represented by a lumped, conceptual approach. In this way WATBAL may be viewed as a compromise between limitations on data availability, the complexity of hydrological response at catchment scale, and the advantages of model simplicity.

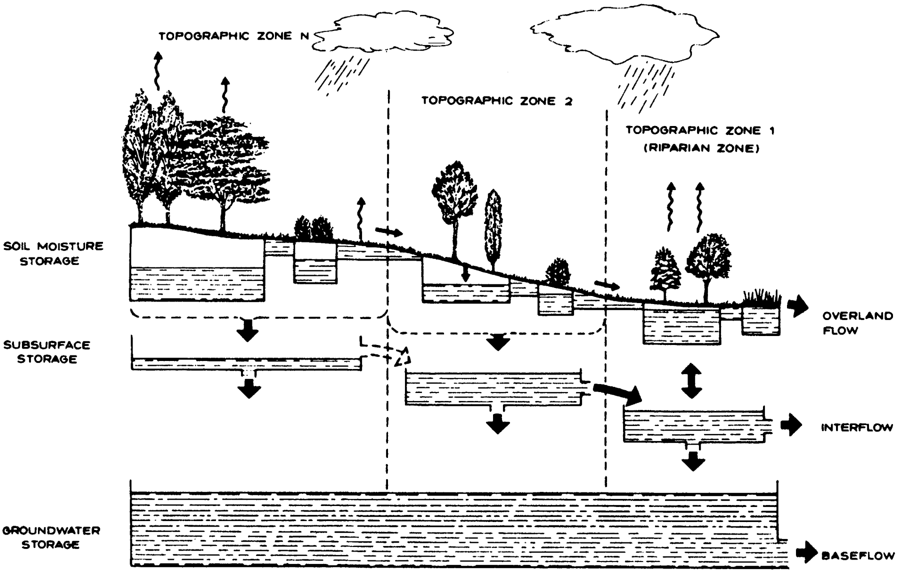


Fig. 1. Principal structure of WATBAL.

Basic Model Structure

Since soil moisture storage exhibits a major control of the evapotranspiration process and influences the generation of overland flow, it is a key variable for representing the water balance of a catchment area as well as for flood predictions. WATBAL has been designed so as to account for the spatial and temporal variations of soil moisture using distributed information on meteorological conditions, topography, vegetation and soil types. In Fig. 1, a sketch of the principal structure of the model is shown, illustrating the distributed approach for representing soil moisture storage.

In this figure it is furthermore illustrated how the model allows the catchment to be divided into various topographic zones. For a catchment encompassing different topographic features WATBAL recognizes that rain falling on upland areas is routed through hillslope zones before entering the stream as overland flow, interflow or as baseflow. The particular path – or paths – taken by the water will depend on the current conditions in the downslope areas. Overland flow generated on upland areas may infiltrate in downslope areas, if a sufficient capacity exists and be stored or percolate to a subsurface storage. From here the water may contribute to the groundwater recharge or move laterally as interflow towards the stream. This structure of the model will enforce a redistribution of water in favor of the zone

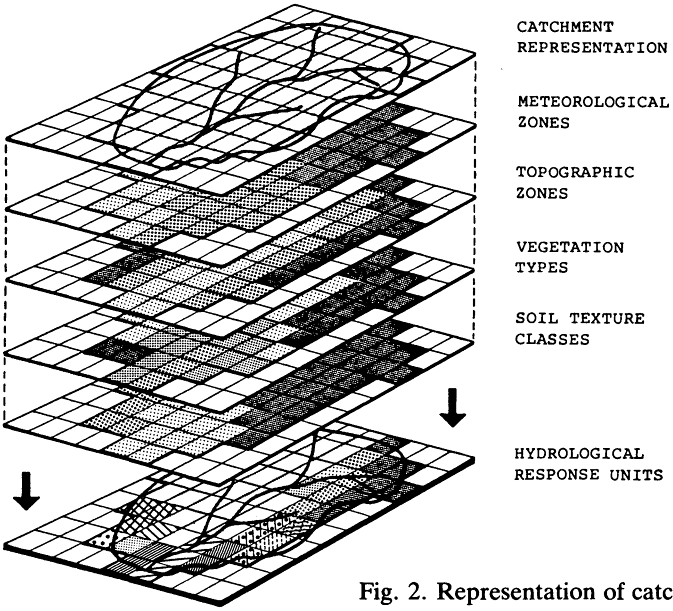


Fig. 2. Representation of catchment characteristics and definition of hydrological response units.

adjacent to the stream. Consequently, this zone will in general have the highest water content (as is common) and hence contribute more to the generation of overland flows and total catchment evaporation. To strengthen this mechanism water held in the subsurface storage within the riparian zone is allowed to contribute to the satisfaction of soil moisture deficits in this zone.

WATBAL is flexible in the sense that it allows the user to define a specific composition of topographic zones as deemed most appropriate for the particular application. This is accomplished through the use of a digital overlay in which case topographic zone numbers are allocated to each grid element, see Fig. 2. The same principle is used to represent the spatial composition of meteorological conditions, vegetation and soil types as illustrated in Fig. 2.

Within each defined meteorological zone, WATBAL assumes the input to be spatially homogeneous whereas the input may differ between the zones. Depending on the spatial variability of rainfall various approaches may be utilized for the demarcation of these zones including Thiessen polygones, isohyetal or hypsometric methods.

The generation of the vegetation overlay will typically be based on the use of classified LANDSAT data for the area. In areas with limited vegetation, LANDSAT data may also provide useful information on the distribution of soil types to support the information available through soil maps. Soil types should preferably be classified in accordance with its texture composition using the USDA classification system, in order to benefit from information on soil parameters, based on the analysis of a considerable number of soil samples as provided by the literature, see Brakensick et al. (1980), Clapp and Hornberger (1978) and Rawls *et al.* (1983).

In Fig. 2, it is shown how the individual overlays finally are used to establish an overlay representing hydrological response units. A response unit is in this context defined as a sample of individual grid cells with identical features regarding the meteorological input, topography, vegetation type and soil texture class. By storing information on the particular composition of catchment characteristics defining each response unit, the aggregation of grid cells will increase the computational efficiency without any loss of information.

Hydrological Processes

The individual processes included in WATBAL for representing the land phase of the hydrological cycle is shown in Fig. 3. As illustrated in this diagram the model operates with five interrelated storages, i.e. interception, surface detention, soil moisture, subsurface and groundwater storage. It should be noted that individual interception and soil moisture storages are operated for each hydrological unit, while separate surface and subsurface storages only are used for each topographic zone as defined by the user, see Fig. 1. Percolation from all subsurface storages is assumed to recharge into a common groundwater storage covering the entire catch-

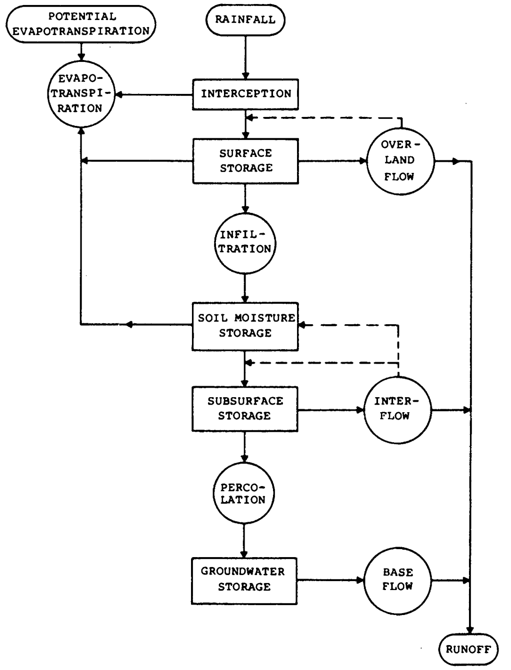


Fig. 3. Flowchart of hydrological subprocesses in WATBAL.

ment. In the following a short introduction to the submodels used for representing individual processes is given.

To represent the process whereby precipitation is retained on leaves, branches and stems of vegetation an *interception* storage is applied. Since interception is dependent on the type of vegetation, WATBAL uses a time varying leaf-area-index for each type of vegetation to derive the current storage capacity. From this storage water is assumed to be subject to evapotranspiration at the potential rate while excess input is transfered to the surface storage. From here water may either infiltrate into the soil or move downslope over the land surface.

For the representation of the *infiltration* process WATBAL uses the Green-Ampt model with its later modifications introduced by Mein and Larson (1971, 73) to describe the pre-ponding and post-ponding stages of the infiltration process as follows

$$f = I \quad ; \quad F = It \leq F_p \qquad \text{(pre-ponding)}$$

$$f = I \quad ; \quad F = F_p = \frac{\Omega S}{(I/K_S) - 1} \qquad \text{(at ponding)}$$

$$f = K_S\left(1 + \frac{\Omega S}{F}\right) \quad ; \quad F = \int f\, dt \geq F_p \qquad \text{(post ponding)}$$

where

I – rainfall intensity (mm/h)
f – infiltration rate (mm/h)
F – infiltrated volume (mm)
F_P – infiltrated volume at time of surface ponding
Ω – soil moisture deficit (vol/vol)
S – suction at the wetting front (mm)
K_S – hydraulic conductivity at field saturation (mm/h)

This model has been chosen due to the physical significance of the parameters and because of the simplicity and flexibility of the model. The model has been verified experimentally, and has been shown to perform satisfactorily under field conditions Idike *et al.* (1977), Slack (1977). Furthermore, the model can be adapted to account for heterogeneous soil profiles and variable rainfall intensity, Bouwer (1969), Chu (1978).

In case the current infiltration capacity is exceeded the excess stays in the surface detention storage and *overland flow* is generated. Several methods for calculating unsteady overland flow exist ranging from purely conceptual approaches to finite difference techniques for solving the governing partial differential equations. In catchment simulation studies approximate methods can be justified to a large extent due to the questionable validity of the sheet flow assumption, computer requirement and the availability of detailed input data required by an exact hydraulic approach. On the other hand, a physical relevance of approximate methods is important to assure a proper description of the attenuation properties and the interaction with the infiltration process.

The overland flow component of the well-known Stanford Watershed Model is an example of an approximate model based on physical parameters. Due to its simplicity and its many successful applications a similar approach has been incorporated in WATBAL. Considering overland flow as a turbulent flow process, a combination of the Chezy-Manning equation and an empirical expression relating outflow depth and detention storage is used to derive the overland flow from each topographic zone. In this expression average values for the length, slope and roughness of the flow plane are used as parameters.

Soil moisture is represented by a two box approach in which case the depth of the upper box currently follows the root depth. Soil moisture is computed currently taking calculated infiltration, actual evapotranspiration and percolation into account. Soil moisture content (vol/vol) is assumed to be uniformly distributed within each box except in case of surface ponding where the saturated wetting front is assumed to move as a 'piston flow'. Drainage of soil moisture above field capacity is computed as pure gravitational flow assuming an unsaturated hydraulic conductivity variation as proposed by Averjanov (1950).

Water held in the interception, surface detention and soil moisture storages are currently subject to *evapotranspiration*. It is assumed that water is removed at the potential rate from the upper two storages while a limited leaf area and/or limited availability of moisture in general will restrict evapotranspiration from the root zone. The actual evapotranspiration from the latter storage is computed using a slightly modified version of the model developed by Kristensen and Jensen (1975), which has been verified experimentally under field conditions, cf. also Holst and Kristensen (1981a). According to this model the transpiration component is derived as follows

$$E_t = E_p \, \phi(L_{ai}) \, \Psi(\theta_r)$$

where

E_t – actual evapotranspiration

E_p – potential evapotranspiration

L_{ai} – leaf area index

θ – actual moisture content

θ_{wp} – moisture content at wilting point

θ_{FC} – moisture content at field capacity

θ_r – is the relative moisture content = $(\theta-\theta_{WP})/(\theta_{FC}-\theta_{WP})$

and ϕ, ψ– are two functions as illustrated in Fig. 4.

In many cases data on the conditions within the saturated zone are very scarce. To correspond with the limited information usually available, a traditional conceptual approach has been used for representing the storage and routing of water below the

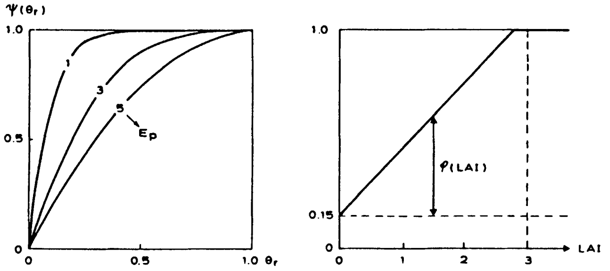


Fig. 4.
Functions used for determining the transpiration component.

root zone. Both the *subsurface* and *groundwater storages* have been represented by a linear reservoir, the groundwater storage as a simple one with one outlet, while two outlets have been included in every subsurface storage to allow a diversion of flow into lateral interflow and groundwater recharge.

The above description of the employed submodels pertains to the case where meteorological data are sufficiently detailed to justify this approach. In general, WATBAL has been designed as a flexible modelling system which allows the user to adjust the representation of physical catchment characteristics and hydrological subprocesses in accordance with the available data and the particular application.

Table 1 – Model parameters for the most advanced mode of operation.

TOPOGRAPHY	Within each topographic zone:
	o length of flow plane
	o slope
	o Manning number
	o depression storage
VEGETATION	For each type of vegetation:
	o leaf area index (time varying)
	o root depth (time varying)
SOIL TYPES	For each texture class:
	o wilting point
	o field capacity
	o total porosity
	o saturated conductivity
	o average suction
SUB-SURFACE REGIME	For each topographic zone:
	o threshold value
	o two time constants (interflow/percolation outlets)
	Groundwater storage:
	o groundwater area relative to catchment area
	o time constant of base flow outlet

Data Requirements

The requirements for parametric and exogenous data for an application of WATBAL depend on the particular mode of operation chosen by the user.

With respect to the exogenous data, time series of rainfall on at least a daily basis and monthly potential evapotranspiration data will be required. If a detailed representation of the infiltration and overland flow processes is selected, more frequent observations on rainfall are required or some estimate on the storm duration in case the model is used for flood predictions.

With respect to the model parameters Table 1 provides a list of the necessary data to operate the model in its most advanced mode.

The physical relevance of the majority of these parameters is noted. In the standardized WATBAL-parameters file, mean values and standard deviations for all soil parameters are given for each texture class. These values may be used unless access to detailed information on the particular soil parameters is available.

Information about the composition and areal extent of each hydrological unit has been omitted, since this information automatically will be generated and stored using the procedure outlined in Fig. 2.

Tests and Applications of WATBAL

Comprehensive tests of the individual components of the entire modelling system have been carried out. As an example, Fig. 5 shows results from a testing of the evapotranspiration and soil moisture components using data measured at an IHP experimental station located in Aversi, Denmark, cf. Holst and Kristensen (1981b). No actual calibration of the submodels was made. Instead, soil parameters were obtained from observations on the site while standardized values on LAI and root depths were used.

Further testings of the complete model have been made on Danish and Tanzanian catchments and in 1984 the first practical application of the model was made in connection with a feasibility study of medium-size dams in Zimbabwe, by Dangroup International (1984).

As a result of an initial identification and classification phase ten potential dam sites for irrigation purposes were selected for feasibility studies. To assess reservoir yield, crop irrigation and reservoir simulation models were developed, see Knudsen and Rasmussen (1986). However, reliable time series of inflow to each potential reservoir did not exist since all ten catchments were ungauged. On the other hand, long time series of rainfall and pan evaporation were available as well as soil and topographic maps. Using LANDSAT satellite imagery to supplement this information and to carry out a vegetation mapping, the physical characteristics and their composition were assessed for each particular catchment. Following this ap-

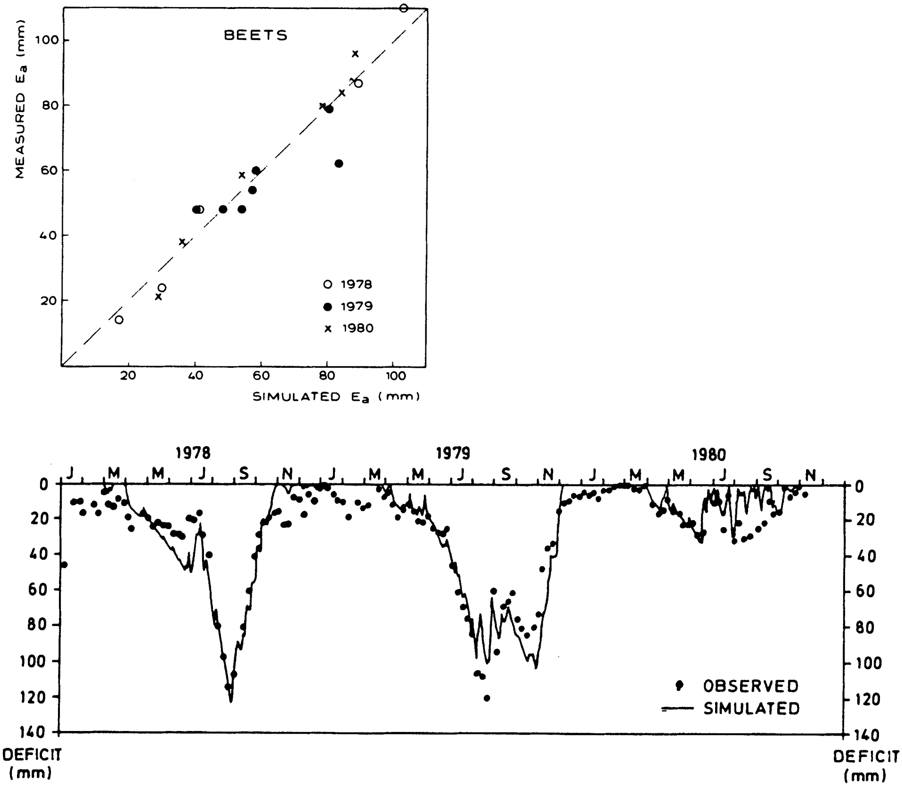


Fig. 5. Comparison of measured and simulated values of monthly evapotranspiration (top) and soil moisture deficits (bottom) for a plot with beets.

proach an individual data base for each catchment was established which subsequently was used by WATBAL for the simulation of inflow time series.

For the purpose of testing the transferability of WATBAL and the adjustment of physical parameters WATBAL was initially applied to two gauged catchments. Using the same approach as outlined above, a traditional setup, calibration and verification was made for one of the catchments (Ngezi), covering 1,090 km^2. In this case approximately 65 hydrological response units were used to account for the different catchment characteristics. In Fig. 6 results from these simulations are presented, showing about the same agreement with observed data which usually is achieved by a lumped, conceptual model.

On the basis of the experience obtained from this application, regarding approximate values of physical parameters, and the separate data base for the other catchment area (Vungu, covering 1,840 km^2) WATBAL was transferred to this area without further calibration. A comparison with the observed runoff was subsequently made, see Fig. 7, reflecting the ability of WATBAL to simulate ungauged

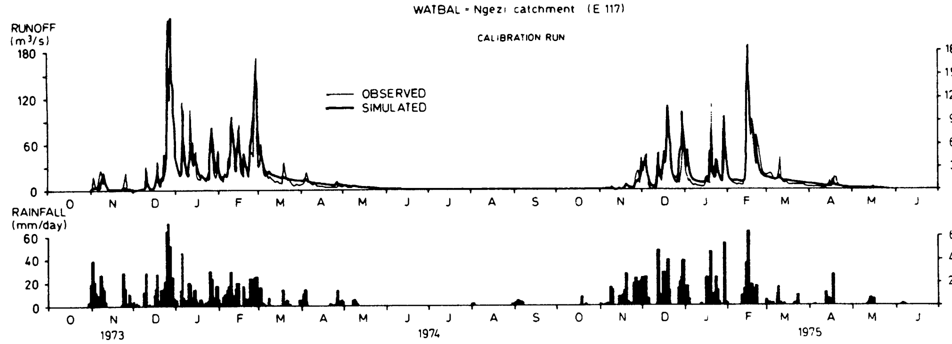
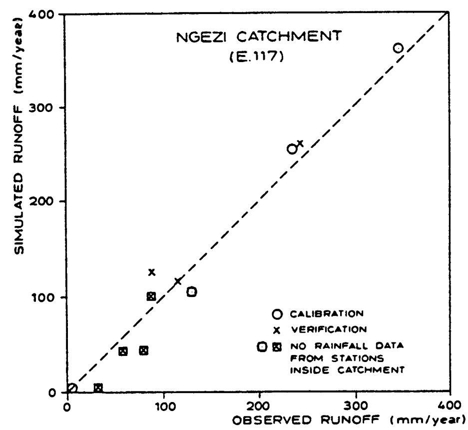
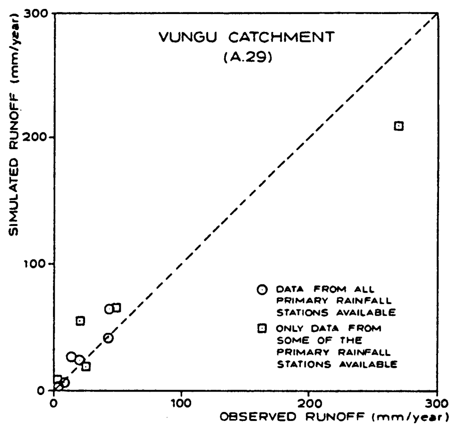


Fig. 6. Comparison of measured and simulated runoffs for the Ngezi catchment, Zimbabwe (traditional calibration and verification).





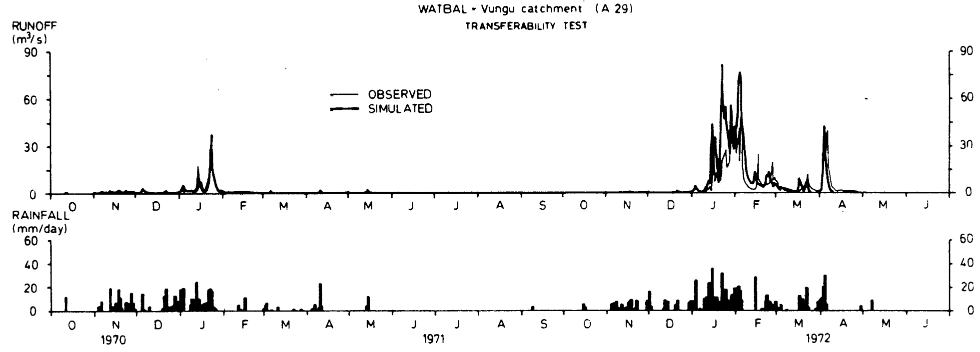


Fig. 7. Comparison of measured and observed runoff for the Vungu catchment, Zimbabwe (transferability test).

catchments.

As expected, this test on model transferability shows that the agreement between simulated and observed flows reduces as compared to the case when a traditional calibration can be made on the basis of measured flows. However, both the annual pattern of runoff (dry/wet years- as well as the seasonal variation are represented quite satisfactory, and the performance of the model is still particular sensitive to the availability of rainfall data from primary stations.

It summary, the performance of the model for the non-calibrated Vungu catchment is satisfactory and encouraging with respect to future tests and applications for ungauged catchments or areas subject to land use changes.

Potential Fields of Applications

For a discussion of the general practical applicability of the WATBAL model the capabilities of this model are assessed and compared to two other models representing typical types of deterministic hydrological models, namely

- The NAM model, a traditional lumped, conceptual rainfall runoff model, cf. Nielsen and Hansen (1973). The NAM model has been used extensively during the past decade as a standard hydrological tool for more than 100 catchments throughout the world.
- The SHE model, a fully distributed, physically based model of the entire land phase of the hydrological cycle, cf. Storm (1986). The SHE model has been tested on about 10 research catchments within the last few years.

The general applicability of the two typical model types and the WATBAL model is discussed in the following and summarized in Table 2.

The *lumped, conceptual models* (as e.g. the NAM model) are especially well suited for simulation of the rainfall-runoff process when hydrological time series sufficiently long for a model calibration exist. Thus, typical fields of application are:

- Extension of short streamflow records based on long rainfall records.
- Real-time rainfall-runoff simulation for e.g. flood forecasting.

On the other hand, the lumped conceptual models are not especially well suited for other types of application, including the prediction of runoff from ungauged catchments, i.e. in catchments where calibration is not possible. In such cases, the success of applying the simple model will depend on the experience of the user and whether a gauged catchment with similar characteristics can be identified.

The *distributed, physically based models* (as e.g. the SHE model) can in principle be applied to almost any kind of hydrological problems. Obviously, there are many problems for which the necessary solutions can be obtained using the cheaper lumped, conceptual models. However, for the more complicated problems, there may be no alternative, but to use a distributed, physically based model. Some examples of typical fields of application are:

- Prediction of the effects of catchments changes due to human interference in the hydrological cycle, such as e.g. changes in land use, urbanization, groundwater development, irrigation. The parameters of the model are direct physical parameters. Therefore, the change in parameter values corresponding to the catchment changes can be obtained directly.
- Prediction of runoff from ungauged catchments and from catchment with very short records (0-2 years). As opposed to the lumped, conceptual models, which require long historical time series of rainfall, runoff, and evaporation data for the parameter assessment, the parameters of the distributed, physically based models can be assessed directly from intensive, short-term field investigations.
- Water quality and soil erosion modelling for which a detailed and physically correct simulation of water flows is essential.

Being distributed, physically based at the root zone processes and lumped, con-

Table 2 – Applicability of different model types to different hydrological problems.

Model type Problem	NAM-model lumped, conceptual	WATBAL-model	SHE-model distributed, physically based
Extension of streamflow records	$\underline{**}$	**	**
Real-time rainfall-runoff simulation	$\underline{**}$	**	**
Prediction of runoff from ungauged catchments	*	$\underline{**}$	**
Water balance studies	*	$\underline{**}'$	$\underline{**}$
Prediction of effects of land use changes	–	$\underline{**}'$	$\underline{**}$
Prediction of effects of other human influence	–	–	$\underline{**}$
Water quality and soil erosion modelling	–	–	$\underline{**}$

–	Not applicable
*	Applicable, but not well suited
**	Technicaly suitable
$\underline{**}$	Technically suitable and most often the economical most feasible choise
$\underline{**}'$	Equivalent to ** for non-groundwater dominated catchments and * for groundwater dominated catchments

ceptual at the overland flow and subsurface processes the *WATBAL* is an intermediate modelling approach as compared to the NAM and the SHE models. WATBAL is technically applicable for all the fields which the NAM model would traditionally be used. However, the main field of application for which the WATBAL is believed to be the most optimal model choice is

- Prediction of runnoff from ungauged catchments, especially in cases where some spatially distributed data on topography, soil and vegetation properties are available either from satellites or from maps.

In addition the WATBAL will be very well applicable to the following two fields of application in catchments where the groundwater component is not very significant:

- General water balance studies as discussed above
- Prediction of the hydrological effects of land use changes

Summary and Discussion

A physically based, semi distributed hydrological model has been described. Basically, the model is a compromise between a lumped, conceptual approach and a completely physically based, fully distributed representation of catchment hydrology. In particular, the model allows full utilization of data on the spatial and temporal variations for rainfall, evaporation, topography, vegetation and soil types, employing well proven relations based on measurable parameters to represent the processes affecting soil moisture. In contrast to this approach, subsurface flows have been represented by lumped conceptual submodels due to the limited information generally available for these processes.

The basic structure of WATBAL, its submodels and data requirements have been presented. The entire modelling system has been designed as a flexible instrument allowing the user to adjust the representation of physical catchment characteristics and hydrological subprocesses in accordance with the available data and the particular application. Computer requirements are relatively modest allowing most applications to be operated on the more powerful personal computers, e.g. IBM AT.

Various tests and applications of WATBAL have been presented. The results provided encouragement with respect to the capability of the model for simulating ungauged catchments or the prediction of hydrological effects of land use changes. However, further tests – and possibly model modifications – are required for a firm confirmation of its capabilities and limitation.

On the basis of applications undertaken with WATBAL so far some experience has emerged, which seems worthwhile to discuss briefly.

First, all applications have confirmed the necessity of incorporating a sufficient representation of catchment variability when a physical approach to hydrologic modelling is applied. In case the variability is underestimated, biased output is very likely. As an example, calibration of physical parameters have been found to violate their likely ranges when areal weighting of rainfall is exaggerated. This experience, in combination with the fact that soil parameters usually varies considerably within the same texture class, caused the development of a special facility to account for such variations.

Secondly, based on the application under Zimbabwean conditions, the usual representation of the temporal variation of vegetation characteristics (*LAI,* root depth) showed certan shortcomings of some importance for an accurate representation of the initial phases of the rainy season. Traditionally, temporal variations are accounted for by deterministic and periodic functions, which imply that crops follow a stable pattern from year to year. However, since the rainy season in some countries may be delayed by several months, and crop development obviously is governed by water availability, certain periods of some years may not be adequately represented. To overcome this shortcoming a dynamic approach is desirable reflecting the dependency of crop development on soil moisture.

Finally, with respect to the capability of WATBAL for modelling ungauged catchments, valuable information can be achieved by a prior calibration on other catchments. Gauged catchments encompassing some or all characteristics of the ungauged area, but not necessarily with the same composition, should be identified. Based on the results obtained from the gauged catchments, calibrated parameter values can be transferred to the ungauged catchments on an objective basis. It is believed that this approach greatly will reduce the uncertainties associated with modelling ungauged catchments.

References

Averjanov, S. F. (1950) About permeability of subsurface soils in case of incomplete saturation, *Engr. Collect. Vol. 7.*

Bouwer, H. (1969) Infiltration of water into non-uniform soil, *J. Irrig. Drain. Div. ASCE, Vol. 95,* 451-462.

Brakensick, D. L., Engleman, R. L., and Rawls, W. J. (1980) Variation within texture classes of soil water parameters, Am.Soc.Agric.Eng. Paper No. 80-2006.

Chu, S. T. (1978) Infiltration during an unsteady rain, *Water Resour. Res., Vol. 14,* 461-466.

Clapp, R. B., and Hornberger, G. M. (1978) Empirical equations for some soil hydraulic properties, *Water Resour. Res., Vol. 14,* 601-604.

Dangroup International (1984) Feasibility study and design for medium size dams in the communal lands in the Midlands Province, Zimbabwe. Feasibility study rep., Vol. 1. Ministry of Energy, Water Resources and Development.

Holst, K. Aa., and Kristensen, K. J. (1981a) Model for bestemmelse af aktuel fordampning, Danish Committee for Hydrology. Report SUSÅ H5 (in Danish).

Holst, K. Aa., and Kristensen, K. J. (1981b) Vandoptagelse fra jord og fordampning fra landbrugsvegetation, Danish Committee for Hydrology. Report SUSÅ H4 (in Danish).

Idike, F., Larson, C. L., Slack, D. C., and Young, R. A. (1977) Experimental evaluation of two infiltration equations. Winter meeting. Am. Soc. Agric. Engrs.

Knudsen, J., and Rasmussen, J. (1986) Integrated reservoir and irrigation demand model, Proceedings Nordic Hydrological Conference, Reykjavik, Iceland, Vol. 2, pp. 573-583.

Kristensen, K. J., and Jensen, S. E. (1975) A model for estimating actual evapotranspiration from potential evapotranspiration, *Nordic Hydrology, Vol. 6,* pp. 70-88.

Mein, R. G., and Larson, C. L. (1971) Modelling the infiltration component of the rainfall-runoff process, Water Resour. Res. Center, Univ. of Minn., Minneapolis, Bulletin 43.

Mein, R. G., and Larson, C. L. (1973) Modelling infiltration during a steady rain, *Water Resour. Res., Vol. 9,* 384-394.

Nielsen, S. A., and Hansen, E. (1973) Numerical simulation of the rainfall runoff process on a daily basis, *Nordic Hydrology, Vol. 4,* pp. 171-190.

Rawls, W. J., Brakensick, D. L., and Miller, N. (1983) Green ampt infiltration parameters from soils data, *ASCE, Jour. Hydraulic Eng. Vol. 109,* No. 1, p. 62-70.

Slack, D. C. (1977) Modelling infiltration under moring sprinkler irrigation systems, ASAE paper No. 77-2557.

Storm, B. (1986) Introduction to the SHE, Système Hydrologique Européen, European Hydrological System. Danish Hydraulic Institute.

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