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AUGMENTED HYDROGRAPH HYPOTHESIS:
DISCUSSION OF PRINCIPLES

by

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ABSTRACT

Traditional catchment models split the rainfall-runoff process into two major components, namely volume reduction and shape transformation, assume that these two components are independent of each other, and apply them to the input in the order volume reduction followed by shape transformation. When an example of such a model, composed of three subsystems, namely runoff ratio, time area diagram and non-linear reservoir, was applied to 66 isolated storm events from the River Ray catchment a relationship was found between the size of the non-linear reservoir and the value of the runoff ratio, thus making the two major components of the model no longer independent of each other. In this report a new model is proposed which supports the idea of splitting the rainfall-runoff relation into two major independent components, but challenges the traditional order in which they are applied. The new model contains the same three subsystems but rearranged so that the non-linear reservoir precedes the runoff ratio, instead of following it. In this new model the gross rainfall hyetograph is applied first to the shape transformation component rather than to that of volume reduction, giving as intermediate output from the model a hydrograph, which is termed the augmented hydrograph. This augmented hydrograph provides an alternative concept to that of the net rainfall hyetograph, which is the intermediate output obtained from traditional models.



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1 GENERAL STRUCTURE OF RAINFALL-RUNOFF MODELS

When formulating models to relate gross rainfall input to flow hydrograph output it is observed firstly that the volume under the flow hydrograph is less than the volume of gross rainfall, and secondly that the input and output for a storm event have different shapes when plotted on the same time axis. These two observations will be accepted as the starting point for our discussion.

In order to recognise this observed relation between input and output the majority of models build into their representation two major components:-

- (a) VOLUME REDUCTION
- (b) SHAPE TRANSFORMATION

The first of these components ensures that the volume of input is reduced to that of the output. The second component ensures that the input shape is changed to that of the output.

Two assumptions are usually made to facilitate construction of models:-

- (i) the order in which the two components are applied is first the VOLUME REDUCTION, followed by the SHAPE TRANSFORMATION;
- (ii) the form of the SHAPE TRANSFORMATION component is not dependent in any way on the VOLUME REDUCTION component.

These assumptions may be illustrated for the unit hydrograph/losses model of the rainfall-runoff relation. First the losses procedure is applied to the gross rainfall to produce the net rainfall, equal in volume to the quick response runoff. Secondly the shape transformation component, the unit hydrograph, is applied to the net rainfall hyetograph to convert its shape to that of the quick response runoff hydrograph. The shape of the unit hydrograph is taken to be the same for all rainfall events, whatever reduction in volume occurs between input and output; it does not take different shapes depending, for example, on the ratio of net rainfall to gross rainfall.

These assumptions are broadly made, but there are instances of individual models which violate one or both of them. For example, in a model possessing a volume reduction component based on the infiltration capacity concept, the shape of the output is dependent to a small extent on the volume reduction component, though mainly on the shape transformation component.

2 THE ISOLATED EVENT MODEL

A simple four parameter conceptual model (IEM4) of catchment response has been developed previously with the object of modelling only isolated storm events and thus providing a useful tool for flood estimation (Flood Studies Report, 1975; O'Donnell & Mandeville, 1975). The model is fitted to such catchments by using an automatic computer optimisation technique to find those values of the model parameters which enable the model to reproduce existing isolated events to an

acceptable degree of accuracy. Approximately 500 isolated storm events over 21 catchments in the United Kingdom, ranging in area from 1.5 km² to 443 km², were used to develop and prove the IEM4 model.

In this discussion an improved version (IEM5) of the isolated event model is considered. The model is split into the traditional two major components of VOLUME REDUCTION and SHAPE TRANSFORMATION as shown in Fig. 1 (a).

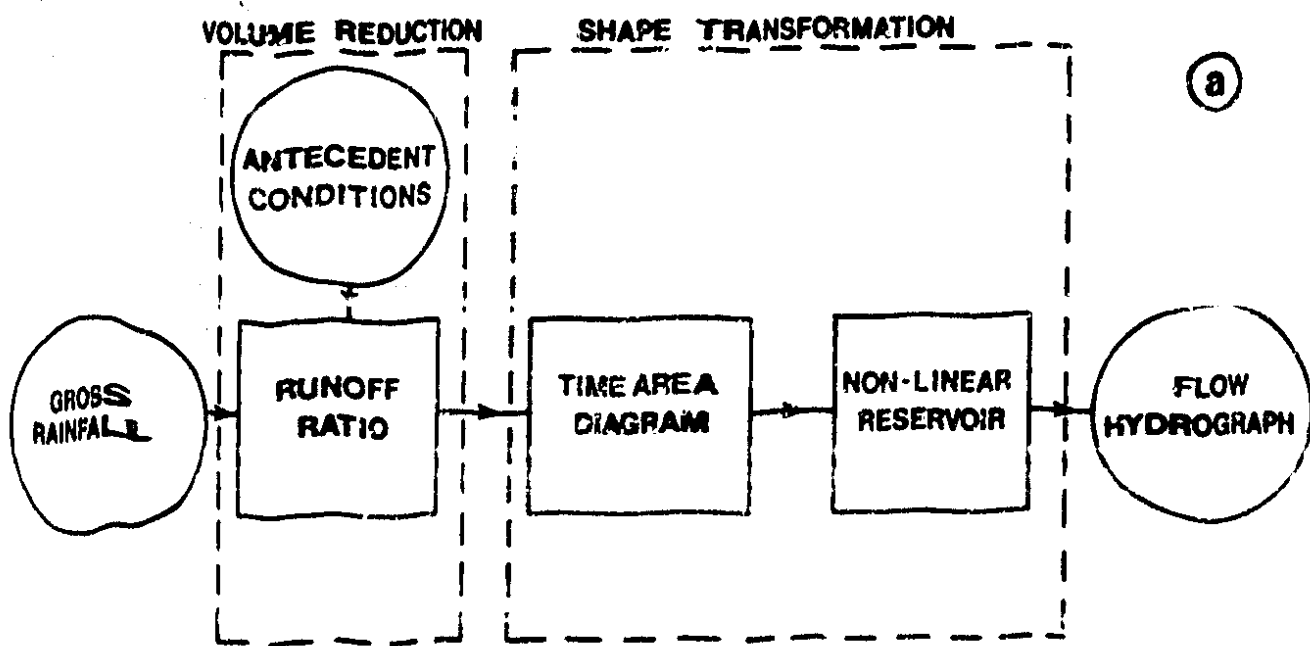
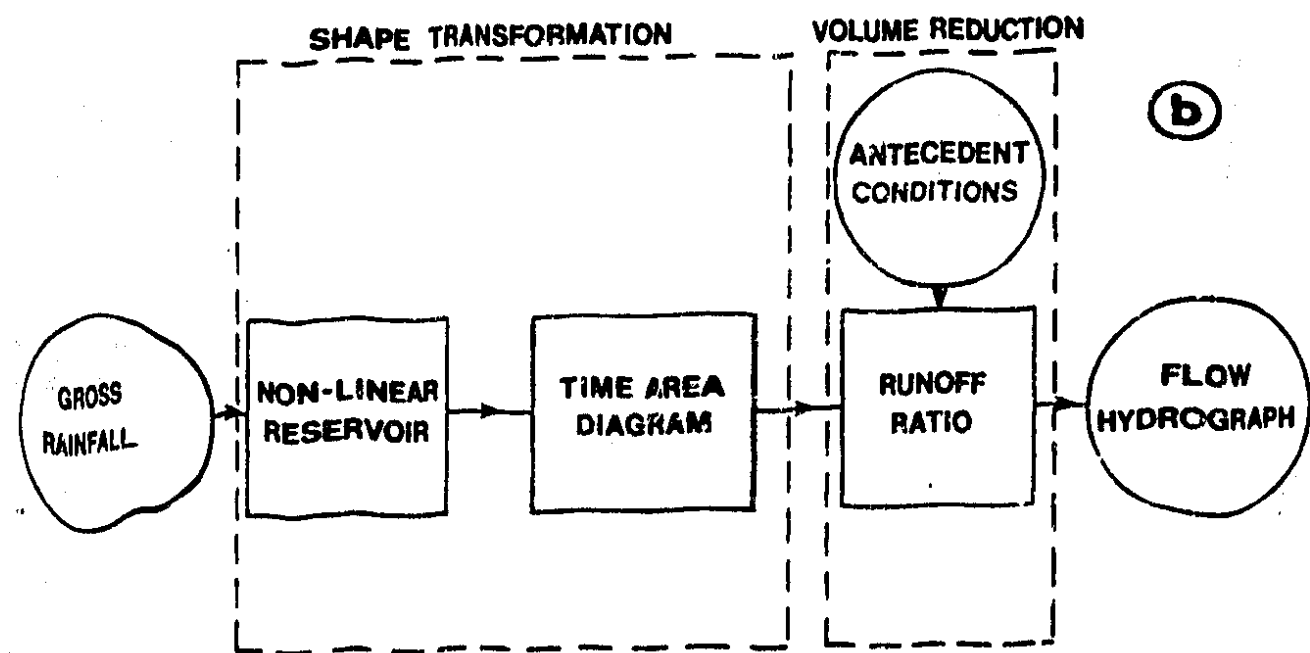


FIGURE 1 SUBSYSTEMS OF TWO RAINFALL-RUNOFF MODELS. (a) Isolated Event IEM5 model



(b) Augmented Hydrograph model

The VOLUME REDUCTION component consists of a runoff ratio, varying within the storm, which is applied to all ordinates of the gross rainfall hyetograph to reduce them to those of the net rainfall hyetograph. This varying runoff ratio is defined by assigning a fixed value of runoff ratio at the time corresponding to the centroid of the gross rainfall hyetograph, while a parameter describes the rate at which the runoff ratio either increases slightly throughout the storm in linear fashion with time, or decreases in a similar way. When the IEM5 model is used either for forecasting future isolated storm events or for reconstructing past ones, the centroidal value of the runoff ratio is related to the antecedent catchment conditions by a two parameter exponential expression; this relationship is the same as that used in the IEM4 model. The overall value of the runoff ratio estimated by this model for a complete isolated storm event is denoted by the expression ROP where

$$ROP = \frac{\text{model runoff volume}}{\text{observed gross rainfall volume}}$$

The SHAPE TRANSFORMATION component is formed of two subsystems, termed the time area diagram and the non-linear reservoir. The time area diagram represents the translation effects of the catchment on the runoff produced at all points within it, and the form used in this model is illustrated in Fig. 2(a). This particular form is a linear system in which, for an input of unit intensity with duration of one time unit, the output consists of a uniform lesser intensity lasting for more than one time unit, but starting some time later than the time of input. This time area diagram has two effects on the input: firstly, it delays the input in time, by an amount equivalent to the period between the centroids of the input and output functions, shown in the figure; secondly, it attenuates the input, by spreading it out over a longer time period. This time area diagram can be considered as a special case of the more general form of the time area diagram shown in Fig. 2(b), which may not necessarily be a linear system.

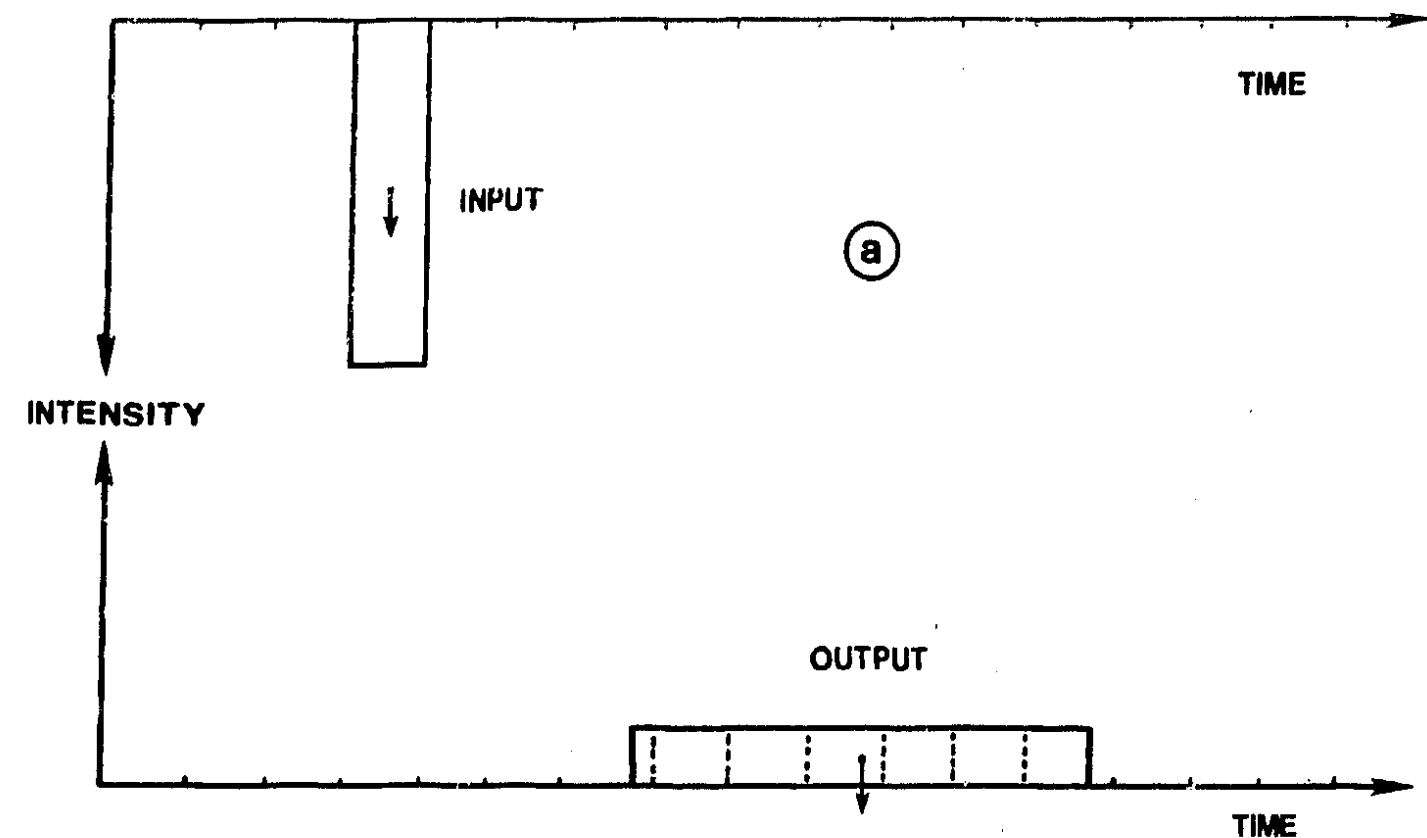


FIGURE 2 TIME AREA DIAGRAMS (a) form used in the IEM5 model

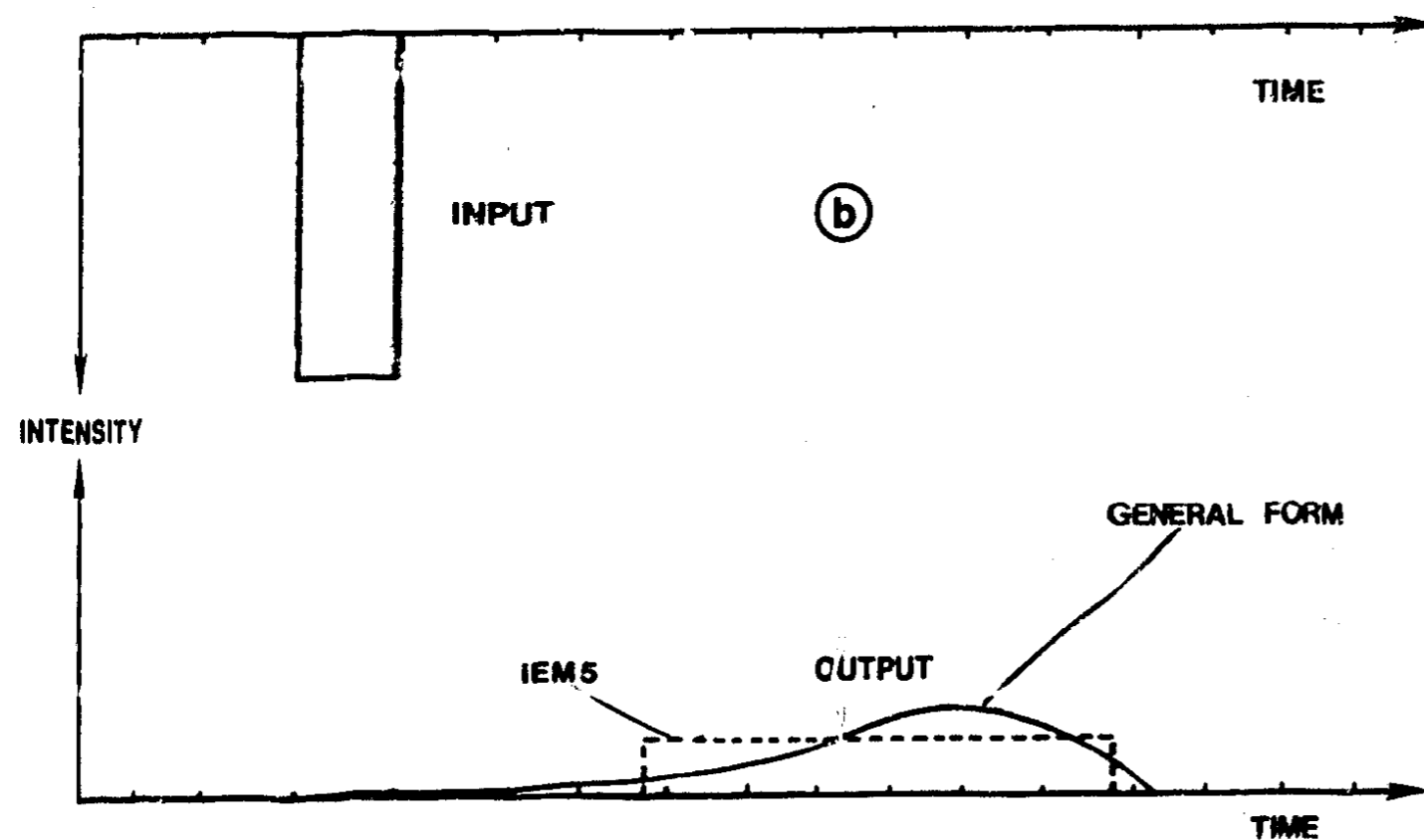


FIGURE 2 TIME AREA DIAGRAMS (b) general form

The non-linear reservoir used in the IEM5 model is represented by the equation

$$S = AC \cdot Q^{\frac{1}{2}} \quad (2)$$

where S is storage, Q is output, and AC is a parameter. The exponent was arbitrarily fixed at a value of $\frac{1}{2}$ because, if made a parameter, there is a certain measure of interdependence between it and the parameter AC ; this causes difficulties in searching for the best fitting values by optimization techniques if both parameters are allowed to vary. If variable I represents the input, and t the time, the operation of the reservoir is found by combining the above equation with the continuity equation

$$\frac{dS}{dt} = I - Q \quad (3)$$

The presence of a non-linear reservoir component in the IEM5 model ensures that the output from the model for a typical isolated storm event possesses both an extended recession after the rainfall input and a preceding recession from a previous event. Consequently, there is no necessity to give separate attention to a 'base flow' to obtain a realistic hydrograph from the model.

The IEM5 model described above follows the two assumptions (i) and (ii) mentioned in Section 1. Firstly, the VOLUME REDUCTION component of runoff ratio precedes the SHAPE TRANSFORMATION component consisting of the time area diagram and non-linear reservoir. Secondly, neither the time area diagram nor the non-linear reservoir are dependent on the runoff ratio value.

3 FITTING THE IEM5 MODEL TO DATA FROM THE RIVER RAY CATCHMENT

When the IEM5 model is fitted to observed isolated storm events, an abridged version is first used in which the centroidal value of runoff ratio instead of being determined from antecedent catchment conditions, is itself allowed to vary like an extra parameter. The parameters describing the time area diagram, non-linear reservoir and linear variation of runoff ratio with time are also varied, and optimization techniques employed to determine those values of the parameters and runoff ratio for which there is the closest possible agreement between the observed hydrograph and the hydrograph reconstructed by the model. The abridged model is fitted to individual events, and a separate set of optimum parameter values obtained for each event.

The abridged version of the IEM5 model was fitted to 66 isolated storm events from the River Ray catchment at Grendon Underwood. This experimental basin of 19 km², on a tributary of the Thames, lies almost entirely on deep impervious clay, and is described more fully by Edwards and Rodda (1970). For this particular catchment the abridged IEM5 model was sufficiently flexible to fit the observed storm events extremely well, and the fitting criterion R_E described in O'Donnell & Mandeville (1975) and Flood Studies Report (1975) ranged from 0.870 to 0.998, with a mean value of 0.981.

In the previous section ROP was defined as

$$ROP = \frac{\text{model runoff volume}}{\text{observed gross rainfall volume}} \quad (1)$$

and, when there is such close agreement between the model hydrograph and the observed hydrograph, ROP closely approximates the expression ROP' where

$$ROP' = \frac{\text{observed runoff volume}}{\text{observed gross rainfall volume}} \quad (4)$$

It follows that the values of ROP used subsequently, although not identical to observed values of runoff ratio, provide a very close approximation to that variable due to the excellent fit of the model to events on this catchment.

Although the exponent value of $\frac{1}{2}$ in the non-linear reservoir equation (2) was found suitable for closely fitting the curvature of the majority of recession curves from storm events for this catchment, the optimum value for each event of the parameter AC appeared to vary from one event to another. More than this, there appeared to be a systematic relation, shown in Fig. 3, between values of AC and the optimum values of runoff ratio, ROP, obtained for each event. In other words the SHAPE TRANSFORMATION component, consisting of the time area diagram and non-linear reservoir, depends directly on the VOLUME REDUCTION component, the runoff ratio, and assumption (ii) no longer holds. However assumption (i) is still valid.

One possible course of investigation would be to accept this situation and construct a feasible model that first of all obtained the value of the runoff ratio from antecedent catchment conditions and applied it to the gross rainfall to obtain the net rainfall. Next, this value of runoff ratio would be used to determine the size of the parameter AC from the relation shown in Fig. 3, and thus the corresponding size of the non-linear reservoir, which, in conjunction with the fixed time area diagram, would be applied to the net rainfall hyetograph to obtain the flow hydrograph.

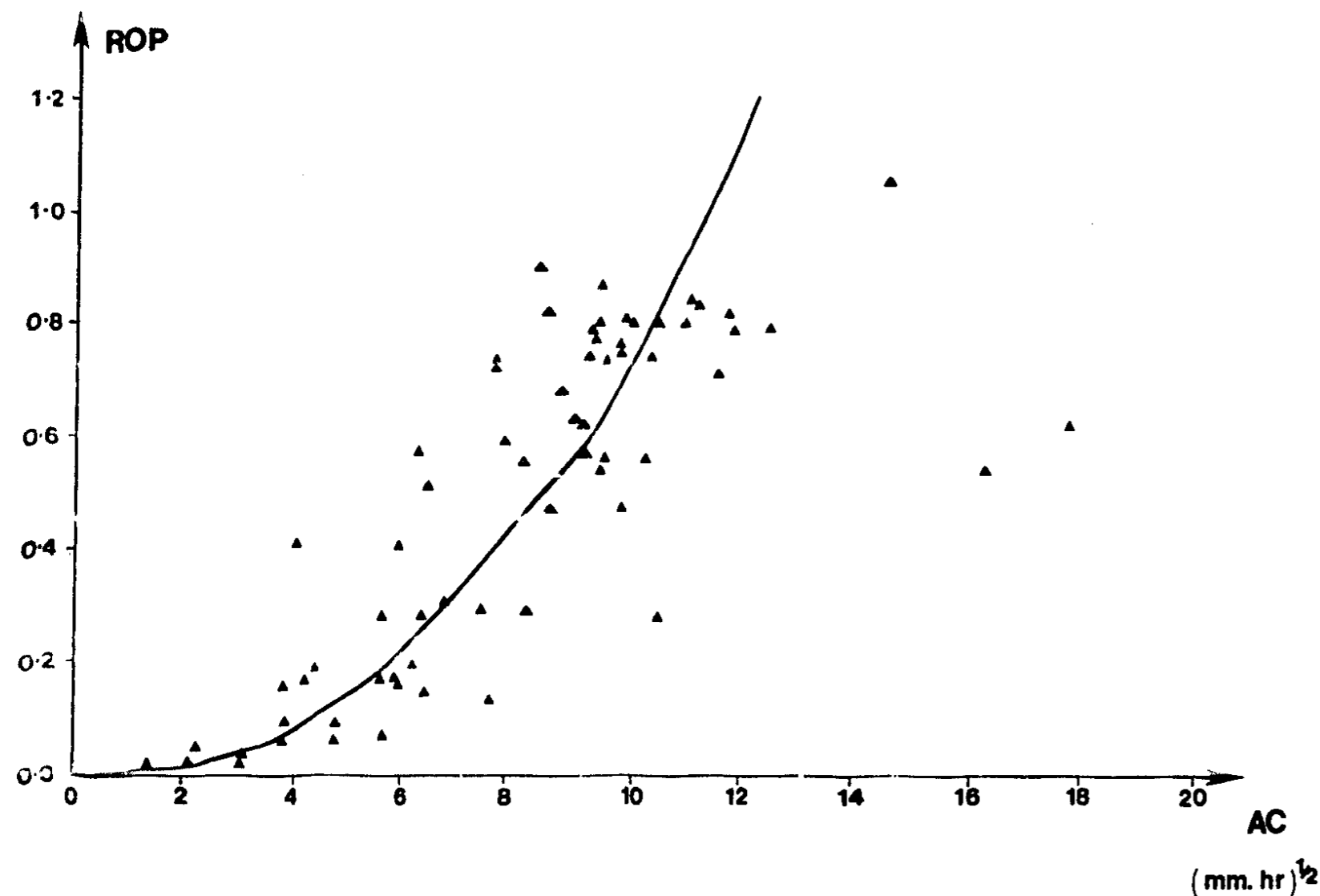


FIGURE 3 RELATION BETWEEN THE OPTIMUM VALUES OF RUNOFF RATIO ROP AND PARAMETER AC OBTAINED WHEN FITTING THE IEM5 MODEL TO THE RIVER RAY CATCHMENT DATA

One intriguing aspect of the variation of the non-linear reservoir between different events is that, although the optimum value of the parameter AC varies between events, the fixed value of $\frac{1}{2}$ for the exponent in equation (2) was found to fit the majority of events very closely. This suggests a measure of similarity of the SHAPE TRANSFORMATION component between events, but some form of interference from the VOLUME REDUCTION component. The question now arises as to whether the structure of the complete model can be altered to allow the non-linear reservoir to remain the same from one event to another, and the model to hold to assumption (ii).

4 ORDER OF THE RUNOFF RATIO AND NON-LINEAR RESERVOIR SUBSYSTEMS

A simple power-law curve passing through the origin was fitted to the data points shown in Fig. 3 and having the form

$$AC = \alpha ROP^\beta \quad (5)$$

A regression of log AC on log ROP gave fitted parameter values of $\alpha = 11.25$, and $\beta = 0.414$. This curve may be closely approximated by the parabola

$$AC = BC \cdot ROP^{\frac{1}{2}} \quad (6)$$

where BC is the fixed value of AC obtained when ROP equals unity.

As mentioned previously the two equations controlling the behaviour of the non-linear conceptual reservoir used in this analysis were

$$S = AC \cdot Q^{\frac{1}{2}} \quad (2)$$

$$\frac{dS}{dt} = I - Q \quad (3)$$

Substituting (6) into (2) and rearranging gives

$$\frac{S}{ROP} = BC \cdot \left(\frac{Q}{ROP}\right)^{\frac{1}{2}} \quad (7)$$

The storage, S, output, Q, and input, I, may be transformed by dividing each of them by the runoff ratio, ROP, as follows

$$S_* = \frac{S}{ROP} \quad (8)$$

$$Q_* = \frac{Q}{ROP} \quad (9)$$

$$I_* = \frac{I}{ROP} \quad (10)$$

Equations (3) and (7) may be expressed in terms of the new variables S_* , Q_* and I_* as

$$\frac{d}{dt} (S_*) = I_* - Q_* \quad (11)$$

$$S_* = BC \cdot (Q_*)^{\frac{1}{2}} \quad (12)$$

provided ROP is assumed constant during each storm event. As the linear variation of runoff ratio with time during a typical storm is only slight (c.f. section 2), this variation may be considered as of second order importance to the much larger variation of storage S with time.

These new equations (11) and (12) show that Q_* may be considered as the output from a non-linear reservoir of storage S_* . However the relation between storage and output, equation (12), now possesses a fixed value of the coefficient BC for all events. In other words, if the IEM5 model variables S, Q and I are transformed by dividing each of their values by the runoff ratio, ROP, for that event, as shown in equations (8), (9) and (10), the relationship between the transformed variables possesses a more stable parameter value than that between the untransformed variables. Subsequently in order to obtain the actual IEM5 model output, Q, it is necessary to reverse the transformation of equation (9); the values of the transformed output, Q_* , should be multiplied by the value of the runoff ratio, ROP, for that event.

This analysis shows that if the order of the two subsystems, namely runoff ratio and non-linear reservoir, is reversed, and the non-linear reservoir precedes the runoff ratio instead of following it, the large variations in the size of the non-linear reservoir obtained when fitting the IEM5 model will be reduced. The new model suggested contains a non-linear reservoir fixed for all events followed by application of the runoff ratio appropriate to any one event. The position of the time area diagram within the order of the other subsystems will be discussed in the next section.

5 POSITION OF THE TIME AREA DIAGRAM SUBSYSTEM

With the other two subsystems being a non-linear reservoir followed by a runoff ratio, there are three potential positions for the time area diagram subsystem; immediately before the non-linear reservoir, in between the other two subsystems, or immediately following the runoff ratio subsystem. One feature of a combination of two linear systems is that the output from the combination, corresponding to a given input, is unaffected by the order of the component systems. Since both the runoff ratio and time area diagram are linear systems, it is impossible to determine their order of application purely by examining the patterns between input and output sequences from their combination. Whilst the non-linear reservoir and time area diagram are not both linear systems, preliminary trials indicate that the output from this particular combination of systems for a given input is also not materially affected by the order of the systems. Therefore the position of the time area diagram subsystem in relation to those of the non-linear reservoir and runoff ratio subsystems is difficult to determine by examining only the patterns between the input and output sequences of their combination; this point requires future investigation, possibly by examining the physical interpretation of each subsystem within the catchment.

6 PROPOSED NEW MODEL

Based on the arguments in the preceding two sections, a new form of model is proposed. The main subsystems of the model are the same as in the previous IEM5 model (Fig. 1(a)), but their order is changed. The new model is composed of a non-linear reservoir, followed by a time area diagram, followed by a runoff ratio component (Fig. 1(b)). The position of the time area diagram is arbitrarily chosen to be between the other two subsystems. In this model the SHAPE TRANSFORMATION component consists of a non-linear reservoir and a time area diagram. The parameters of these two subsystems are unchanged from storm event to storm event, and do not depend in any way on the value of the runoff ratio. Consequently this new model upholds assumption (ii) mentioned in Section 1. On the other hand the general structure of the model is such that the SHAPE TRANSFORMATION component precedes the VOLUME REDUCTION component. Thus in order to satisfy assumption (ii) it has been found necessary to dispense with assumption (i). No way has yet been found to construct the non-linear model in order to satisfy both assumptions.

If the new model is to be employed for reconstructing isolated storm events on catchments other than the River Ray it is permissible to generalize each subsystem. For example, a value other than $n = \frac{1}{2}$ could be used as exponent in equation (2) describing the non-linear reservoir, provided that this value was used consistently for all events from a single catchment. Again, a triangular time area diagram could be employed to replace the one described in Fig. 2(a), provided it retained the property of linearity.

The main proposition put forward in this report is the overall structure of the new model, rather than details of its subsystems. The subsystems of the model are still relatively simple and a simple change has been made to the usual order of the subsystems. It will be useful, therefore, to explore this new form of model further.

7 CONCEPT OF THE AUGMENTED HYDROGRAPH

The IEM5 model follows the traditional order of application of the VOLUME REDUCTION and SHAPE TRANSFORMATION components (Fig. 4). Firstly, the gross rainfall hyetograph is applied to the runoff ratio to give the net rainfall hyetograph. Secondly the net rainfall hyetograph is applied in sequence to the time area diagram and non-linear reservoir to give as output the flow hydrograph.

In the new model, the SHAPE TRANSFORMATION component (ie the non-linear reservoir followed by the time area diagram) is applied first. When the gross rainfall hyetograph is applied as input to this SHAPE TRANSFORMATION component, the output is a hydrograph with the same volume as that under the gross rainfall hyetograph, but a different shape (Fig. 4). This intermediate hydrograph will be termed the augmented hydrograph. Next, the augmented hydrograph is applied as input to the VOLUME REDUCTION component of the model, in which each of its individual ordinates is reduced by multiplying by the runoff ratio to give as output the flow hydrograph.

The augmented hydrograph has the same shape as the flow hydrograph, but a larger volume. It may also be defined as the hydrograph that would occur during a storm event if the runoff ratio ROP happened, in theory, to take the value 1.0; in practice ROP would not normally reach this limit. For an observed isolated storm event the augmented hydrograph may be estimated by comparing the volumes of gross rainfall and observed runoff, calculating the corresponding runoff ratio, and dividing each individual ordinate of the observed hydrograph by this value of the runoff ratio to 'augment' their size (Fig. 5).

8 HISTORICAL PERSPECTIVE

This new structure of model has the advantage of allowing a fresh approach to the way of looking at the rainfall-runoff relation, even if it appears to reverse the

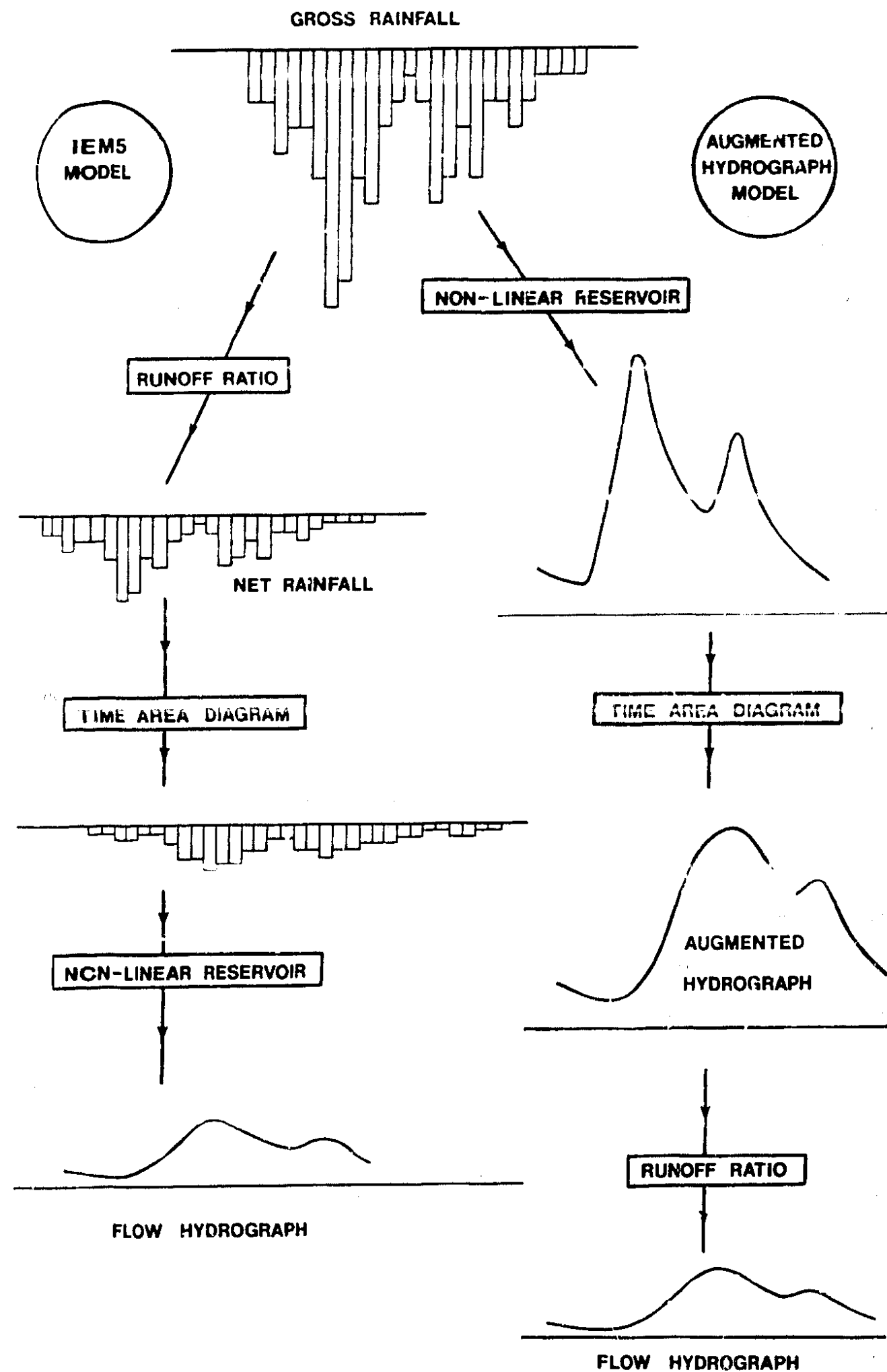


FIGURE 4 COMPARISON BETWEEN INTERMEDIATE RESPONSES OF IEM5 AND AUGMENTED HYDROGRAPH MODELS

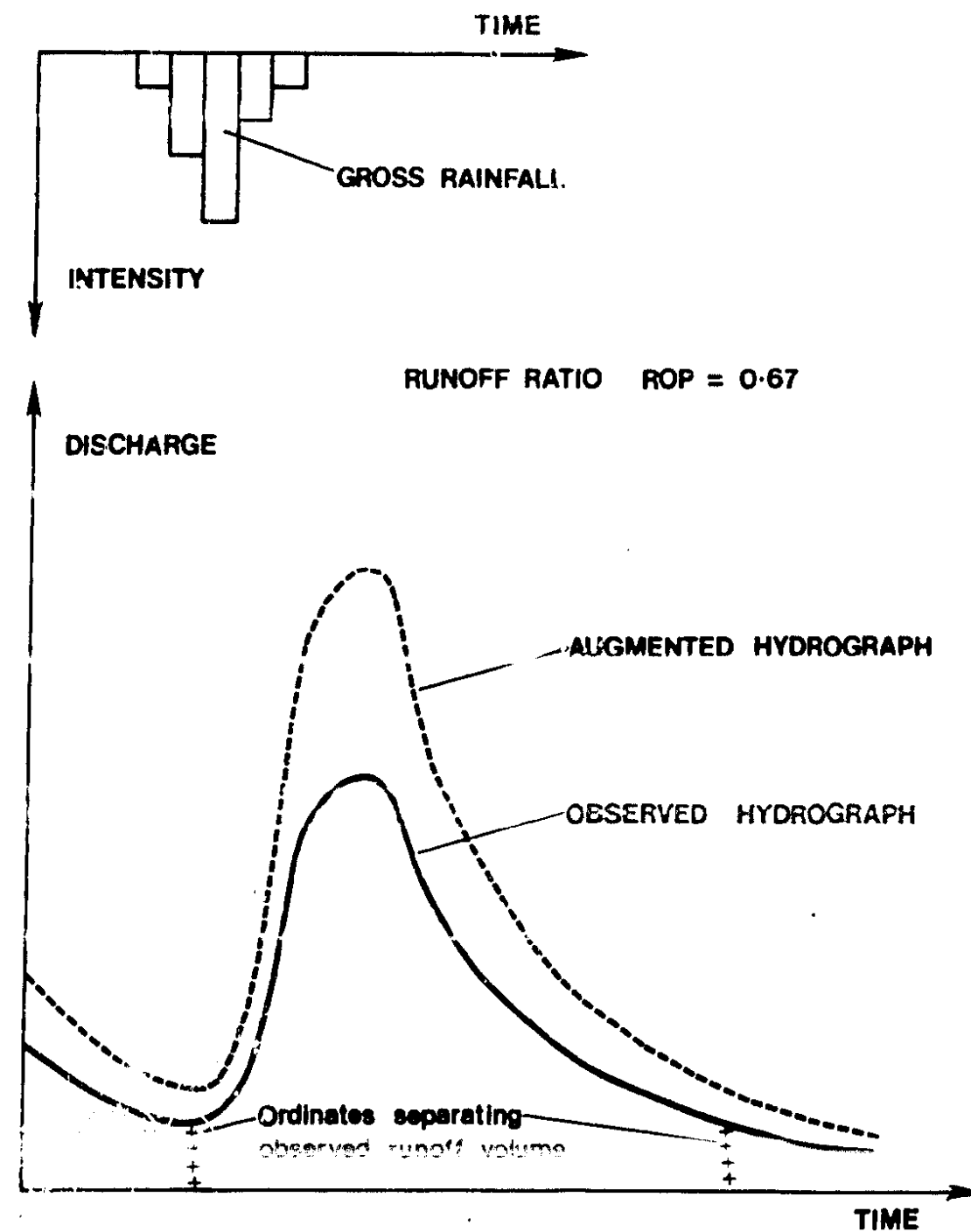


FIGURE 5 DERIVATION OF AUGMENTED HYDROGRAPH FOR AN OBSERVED ISOLATED STORM EVENT

structure of the majority of traditional models. Nearly all rainfall-runoff models have a structure in which the VOLUME REDUCTION component is applied first to the gross rainfall hyetograph to give the net rainfall hyetograph, which is itself input to the SHAPE TRANSFORMATION component to give the flow hydrograph. However some models in the early study of the rainfall-runoff relation did not exhibit this feature. For example, Bernard (1934) introduced the idea of the distribution graph and pluviograph; after development by the US Geological Survey (Hoyt et al, 1936), the method was used by other hydrologists, for example Brater (1939) and O'Kelly (1955), in practical applications.

The distribution graph is defined to be similar in shape to the unit hydrograph but it is derived from the latter's ordinates by dividing by the total volume of runoff; its ordinates therefore represent the proportional distribution of quick response runoff with respect to time. The convolution of the gross rainfall hyetograph with the distribution graph defines the pluviograph for an isolated storm event. Next all ordinates of the pluviograph are multiplied by a runoff coefficient to yield a quick response hydrograph; finally to this is added a base flow to give the output flow hydrograph from the model.

The concept of the augmented hydrograph is therefore broadly equivalent to the concept of the pluviograph. However, the method of deducing the augmented hydrograph differs in two respects from the method used to deduce the pluviograph. Firstly, no prior separation or final addition of base flow is required; secondly, a non-linear relation is assumed between the gross rainfall hyetograph and the augmented hydrograph. Indeed, since the distribution graph and the runoff coefficient are linear systems, the order of application of these two systems is, as noted in Section 5, immaterial, so the model involving the use of the pluviograph is equivalent to the better known model consisting of a runoff coefficient followed by a unit hydrograph. This may account for why the pluviograph concept went out of fashion after a few years, and the traditional order of components became accepted practice.

In the Augmented Hydrograph model the presence of the non-linear reservoir subsystem ensures that it is not possible to rearrange the order of subsystems to replace it by an equivalent traditional form of model. But even if such a model as the IEM5 type had been proposed in the 1930s, the lack of electronic computers would have made it virtually impossible to fit this model to a large group of isolated storm events. Therefore the traditional linear form of model has been the most suitable practical approach to the rainfall-runoff relation over past years.

COMPARISON BETWEEN THE AUGMENTED HYDROGRAPH AND NET RAINFALL CONCEPTS

For any hydrologist studying the rainfall-runoff relation, the finding of net rainfall as a first step in his models is firmly established, and it may be difficult to conceive of an alternative procedure. However, it must be emphasized that net rainfall is no more than a concept introduced to simplify the representation of the rainfall-runoff relation; it is not possible to go out into the field and measure net rainfall.

The argument used occasionally to support the net rainfall concept may be illustrated for the IEM5 model in Fig. 4. As the runoff ratio value approaches unity, the net rainfall hyetograph tends to identity with the gross rainfall hyetograph, so giving it some physical reality. However, to counter this argument, turning to the Augmented Hydrograph model in the same figure, the same change in the runoff ratio ensures that the augmented hydrograph tends to identity with the flow hydrograph, so giving the augmented hydrograph some physical reality as well.

Another difference between the augmented hydrograph and net rainfall concepts is their effect on the response of the models to very intense rainfall. This may be illustrated by considering two storms, one a summer storm with rainfall of 100 mm in 1 time unit and runoff ratio of 0.08, the other a winter storm of 10 mm rainfall in 1 time unit and runoff ratio of 0.80. Applying these two storms as inputs to a model incorporating the net rainfall concept, for example the IEM5 model, the net rainfalls resulting are identical bursts of 8 mm in 1 time unit for both storms. If these two net rainfalls are applied to the shape transformation component of the model, the two flow hydrographs resulting must have identical shapes with the same volume of 8 mm of runoff. On the other hand if the two storms are applied as inputs to the Augmented Hydrograph model, the volume of the augmented hydrograph for the summer storm is 100 mm, whilst that

for the winter storm is 10 mm. Due to the presence of the non-linear reservoir both augmented hydrographs will have recession curves drawn from the identical outflow curve from this reservoir, but the summer storm will have a more spiky augmented hydrograph than that from the winter storm. Even after application of their respective runoff ratios the summer storm flow hydrograph will retain this feature of a more spiky hydrograph, although both summer and winter flow hydrographs will possess the same volume of 8 mm (Fig.6).

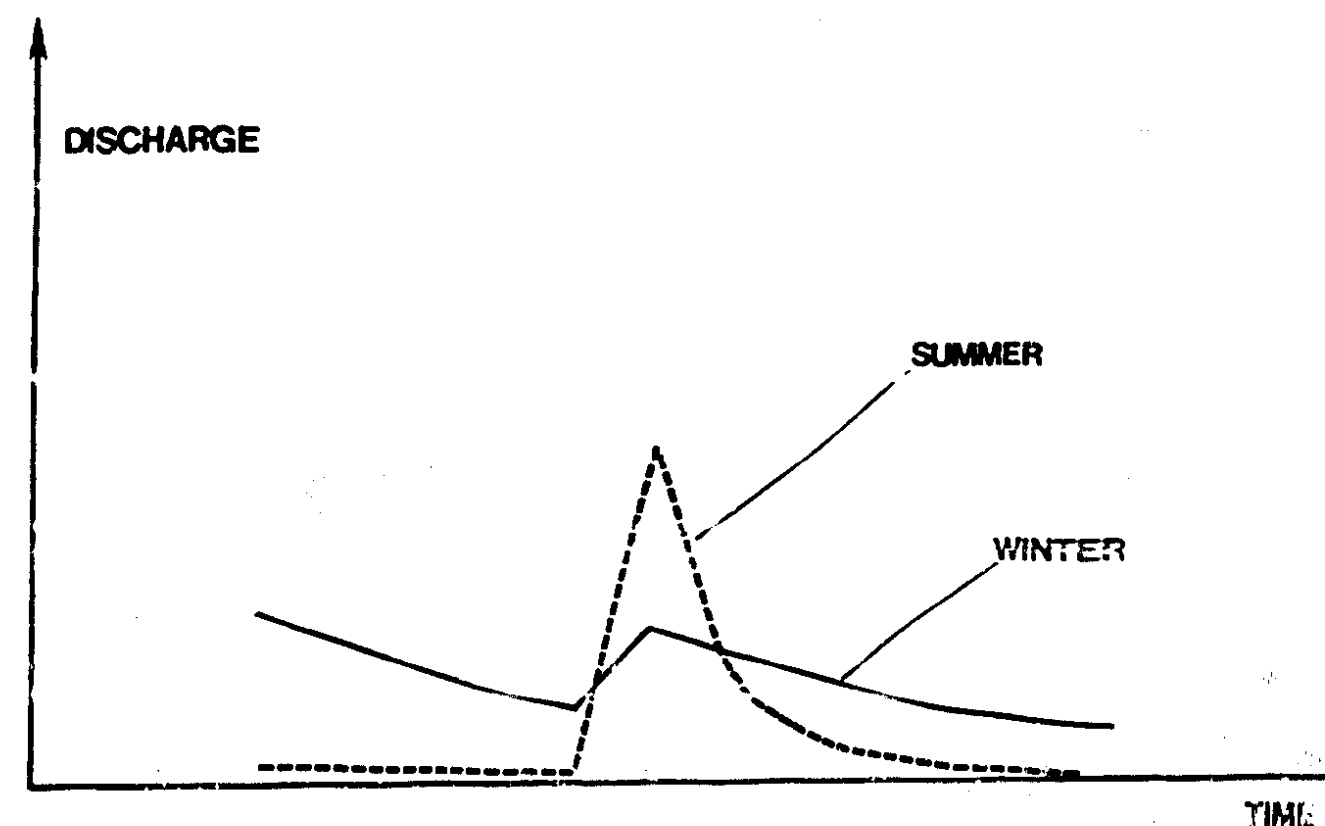


FIGURE 6 CONTRAST BETWEEN AUGMENTED HYDROGRAPH MODEL RESPONSES TO A SUMMER AND WINTER STORM

Since it is only a concept, the idea of net rainfall must be able to withstand scrutiny and measure up to alternative concepts as they arise. This is particularly true if the alternative concept, the augmented hydrograph proposed in this report, has a measure of support from analysis of data drawn from observed isolated storm events.

10 SUMMARY AND CONCLUSIONS

(i) Traditional catchment models split the rainfall-runoff process into two major components, namely volume reduction and shape transformation. Such models assume firstly that these two components are independent of each other, and secondly, that they are applied in the order volume reduction followed by shape transformation.

(ii) A model composed of three subsystems, namely a runoff ratio, time area diagram, and non-linear reservoir, was applied to 66 isolated storm events from the River Ray catchment. A relationship was found between the size of the non-

linear reservoir and the value of the runoff ratio, thus making the two major components of the model no longer independent of each other.

(iii) A new model was proposed containing the same three subsystems but in which the non-linear reservoir precedes the runoff ratio. When fitting this model to the same set of storm events, both the variation in the size of the non-linear reservoir and its previous dependence on the runoff ratio value are considerably reduced.

(iv) The position of the time area diagram subsystem within the model was difficult to determine from studying only the patterns between the input and output sequences of the model, and this problem requires future investigation.

(v) If the time area diagram takes some position other than last, then the shape transformation component precedes the volume reduction component within the new model. The new model supports the idea of splitting the rainfall-runoff relation into two major components, both of which are independent of each other, but challenges the traditional order in which they are applied.

(vi) A further consequence of reversing the traditional order of the major components within the new model is that the intermediate output obtained from applying the gross rainfall hyetograph to the first component takes the form of a hydrograph rather than a hyetograph. This so-called augmented hydrograph provides an alternative concept to that of net rainfall which is the intermediate output from traditional models.

(vii) The hypothesis proposed in this report is based mainly on the results from a detailed study of a single catchment, although other evidence, not described in this report, was also considered (Mandeville, 1975). Preliminary trials on four other catchments show promising support for the hypothesis, and further tests are planned.

ACKNOWLEDGEMENTS

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REFERENCES

- Bernard, M.M., 1934. An approach to determinate stream flow. Proc. A.S.C.E., 60, 3-18.
- Brater, E.F., 1939. The unit hydrograph principle applied to small watersheds. Proc. A.S.C.E.
- Edwards, K.A. and Rodda, J.C., 1970. A preliminary study of the water balance of a small clay catchment. J. Hydrol. (New Zealand), 9(2), 202-218.
- Flood Studies Report. 1975. (Natural Environment Research Council, London), Vol. 1, Sec. 7.3, 513-531.
- Hoyt, W.G. *et al*, 1936. Studies of relations of rainfall and runoff in the United States. U.S. Dept. Int., Geol. Survey, Water Supply Paper 772.
- Mandeville, A.N., 1975. Non-linear conceptual catchment modelling of isolated storm events. Unpublished Ph.D. thesis, University of Lancaster.
- O'Donnell, T. and Mandeville, A.N., 1975. Conceptual catchment modelling of isolated storm events. Proc. Int. Symp. Mathematical models in Hydrology and Water Resources Systems, Bratislava, IAHS Publ. No. 115.
- O'Kelly, J.J., 1955. The employment of unit hydrographs to determine the flows of Irish arterial drainage channels. Proc. I.C.E., Pt 3(4).