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A DISTRIBUTED HYDROLOGICAL MODEL BASED ON THE CONCEPT OF GROUNDWATER RECHARGE, TRANSMISSION, AND DISCHARGE*

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ABSTRACT

A conceptual model is proposed which is distributed on the basis of groundwater flow systems. The fundamental unit of the model is a vertical section in which four groundwater regions are distinguished: a recharge region, a transmission region, a discharge region and a bank storage region. Each region is subdivided into a groundwater zone and a soil moisture zone. The storage and transmission equations are formulated, and a procedure is outlined for routing precipitation through the model.

INTRODUCTION

A distributed hydrological model is proposed which is based on several simplifying concepts concerning the subsurface portion of the hydrological cycle. The model assumes that it is possible to subdivide any basin into four areas: (1) an area which is characterized by net groundwater recharge, i.e. groundwater recharge greater than groundwater discharge; (2) an area of groundwater transmission, i.e. groundwater recharge equal to groundwater discharge; (3) a groundwater discharge area, i.e. groundwater discharge greater than groundwater recharge; and (4) an area where bank storage modifies stream flow. Four well known components of groundwater runoff are recognizable in the model: (1) a 'regional' baseflow component which is routed through the underflow zone; (2) a 'local' baseflow component which is routed through the bank storage zone; (3) a bank storage component; and (4) a soil moisture (interflow) component which is routed across the discharge and bank storage regions under appropriate soil moisture conditions.

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The model has not been developed any further than this presentation. It is hoped that the integration of the simple concepts presented here will further stimulate the development of distributed models, because – in the author's opinion – such models are fruitful media for applied research which will link the lumped models of engineering practice with the classical models of mathematical physics.

THE BASIC CONCEPTS

The proposed model is based on the concept of groundwater recharge in upland areas, groundwater transmission along valley walls, and groundwater discharge in valley bottoms. The groundwater discharge region is conceived as being connected to the stream by a bank storage region. Thus, four subsurface regions are employed in the conceptual model: a recharge region, a transmission region, a discharge region, and a bank storage region. Each region is subdivided into two zones, a groundwater zone and a soil moisture zone. The bank storage region contains two additional zones, the underflow zone and the stream zone. The fundamental unit of the model is illustrated in Fig. 1, which is a schematic, vertical cross section from a major divide to a permanent stream.

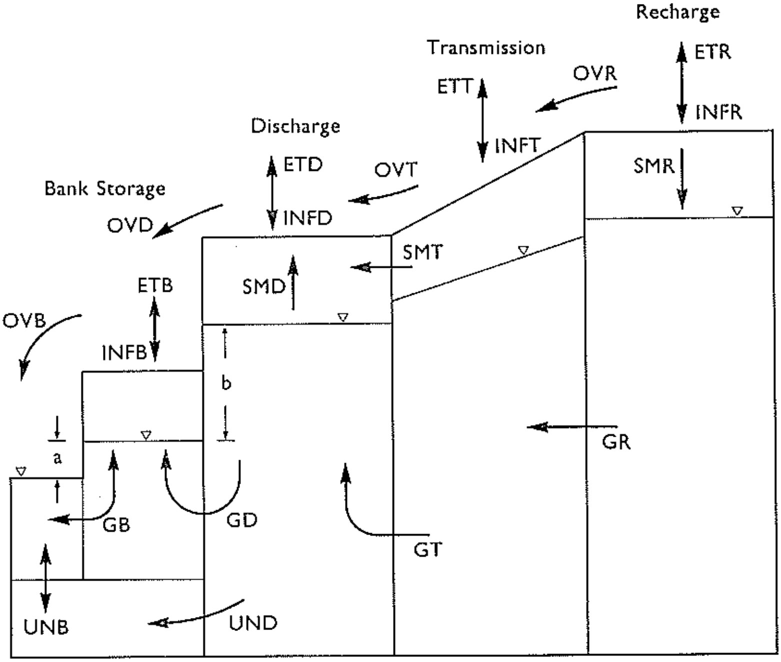

FIG. 1 — The fundamental model unit.

It has been shown that groundwater flow systems are essentially steady-state phenomena and that the non-steady state apparent 'in detail' is due to the distribution and intensity of rainfall, the accumulation and melting of the snowpack, and the mechanisms of recharge and discharge (Lawson, 1970). The steady-state concept is incorporated into the proposed model by fixing the water table depth in the transmission region and routing the groundwater flux from the recharge region to the discharge region without any losses. The non-steady-state concept is incorporated by permitting the water table to fluctuate in the recharge, discharge, and bank storage regions. This permits changes in groundwater storage in these regions. Changes in soil moisture storage are accounted for by varying the volumetric water content.

When infiltration occurs in the recharge region the volumetric water content of the soil moisture zone is increased to accommodate the amount infiltrated. A soil moisture flux to the groundwater zone and the change in the water table depth to accommodate this flux are then calculated. The volumetric water content of the soil moisture zone is then adjusted to account for its depletion by the flux to the water table. During periods when there is no infiltration, both the flux to the water table and evapotranspiration decrease the volumetric water content of the soil moisture zone. The constant groundwater flux from the recharge region to the transmission region is balanced by a fall in the water table.

Infiltration and evapotranspiration in the transmission region are accommodated by varying the volumetric water content of the soil moisture zone. No changes in groundwater storage occur in this region. There is, however, a soil moisture flux out of this region into the discharge region (=interflow), and the volumetric water content in the transmission zone is adjusted so as to supply this flux.

The storage changes in the groundwater recharge and discharge regions are very nearly the opposite of one another. When infiltration occurs in the discharge region the volumetric water content of the soil moisture zone is increased to accommodate the amount infiltrated. However, the soil moisture flux from the water table is always assumed to be vertically upward. The soil moisture flux and the change in the water table depth to accommodate this flux are calculated, and the volumetric water content of the soil moisture zone is adjusted to account for the flux from the water table and the flux from the transmission region. The constant groundwater flux from the transmission region contributes to a rising water table. Two other groundwater fluxes contribute to a falling water table, the variable flux to the groundwater zone in the bank storage region (=the bank storage zone) and the constant flux to the underflow zone. The variable groundwater flux is a function of the difference in water table elevation between the discharge region and the bank storage region.

Infiltration and evapotranspiration in the bank storage region are accommodated by varying the volumetric water content. No fluxes to or from the water table are considered. The water flux to or from the stream is a function of the difference in elevation between the water table and the stream level. Thus, this flux can contribute towards a rising or falling water table. The groundwater flux from the discharge area contributes to a rising water table.

There are two fluxes out of the bank storage region into the bank storage region of the adjacent downstream model unit: a flux out of the underflow zone, and the stream flow. Similarly, there are two corresponding fluxes into the considered bank storage region. The difference between the underflow input and output (including the input from the discharge region) is routed to or from the stream. The surface water flux into and out of the stream zone is a function of the stage of the stream in the considered unit and its upstream neighbour. The stage height for each fundamental unit is determined using a mass balance involving the overland flow to the stream, the flux between the bank storage zone and the stream, the flux to or from the interflow zone and the net surface water flux.

Basin-wide application of the model requires the horizontal distribution of the fundamental model unit described above, i.e. the determination of the number of fundamental units required to describe the basin and the determination of the thickness of each of these units. A preliminary estimate of the number and thickness of the units can be obtained by a study of the basin physiography, precipitation and evapotranspiration. This estimate can then be improved by an optimizing procedure.

Thus, this conceptual model proposes a simultaneous routing of the precipitation on each fundamental unit to its bank storage region, followed by a downstream routing through the bank storage region of each fundamental unit to the basin outlet. The routing details are presented in Appendix 1.

FURTHER CONSIDERATIONS

To facilitate the presentation of the basic concepts of the proposed model, the simplest case has been considered. In particular, the case of precipitation in the form of snow has been omitted. This case would require a third unsaturated zone in each region. It is also possible to subdivide the soil moisture zone into sub-zones with different storage and transmission properties, e.g. a near-surface zone to budget infiltration and evapotranspiration, and a near-water table zone to recharge, discharge and transmit soil moisture. Depression storage has not been considered.

REFERENCE

Lawson, D. W. 1970: A rational approach to groundwater investigations in representative basins. In: *Proceedings of the Symposium on the Results of Research on Representative and Experimental Basins, Wellington, 1970*. IASH Publication No. 96. pp. 652–667.

APPENDIX 1 — Routing Details.

Recharge Region

Consider the routing of a rainfall input PR in the recharge region. The volumetric water content $\varphi(R)$ will be known, the infiltration $INFR$ can be estimated, and the overland flow OVR is calculated as

$$OVR = PR - INFR.$$

A negative calculation for OVR indicates that $OVR=0$ and that $INFR=PR$. Knowing the surface area of the recharge region AR it is possible to calculate a new value for $\varphi(R)$

$$\varphi(R) \leftarrow \varphi(R) + \left(\frac{INFR - ETR}{AR \times HR}\right)$$

where HR is the depth to the water table, and ETR is the evapotranspiration during periods when $PR=INFR=0$. The flux to the water table SMR can be calculated (during both periods of infiltration and evapotranspiration) and knowing the groundwater output to the transmission region GR and the effective porosity $\Phi(R)$, the change in water table depth is

$$\Delta HR = \frac{GR - SMR}{AR \times [\Phi(R) - \varphi(R)]}$$

and the new depth to the water table is

$$HR \leftarrow HR + \Delta HR.$$

The final volumetric water content is then calculated as

$$\varphi(R) \leftarrow \varphi(R) - \left(\frac{SMR}{AR \times HR}\right).$$

Transmission Region

The input to the transmission region is the rainfall *PT* plus the overland flow from the recharge area *OVR*. Overland flow from the transmission region *OVT* is calculated as

$$OVT = PT + OVR - INFT$$

where *INFT* is the infiltration in the transmission region. A new value is calculated for the volumetric water content $\varphi(T)$

$$\varphi(T) \leftarrow \varphi(T) + \left(\frac{INFT - ETT}{VT}\right)$$

where *ETT* is the evapotranspiration, and *VT* is the volume of the soil moisture zone in the transmission region. The interflow to the discharge region *SMT* necessitates a second calculation of $\varphi(T)$

$$\varphi(T) \leftarrow \varphi(T) - \left(\frac{SMT}{VT}\right)$$

Discharge Region

The overland flow from the discharge region *OVD* is given by

$$OVD = PD + OVT - INFD$$

where *PD* and *INFD* are the precipitation and infiltration in the discharge area. If the volumetric water content $\varphi(D)$ is equal to unity, *SMT* is added to *OVD*; otherwise, the new value of the volumetric water content is given by

$$\varphi(D) \leftarrow \varphi(D) + \left(\frac{INFD - ETD + SMT}{AD \times HD}\right)$$

where *ETD* is the evapotranspiration, *AD* is the surface area and *HD* is the depth to the water table in the discharge region. The flux from the water table *SMD* can be calculated; and knowing the groundwater input from the transmission region *GT*, the underflow to the bank storage region *UND*, the effective porosity $\varphi(D)$, and the groundwater flux to the bank storage zone $GD(b)$,

$$\Delta HD = \frac{UND + GD(b) + SMD - GT}{AD \times [\Phi(D) - \varphi(D)]}$$

where *b* is the difference in water table elevation between the discharge region and the bank storage region. The new depth to the water table is thus

$$HD \leftarrow HD + \Delta HD$$

and the final volumetric water content is

$$\varphi(D) \leftarrow \varphi(D) + \left(\frac{SMD}{AD \times HD}\right).$$

Bank Storage Region

The overland flow to the stream *OVB* is

$$OVB = PB + OVD - INFB$$

where *PB* and *INFB* are the precipitation and infiltration in the bank storage region. There are no soil moisture fluxes to or from the water table, and the volumetric water content $\varphi(B)$ is given by

$$\varphi(B) \leftarrow \varphi(B) + \left(\frac{INFB - ETB}{AB \times HB}\right)$$

where *ETB* is the evapotranspiration, *AB* is the surface area and *HB* is the depth to the water table in the bank storage region. The change in the depth to the water table ΔHB is calculated as

$$\Delta HB = \frac{GB(a) - GB(b)}{AB \times [\Phi(B) - \varphi(B)]}$$

where $GB(a)$ is the flux to (= a bank storage component of groundwater runoff *or* baseflow) or from the stream, a is the difference in elevation between the water table and the stream surface, $\Phi(B)$ is the effective porosity, and *AB* is the surface area of the bank storage region. The depth to the water table is thus

$$HB \leftarrow HB + \Delta HB.$$

Further routing in the bank storage region involves horizontal fluxes to and from the adjacent bank storage regions. This routing begins at the fundamental unit furthest upstream and ends at the unit which produces the runoff hydrograph. It may be necessary and convenient to subdivide the bank storage region of each fundamental unit into a number of smaller units, i.e. units which are not as thick as the fundamental unit. This downstream routing is conducted as indicated in the following paragraph.

Knowing the underflow input from the upstream bank storage region $UND(U)$, the output to the downstream bank storage region $UND(D)$ and the input from the discharge region *UND*, it is possible to calculate the underflow flux to

(= baseflow) or from the stream UNB

$$UNB = UND(U) - UND(D) + UND.$$

This value is then used in the stream flow routing to calculate the change in stage ΔHS

$$\Delta HS = \frac{OVB + UNB + GB(a) + S(U) - S(D)}{AS}$$

where $S(U)$ is the stream flow input from the upstream bank storage region, $S(D)$ is the stream flow output to the downstream bank storage region and AS is the area of the stream. $S(U)$ is a function of the stream stage in the upstream region and $S(D)$ is a function of the stream stage in the region under consideration.

NOTE:

The symbol ← indicates that the quantity on the left hand side of the symbol is the result of updating the current value of the quantity, thus

$$A \leftarrow A + B$$

indicates that A is to be replaced by the available value of A plus B.