STOCHASTIC MODEL FOR THE WATER CYCLE*

By

I. Kontur

Department of Hydraulic Engineering, Institute of Water Management and Hydraulic Engineering, Technical University, Budapest

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Presented by Prof. Dr. M. Kozák

In engineering practice, hydrology is defined as a discipline concerning the terrestrial circulation of water. The water balance or hydrological equation, more exactly, the conservation of matter or continuity equation is a fundamental relationship which always can successfully be applied. In this paper the hydrologic cycle will be investigated and a general model established for simulating the water cycle. The water movement follows a probability law: namely, the transition probability matrix. The transition probability matrix, of stochastic character, will be used for continuity equation.

1. Fundamentals

1.1. *The water particle*

The hydrologic cycle will be described by the movement of the water particle, understood here, rather than in its everyday meaning, as an infinitesimal undivisible (atomic) volume unit, either e cm^3, e litre, e m^3 or any other volume e arbitrarily selected for unit.

1.2. *Segments*

The investigation of the water cycle or water balance is always related to a zone of the atmosphere or earth exactly circumscribed by segments. Remind that segments represent a wider class in that also segments beyond the geometric boundaries can be imagined, however, without geometrical interpretation.

* Exposition of a principle by the author awarded the second price at the Bogdánfy Competition in 1973. [1].

Let vector Γ denote the boundaries $\Gamma(\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_l)$ where $\gamma_1, \gamma_2, \ldots, \gamma_l$ totally surround the tested space:

$$\gamma_1 \cup \gamma_2 \cup \ldots \cup \gamma_l = E \tag{1}$$

(read: the union of $\gamma_1, \gamma_2, \ldots, \gamma_l$ is equal to the unit).

Besides:

$$\gamma_i \cap \gamma_j = 0 \qquad i,j = 1, 2, \ldots, l, \tag{2}$$

i.e., the segments γ_i; γ_j do not overlap.

1.3. *States*

It is also important to determine the position of the water particle within the system, helped by the states. They are a wider class than the geometric location in that there are more states than necessary for locating the water particle. For example, snow and molten snow found in the same place designate states in the strict sense of the word.

It should be noted that such an interpretation of the wider class of states permits to simulate not only the hydrologic cycle quantitatively but also the change of water quality, significant field of future research investigations.

Let vector $\Sigma(s_1, s_2, \ldots, s_m)$ denote the states within the space investigated.

Be

$$s_1 \cup s_2 \cup \ldots \cup s_m = E, \tag{3}$$

further

$$s_i \cap s_j = 0 \qquad i,j = 1, 2, \ldots, m \tag{4}$$

The definitions of the states and segments together mean physically that the closing segments are quite closed (1), with no overlappings (2), on the other hand, in the internal space all of the possible states are denominated (3), but also can be distinguished (4).

The probability that the water particle enters (or leaves) the system through segment $\gamma_1, \gamma_2, \ldots, \gamma_l$ equals complete certainty:

$$\sum_{i=1}^{l} P(Y \mid \gamma_i) = 1 \tag{5}$$

where Y denotes the event of entering (leaving). Further, the probability that the water particle being within the system is either in the state s_1 or $s_2, \ldots,$ or s_m equals complete certainty:

$$\sum_{j=1}^{m} P(X \mid s_j) = 1 \tag{6}$$

wherein X denotes the event of staying within the system.

Eqs (1) to (4) and (5), (6) may be read off the exemptness of sources or sinks either on the system boundary or within the system. Or else, if such exist, they are denominated by segments and states.

1.4. *The time*

To describe the movement of the water particle needs to define the concept of time.

The water particle changes its state or is moving at moments $t_1, t_2, \ldots$ $\ldots, t_n$.

Be $t_1 < t_2 < \ldots < t_n$,
and further simplifying the definition of the moments to

$$t_i - t_{i-1} = \Delta t = 1, \qquad i = 2, 3, \ldots n \tag{7}$$

it is sufficient to designate the moments by numbers 1, 2, . . . , n.

Be Δt $[T]$ the time unit, and e $[L^3]$, the water particle unit, the unit of the water discharge will be:

$$\frac{e[L^3]}{\Delta t[T]}.$$

1.5. *State changes. The motion*

In the following, the motion of the water particle will be defined. The water particle can pass from state i to j at every moment $t_1, t_2, \ldots, t_n$ with a probability P_{ij} where, for convenience, the state might also mean a segment. Namely, the water particle can pass from states $\gamma_1 \ldots \gamma_l$ and $s_1 \ldots, s_m$, of a number $(l + m)$ to states $\gamma_1, \ldots \gamma_l$ and $s_1, \ldots s_m$, of a number $(l + m)$.

Or written in hypermatrix form:

$$\begin{matrix} & \overbrace{\quad}^{\Gamma} \; \overbrace{\quad}^{\Sigma} \\ \begin{matrix} \Gamma\{ \\ \Sigma\{ \end{matrix} & \left[\begin{array}{c|c} \mathbf{Q} & \mathbf{V} \\ \hline \mathbf{U} & \mathbf{P} \end{array}\right] \end{matrix} \tag{8}$$

where:

Q — square matrix size $(l \times l)$ with elements q_{ij} involving probabilities of passing from one segment to the other;

P — square matrix size $(m \times m)$ with elements p_{ij} including probabilities of passing from one internal state to the other;

U — rectangular matrix size $(m \times l)$ with elements u_{ij}, including probabilities of passing from an internal state to a segment;

V — rectangular matrix size $(l \times m)$ with elements v_{ij} including probabilities of passing from a segment to an internal state.

Let vector $y(t)$ $[y_1, y_2, \ldots, y_l]$ designate the probability $y_1, y_2, \ldots, y_l$, of that at moment t the water particle is in segment $\gamma_1, \gamma_2, \ldots, \gamma_l$, and the vector $x(t)$ $[x_1, x_2, \ldots, x_m]$ the probability $x_1, x_2, \ldots, x_m$ of that the water particle is in state $s_1, s_2, \ldots, s_m$.

In knowledge of hypermatrix **Q**, **P**, **U**, **V** (8), with $y(t)$, $x(t)$ known, also the probability of the water particle to be at moment $t + 1$ in $y(t + 1)$ and $x(t + 1)$, may be determined :

$$[y(t+1), x(t+1)] = [y(t), x(t)] \cdot \left[\begin{array}{c|c} \mathbf{Q} & \mathbf{V} \\ \hline \mathbf{U} & \mathbf{P} \end{array}\right]. \tag{9}$$

This formula is of decisive significance in the following. Namely, matrix (8) is a stochastic matrix, therefore

$$\sum_{j=1}^{l} q_{ij} + \sum_{j=1}^{m} v_{ij} = 1 \qquad i = 1, 2, \ldots, l$$

and

$$\sum_{j=1}^{m} u_{ij} + \sum_{j=1}^{l} p_{ij} = 1 \qquad i = 1, 2, \ldots, m. \tag{10}$$

As mentioned earlier, Eq. (10) includes the continuity equation, i.e., no water particle is lost or arising.

Rather than in changes of state of a single water particle, we are, however, interested in the motion of N units, N water particles. The law of motion, the probability of state changes of N water particles is supposed to be the same as for a single water particle, which means linearity of this system.

Namely if there are N water particles in segment i at moment t, then at moment $t + 1$, $q_{ij} \cdot N$ water particles get in segment j, and $v_{ik} \cdot N$ water particles get to state k, where $i, j = 1, 2, \ldots, l$ and $k = 1, 2, \ldots, m$. Again, if at moment t, N particles of water are in state i so, at moment $t + 1$, $p_{ij} \cdot N$ water particles get to state j, and $u_{ik} \cdot N$ particles get to segment k, where $i, j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, l$.

Since $0 \leqq q_{ij}, v_{ij}, u_{ij}, p_{ij} \leqq 1$, for every i and j, therefore only a fraction of the water of mass N is passing on.

1.6. *Graph representation*

The presented model of the hydrologic cycle may be well illustrated by graphs. There is a well-known analogy between the graph representation of the stochastic matrices and the graphs written in matrix form. The graph nodes mean the states and segments; the graph edges the direction of moving of the water particle, i.e., the transitions.

The transition probability matrix may often significantly be simplified because many of its elements are zero. This may be determined in advance on the basis of physical consideration, if e.g. the water particle cannot pass from one state to the other in a single step Δt. Since these graph edges disappear, also the graph of the hydrologic cycle will be simplified.

2. Examples

2.1. *Modelling of the catchment area*

A very simplified hydrologic cycle will be investigated by considering the runoff of the catchment. Consider, for example, a catchment area (Fig. 1a) with a segment γ_1 at the air side, a segment γ_2 under the soil surface and a segment of effluent γ_3, identical to the cross section of the runoff. Be the water under the soil surface in state s_1, the water under the soil surface in state s_2, that is, $\Gamma(\gamma_1, \gamma_2, \gamma_3)$ and $\Sigma(s_1, s_2)$. The transition probability matrix will be written in detail on the basis of (8), then the sequence of ideas simplifying the matrix on physical considerations will be followed.

The transition probability matrix of the system shown in Fig. 1b is:

$$\begin{array}{c} \\ \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ s_1 \\ s_2 \end{array}
\begin{array}{c} \begin{array}{ccccc} \gamma_1 & \gamma_2 & \gamma_3 & s_1 & s_2 \end{array} \\
\left[\begin{array}{ccc|cc}
q_{11} & q_{12} & q_{13} & v_{11} & v_{12} \\
q_{21} & q_{22} & q_{23} & v_{21} & v_{22} \\
q_{31} & q_{32} & q_{33} & v_{31} & v_{32} \\
\hline
u_{11} & u_{12} & u_{13} & p_{11} & p_{12} \\
u_{21} & u_{22} & u_{23} & p_{21} & p_{22}
\end{array}\right] \end{array}
= \left[\begin{array}{c|c} \mathbf{Q} & \mathbf{V} \\ \hline \mathbf{U} & \mathbf{P} \end{array}\right] \qquad (11)$$

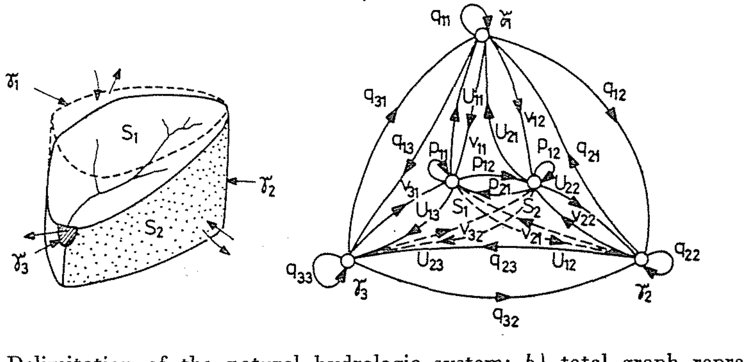


Fig. 1. a) Delimitation of the natural hydrologic system; *b)* total graph representation

Let us see, in turn, each transition probability. From the moisture retained in the atmosphere, some remain there with a probability q_{11}. From here, the particle passes to the subsoil segment γ_2 and the effluent segment γ_3 with zero probability, i.e., $q_{12} = q_{13} = 0$. The water particle comes from the atmosphere to the soil surface with a probability v_{11}, but of getting to the subsurface reservoir s_2, the probability is zero ($v_{12} = 0$).

From the subsurface segment γ_2 the water particle cannot pass directly either to the atmosphere γ_1 or to the effluent segment γ_3 or to the soil surface s_1, i.e., $q_{12} = q_{23} = v_{21} = 0$. But $q_{22} \neq 0$ and $v_{22} \neq 0$.

The water particle passing over the effluent cross section cannot get but in segment γ_3 with a probability of 1 and then, either the outflow in segment γ_3 will be summarized, or $q_{33} = 0$ yielding the water discharge. From the above it follows that $q_{31} = q_{32} = v_{31} = v_{32} = 0$.

The water particle may get from state s_1 in segments γ_1 and γ_3 to states s_1 or s_2. This means that the water either evaporates from the catchment surface with a probability u_{11} or runs off with a probability u_{13} or infiltrates into the soil with a probability p_{12}, or remains in place with a probability p_{11}.

From the water under the soil surface the water particle leaves through the segment γ_2 with a probability u_{22} or comes to the surface s_1 with a probability p_{21} or remains in place with a probability p_{22}. Thus, $u_{21} = 0$ and $u_{23} = 0$.

With the above simplifications, the transition probability matrix (11) of the system becomes:

$$\left[\begin{array}{ccc|cc} q_{11} & 0 & 0 & v_{11} & 0 \\ 0 & q_{22} & 0 & 0 & v_{22} \\ 0 & 0 & q_{33} & 0 & 0 \\ \hline u_{11} & 0 & u_{13} & p_{11} & p_{12} \\ 0 & u_{22} & 0 & p_{21} & p_{22} \end{array}\right].$$

The graph of the simplified system is seen in Fig. 2.

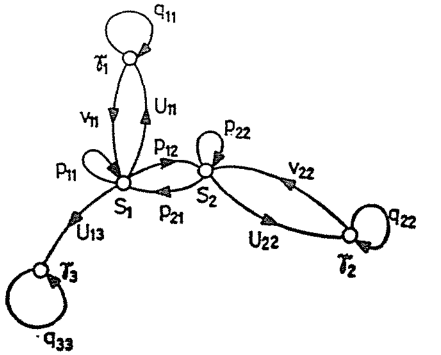


Fig. 2. **Simplified graph representation of the hydrologic system**

2.2. *Stochastic model of the hydrologic cycle in the Tisza river*

Let us now examine in what steps the transition probability matrix may be established from the measurement data, based on average statistical characteristics. The data collection relating to the hydrological regimen of the Tisza compiled by L. SZLÁVIK [2] lent a useful help in this work. For objective reasons, data in the collection originated from the measurement stations' network over the historical area of Hungary, referring to the period from 1890 to 1918, of cause, irrelevant to the procedure of establishing the transition probability matrix. As a matter of course, the runoff conditions might change during the last 62 years, but no acceptable measurement data are available for this period.

Let us examine the characteristic components of the hydrological regimen of the Tisza at the River Stations Tiszabecs and Tokaj (Table 1):

Table 1

		Tiszabecs	Tokaj
F,	Catchment areas (km^2)	9710	49 450
C,	Rainfall (mm/year)	1073	805
L,	Runoff (mm/year)	613	295
P,	Evaporation (mm/year)	460	510
$\alpha = \frac{L}{C}$	Runoff coefficient [−]	0.565	0.366
$\beta = \frac{P}{C}$	Evaporation coefficient [−]	0.435	0.634
L_a	Groundwater runoff mm/year	222	127
B	Infiltration mm/year	682	637

Similarly to the runoff coefficient, the part evaporated of the rainfall is called evaporation coefficient β. There are, in this case, two segments, one of them towards the atmosphere (γ_1), the other being the flow sections at Tiszabecs and Tokaj (γ_2) and the inflow and outflow under the soil surface are assumed to be zero. This means that the rainfall leaves through the effluent cross section with a probability $p = \alpha$ and through the segment of the atmosphere side, i.e., evaporates, with a probability $p = \beta$.

In [2] also the values of the groundwater runoff and infiltration were available, permitting to calculate also the state of underground storage s_1.

Water resources in the river bed of the Tisza and in surface reservoirs may be assumed to be only an insignificant part of subsurface water resources, therefore the surface water quantity needs not be separately denoted, it being an approximate analysis. For the sake of computer treatment, because of process simulation by a transition probability matrix, rainfall evaporation obtained separate segments γ_1 and γ_2. The cross section of the outflow is segment γ_3. The catchment area is characterized by a single state s_1.

According to [2], the average and the maximum of the water amount stored on the surface and participating in the surface water cycle were 323 mm and 665 mm, resp., in the cross section of Tiszabecs, and 240 mm and 637 mm, resp., at the Tokaj River Station. Therefore water resources on the surface and in underground reservoirs may be assumed with a great probability to renew every year; namely, the average period of water exchange is 3,5 or 3,6 months, equivalent to 3 or 4 per cent of stagnation probability. This value may be neglected, therefore $p_{11} = 0$.

Let us determine the probabilities q_{13}, v_{11}, u_{12} and u_{13} from the water balance data (Table 2).

Table 2

		Tiszabecs	Tokaj
Immediate surface runoff from rainfall	$q_{13} = \frac{C-B}{C}$	$\frac{1073-682}{1073} = 0.364$	$\frac{805-637}{805} = 0.21$
Infiltration from rainfall (storage)	$v_{11} = \frac{B}{C}$	$\frac{682}{1073} = 0.636$	$\frac{637}{805} = 0.79$
Evaporation from storage	$u_{12} = \frac{P}{B}$	$\frac{460}{682} = 0.675$	$\frac{510}{637} = 0.80$
Subsurface (indirect) runoff from storage	$u_{13} = \frac{L_a}{B}$	$\frac{222}{682} = 0.325$	$\frac{127}{637} = 0.20$

Thus, the probability matrix for the case of the Tiszabecs River Station:

$$\left[\begin{array}{ccc|c} 0 & 0 & 0.364 & 0.636 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 0.675 & 0.325 & 0 \end{array}\right]$$

and for the Tokaj River Station:

$$\left[\begin{array}{ccc|c} 0 & 0 & 0.21 & 0.79 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 0.80 & 0.20 & 0 \end{array}\right].$$

Or, in graph representation (Fig. 3):

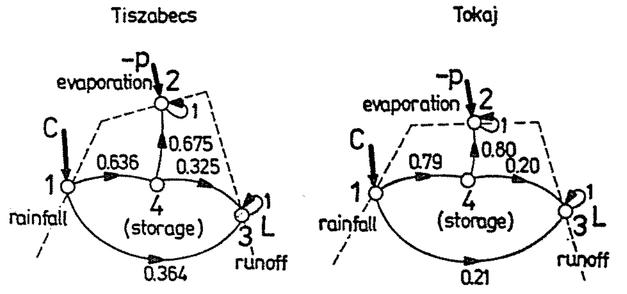


Fig. 3. Graph representation for the River Stations Tiszabecs and Tokaj on the basis of a yearly water balance

Fixing the yearly moments is but a rough description of the process, and neglects just the internal storage of the system.

Taking the monthly water balances with two internal states into consideration, for the Tiszabecs and Tokaj River Stations the following transition probability matrices have been established:

for Tiszabecs:

	C	P	L	s_1	s_2
C	0	0	0.3	0.6	0.1
P	0	0	0	1	0
L	0	0	1	0	0
s_1	0	0	0.2	0.3	0.5
s_2	0	0	0.2	0.1	0.7

and for Tokaj:

	C	P	L	s_1	s_2
C	0.337	0	0.163	0.5	0
P	0.2323	0.0667	0	0.5	0.2
L	0	0	1	0	0
s_1	0	0	0.3	0.2	0.5
s_2	0	0	0.2	0.2	0.6

The graph representation of the probability matrices describing the monthly water balance is seen in Fig. 4.

The model of the Tisza catchment area represents the case where also evaporation is an external active factor to be taken, however, with a negative sign in the water balance into account.

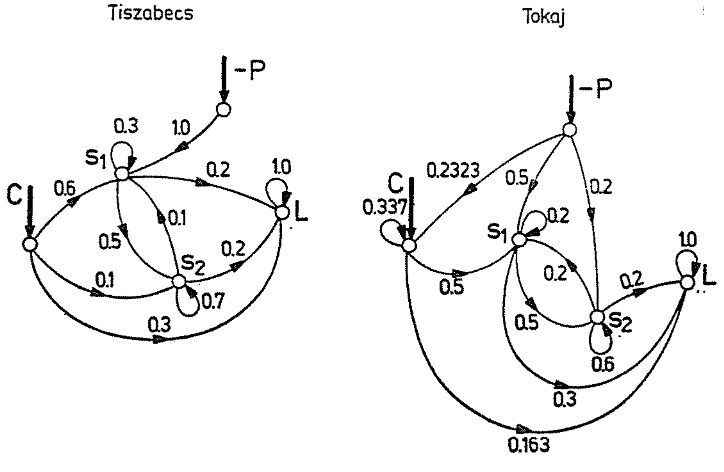


Fig. 4. Graph representation for the River Stations Tiszabecs and Tokaj on the basis of a monthly water balance

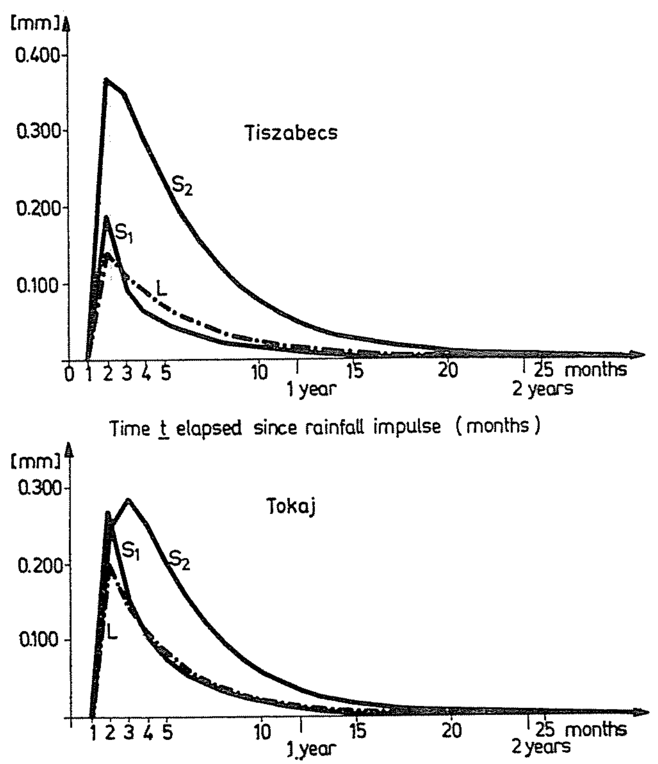


Fig. 5. Response functions to the rainfall impulse in the surface (s_1), subsurface (s_2) storages and in the runoff (L) of the River Stations Tiszabecs and Tokaj

Raising the transition probability matrix to power yields the runoff wave pattern from unit rainfall (1 mm/month), i.e., the response to unit pulse input, as well as the development of the water resources in the surface and subsurface reservoirs s_1 and s_2 under the impact of unit rainfall. Response functions to unit pulse rainfall input have been plotted in Fig. 5. Similar to the rainfall pulse, also the water losses due to unit evaporation (1 mm/month) from surface and subsurface storages as well as through the effluent segment may be studied (Fig. 6). The response functions to unit pulses may simply be established by raising the transition probability matrices to power. (For details see [3].)

By making use of the transition probability matrix as well as of the rainfall and evaporation hydrograph as input data, the runoff hydrograph

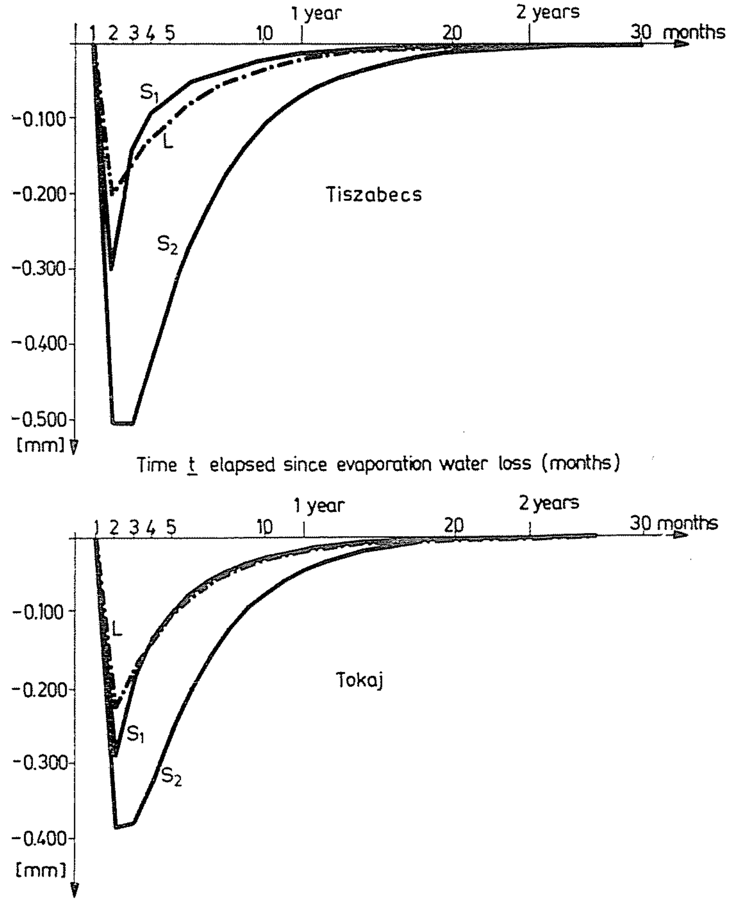


Fig. 6. Response functions to 1 mm/month losses of evaporation in the surface (s_1), subsurface (s_2) storages and in the runoff (L) of the River Stations Tiszabecs and Tokaj

may be established [1]. By comparing the measured and the calculated runoff hydrographs, the elements of the transition probability matrix can be improved and statistically optimized [1, 5, 6].

Special cases of the stochastic model of the hydrologic cycle are cascade-type water catchment models [7, 8, 9]. In the case of cascade-type catchment models for either free or forced water collection, the resulting special probability matrix of transition is advantageous for the calculation.

2.3. *The stochastic water-balance model of the world*

Data relating to the global water balance of the world are, in general, available [10]. The water balance of the world may be established to different depths, referring to water resources in the soil, rivers, lakes, in form of biological water, groundwater, etc. Here only four states of the water resources of the Earth will be distinguished: water particles in the atmosphere (s_1), or on land (in rivers, lakes, in the soil) (s_2), in the oceans (s_3), or in the polar ice sheet (s_4). The yearly water circulation between the four states in units of 10 km^3/year has been compiled in Table 3.

Table 3

	To atmosphere (s_1)	To land (s_2)	To oceans (s_3)	To ice sheet (s_4)
From atmosphere (s_1)	474.5	108.0	416.0	1.8
From land (s_2)	71.7	6400.0	38.0	0.0
From ocean (s_3)	454.0	0.0	380.5	0.0
From ice sheet (s_4)	0.1	0.0	1.2	1.6

The items along the diagonals in Table 3 have been calculated from the volume and from the turnover time of the water in atmosphere, land, oceans and ice sheets (Table 4).

Table 4

	Volume of water V 10^3 km^3	Turnover time T year	$\frac{V}{T}$ $\frac{10^3 \text{ km}^3}{\text{year}}$
Atmosphere	13	10/365	474.5
Land	64 000	(10)	6400
Oceans	1 370 000	3 600	380.5
Ice sheet	24 000	15 000	1.6

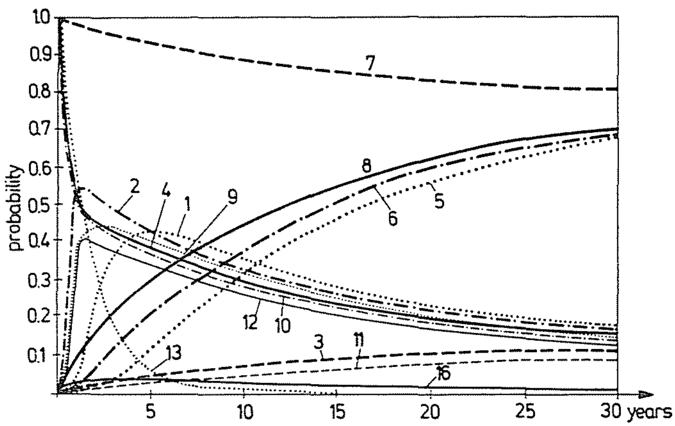
One year seems to be a rather unreliable period for the turnover time and it would be more correct to rely on a longer period. It is to the detriment of the final result accuracy but suits demonstration of the method.

The water balance of the world is in equilibrium, namely water may be assumed not to arise and not to disappear, and the four states mentioned above include all forms of water.

From the point of view of water management, the world is a closed unit, hence there are only internal states (s_1, s_2, s_3, s_4) and no segments. The transition probability matrix may, accordingly, be calculated from the data in Table 3, so that row-wise summations yield the unity:

$$\mathbf{P} = \begin{bmatrix} 0.47436 & 0.10797 & 0.41587 & 0.000180 \\ 0.01101 & 0.98314 & 0.00585 & 0.0 \\ 0.54404 & 0.0 & 0.45596 & 0.0 \\ 0.03448 & 0.0 & 0.41379 & 0.55173 \end{bmatrix}.$$

Raising the transition probability matrix to power yields the probability for a water particle starting from the atmosphere, land, oceans or from the polar ice cap, to be found in the atmosphere, land, in the oceans and in the polar ice sheet after 1, 2, . . .,t years. The above $4 \times 4 = 16$ different probabilities plotted versus time are shown in Fig. 7. On the basis of the transition prob-



from the polar ice sheet	from the oceans	from the land	from the atmosphere	
1	2	3	4	to the atmosphere
5	6	7	8	to the land
9	10	11	12	into the oceans
13	14	15	16	to the polar ice sheet

Fig. 7. Development in time of the water balance probabilities of the world

ability matrix, the vector of the limit probability approximately is: 0.14; 0.71; 0.14; 0.01; that is, after an infinite period, practically after 50 to 100 years, there is a probability of 14 percent that a water particle starts in the atmosphere, 71 percent that on the land, 14 percent that in the oceans and 1 percent that in polar ice sheets.

It should be noted that the markedly high value for the land is due to the turnover time of one year assigned.

According to the examples presented above, the transition probability matrix may also be written for different units of the hydrologic system in knowledge of the water balance components and the turnover time.

Summary

A new approach to the hydrological cycle is presented, permitting to formulate it rather precisely, clearly and in a simple mathematical, computerizable form. The starting idea relies on the probability simulation of the travel of the water particle, finally, leading to the state description by Markov's chains, arriving at in a physical way, by following the travel of the water particle. The mathematical formulation permits to characterize, to simulate and to forecast the hydrological system.

Application of the stochastic model of the hydrological cycle has been illustrated on examples. Practical instruction has been given to the determination of elements of the transition probability matrix describing the hydrological cycle from components of the water balance. The two examples presented referred to two gauge lines of the Tisza river and to the world water-balance.

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Dr. István Kontur, H-1521, Budapest

* In Hungarian