The impasses of modern "physically-based" hydrological modelling

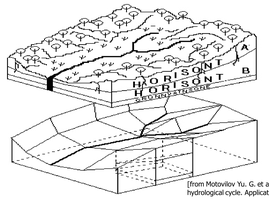
VIOLATION OR

[pretending to know the physics of the runoff processes?]

Approximation of the basin surface by set of finite elements

AND

Use of an inadequate equations



[from Motovilov Yu. G. et al. ECOMAG: Regional model of hydrological cycle. Application to the NOPEX region]

Water dynamics in soil Richard's equation

$$\frac{\partial\theta}{\partial t}=\frac{\partial\left[D(\theta)\frac{\partial\theta}{\partial z}-K(\theta)\right]}{\partial z}$$

θ – volume moisture, $\boldsymbol{D(\theta)}$ – moisture diffusion coefficient, $\boldsymbol{K(\theta)}$ – hydraulic conductivity, $\boldsymbol{t}$ – time, $\boldsymbol{z}$ – soil depth

1. Parallel between the "diffusion of soil water" and heat conductivity: ***suspended moisture existence is impossible?***
2. The Hallaire's effect
3. Nonlinearly dependence of ***D*** and ***K*** on soil moisture
4. Change of ***D*** in 10^4 and ***K*** in 10^5 - 10^7 times corresponds to the range of natural variation of soil moisture

Slope and channel flow Saint-Venant equation

$$\alpha_1\frac{\partial V}{\partial t}+\alpha_2 V\frac{\partial V}{\partial x}+g\frac{V|V|}{C^2H}+\frac{Vq}{H}=g(\sin\alpha-\frac{\partial H}{\partial x})$$

$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}+H\frac{\partial V}{\partial x}=q$$

$\boldsymbol{t}$ - time, $\boldsymbol{x}$ – distance;$\boldsymbol{H}$ – depth, $\boldsymbol{V}$ – velocity, $\boldsymbol{q}$ – inflow, $\boldsymbol{C}$ – Chezy coefficient, α_1, α_2 – coefficients

1. Water movement is represented by a thin continuous water layer
2. Disagreement between units of flow depth (mm) and grid sizes (km)
3. Requirement for absent information (morphology, roughness)
4. No possibility to evaluate the described process except by runoff at the outlet
6. Exaggeration of slope distances and underestimation of slope inclination in spatial schematization

Underground flow Boussinesq equation

$$\mu\frac{\partial H}{\partial t}=K\frac{\partial\left(H\frac{\partial H}{\partial x}\right)}{\partial x}$$

$\boldsymbol{K}, \mu$ – filtration and water yield coefficients of rock, $\boldsymbol{H}$ – level of ground waters over the surface of impervious bed or piezometric head in the case of heady movement, $\boldsymbol{t}$ – time, $\boldsymbol{x}$ – distance

1.True structure of the underground aquifers is unknown
2. Information on quantity and stratigraphy of impervious beds and aquifers is required and ABSENT (e.g. capacity, inclinations, connection with underground and external channel system, filtration and water yield coefficients

CALIBRATION DEPENDENCY (ADDICTION?):

1) different methods = different parameters 2) no way to transfer parameters from one basin into another

MAIN PROBLEMS OF HYDROLOGICAL MODELLING *[BEVEN, 2001]*

Nonlinearity

- It's caused by the use of nonlinear differential equations. "…Why the linear systems are so important? The answer is easy: because we can solve linear equations" (R. Feynman, 1965).
- Only the averaging of calculated results, and not of the model's parameters, is admissible.
- Nonlinear finite equations are simple and effective in hydrology.

SCALE

The scale problem calls for a conflict with essential fundamentals of physics suggesting that the process of runoff formation must be the same in any point of space. The latter implies that mathematical theory and parameters must be the same for all scales if the model is adequate to the natural processes.

Uncertainty

?

Our comments

Equifinality

- It's caused by calibration;
- Multiple implementation of the models at the variety of basins (different conditions, sizes…) can easily eliminate this problem

Uniqueness

This problem can be solved by use of physically-based parameters and their systematization for given landscape types.

EXAMPLE OF AN ALTERNATIVE APPROACH

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MAINTANANCE OF MAIN MODELLING RULES (LAWS?)

The parameters of equations should not depend on the arguments or sought functions

Adequacy to natural processes

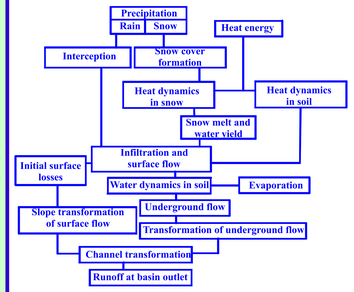
Use of only available data (otherwise, simplification of the model)

LOOKING FOR THE UNIVERSALITY : THE 'HYDROGRAPH' MODEL

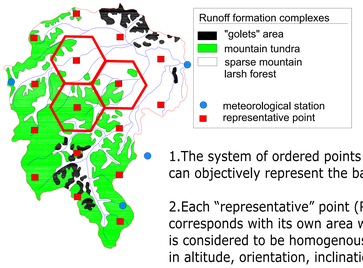
In general

- Universal (any geographical zone, basins of any size)
- Spatial and vertical distribution of model parameters
- 24-hour or less calc.interval
- Aprioiri evaluation of most parameters
- Input: air temperature, deficit of moisture, precipitation
- Output – runoff hydrographs, distributed variable states, water balance elements

I.Model flowchart



II. Basin schematization (system of ordered points + runoff formation complexes)



1.The system of ordered points can objectively represent the basin.

2.Each "representative" point (RP) corresponds with its own area which is considered to be homogenous in altitude, orientation, inclination...

3.Runoff variables from each RP are summed up at the basin outlet according to their travel time.

Runoff formation complex (RFC) (= landscape)
is the area with relatively homogeneous type of runoff formation (soil, vegetation, basin surface)

Main model parameters are systematized by RFC:

- Soil properties: density; porosity; maximum water holding capacity;infiltration coefficient; specific heat capacity and conductivity; the index of ice content influence at infiltration; the contribution ratio to evaporation...
- Vegetation cover: phenological dates; maximum and minimum values of seasonal shadow fraction by vegetation cover, interception water capacities, landscape albedos, the coefficients of potential evaporation...
- Slope surface: maximum and minimum values of the snow redistribution coefficient;spatial variation coefficient of SWE in snow cover; spatial variation of infiltration capacity of upper soil layer; maximum ponding fraction; maximum surface depression storage; orographic shadow fraction...

III. The concept of runoff elements

The basin is constituted by the set of elementary slopes or watersheds, which, in their turn, consist of runoff elements system. A runoff element is a part of a surface or underground elementary slope or watershed limited by micro-divides which is directed with its open part to the slope non-channel or underground drainage system.

The runoff elements can be surface, subsurface (soil) and underground. Their linear dimensions change over an extremely wide range: from several centimetres (at the surface of eroded slopes) to many (tens, hundreds, thousands) kilometres (in the underground lithosphere structures).

For each runoff element there is the usual water balance relation

$$dW/dt=S-R \qquad (1)$$

where W is the water volume that is accumulated by runoff element (m^3), S and R – inflow and outflow to/from it ($m^3\ sec^{-1}$). There is the unique nonlinear relation between W and outflow discharge R :

$$R=b[\exp(aW)-1] \qquad (2)$$

Then, the corresponding equation of the outflow hydrograph from runoff elements of a given layer is the following:

$$R=(S+b)/\{1+[(S-R_0)/(R_0+b)]\exp[-a\Delta t(S+b)]\}-b \qquad (3)$$

Here R_0 is the initial value of runoff R and S is the runoff rate ($m^3\ s^{-1}$); Δt is the computational time interval (sec) during which S is constant; where a, b - hydraulic coefficients (which determine the conditions of outflow) with dimension m^{-3} and $m^3\ s^{-1}$

The number of runoff elements is proportional to the basin area F (m^2) or its part ΔF (for distributed models), and then $a=a^*?F^{-1}$ and $b=b^*?F$.

It is useful to attach to the coefficient a^* the status of a conditional constant systematized by types of flow and the coefficient b^* to put into the list of main parameters of runoff model. The units are the following: a^* – m^{-1}, b^* – m sec^{-1}, F – m^2.

$$1/ab=1/a^*b^*=\tau^* \qquad (4)$$

is the specific time of discharging of a runoff element.

The specific values of outflow q and water storage H are also determined by the values of the conditional constant a^*, parameter b^* and are connected by the relation

$$H=\ln(q/b^*+1)/a^* \qquad (5)$$

Next we offer the following hierarchical system of layers located each under another layer of runoff elements, feeding the river and corresponding types of underground flow (Table).

All specific values of runoff elements are determined by the conditional constant a^* and the median value of parameter $b^*=10^{-6}$ m sec^{-1}. The "constant" itself is sequentially determined by expression $a^*=10^i$, where $i=3$ for surface flow, $i=2$ for subsurface flow, and further for different layers of underground flow from $i=1$ to $i=-6$ with step $\Delta=0,5$.

We accept some logical and expected assumption: the infiltration capacity of water-holding rocks naturally decrease with increase of deepness. At the same time there is the decrease of outflow rate and the simultaneous increase of water storage with depth in groundwater aquifers.

The total sum of specific stores of water in the system of underground runoff elements of different layers which amounted 67256 mm (without 15th layer 45716 mm) is within the range of data from different sources: from 45000 to 70800 mm.

THE SYSTEM OF RUNOFF ELEMENTS

№	Type of runoff	a*, m^{-1}	Time (τ)	Outflow intensity, $dm^3\ sec^{-1}\ km^2$	Water storage, mm
–	Surface	1000	17 minutes	10^5	4.6
–	Subsurface	100	2,8 hours	10^4	24
1 – 3	Rapid ground	10 – 1	1.2 – 11.6 days	10^3 – 215	69.3 – 195
4 – 6	Ground	0.3162 – 0.03162	12 months – 1 year	100 – 21,5	301 – 674
7 – 9	Upper underground	10^{-2} – 10^{-3}	3.2 – 32 years	10 – 2,15	995 – 2152
10 – 12	Deep underground	$3.162*10^{-4}$ – $3.162*10^{-5}$	100 – 1000 years	1 – 0,215	3161 – 6812
13 – 15	Historical underground	10^{-5} – 10^{-6}	3200 – 32000 years	0,1 – 0,0215	10000 – 21450
∑ (1 – 15)					67256

The concept of runoff elements is the unified methodological approach to modelling the surface, subsurface and underground runoff of different layers. It offers the solution of the multiple-scale problem by means of directly including the basin area into the algorithms of conversion of runoff elements parameters into coefficients of main calculating equations.

Any direct data for confirmation of the proposed underground runoff types and their tentative quantitative characteristics are absent. But they don't contradict the known hydro-geological items and correspond to observed curves of runoff depletion for the basins of various sizes, and to the materials of isotope hydrology. Possibly, historical underground runoff can be referred to hydrological illusions but it gives some completeness to the given schematization.

IV. Routing approach

Two assumptions are accepted:

1. The lag time of water channel run to the basin outlet is accepted to be a constant for each point chosen in the basin.
2. Observations of directly measured mean flow velocities for cross-sections of river channel is used.

To illustrate the proposed approach, the velocity values for the four large rivers of Eastern Siberia are presented in the Table. These velocities are computed by averaging the velocities corresponding to the top 25% of flow values for each of the rivers.

A great many factors affecting the acceleration or conversely slowing down of flow velocity surprisingly lead to general order, steadiness and relative constancy as a result of some "self-regularity".

Characteristics of average flow speed (m s^{-1}) observed at the hydrometric stations in main rivers of Eastern Siberia.

The range of basin scales (km^2)	The Lena river		The Yana river		The Indigirka river		The Kolyma river	
	V	C_V	V	C_V	V	C_V	V	C_V
<100	0.94	0.42	1.28	0.22	1.4	0.16	1.60	0.14
100 – 1 thousand	1.31	0.34	1.31	0.32	1.52	0.18	1.62	0.15
1 – 10 thousands	1.10	0.42	1.60	0.32	1.77	0.21	1.90	0.11
10 – 100 thousands	1.55	0.20	–	–	2.15	0.19	2.14	0.23
> 100 thousands	1.72	0.19	–	–	–	–	–	–
Average	1.40	0.30	1.39	0.28	1.52	0.25	1.65	0.21
The number of observational stations	228		50		46		117	

Here C_V – absolute variation coefficient of averaged velocities

The values on the Table indicate that the increase in flow velocities resulting from an increase in basin area and spatial variability is negligible. In such a way the averaged minimum value of lag time (corresponding to maximum velocities) is taken as the calculating value. It is due to the fact that short time lags correspond to peak limb of flow hydrograph.

At the same time the underestimated shift of hydrograph shape during the period of low flow can not affect the resulting runoff significantly.

Summing up the described above approaches we advance the following slogan:

WHY TO OPPOSE THE SIMPLICITY OF NATURE WITH OUR PRETENTIOUS SELF-CONFIDENCE?

Results/ Conclusions

To see the modelling results and drawn conclusions, please, see now the **poster A94** (current session)

INTERESTED?

Please, visit:

1) NP3.5/HS13.08
oral presentation
Room 15, Wed, 22 Apr, 10:45

2) HS5.16 poster A197
Hall A, Fri,24 Apr, 08:00-19:30

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