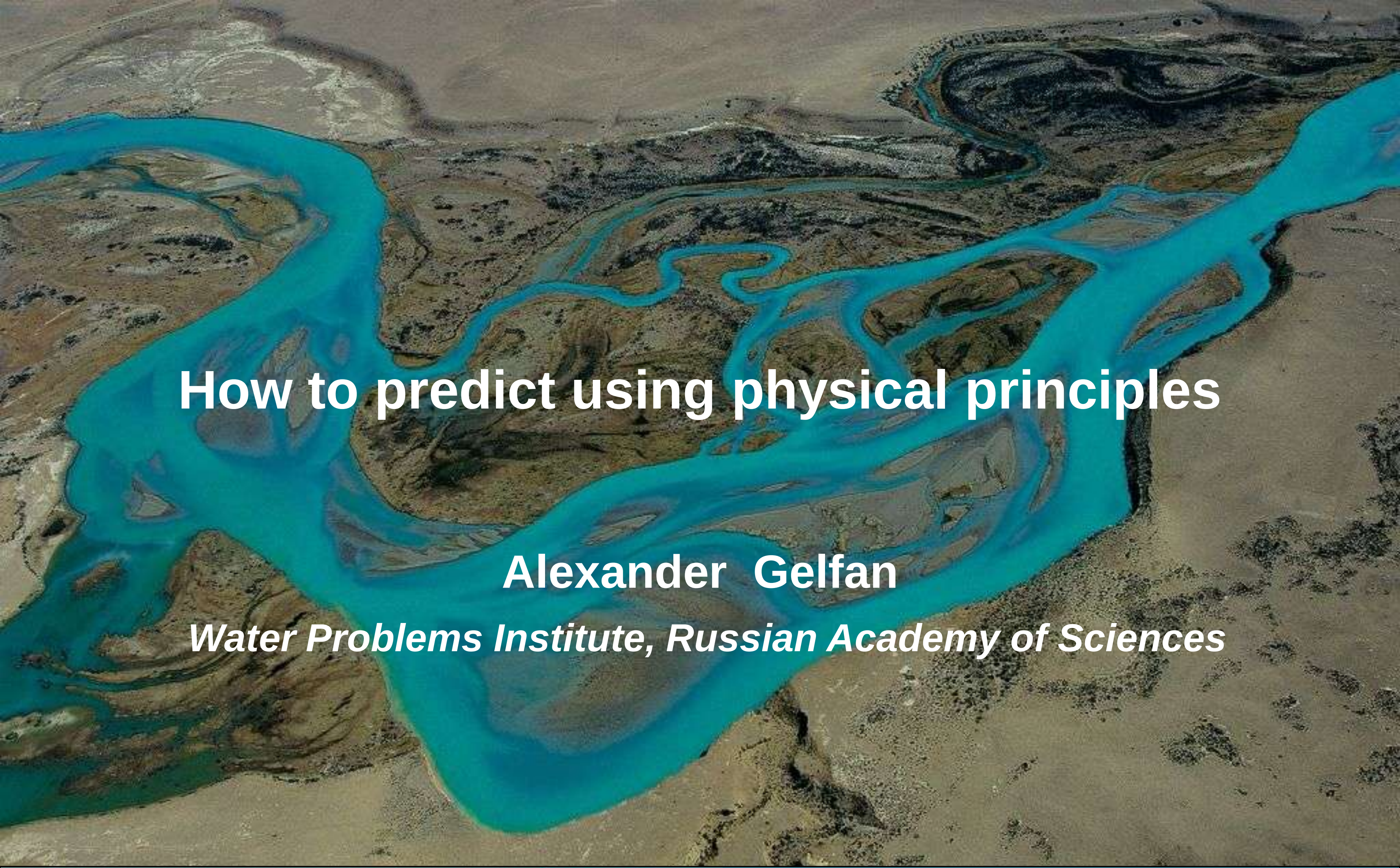

How to predict using physical principles

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pub Predictions in Ungauged Basins

International PUB Workshop
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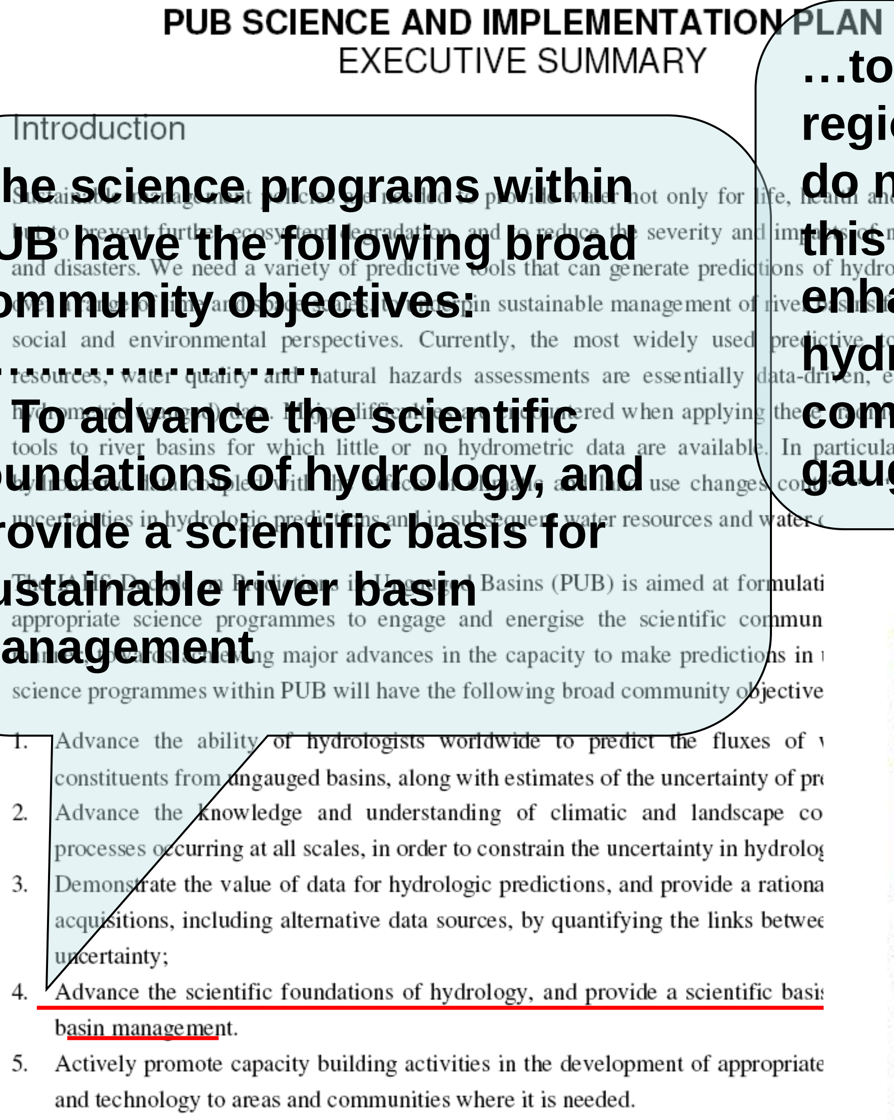


PUB SCIENCE AND IMPLEMENTATION PLAN

EXECUTIVE SUMMARY

Introduction

Sustainable management policies are needed to provide water not only for life, health and development but to prevent further ecosystem degradation, and to reduce the severity and impacts of natural hazards and disasters. We need a variety of predictive tools that can generate predictions of hydrologic systems, over a range of time and space scales, to underpin sustainable management of river basins from economic, social and environmental perspectives. Currently, the most widely used predictive tools for water resources, water quality and natural hazards assessments are essentially data-driven, estimated from hydrometric (gauged) data. Major difficulties are encountered when applying these conventional predictive tools to river basins for which little or no hydrometric data are available. In particular, the lack of hydrometric data coupled with the effects of climate and land use changes contribute to considerable uncertainties in hydrologic predictions and in subsequent water resources and water

The IAHS Decade on Predictions in Ungauged Basins (PUB) is aimed at formulati
appropriate science programmes to engage and energise the scientific commun
manner, towards achieving major advances in the capacity to make predictions in u
science programmes within PUB will have the following broad community objective

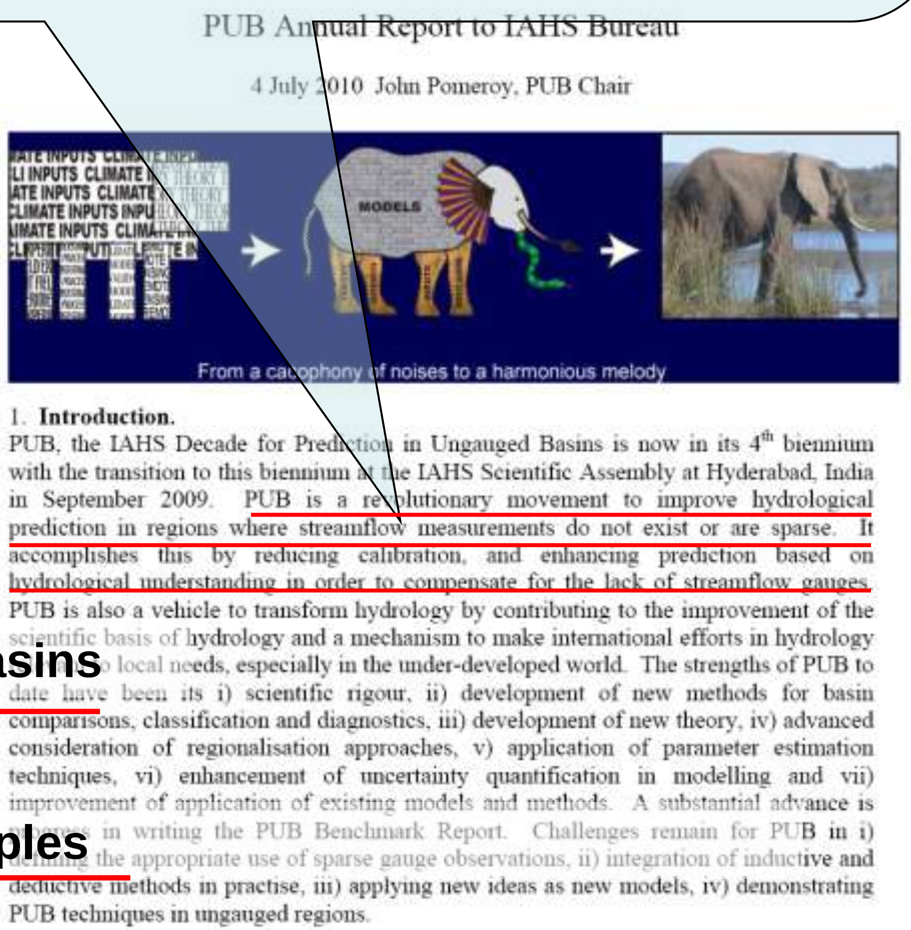
1. Advance the ability of hydrologists worldwide to predict the fluxes of
constituents from ungauged basins, along with estimates of the uncertainty of pr
2. Advance the knowledge and understanding of climatic and landscape co
processes occurring at all scales, in order to constrain the uncertainty in hydrolog
3. Demonstrate the value of data for hydrologic predictions, and provide a rationa
acquisitions, including alternative data sources, by quantifying the links betwee
uncertainty;
4. Advance the scientific foundations of hydrology, and provide a scientific basis
basin management.
5. Actively promote capacity building activities in the development of appropriate
and technology to areas and communities where it is needed.

The science programs within PUB have the following broad community objectives:

……………………

4. To advance the scientific foundations of hydrology, and provide a scientific basis for sustainable river basin management

…to improve hydrological prediction in regions where streamflow measurements do not exist or are sparse. It accomplishes this by reducing calibration, and enhancing prediction based on hydrological understanding in order to compensate for the lack of streamflow gauges.



PUB Annual Report to IAHS Bureau

4 July 2010 John Pomeroy, PUB Chair

From a cacophony of noises to a harmonious melody

1. Introduction.

PUB, the IAHS Decade for Prediction in Ungauged Basins is now in its 4th biennium with the transition to this biennium at the IAHS Scientific Assembly at Hyderabad, India in September 2009. PUB is a revolutionary movement to improve hydrological prediction in regions where streamflow measurements do not exist or are sparse. It accomplishes this by reducing calibration, and enhancing prediction based on hydrological understanding in order to compensate for the lack of streamflow gauges. PUB is also a vehicle to transform hydrology by contributing to the improvement of the scientific basis of hydrology and a mechanism to make international efforts in hydrology relevant to local needs, especially in the under-developed world. The strengths of PUB to date have been its i) scientific rigour, ii) development of new methods for basin comparisons, classification and diagnostics, iii) development of new theory, iv) advanced consideration of regionalisation approaches, v) application of parameter estimation techniques, vi) enhancement of uncertainty quantification in modelling and vii) improvement of application of existing models and methods. A substantial advance is progress in writing the PUB Benchmark Report. Challenges remain for PUB in i) defining the appropriate use of sparse gauge observations, ii) integration of inductive and deductive methods in practise, iii) applying new ideas as new models, iv) demonstrating PUB techniques in ungauged regions.

Prediction Ungauged Basins

Prediction Using Physical Princeples

Outlines

Preliminary notes

Can empirical data deficit be compensated by a priori information on runoff generation physics?

How can information gleaned from data-rich basins be transferred to data-poor basins?

WPI System of Physically Based Hydrological Models

Hydrological similarity: study basins and the corresponding proxy-basins

Transferring the model parameters from the proxy-basins to the study basins: examples for different physiographic zones

"Putting PUB into Practice": Flood risk assessment for data-poor basins

Motivations for invoking knowledge of a flood generation physics in flood frequency analysis

Dynamic-stochastic approach to flood risk assessment

Sensitivity of extreme floods to land use changes

Preliminary notes

1. **Choice of the techniques (models) for runoff prediction in an ungauged or poorly gauged basin depends on:**
   (a) specific mechanisms of runoff genesis;
   (b) available observations;
   (c) the specific hydrological problem to be solved by the model
   Because of great diversity of these specifics, many different models have been suggested

2. **There are many different ways of classifying models in watershed hydrology. From the viewpoint of PUB, the most important distinguishing feature is the nature of the basic algorithms (e.g. Grayson, Blöschl, 2000) or, strictly saying, the relationship between *a priori* (theoretical) and *a posteriori* (based on data) information accumulated by the model (Kuchment, 1971).**

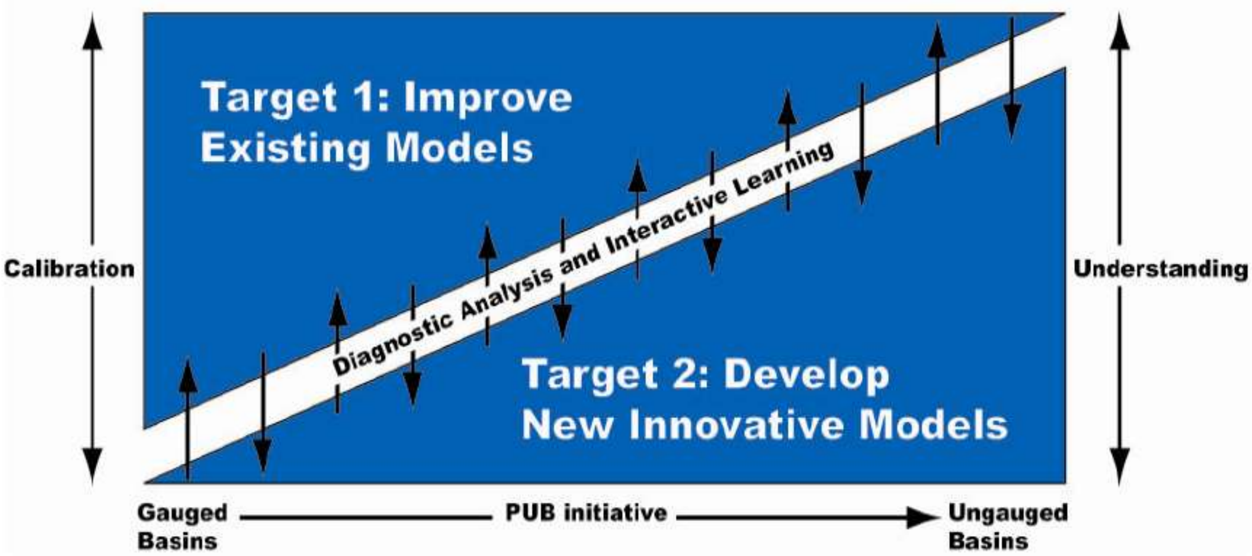
Empirical, regression or "black-box" models: based on input–output relationships without any attempt to describe the individual processes.

Conceptual–empirical models wherein the basic processes (interception, infiltration, evaporation, surface and subsurface runoff etc.) are separated, but the algorithms that are used to describe the processes are essentially calibrated input–output relationships

Physically based models based as much as possible on the fundamental physics and governing equations of water and heat transfer through and over watershed

The accuracy of runoff prediction with the models of the first two types depends on the availability of streamflow data for their calibration. In the case of ungauged or poorly gauged basins, data deficit may be compensated, to some extent, by assimilating information on physical processes.

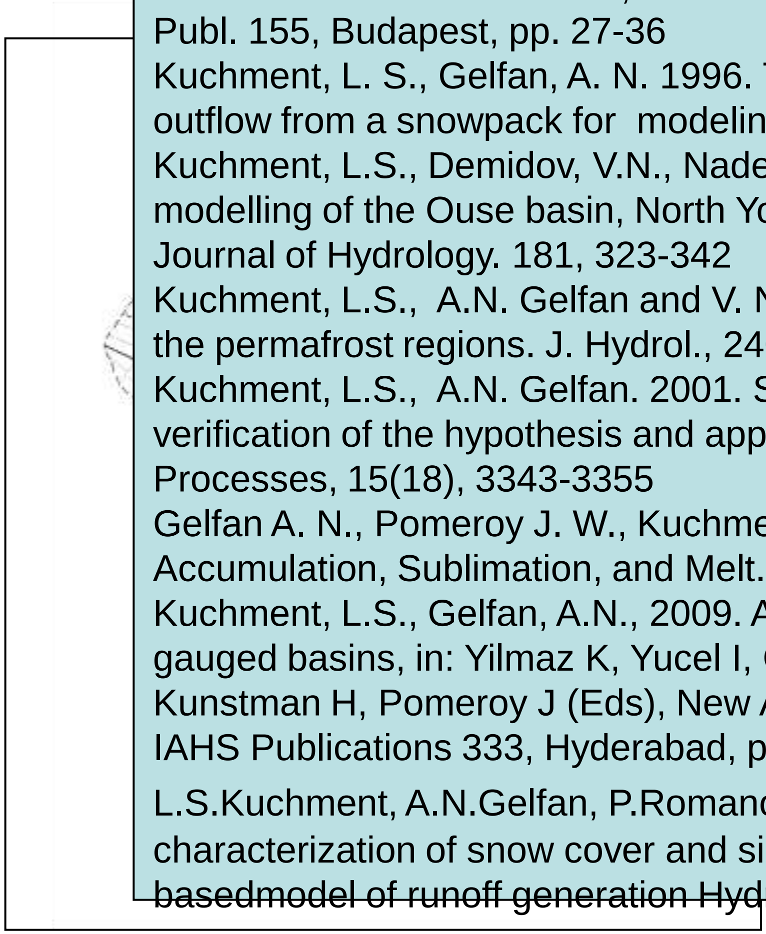
Towards Paradigm Change – From Calibration to Understanding



Thus, from the viewpoint of PUB, the physical structure of the model looks the most attractive because parameters of such model have clear physical meanings and may be related to measurable characteristics of river basins, such as topography, soils, vegetation, etc. Combined with and resulting from the physical background of the model, this feature provides opportunity to minimize the need for model calibration.

WPI System of Physically Based Models of Runoff Generation

WPI System n the finite-element schematization of the river basin w ut taking into account the river basin



Selected publications

Kuchment, L.S., Demidov, V.N., Motovilov, Y.G., 1986. A physically-based model of the formation of snowmelt and rainfall-runoff, in: Morris EM (Ed), Modeling Snowmelt-Induced Processes. IAHS Publ. 155, Budapest, pp. 27-36

Kuchment, L. S., Gelfan, A. N. 1996. The determination of the snowmelt rate and the meltwater outflow from a snowpack for modeling river runoff generation. *J. Hydrol*., 179, 23-36.

Kuchment, L.S., Demidov, V.N., Naden, P.S., Cooper, D.M., Broadhurst, P., 1996 Rainfall-runoff modelling of the Ouse basin, North Yorkshire: an application of a physically based distributed model. Journal of Hydrology. 181, 323-342

Kuchment, L.S., A.N. Gelfan and V. N. Demidov. 2000. A distributed model of runoff generation in the permafrost regions. J. Hydrol., 240(1-2), p. 1-22

Kuchment, L.S., A.N. Gelfan. 2001. Statistical self-similarity of spatial variations of snow cover: verification of the hypothesis and application in the snowmelt runoff generation models. Hydrol. Processes, 15(18), 3343-3355

Gelfan A. N., Pomeroy J. W., Kuchment L. S. 2004. Modelling Forest Cover Influences on Snow Accumulation, Sublimation, and Melt. J. Hydrometeorology. Vol. 5, No. 5, pp. 785–803.

Kuchment, L.S., Gelfan, A.N., 2009. Assessing parameters of physically-based models for poorly gauged basins, in: Yilmaz K, Yucel I, Gupta VH, Wagener T, Yang D, Savenije H, Neale C, Kunstman H, Pomeroy J (Eds), New Approaches to Hydrological Prediction in Data Sparse Regions. IAHS Publications 333, Hyderabad, pp. 3-10

L.S.Kuchment, A.N.Gelfan, P.Romanov, V.N.Demidov (2010) Use of satellite-derived data for characterization of snow cover and simulation of snowmelt runoff through a distributed physicall basedmodel of runoff generation Hydrol. Earth Syst. Sci., 14, 339–350.

Descriptions of the hydrological processes can be modified depending on the physiographic conditions of the specific basin and the available measurements

Overland flow

$$\frac{\partial(hB)}{\partial t}+\frac{\partial(qB)}{\partial x}=q_c$$

$$q=i^{0.5}h^{1.67}Bn^{-1}$$

Channel flow

Saint-Venant or advection-diffusion or kinematic wave equations

Subsurface flow

$$\left(\theta_m-\theta_f\right)\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=G$$

$$q=K(H)i_0h$$

$$K=K_0\exp(-\varphi H)$$

Vertical soil moisture transfer and evapotranspiration

Transpiration

$$E_f=\rho_a\cdot\frac{q^*(T_f)-q_a}{r_a+r_s}\cdot(1-\eta)\cdot LAI$$

$$r_s=r_0\,\frac{\theta_{fc}-\theta_r}{\theta-\theta_r}\left(1+\frac{\gamma}{PAR}\right)$$

Evaporation from bare soil

$$E_g=\rho_a\cdot\frac{r\cdot q^*(T_g)-q_a}{r_{ag}}$$

Vertical soil moisture transfer

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

$$S_k(\theta,z)=-K(\theta)\left[\psi_\kappa(\theta)-\psi(\theta)\right]b_k\rho_\kappa(z)$$

Snow accumulation and melt

Distributed model

$$\frac{\partial w}{\partial t} = -\frac{1}{\rho_w}\frac{\partial q_w}{\partial z} - \frac{\rho_I}{\rho_w}\frac{\partial i}{\partial t}$$

$$C_{ef}\,\frac{\partial T_s}{\partial z} = \frac{\partial}{\partial z}(\lambda_{ef}\,\frac{\partial T_\rho}{\partial z}) + \rho_I L_1\,\frac{\partial i}{\partial t}$$

One-layer (integrated) model

$$\frac{dH}{dt} = \rho_w\left[X_s\rho_0^{-1} - (S + E_s)(\rho_i I)^{-1}\right] - V$$

$$\frac{d}{dt}(\rho_i I H_s) = \rho_w(X_s - S - E_s) + S_i$$

$$\frac{d}{dt}(\rho_w w_s H_s) = \rho_w(X_l + S - R_s) - S_i$$

Infiltration into a frozen soil, soil freezing and thawing

$$\frac{\partial \theta}{\partial t} = -\frac{\rho_i}{\rho_w}\frac{\partial I}{\partial t} + \frac{\partial}{\partial z}\left(D\frac{\partial \theta}{\partial z} + D_I\,\frac{\partial I}{\partial z} - K\right)$$

$$c_T\,\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z}) + \rho_w c_w(D\frac{\partial \theta}{\partial z} + D_I\,\frac{\partial I}{\partial z} - K)\frac{\partial T}{\partial z} + \rho_w\chi\,\frac{\partial W}{\partial t}$$

Detention by a basin storage

$$DET = D_0\left[1 - \exp\left(-\frac{R_t}{D_0}\right)\right]$$

Three-step procedure of transferring the model parameters from hydrologically similar basin to poorly gauged basins (PGB):

1. **Selection of the proxy-basin** hydrologically similar to PGB but having long-term measurement data

2. **Assessment of the model parameters for the proxy-basin.**
A part of the model parameters are either assessed from the available measurements or derived from the catchment attributes. A part of the parameters are adjusted through calibration against streamflow measurements. By the sensitivity analysis, the parameters are ranked in significance, and this ranking is assumed to be the same for the PGB and for the proxy-basin (it may be part of the PGB).

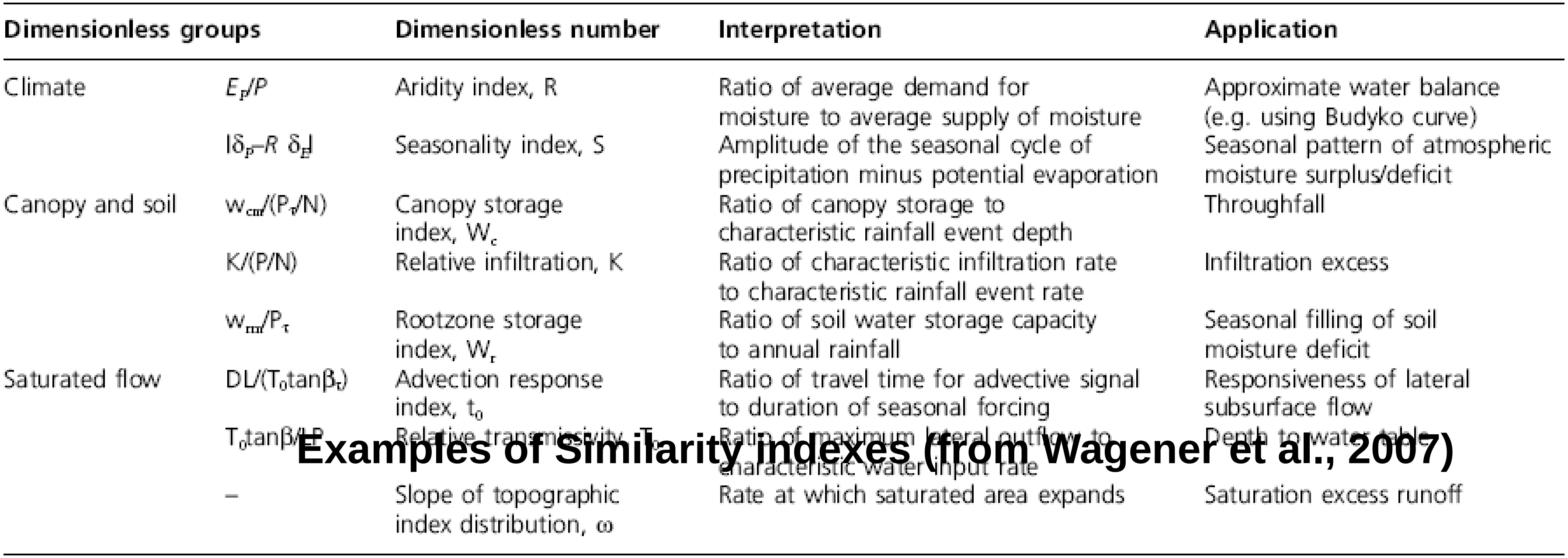
3. **Assessment of the model parameters for the PGB.**
The parameters are assigned using the results obtained for the proxy-basin and taking into account difference in area between the proxy-basin and PGB. A few key-parameters are refined by calibration against available short-term sreamflow measurements at the PGB.

Hydrological similarity

A number of hydrological similarity concepts have been proposed in the literature:

1. **Spatial proximity**: catchments that are close to each other are assumed to behave in hydrological similar manner

2. **Similar catchment attributes:** catchments that have similar attributes such as topographic characteristics, soil



Dimensionless groups		Dimensionless number	Interpretation	Application
Climate	E_P/P	Aridity index, R	Ratio of average demand for moisture to average supply of moisture	Approximate water balance (e.g. using Budyko curve)
	$\lvert\delta_P - R\,\delta_E\rvert$	Seasonality index, S	Amplitude of the seasonal cycle of precipitation minus potential evaporation	Seasonal pattern of atmospheric moisture surplus/deficit
Canopy and soil	$w_{cm}/(P_\tau/N)$	Canopy storage index, W_c	Ratio of canopy storage to characteristic rainfall event depth	Throughfall
	K/(P/N)	Relative infiltration, K	Ratio of characteristic infiltration rate to characteristic rainfall event rate	Infiltration excess
	w_{rm}/P_τ	Rootzone storage index, W_r	Ratio of soil water storage capacity to annual rainfall	Seasonal filling of soil moisture deficit
Saturated flow	$DL/(T_0\tan\beta_t)$	Advection response index, t_0	Ratio of travel time for advective signal to duration of seasonal forcing	Responsiveness of lateral subsurface flow
	$T_0\tan\beta/LP$	Relative transmissivity, T_0	Ratio of maximum lateral outflow to characteristic water input rate	Depth to water table
	–	Slope of topographic index distribution, ω	Rate at which saturated area expands	Saturation excess runoff

Examples of Similarity indexes (from Wagener et al., 2007)

Similarity indexes (from Kuchment & Gelfan, 2005)

In comparing hydrological systems, we can look at the similarity of individual processes alone, such as vertical water movement (infiltration and evaporation), horizontal flow through the catchment slopes and channels, spatial variations of catchment characteristics, etc.

$$\frac{K_s H_0}{D_0} = idem$$ (Peclet number)

$$\frac{K_s T_0}{\theta_m H_0} = idem$$ (characteristic of free soil capacity)

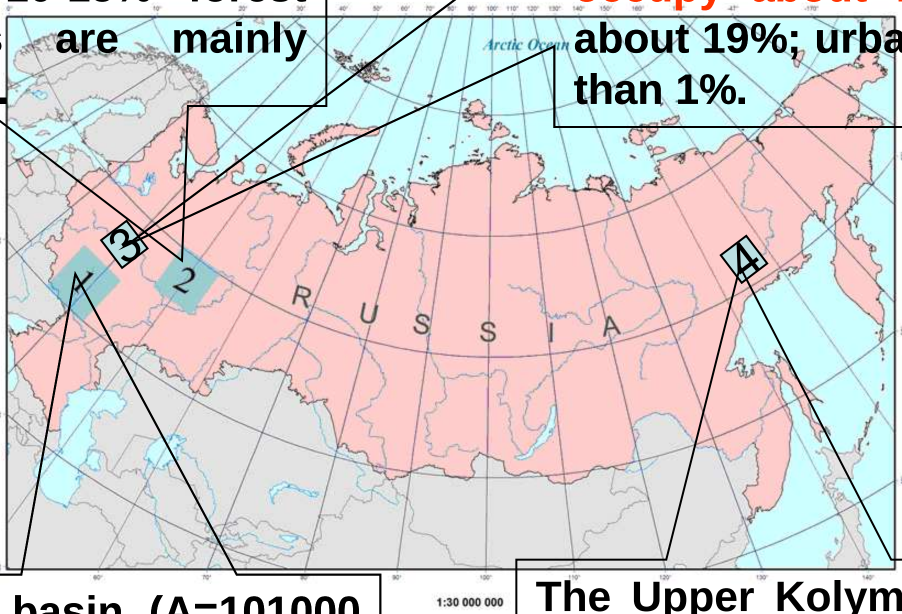
$$\frac{K_s}{P} = idem$$ (efficiency of gravitational filtration)

T_0 - characteristic scales of time, H_0 – soil depth, θ_{max} - soil porosity, D_0 – coefficient of soil moisture diffusion; K_s - saturated hydraulic conductivity; P – mean annual precipitation rate

Study basins

The Vyatka River basin (A=124000 km^2) has a flat terrain with mixed vegetation cover. In the northern part of the region more than 80% of the area is covered by forests. The southern part is mostly agricultural land with less than 10-15% forest cover fraction. Soils are mainly podzol and mixed types.

The Upper Seim River basin (A=7460 km^2). The relief of the basin is a rugged plain with many river valleys, ravines, and gullies. The soils are mainly chernozem and podzol. Most part of the basin (about 70%) is ploughed; forests occupy about 10%; pastures take up about 19%; urbanized lands occupy less than 1%.



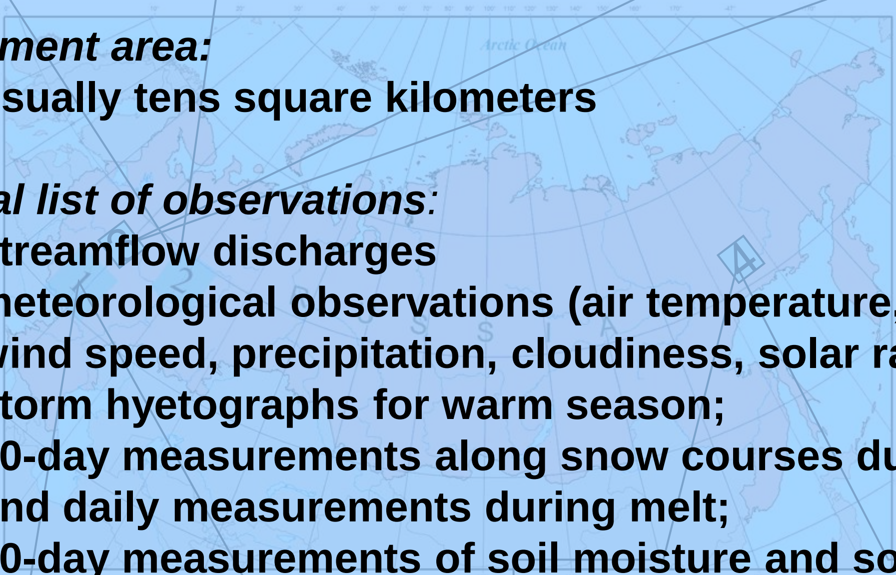
The Upper Don river basin (A=101000 km^2) is a rugged plain with many river valleys, ravines and gullies. The area is mostly agricultural, plain area with less than 10% forest cover fraction. Mostly, deciduous forests cover the upper part of the watershed. Soils are mainly chernozem, podzol, gley and meadow soils.

The Upper Kolyma River basin (A=99000 km^2). is situated in the zone of continuous permafrost. The major part of the basin is occupied by tundra and taiga. A significant part of mountainous slopes is the barren ground. The dominant soils are coarse-grained mountain-tundra podzols with large content of gravels. The peatlands occupy about 2% of the basin area.

The Medvenka Creek basin (A=11 km^2) has a flat terrain with mixed vegetation cover. About 75% of the area is covered by forests. Soils are mainly podzol. “Podmoskovnaya” WBS is located at the Medvenka Creek basin

The Yasenok Creek basin (A=19 km^2). The relief of the basin is a rugged plain. The soils are mainly chernozem and meadow soils. The basin is ploughed. “Nizhnedevitskaya” WBS is located at the Yasenok Creek basin

Corresponding proxy-basins



The Sosna river basin is the sub-basin of the Don River basin. The area is mostly agricultural, plain area with less than 5% forest cover fraction. Soils are mainly chernozem, podzol, gley and meadow soils. Special long-term measurements were organized at the basin by the State Hydrological Institute

The Kontaktovyi Creek basin (A=21 km2). is situated in the zone of continuous permafrost. Mountainous slopes are covered by the barren ground. The depth of the active layer ranges within 0.5-3.0 m. “Kolymskaya” WBS is located at the Kontaktovyi Creek basin

<u>List of observations at the Russian Water Balance Stations (WBS):</u>

Period of observations:

usually more than 40 years (typically from 1930-1940 to the beginning of 1990th; some WBS’s are working now)

Catchment area:

usually tens square kilometers

Typical list of observations:

streamflow discharges
meteorological observations (air temperature, humidity, wind speed, precipitation, cloudiness, solar radiation, etc);
storm hyetographs for warm season;
10-day measurements along snow courses during cold season and daily measurements during melt;
10-day measurements of soil moisture and soil temperature
level of ground water
10-day measurements of soil freezing depth
10-day measurements of soil water evaporation.
measurements of snow evaporation

Criteria of hydrological similarity for the basins located in the different physiographic zones

Criterion	Upper Kolyma	Kontaktovyi Creek
Peclet number	1.80	1.56
Free soil capacity	2.50	2.32
K_s/R	221.4	191.3

Criterion	Upper Seim	Yasenok Creek
Peclet number	0.49	0.38
Free soil capacity	1.91	1.78
K_s/R	83.7	66.7

Criterion	Vyatka	Medvenka Creek
Peclet number	1.14	0.81
Free soil capacity	2.33	2.08
K_s/R	123.0	109.9

Criterion	Upper Don	Sosna River
Peclet number	0.58	0.55
Free soil capacity	1.81	1.88
K_s/R	77.4	60.9

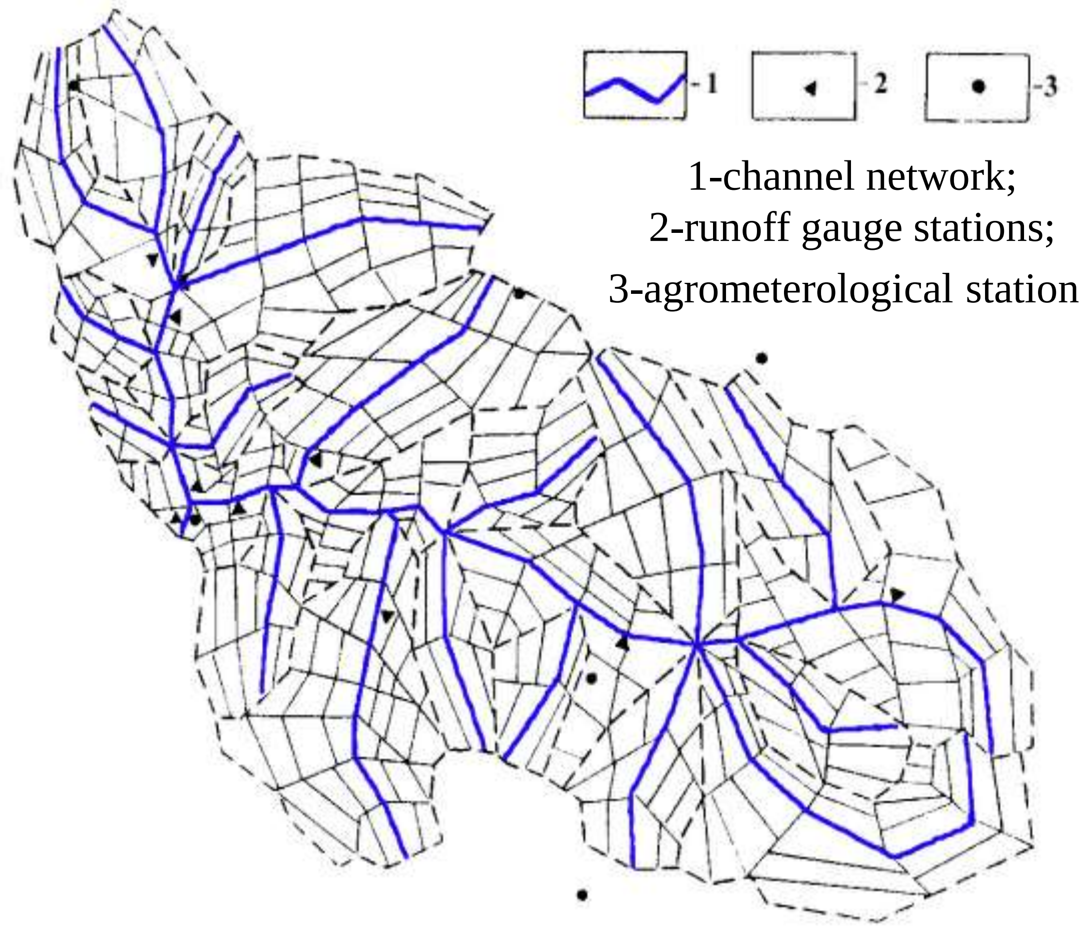
Conclusion:

the criteria differ more visibly between the basins of similar catchment area but located within the different zones

than between the basins located within the same zone

Applications of the proposed procedure (1st example: Seim River – Yasenok Creek basins; *Kuchment, Gelfan, 2002; 2007; 2009*)

<u>Overland and channel flow</u> are described by the kinematic wave equations. Subsurface flow is negligible in this basin.



1-channel network;
2-runoff gauge stations;
3-agrometerological stations

1st Step: Assessing the model parameters for the proxy-basin (Yasenok Creek)

Hydraulic and thermal parameters of soil (*K, D, D_I, c_T*)

$$\frac{\partial\theta}{\partial t} = -\frac{\rho_i}{\rho_w}\frac{\partial I}{\partial t} + \frac{\partial}{\partial z}\left(D\frac{\partial\theta}{\partial z} + D_I\frac{\partial I}{\partial z} - K\right);$$

$$c_T\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z}) + \rho_w c_w(D\frac{\partial\theta}{\partial z} + D_I\frac{\partial I}{\partial z} - K)\frac{\partial T}{\partial z} + \rho_w\chi\frac{\partial W}{\partial t}$$

1. Parameters of water retention curve

Unfrozen soil (van Genuchten, 1980)

$$\psi_u = -\frac{\left(S_u^{-1/m} - 1\right)^{1/n}}{\alpha_g}$$

$$K_u = K_0 S_u^{0.5}\left[1 - \left(1 - S_u^{1/m}\right)^m\right]^2$$

Frozen soil (Gelfan, 2006)

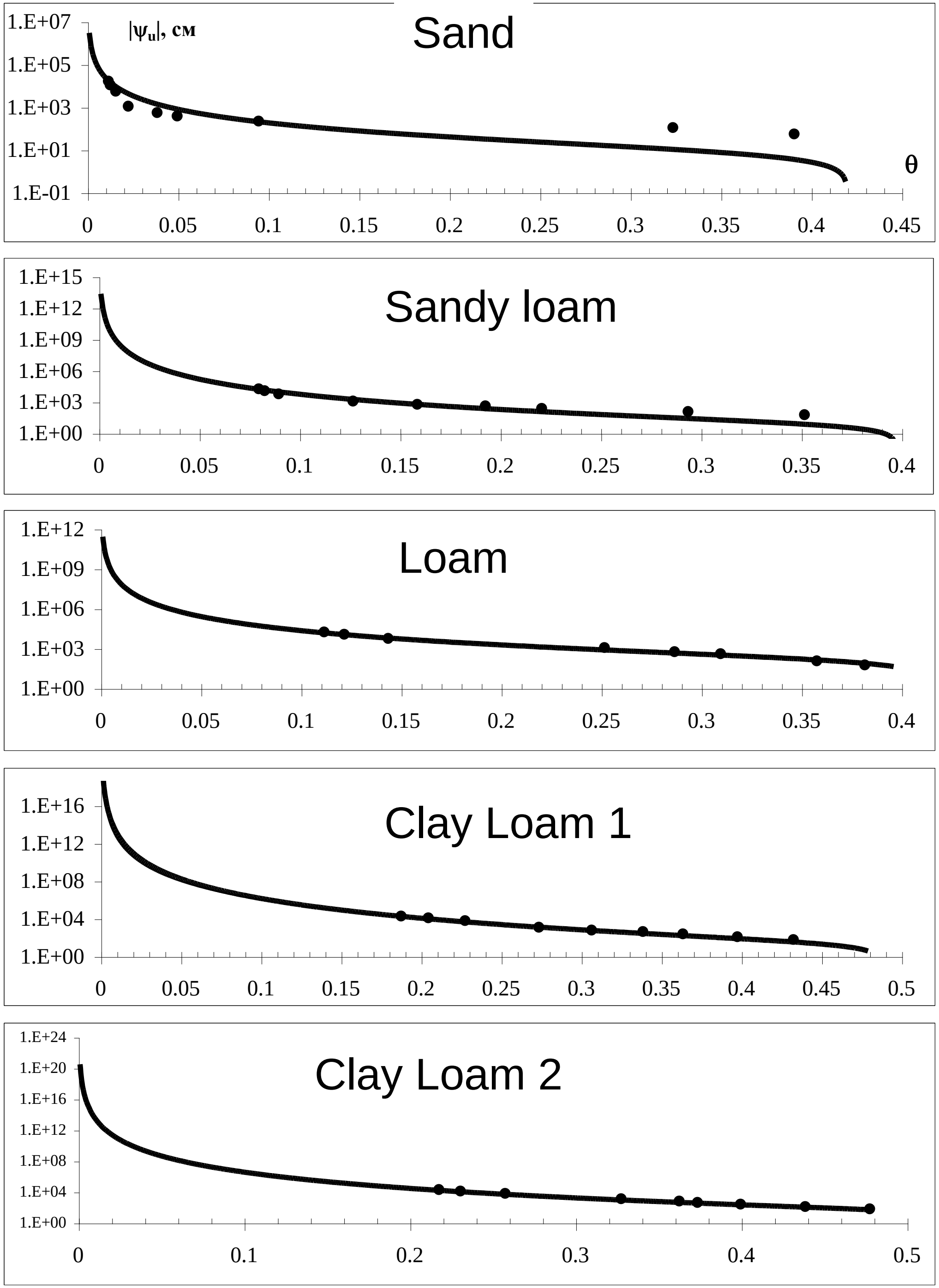
$$\psi(\theta, I) = -\frac{\left(S^{-1/m} - 1\right)^{1/n}}{\alpha_g} \times \left[\frac{\theta_s - \theta_r}{\theta_s - I - \theta_r} + \frac{\theta_r}{\theta}\left(1 - \frac{\theta_s - \theta_r}{\theta_s - I - \theta_r}\right)\right](1 + 8I)^2$$

$$K = K_0 S^{0.5}\left[\frac{1 - \left(1 - S^{1/m}\right)^m}{(1 + 8I)}\right]^2 \qquad D = K\left(\frac{\partial\psi}{\partial\theta}\right)_I \qquad D_I = K\left(\frac{\partial\psi}{\partial I}\right)_\theta$$

Dependences of the hydraulic parameters on the measured soil characteristics, field capacity (FC) and wilting point (WP) (Gelfan, 2006)

$$\left(\frac{S_{FC}^{-1/m}-1}{S_{WP}^{-1/m}-1}\right)^{1-m} = \frac{\psi_{FC}}{\psi_{WP}}$$

$$\alpha_g = \frac{\left(S_{FC}^{-1/m}-1\right)^{1-m}}{\left|\psi_{FC}\right|}$$



Relationships between soil matrix potential and soil moisture measured (points) and calculated (lines) for the soil types of the Yasenok Basin.

Thermal soil parameters

Heat capacities of a frozen soil (c_T)

$$c_T = \begin{cases} \rho_g c_g (1-P) + \rho_w c_w \theta + \rho_i c_i I + \rho_w \chi \dfrac{5\theta_{-5}\theta_0\left(\theta_0 - \theta_{-5}\right)}{\left[5\theta_{-5} - T\left(\theta_0 - \theta_{-5}\right)\right]^2}, & 0^\circ C \geq T > -5^\circ C \\ \rho_g c_g (1-P) + \rho_w c_w \theta + \rho_i c_i I & T \leq -5^\circ C \end{cases}$$

Thermal conductivity of a frozen soil

$$\lambda = (a_\lambda \lg\theta + b_\lambda)\left(1 + I\right)$$

Dependences on the measured soil characteristics, field capacity (FC) and wilting point (WP) (Kalyuzhnyi et al, 1988; Koren, 1991)

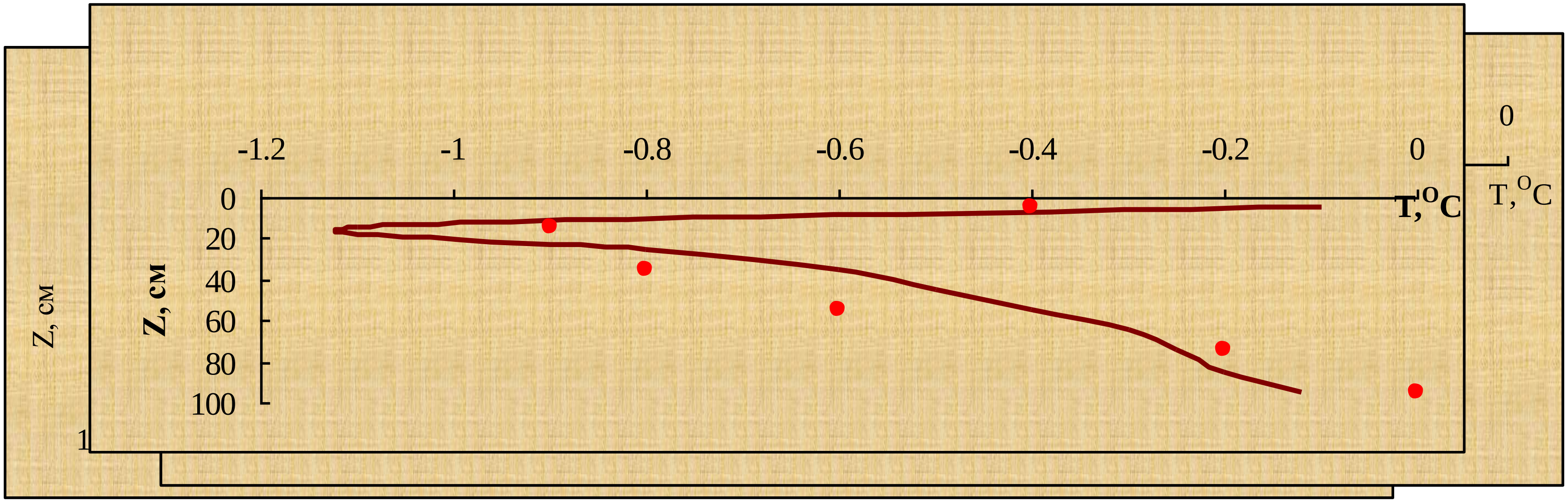
$$\theta_0 = 1.04\theta_{FC} - 0.06$$

$$\theta_{-5} = 0.94\theta_{WP} + 0.017$$

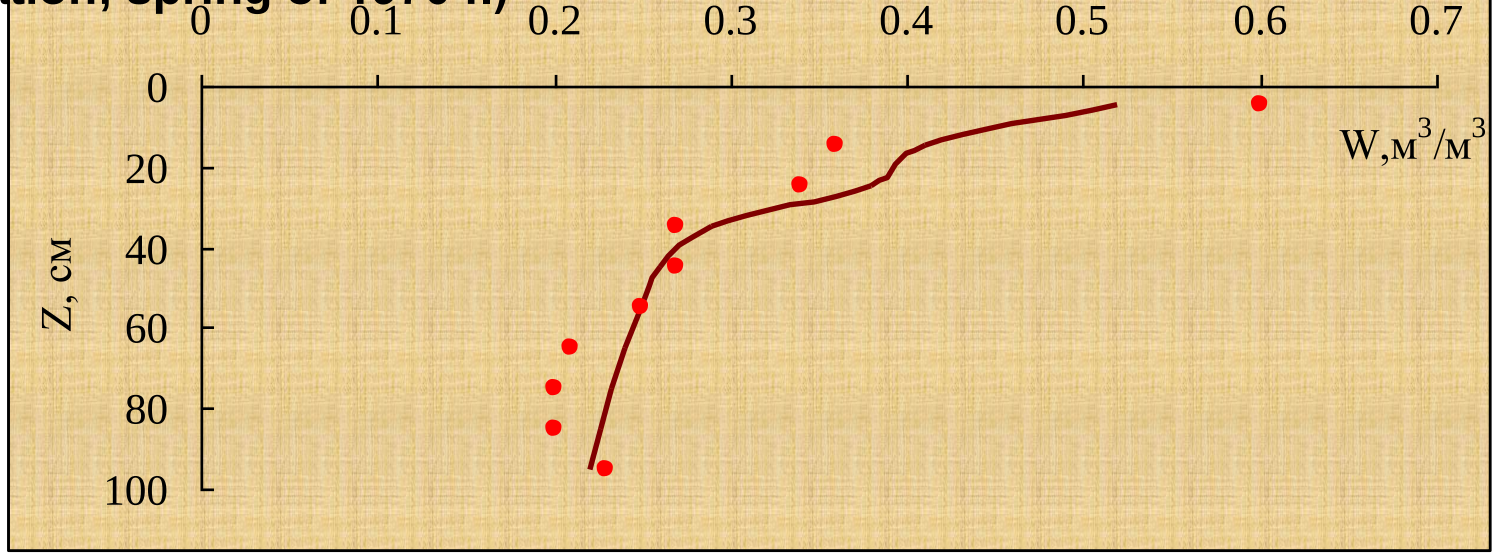
$$a_\lambda = 1.5 \times 10^{-4} \rho_b - 0.09$$

$$b_\lambda = -2.0 \times 10^{-5} \rho_b + 0.006$$

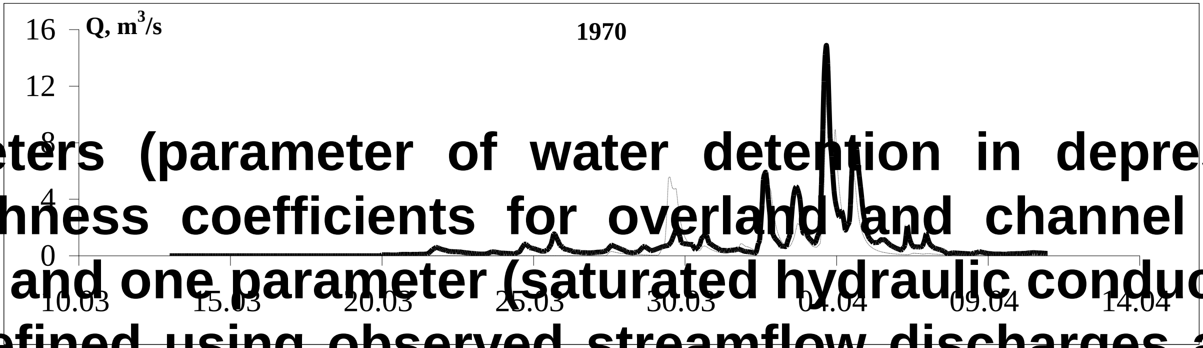
Calculated and measured profiles of soil temperature (period of wmelt water infiltration; spring of 1970 г.)

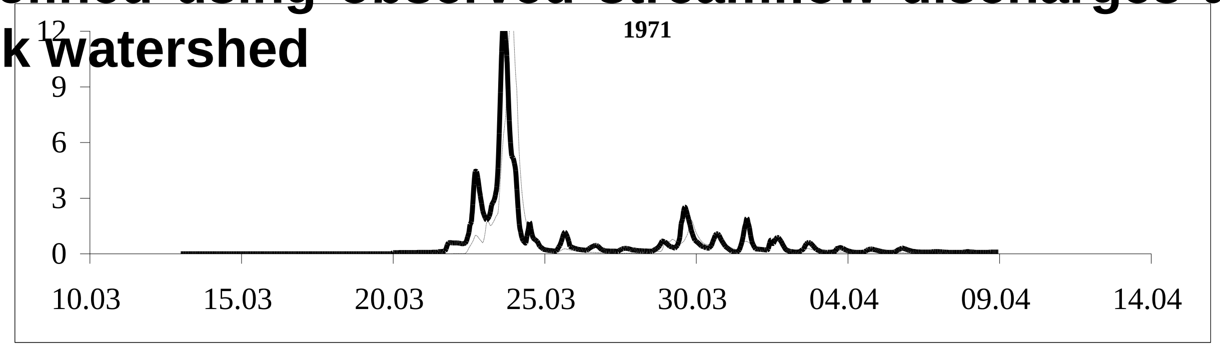


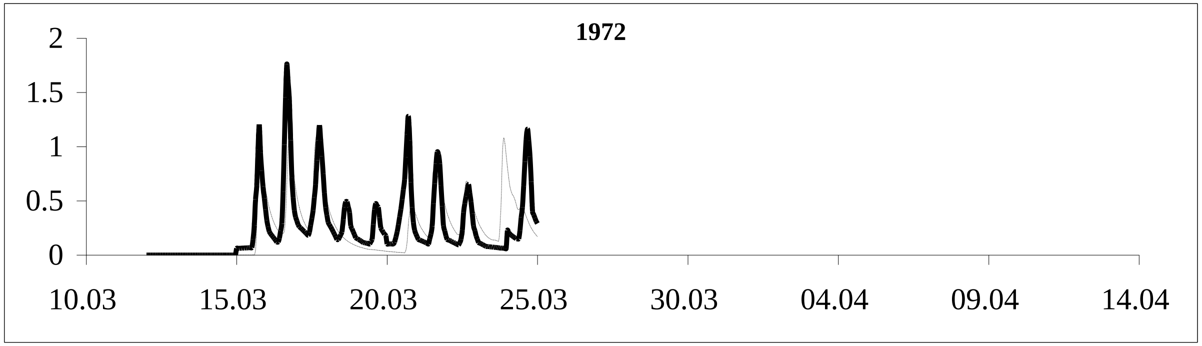
Calculated and measured profiles of soil moisture (period of snowmelt infiltration; spring of 1970 г.)

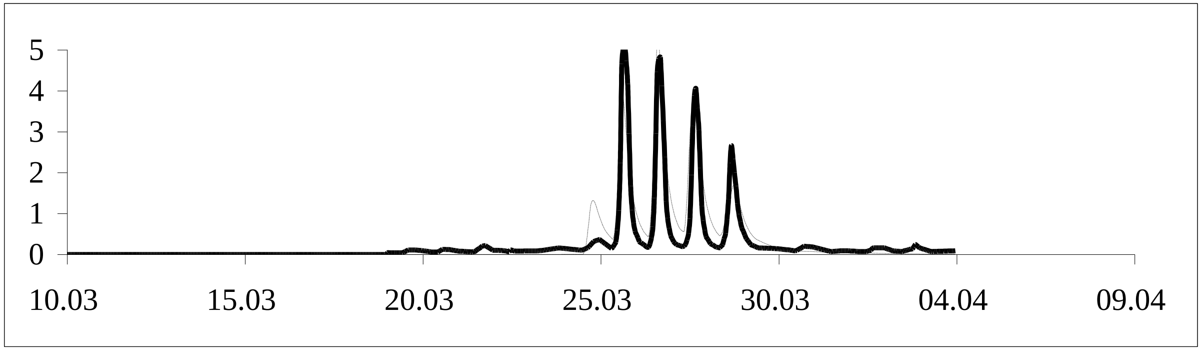


Three parameters (parameter of water detention in depression storage, roughness coefficients for overland and channel flow) were adjusted and one parameter (saturated hydraulic conductivity of soil) was refined using observed streamflow discharges at the Yasenok Creek watershed









Scaling transformation of spatial variance of snow water equivalent (SWE) before melt (Kuchment, Gelfan, 2001)

The probability distribution of SWE within any area *f* located within the area F is the same as the distribution over the whole area *F* if a scaling transformation of this variable within *f* is made. Such a scaling transformation is when the variable *SWE* is multiplied by a factor r^H, where *r* is a constant depending on the ratio of *f* to *F*, and *H* is the constant depending on a measure of spatial correlation of *SWE.*

$$\sigma_F^2 = r^H \sigma_f^2$$

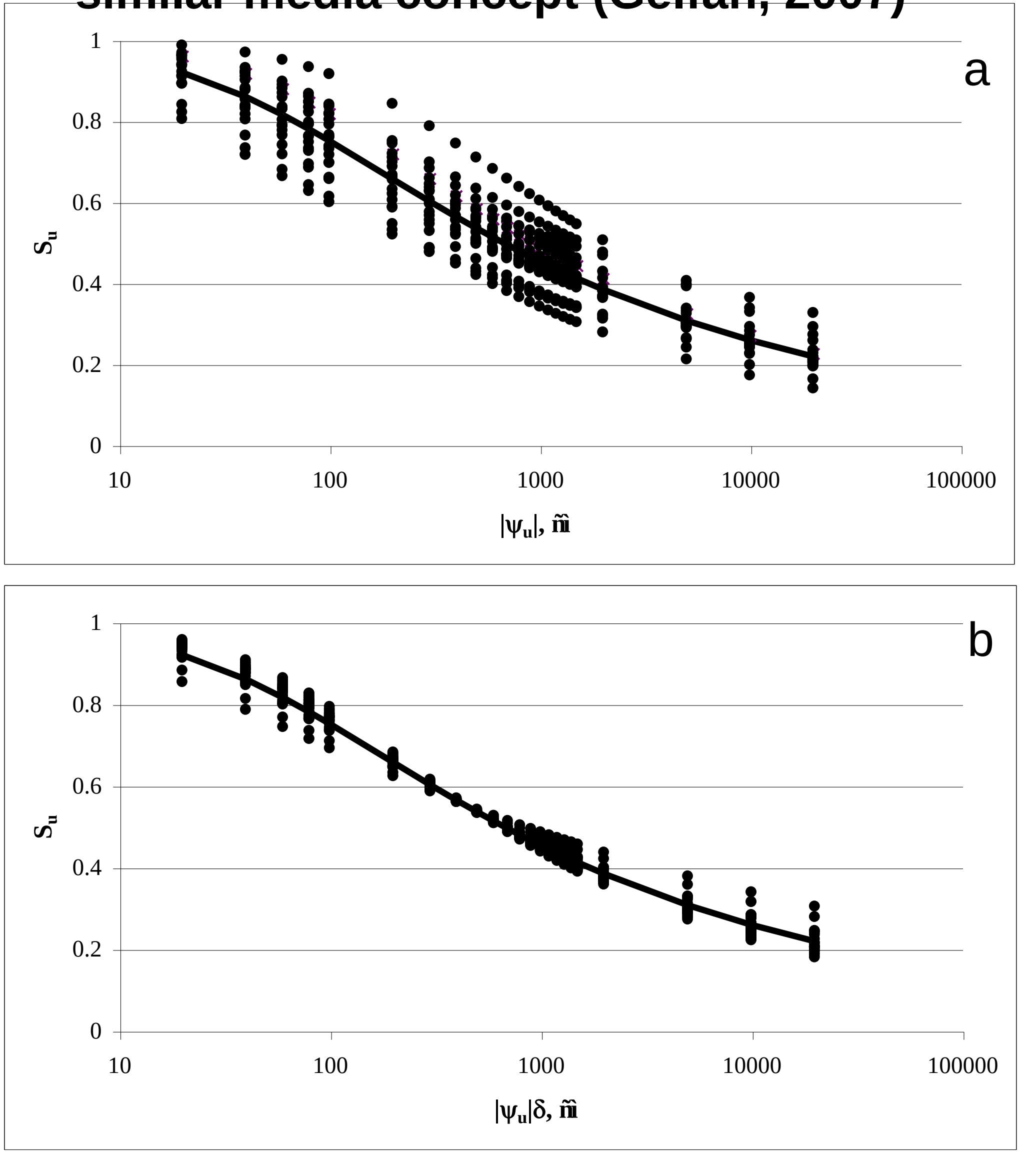
$$r = \sqrt{\frac{F}{f}}$$

σ_F^2 is the variance of snow water equivalent over the area *F* (PGB basin)

σ_f^2 is the variance of snow water equivalent over the area *f* (proxy-basin)

For the forested-steppe zone of Russia *H* was found to be equal 0.14 (Kuchment, Gelfan, 2001)

Scaling transformation of soil hydraulic properties using similar media concept (Gelfan, 2007)

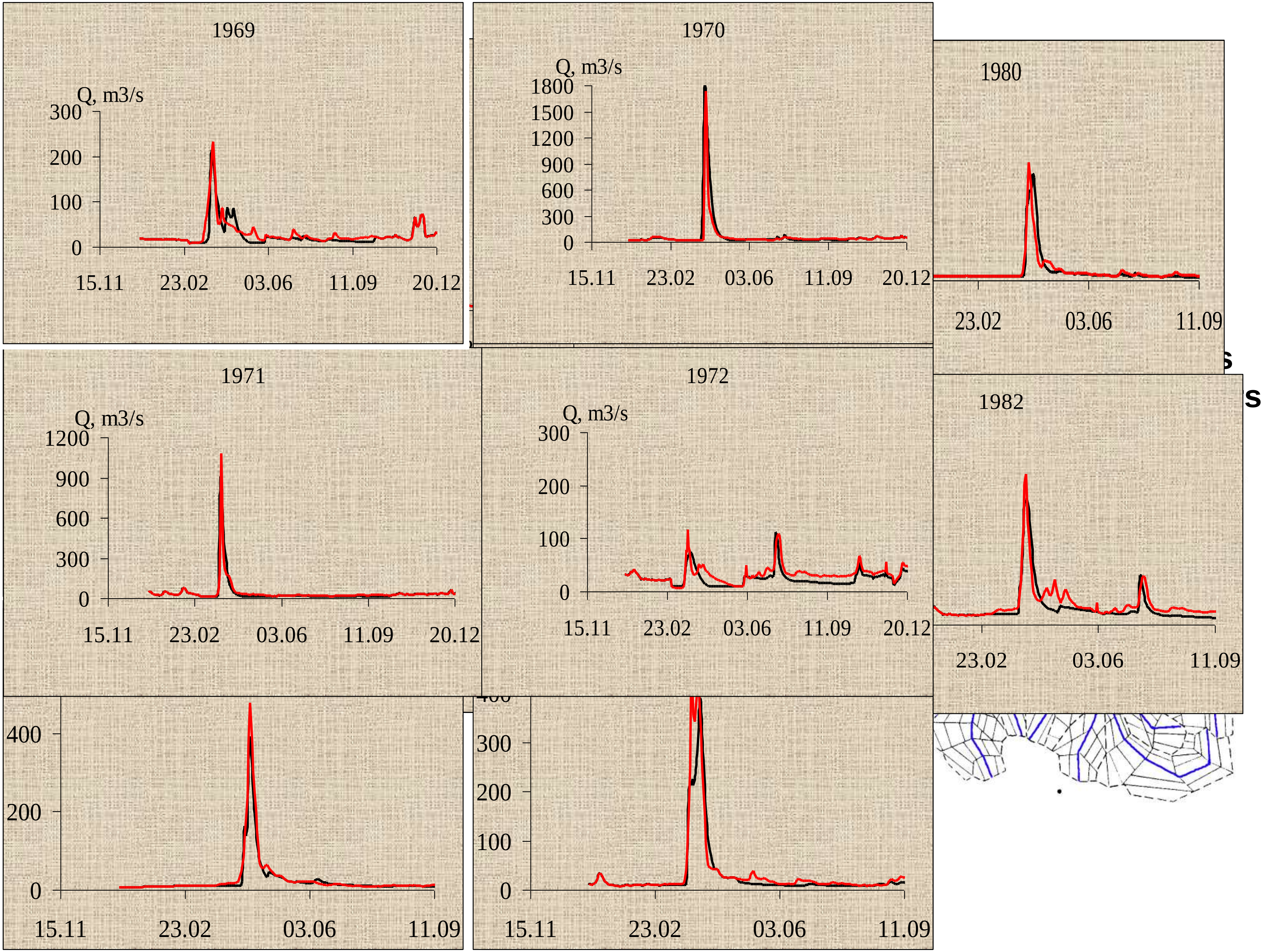


At any given degree of soil saturation, matrix potential and hydraulic conductivity of a chosen soil are related to the respective properties of the reference soil as

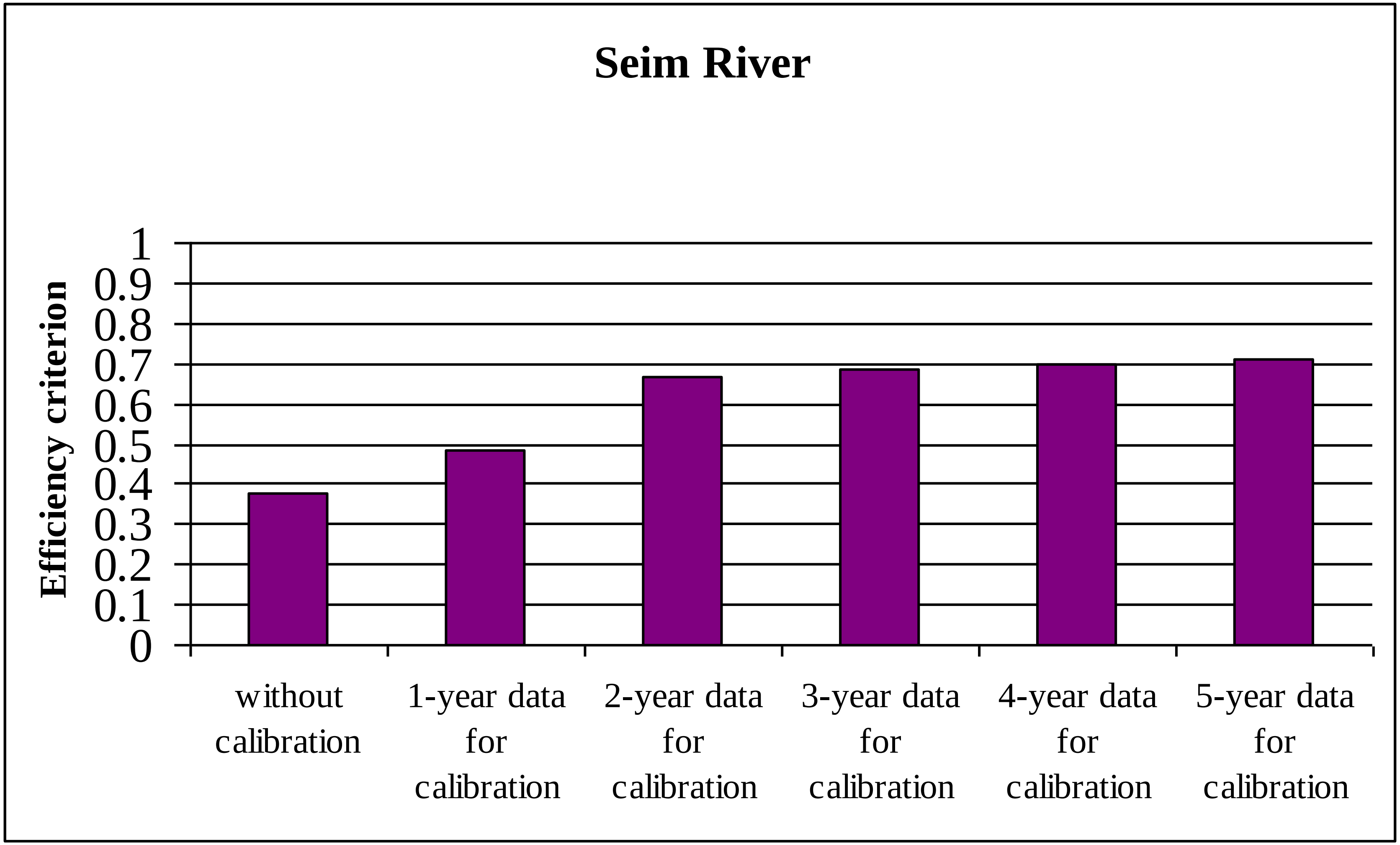
$$\psi_u = \psi_u^* \times \delta^{-1}$$

$$K_u = K_u^* \times \delta^2$$

Soil water characteristics data for 20 soil types over the Seim basin: (a) unscaled; (b) scaled


1969
Q, m3/s
300
200
100
0
15.11
23.02
03.06
11.09
20.12
1970
Q, m3/s
1800
1500
1200
900
600
300
0
15.11
23.02
03.06
11.09
20.12
1980
23.02
03.06
11.09
1971
Q, m3/s
1200
900
600
300
0
15.11
23.02
03.06
11.09
20.12
1972
Q, m3/s
300
200
100
0
15.11
23.02
03.06
11.09
20.12
1982
23.02
03.06
11.09
400
200
0
15.11
23.02
03.06
11.09
300
200
100
0
15.11
23.02
03.06
11.09

Changes of the Nash-Sutcliffe efficiency criterion under the different period of the model calibration



Applications of the proposed procedure
(2nd example: Kolyma River – Kontaktnyi Creek basins;

Kuchment et al., 2000; Gelfan, 2005; Kuchment, Gelfan, 2007; 2009)

Thawing of the ground (active layer)

$$C_f \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_f \frac{\partial T}{\partial z} \right), \; H(t) < z < L$$

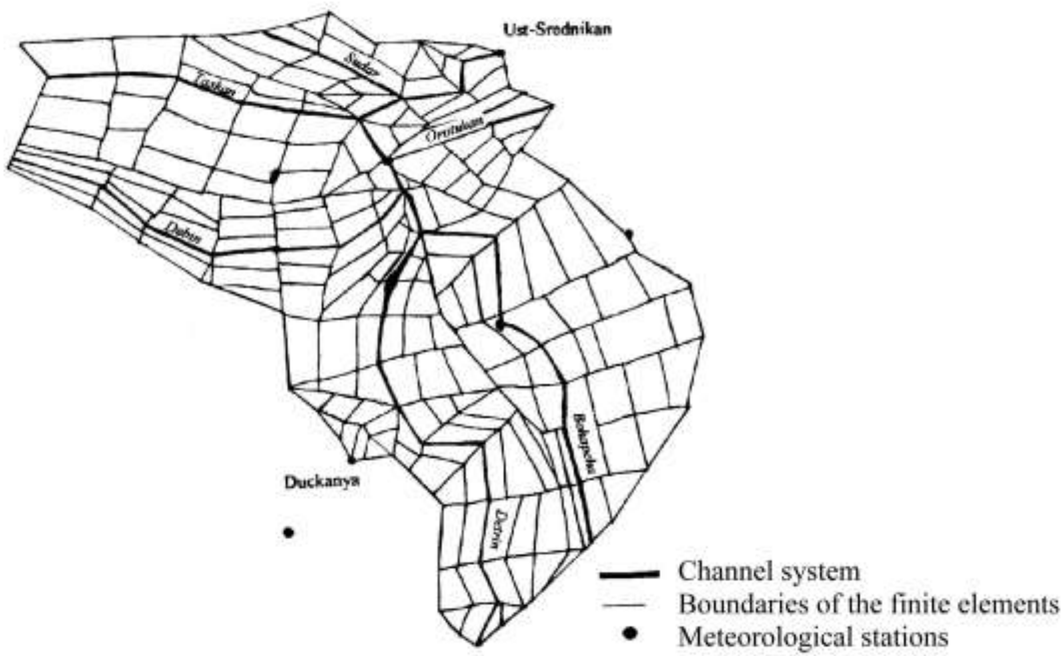
$$C_{uf} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{uf} \frac{\partial T}{\partial z} \right), 0 < z < H(t)$$

$$\lambda_{uf} \frac{\partial T}{\partial z}\Big|_{z=H-0} = \lambda_f \frac{\partial T}{\partial z}\Big|_{z=H+0} + \chi \frac{\rho_i}{\rho_w} I \frac{dH}{dt}$$

Water content of the active layer

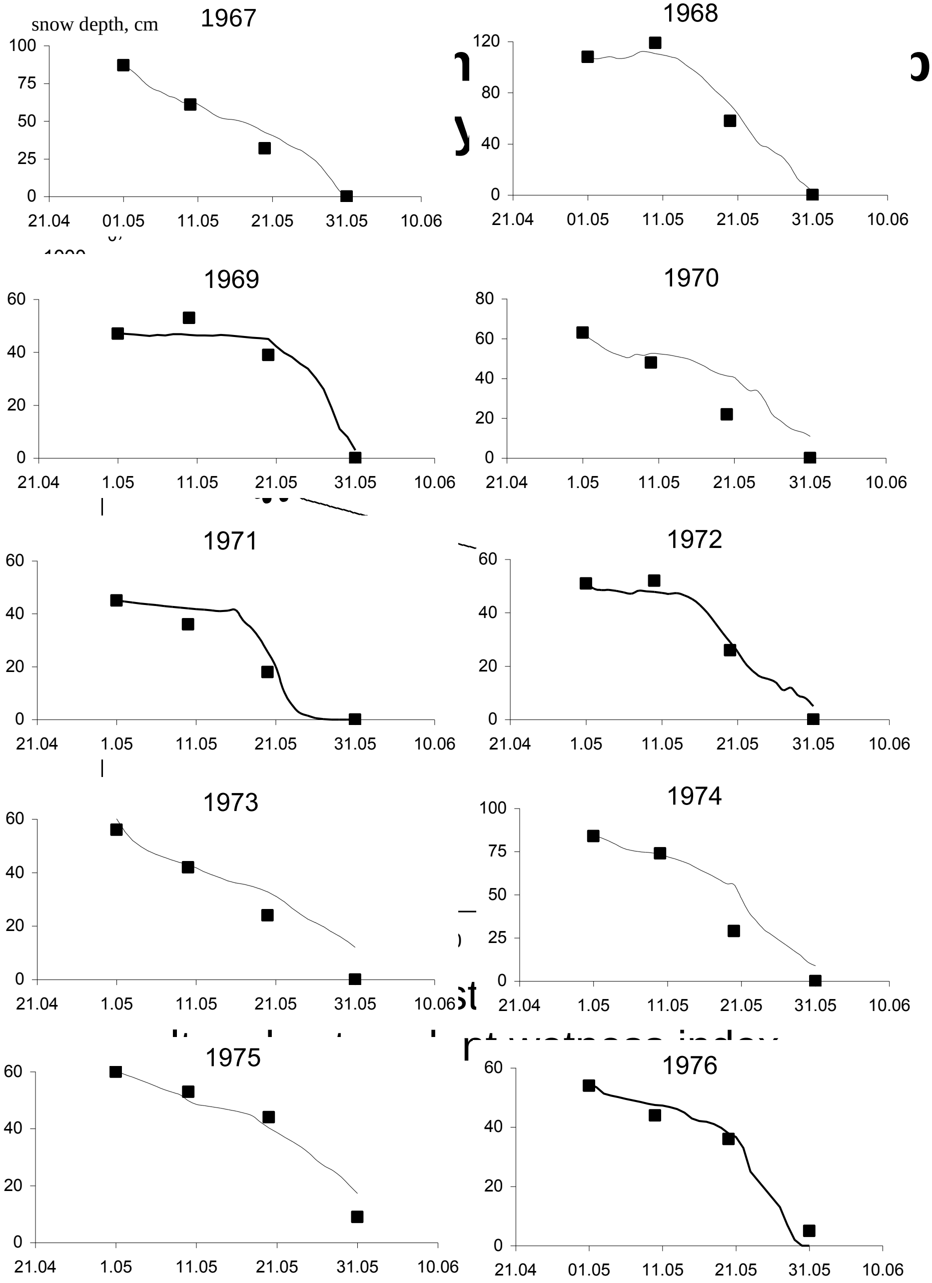
$$\frac{d}{dt}(\theta H) = \frac{dD}{dt} - E + I \frac{\rho_i}{\rho_w} \frac{dH}{dt}$$

$$G = \frac{dD}{dt} - E + I \frac{\rho_i}{\rho_w} \frac{dH}{dt}$$

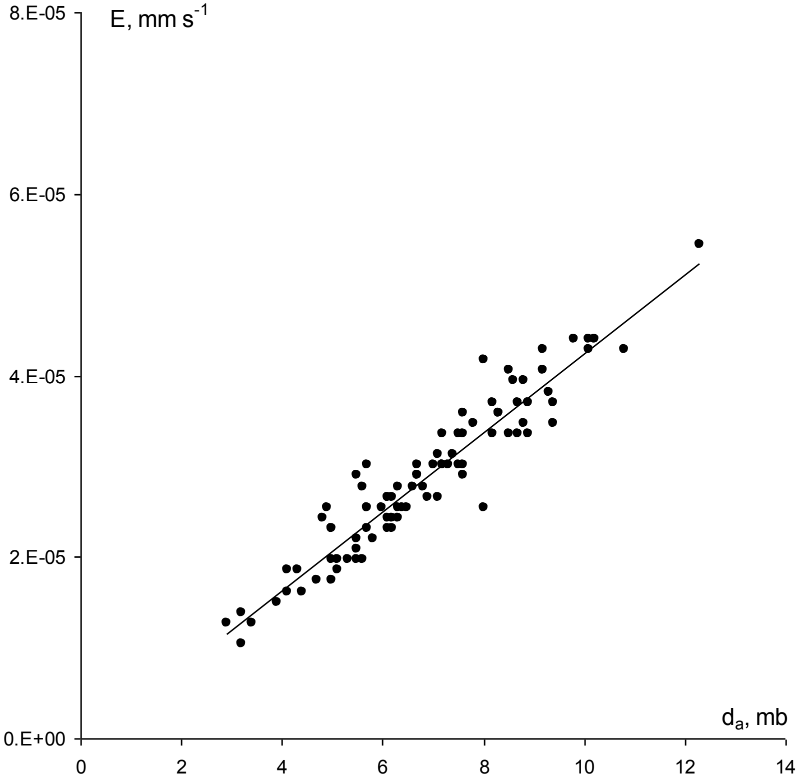


by the measurements at the proxy-

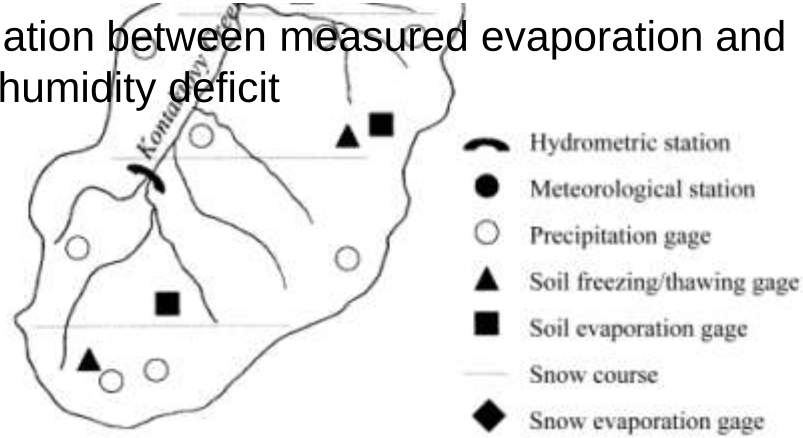
sin

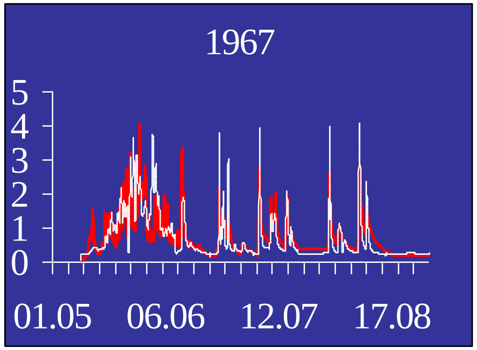


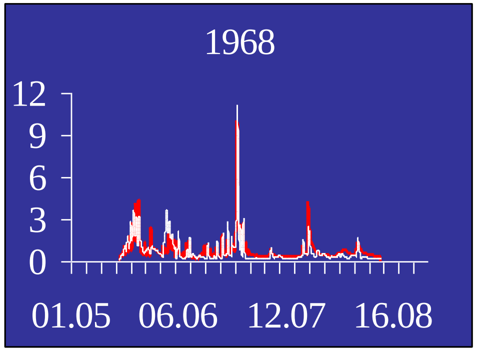
Measured (points) and calculated snow depths

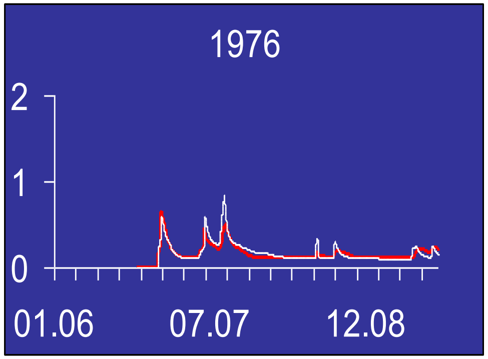


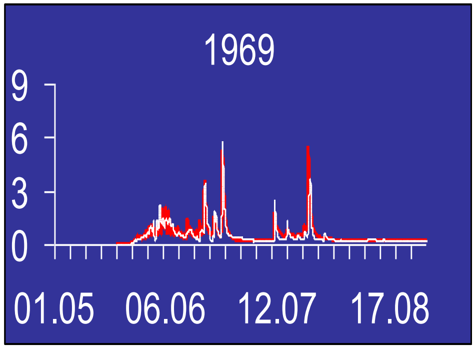
Relation between measured evaporation and air humidity deficit

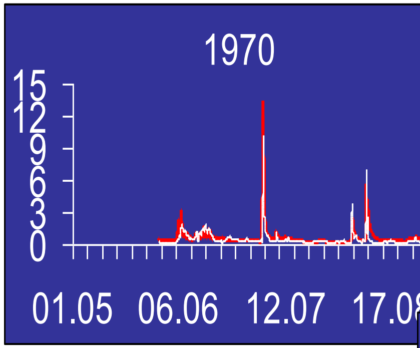




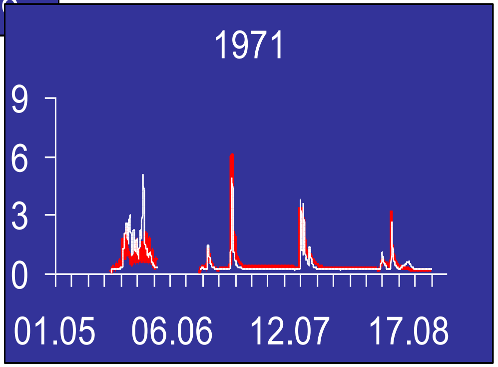


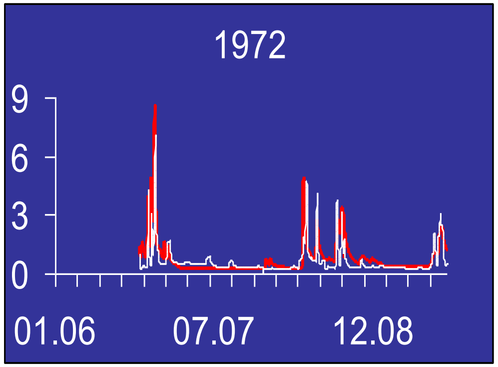


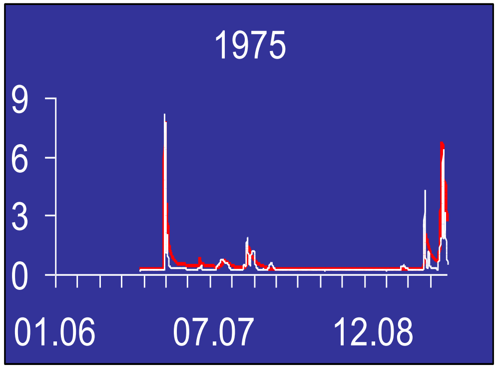


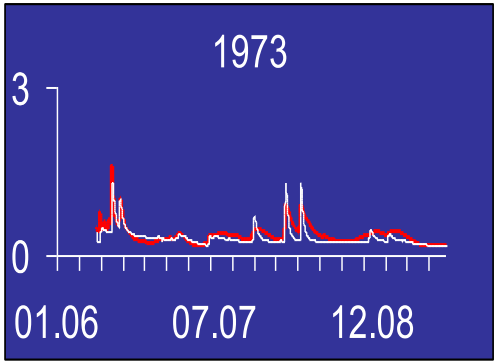


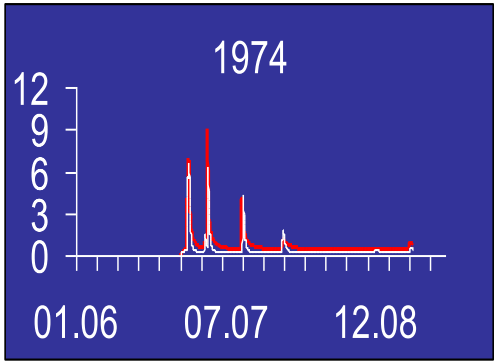
Comparison between calculated (white line) and measured (red line) hydrographs (Kontaktnyi Creek basin)

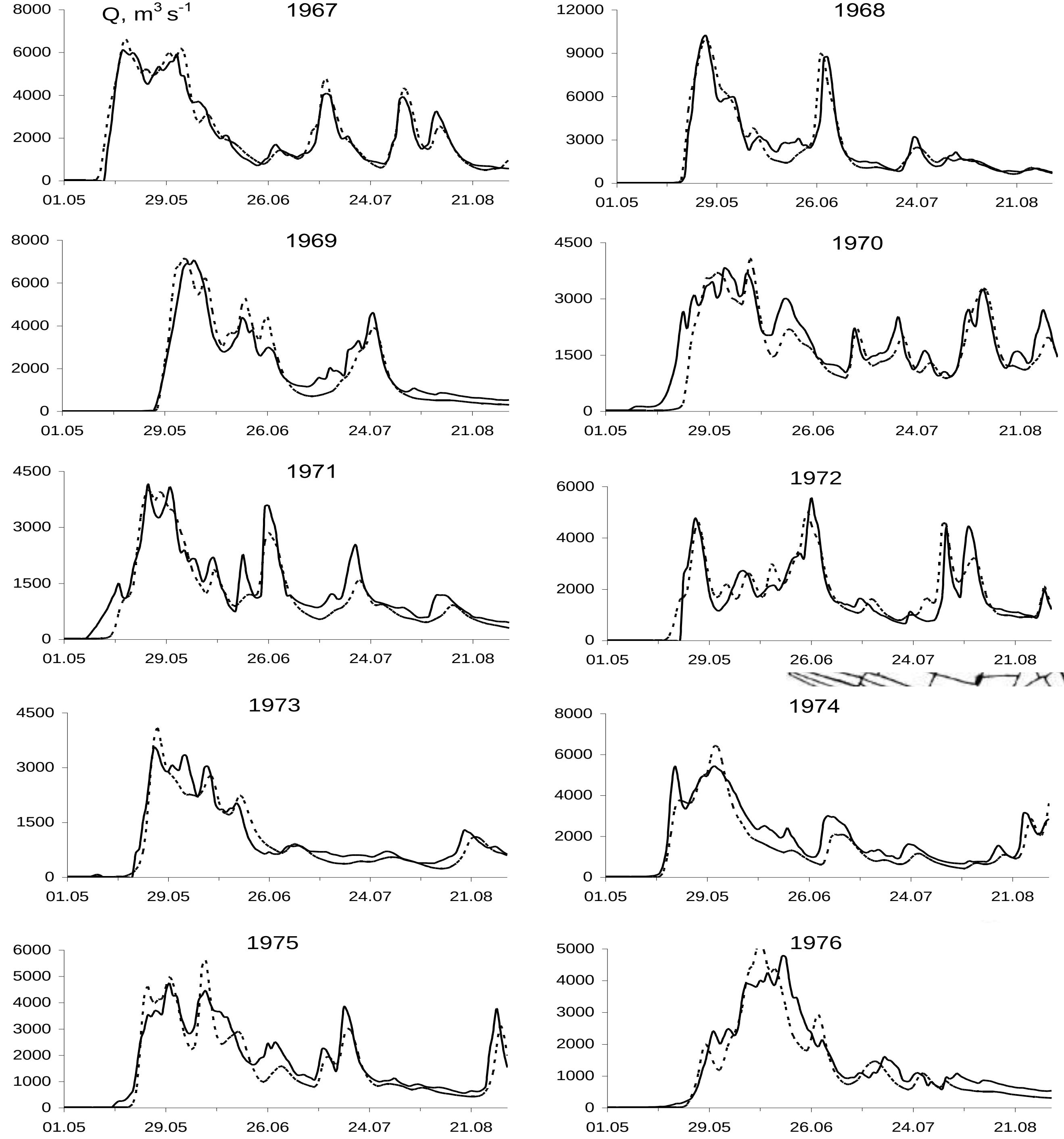








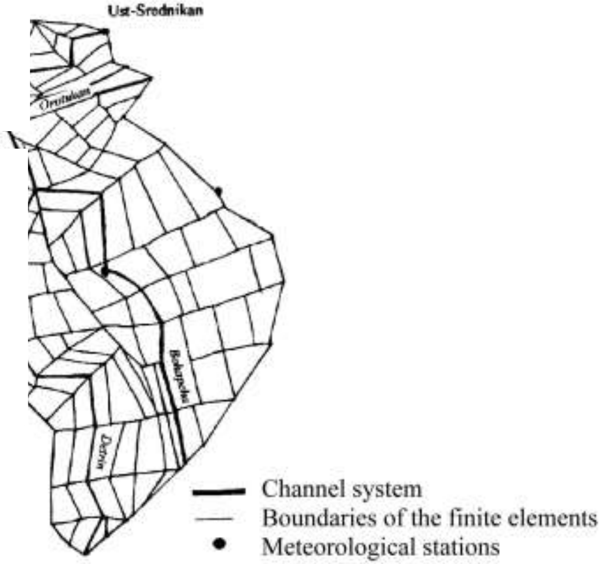




Kolyma River basin:

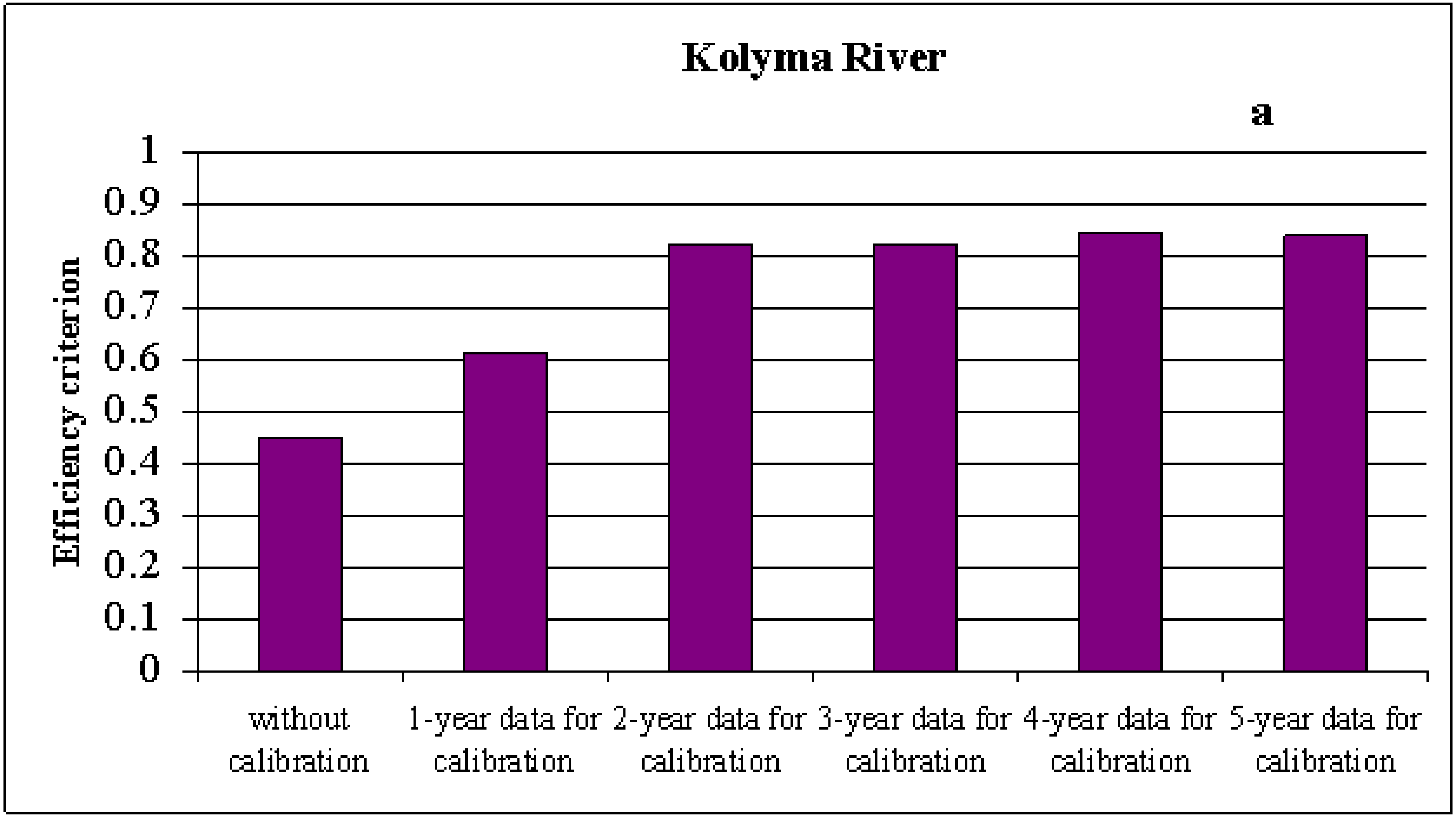
Calibration period 3 years

Validation period – 7 years



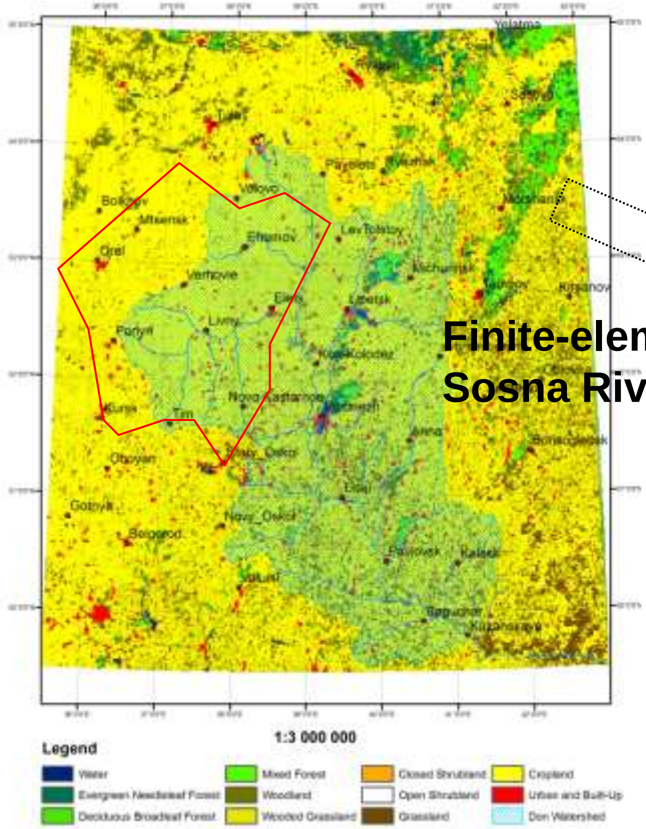
- Channel system
- Boundaries of the finite elements
- ● Meteorological stations

Changes of the Nash-Sutcliffe efficiency criterion under the different period of the model calibration



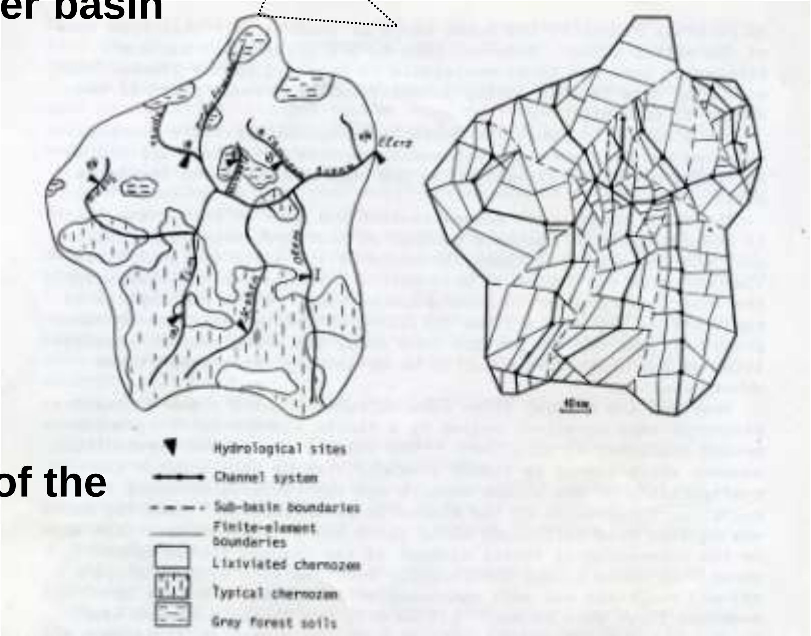
Applications of the proposed procedure (3rd example: Don River – Sosna River basins; *Kuchment et al, 1986; 1990; in press*)

<u>**The model is close to the one used for the Seim River basin**</u>



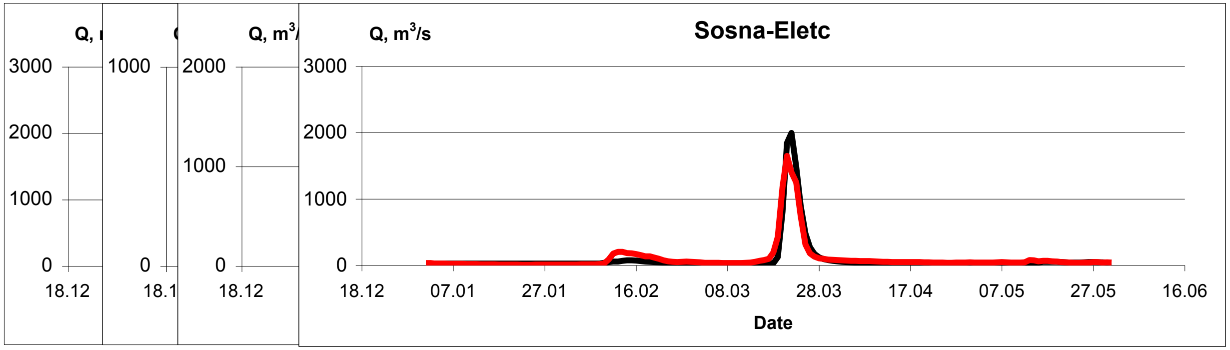
Finite-element schematization of the Don River basin

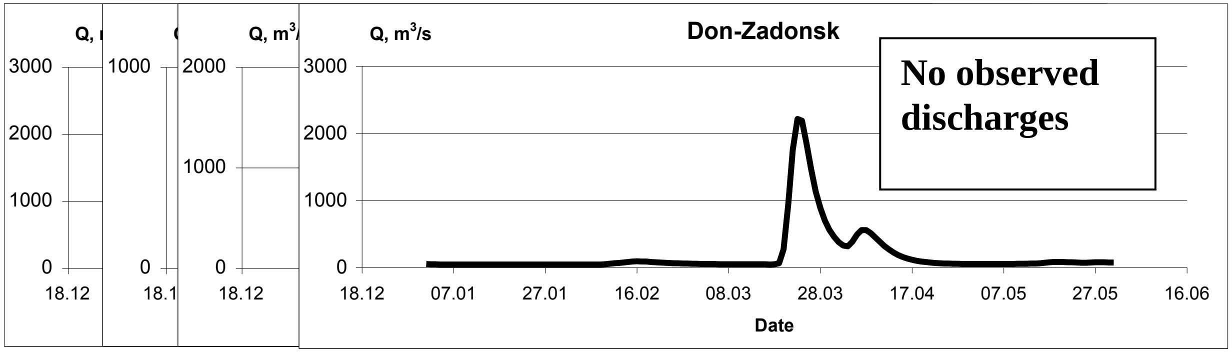
Finite-element schematization of the Sosna River basin



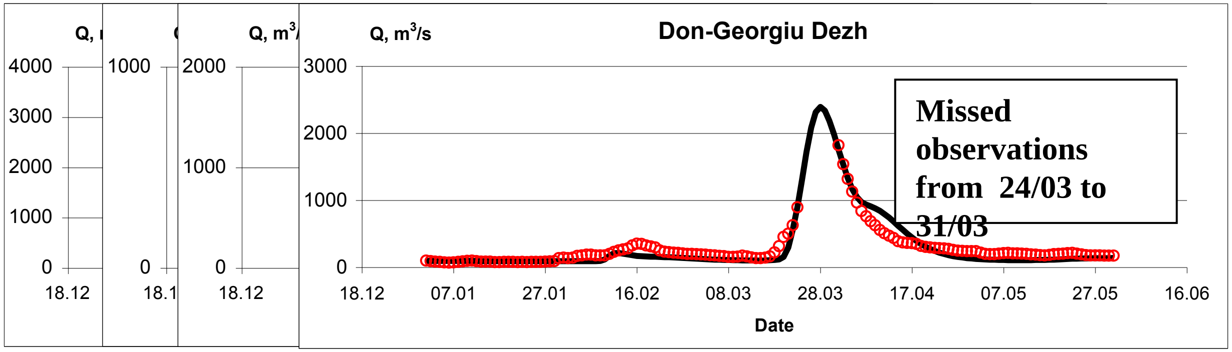
Don River basin:

Calibration period 3 years
Validation period – 7 years

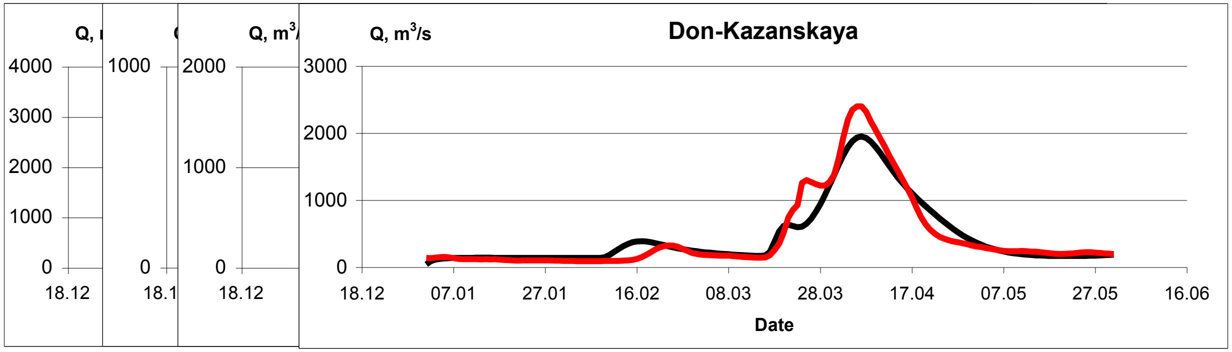


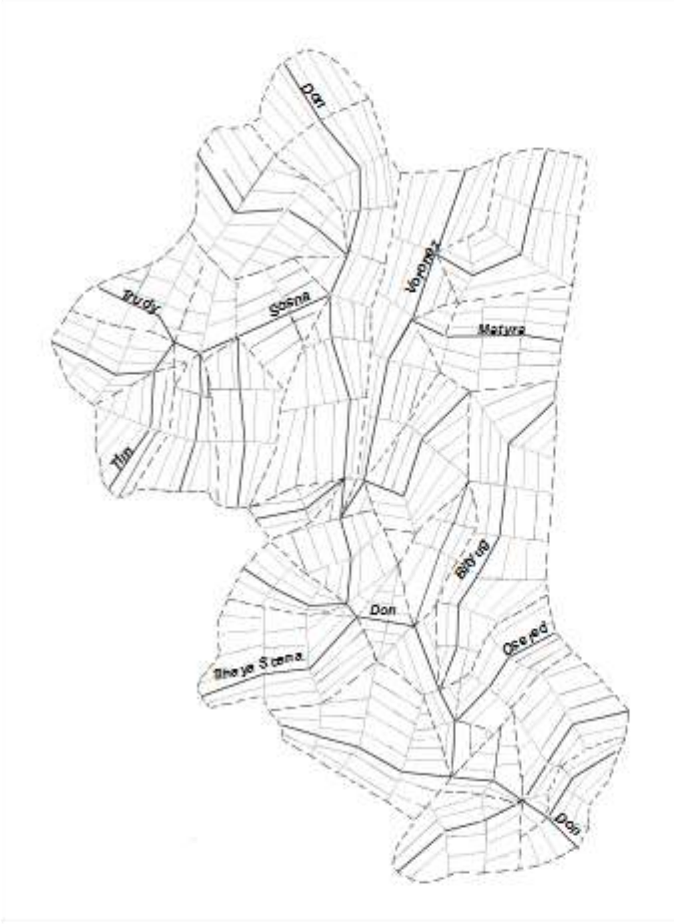


No observed discharges

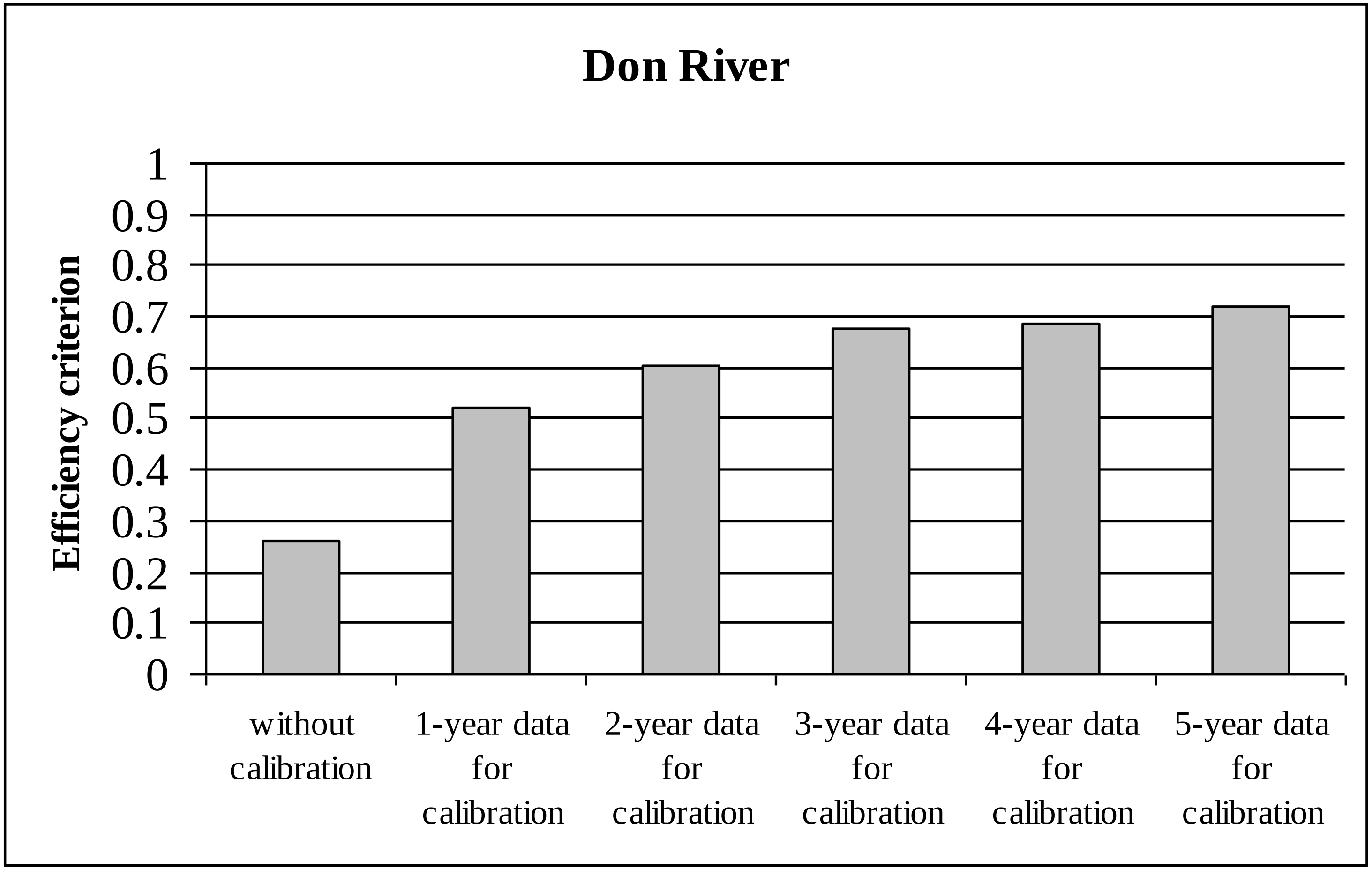


Missed observations from 24/03 to 31/03





Changes of the Nash-Sutcliffe efficiency criterion under the different period of the model calibration



Intermediate Conclusions

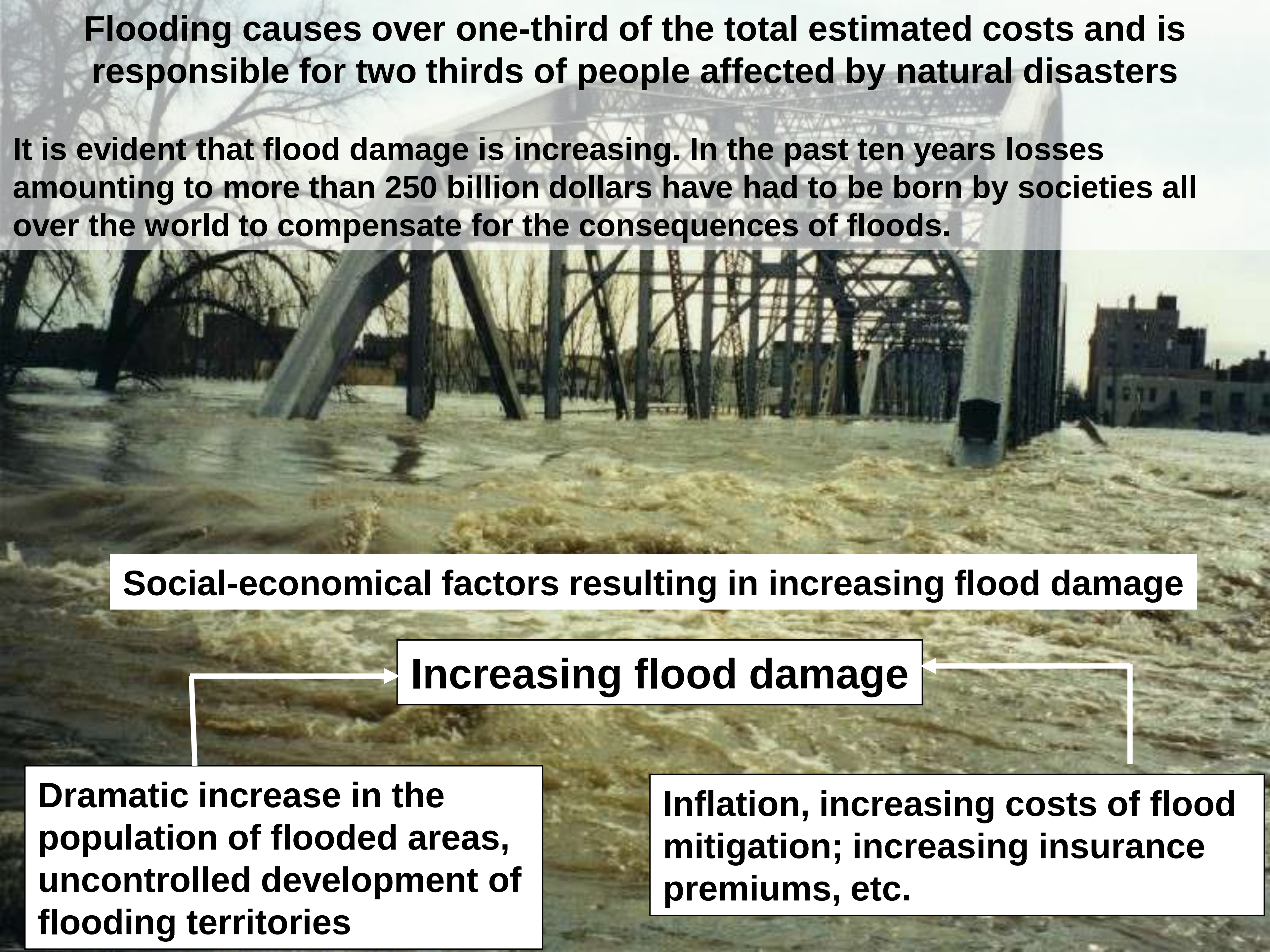
1.Physically-based models of runoff generation can assimilate *a priori* information that compensate, to a certain extent, insufficiency of runoff measurements in poorly gauged basins. However some of the model parameters must be adjusted through calibration against runoff data to achieve needed accuracy of runoff prediction. Our studies show that relatively short series (3-5 years) of observations can be enough to obtain satisfactory simulation results

2. The data obtained from experimental measurements and modelling of runoff in proxy-basins give the opportunity to find *a priori* values of most parameters, resulting in substantial reduction of the length of runoff measurement series needed for calibration. The data from the water-balance stations and experimental river basins can be of great importance in choosing the proxy-basins.

Putting PUB into Practice: Assessment of Disastrous Flood Risk in a Changing Environment

PUB Objectives:
…To provide a scientific basis for sustainable river basin management

Flooding causes over one-third of the total estimated costs and is responsible for two thirds of people affected by natural disasters



It is evident that flood damage is increasing. In the past ten years losses amounting to more than 250 billion dollars have had to be born by societies all over the world to compensate for the consequences of floods.

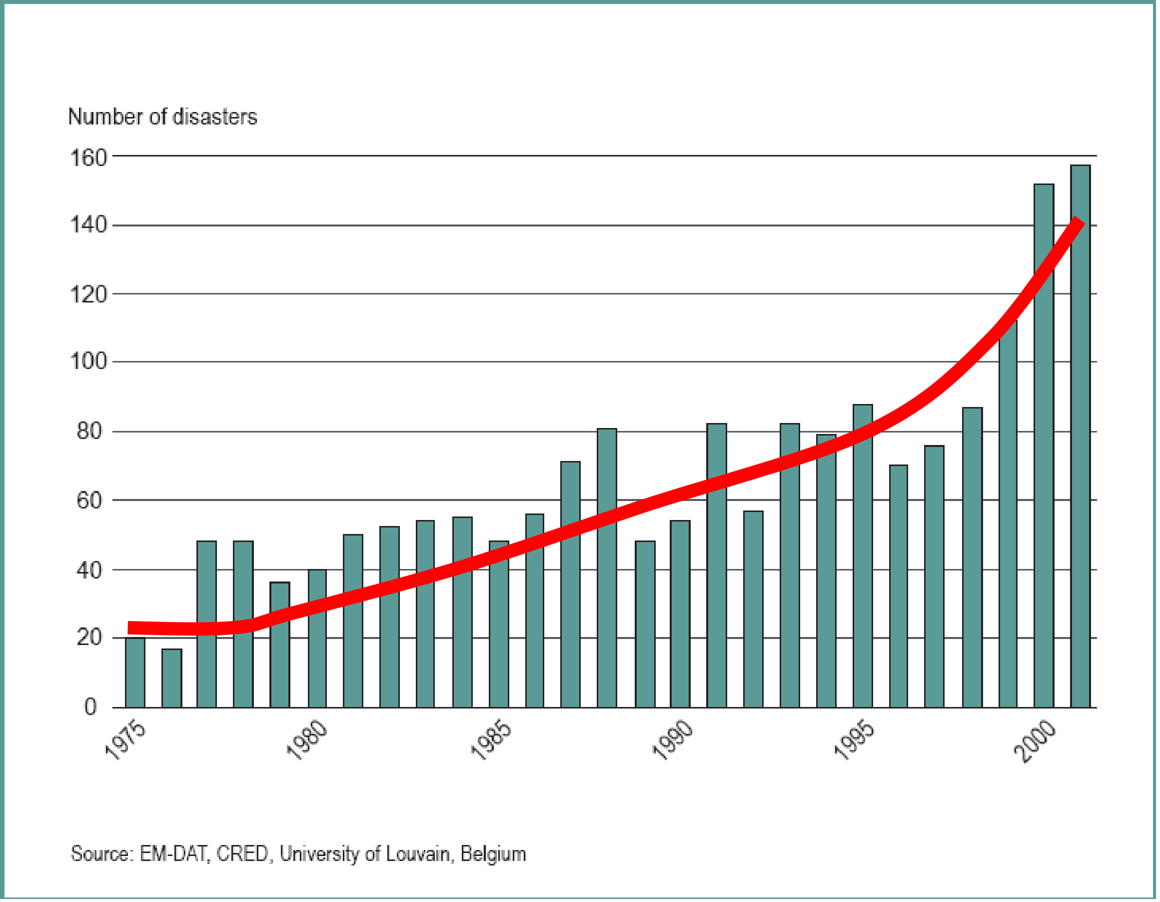
Social-economical factors resulting in increasing flood damage

Increasing flood damage

Dramatic increase in the population of flooded areas, uncontrolled development of flooding territories

Inflation, increasing costs of flood mitigation; increasing insurance premiums, etc.

Number of disasters attributed to floods, 1975-2001



Source: EM-DAT, CRED, University of Louvain, Belgium

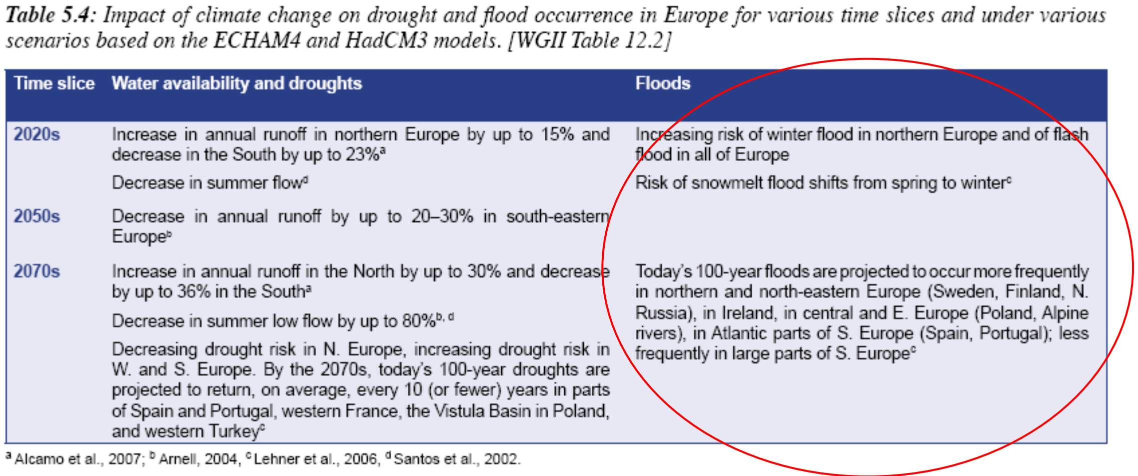


Table 5.4: Impact of climate change on drought and flood occurrence in Europe for various time slices and under various scenarios based on the ECHAM4 and HadCM3 models. [WGII Table 12.2]

Time slice	Water availability and droughts	Floods
2020s	Increase in annual runoff in northern Europe by up to 15% and decrease in the South by up to 23%[a] Decrease in summer flow[d]	Increasing risk of winter flood in northern Europe and of flash flood in all of Europe Risk of snowmelt flood shifts from spring to winter[c]
2050s	Decrease in annual runoff by up to 20–30% in south-eastern Europe[b]	
2070s	Increase in annual runoff in the North by up to 30% and decrease by up to 36% in the South[a] Decrease in summer low flow by up to 80%[b, d] Decreasing drought risk in N. Europe, increasing drought risk in W. and S. Europe. By the 2070s, today's 100-year droughts are projected to return, on average, every 10 (or fewer) years in parts of Spain and Portugal, western France, the Vistula Basin in Poland, and western Turkey[c]	Today's 100-year floods are projected to occur more frequently in northern and north-eastern Europe (Sweden, Finland, N. Russia), in Ireland, in central and E. Europe (Poland, Alpine rivers), in Atlantic parts of S. Europe (Spain, Portugal); less frequently in large parts of S. Europe[c]

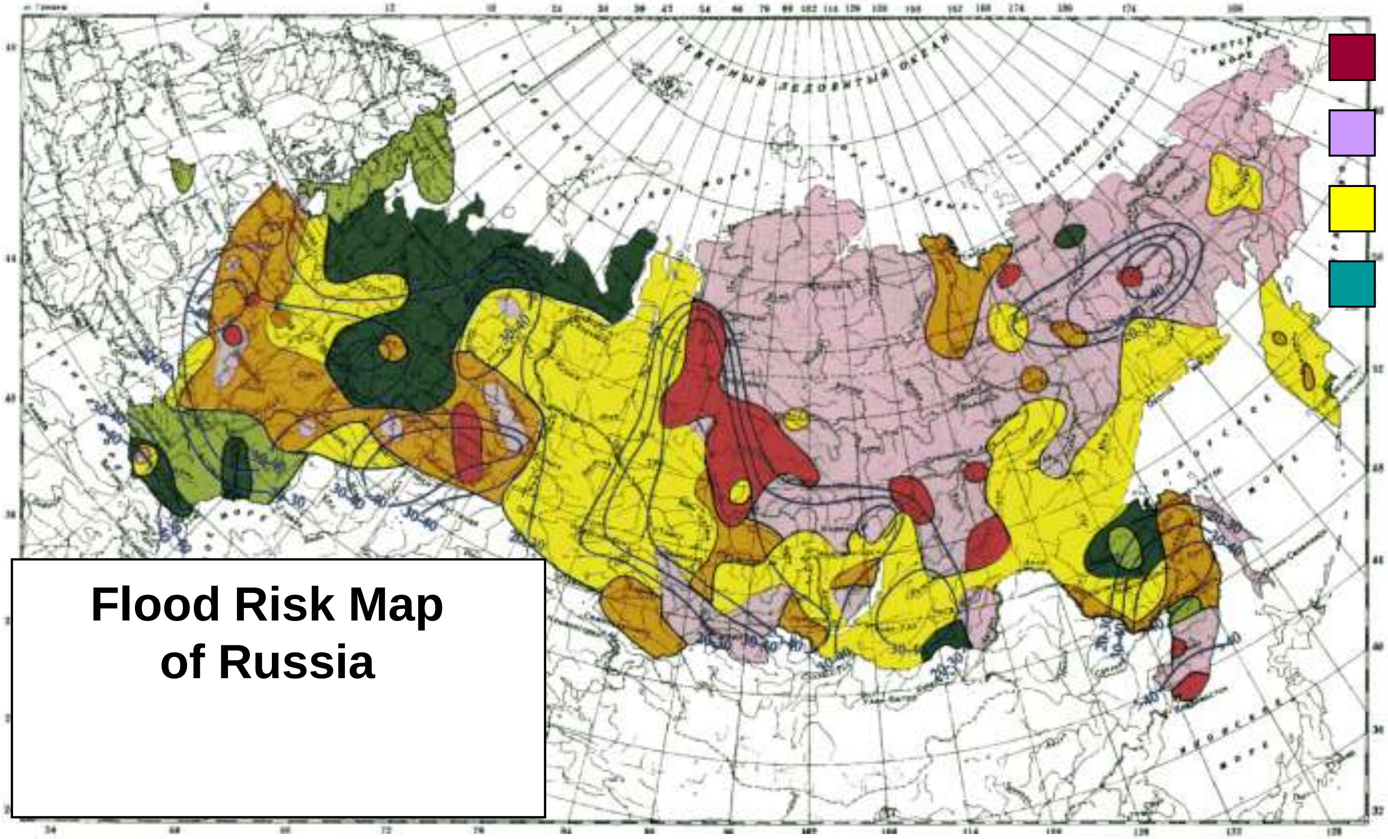
[a] Alcamo et al., 2007; [b] Arnell, 2004, [c] Lehner et al., 2006, [d] Santos et al., 2002.

In addition to socio-economic reasons increasing flood damage is caused by rising frequency and magnitude of disastrous floods: in the world in the last decade floods happened twice in the thirty years from 1951 to 1980.

The main reasons are environmental changes caused by anthropogenic impacts (e.g. deforestation and urbanization of watersheds) and climate change

In Russia, total potentially flooded area is about 400,000 km^2, of which 50,000 km^2 are flooded every year. The risk of flooding exists for 746 cities, thousands of settlements with a total population of about 4,6 million people, more than 7 million hectares of agricultural lands

Annual damage from flooding is about $80 million per year. More than 60% of disastrous floods in Russia is of snowmelt origin



Flood Risk Map of Russia

- 🟥 **- critical level of ris**
- 🟪 **- high level**
- 🟨 **- moderate level**
- 🟦 **- low level**

In Canada, flooding is a common natural hazard that has caused 260 known disasters since 1900, resulting in the loss of 235 lives and 8.7 billion dollars in damage.

The five most damaging floods were:

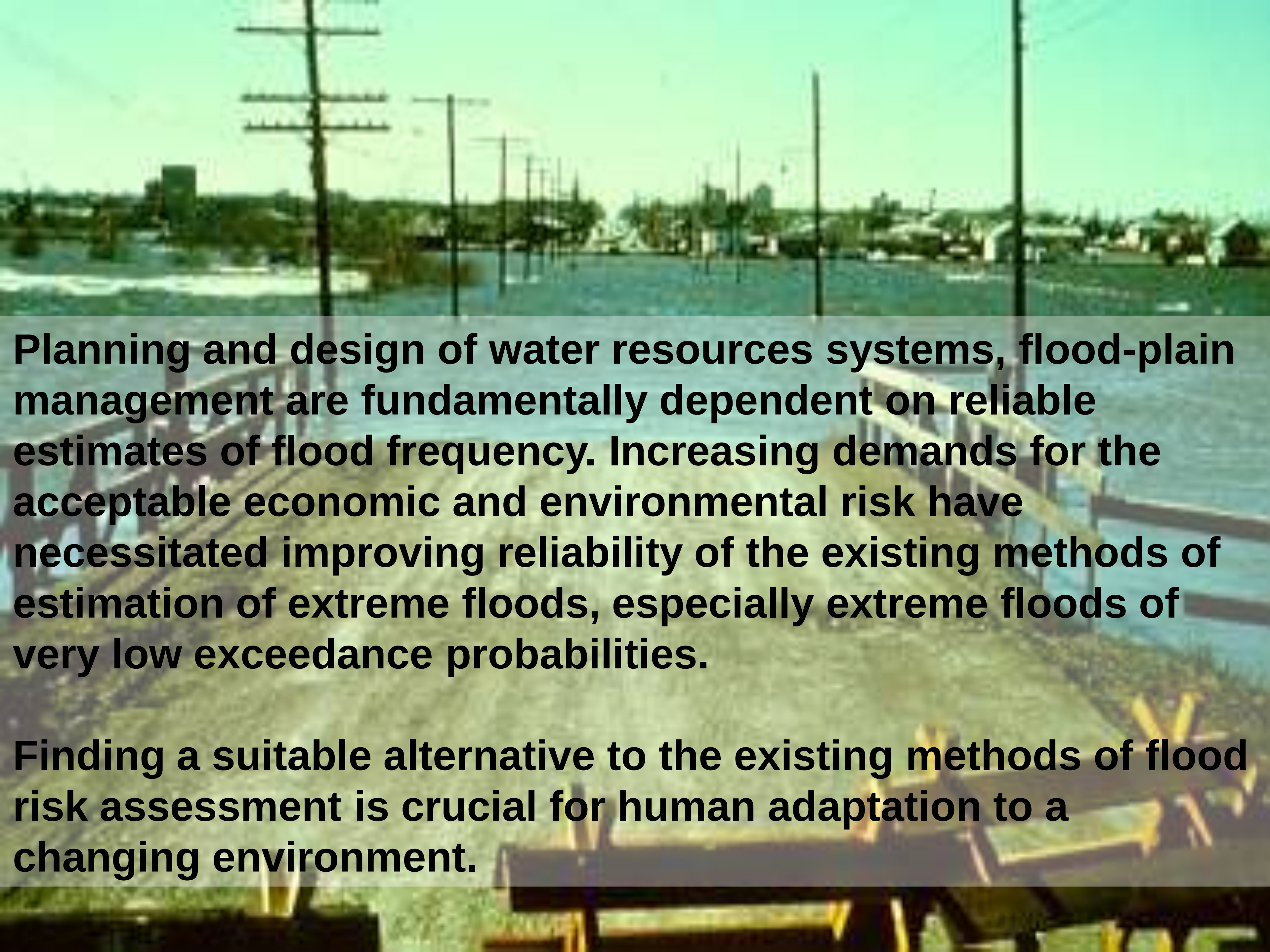
1996 Saguenay flood ($1.7 billion)
1950 Red River flood ($1.1 billion)
1954 flooding arising from Hurricane Hazel ($1.1 billion)
1997 Red River flood ($817 million)
1948 Fraser River flood ($425 million)

- *1948 Fraser River flood*

- ***1997 Red River flood***

- ***2009 Red River flood***

2011 Red River Flood



Planning and design of water resources systems, flood-plain management are fundamentally dependent on reliable estimates of flood frequency. Increasing demands for the acceptable economic and environmental risk have necessitated improving reliability of the existing methods of estimation of extreme floods, especially extreme floods of very low exceedance probabilities.

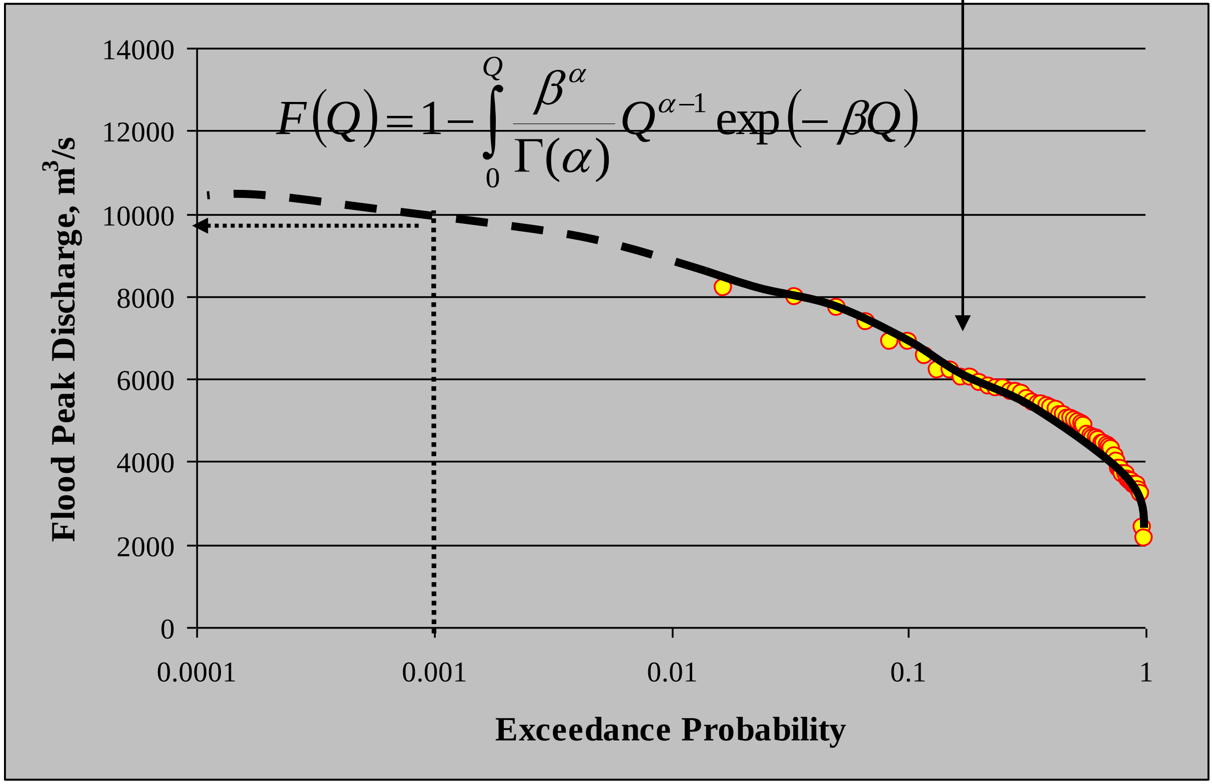
Finding a suitable alternative to the existing methods of flood risk assessment is crucial for human adaptation to a changing environment.

Traditional flood frequency analysis is based on

1. acquisition of data of flood peak discharges,
2. computation of observed probabilities of occurrence,
3. fitting of the appropriate probability distribution to the observed probabilities and extrapolation to the desired probabilities
4. estimation of flood quantiles of the desired probabilities.

N п/п	Год	Qmax	P,%
1	1882	16200	0.97
2	1916	13800	1.94
3	1914	12950	2.91
4	1899	12400	3.88
5	1927	11500	4.85
……………………			
98	1937	3020	95.15
99	1931	2835	96.12
100	1984	2300	97.09
101	1935	2120	98.06
102	1967	1970	99.03

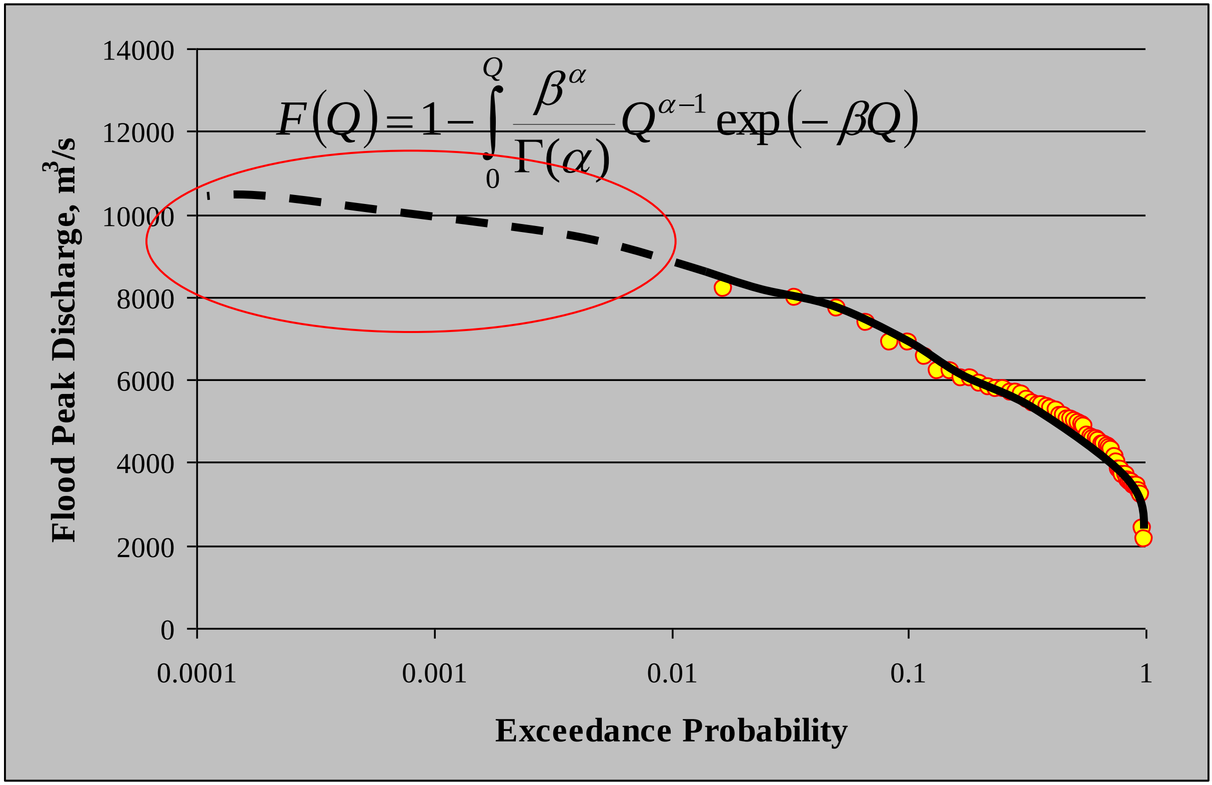
$Q_{0.001}=10000\ m^3/s$

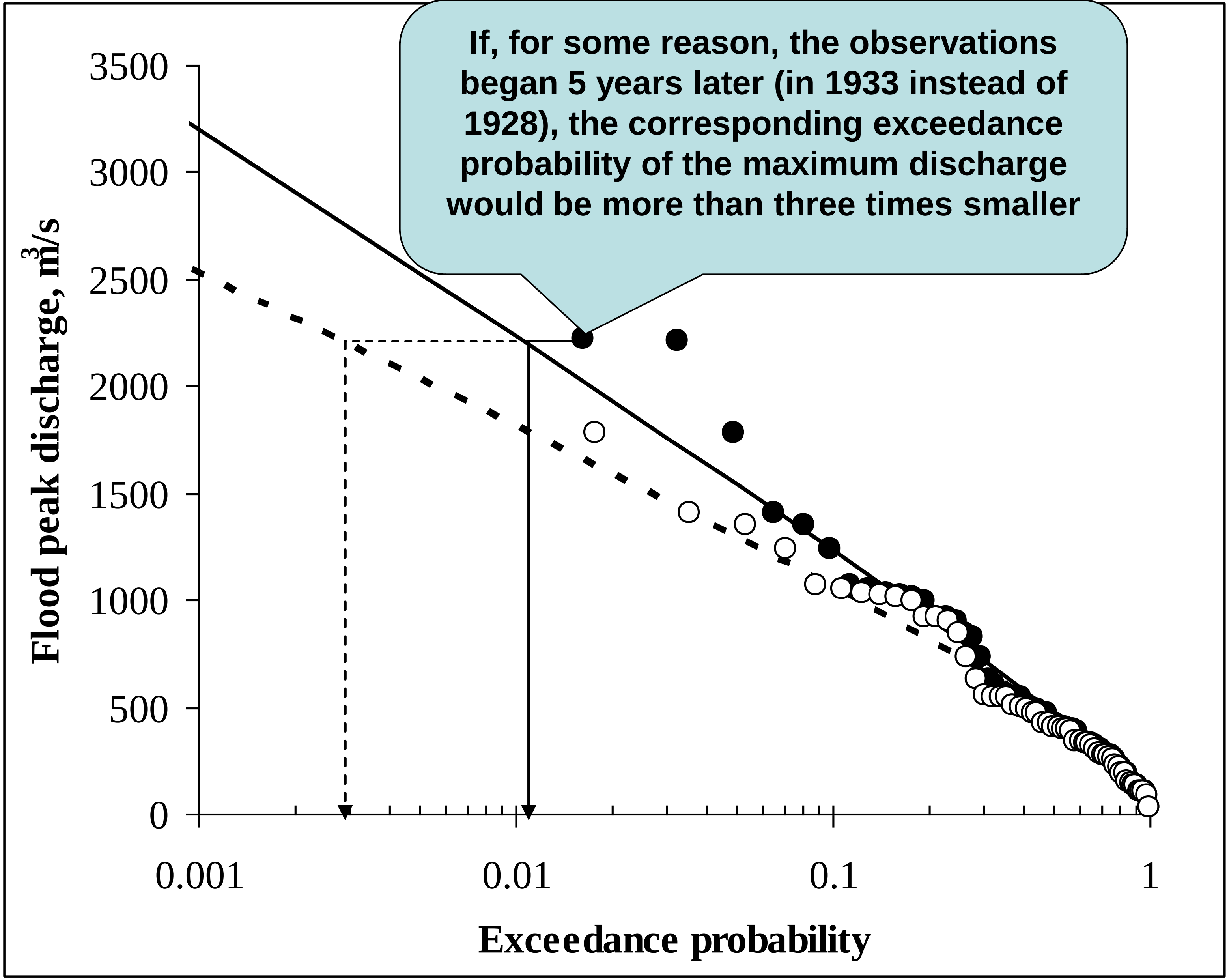


$$F(Q)=1-\int_0^Q \frac{\beta^\alpha}{\Gamma(\alpha)}Q^{\alpha-1}\exp(-\beta Q)$$

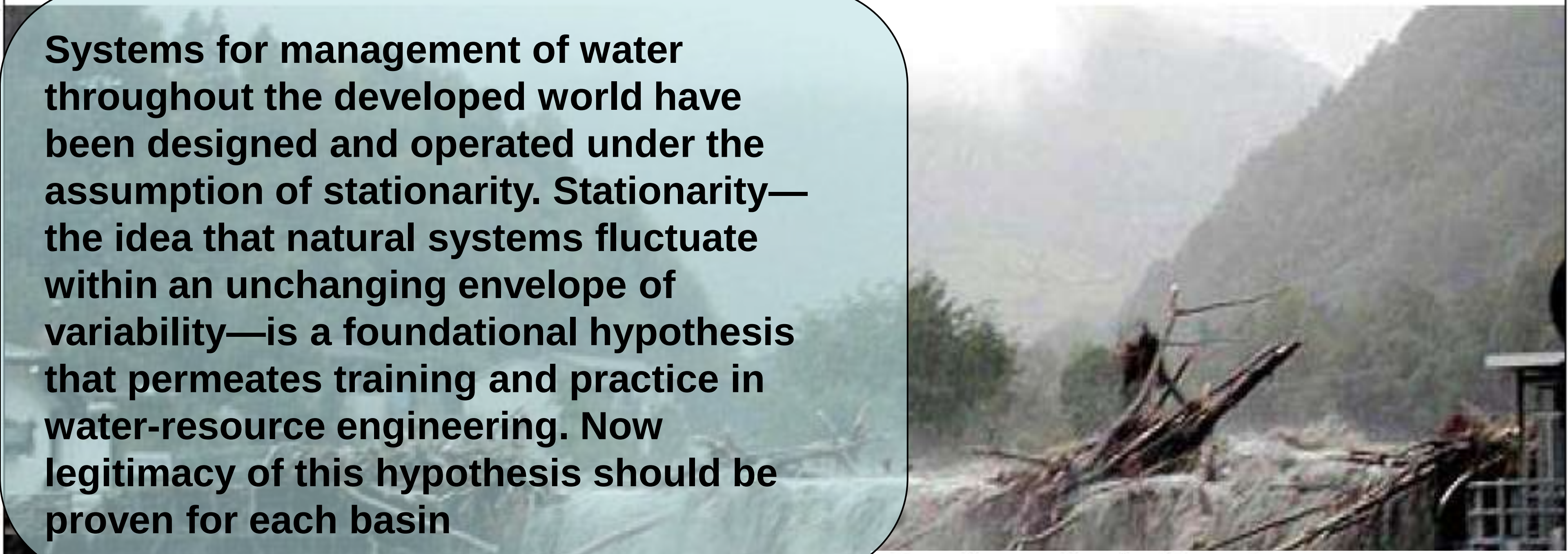
The fundamental weakness of this approach has been clearly identified more than half a century ago by the world famous Australian statistician and probabilist, Professor P. A. P. Moran:

"... the form of the distribution is not known and any distribution used must be guessed ... since the part of the distribution we are interested in is well away from the part where observations provide some information... [this difficulty] cannot be overcome by mathematical sleight of hand« **(citation from Klemeŝ, 1993)**





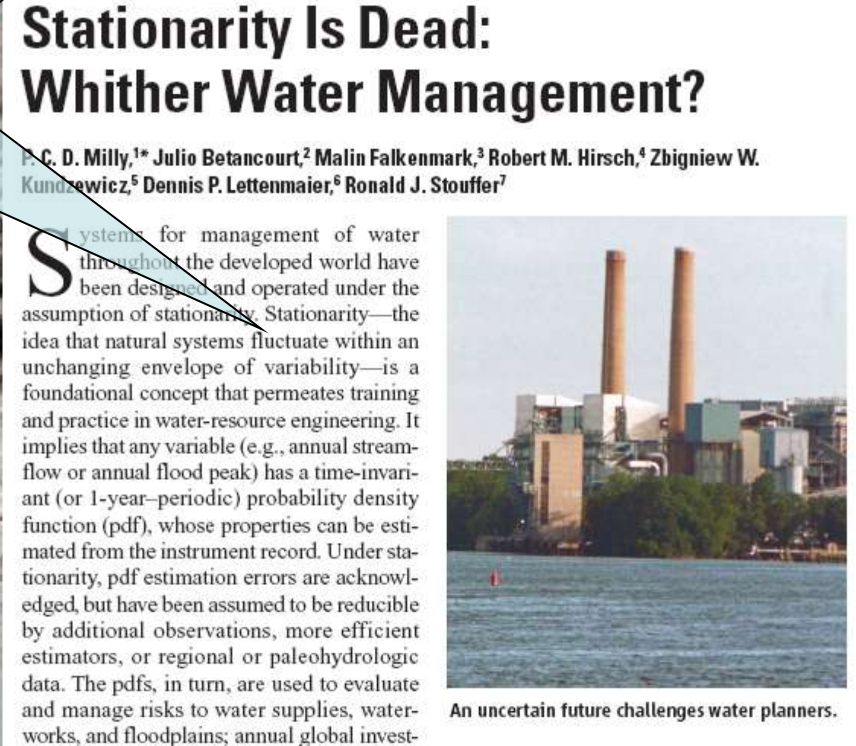
Log-Pearson III distribution curves fitted to 61-year (solid line; black points) series of observations at the Seim River beginning from 1928 and 56-years (dashed line; white points) series beginning from 1933



Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational hypothesis that permeates training and practice in water-resource engineering. Now legitimacy of this hypothesis should be proven for each basin

"In order to apply any theory we have to suppose that the data are homogeneous, i. e. that no systematical change of climate and no important change in the basin have occurred within the observation period and that no such changes will take place in the period for which extrapolations are made."

Emil Gumbel ("The return period of flood flows," *Ann. Math. Stat.*, 1941)



Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global invest-

An uncertain future challenges water planners.

Motivations for invoking knowledge of a flood generation physics in flood frequency analysis

1. **Extreme floods can be caused by unusual combinations of hydrometeorological factors that may be unrecorded during the period of observations**

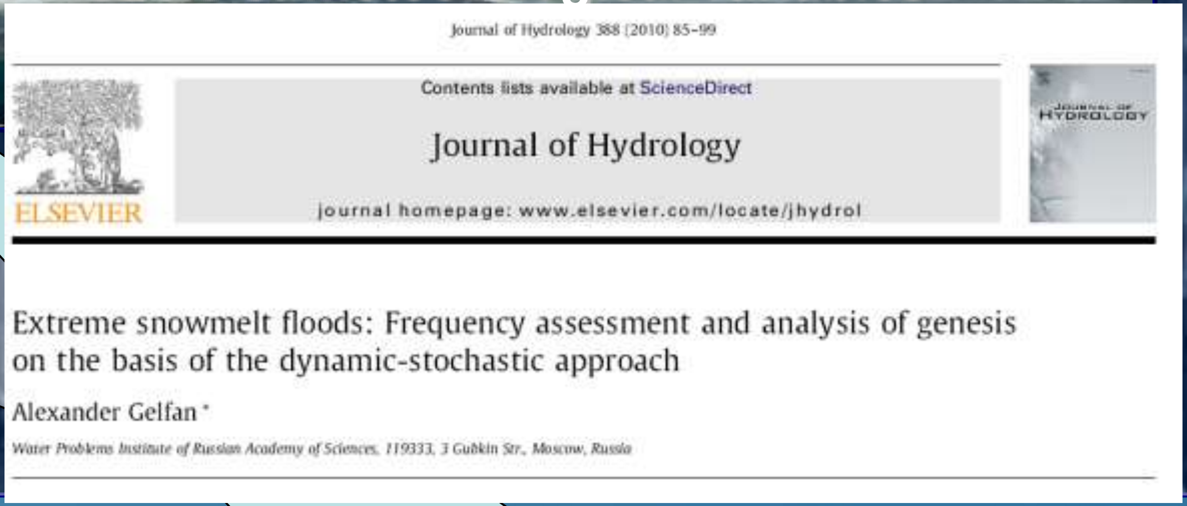
2. **Physical mechanisms of extreme flood formation are often quite different from ones of ordinary flood, because of non-linearity of hydrological systems**

3. **Physical mechanisms of flood generation have been changed because of man-induced changes of watershed and climate change**

New generation of methods for flood risk assessment should be founded on physical principles

Dynamic-stochastic approach to flood risk assessment*

Stochastic models of meteorological variables



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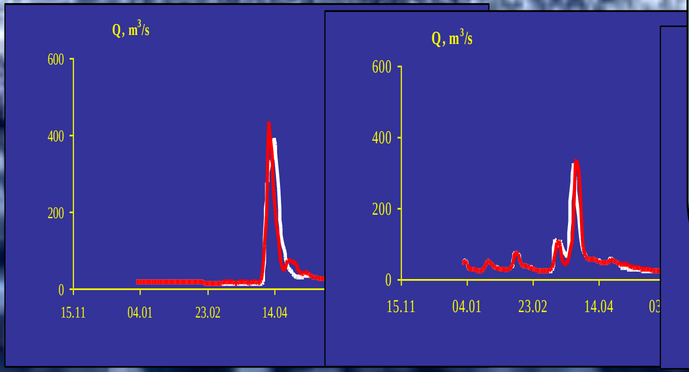
Extreme snowmelt floods: Frequency assessment and analysis of genesis on the basis of the dynamic-stochastic approach

Alexander Gelfan *

Water Problems Institute of Russian Academy of Sciences, 119333, 3 Gubkin Str., Moscow, Russia

Physically B



"In seeking to understand the behavior of hydrologic systems of interest it is necessary to draw on standard results from both the statistical study of random systems and the deterministic analysis of classical fluid mechanics and hydraulics.…Progress in both areas [deterministic and stochastic hydrology] would benefit if they were considered as complementary rather than separate fields of investigation.

J. C. I. Dooge "Bringing it all together".

Stochastic Weather Generator

Precipitation

Daily Precipitation Occurrence
(first-order, two-state Markov chain)

Da itation Amount
(gam
indepen

Air Temperature

✓Contin
and s.d.
✓Fourie
✓AR(1)
seasonal

Air Humidity

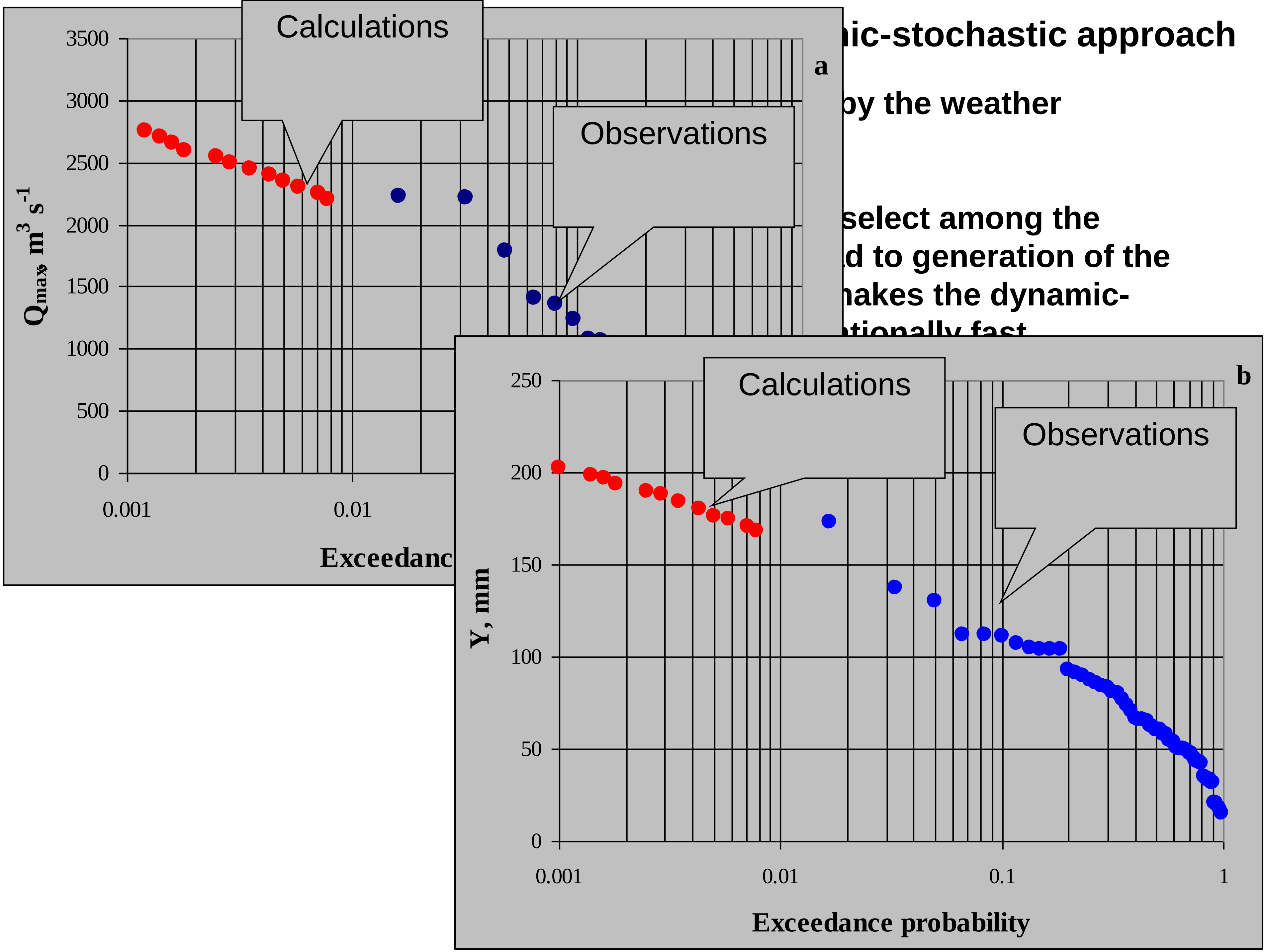
Daily air humidity deficit on the dry is assumed to be lognormal distributed, independent variable; on a wet day the humidity deficit was assumed equal zero

Definition
Stochastic Weather Generator is a set of stochastic models that use existing weather records to produce long series of synthetic daily weather variables, which statistical properties are expected to be similar to those of the actual data

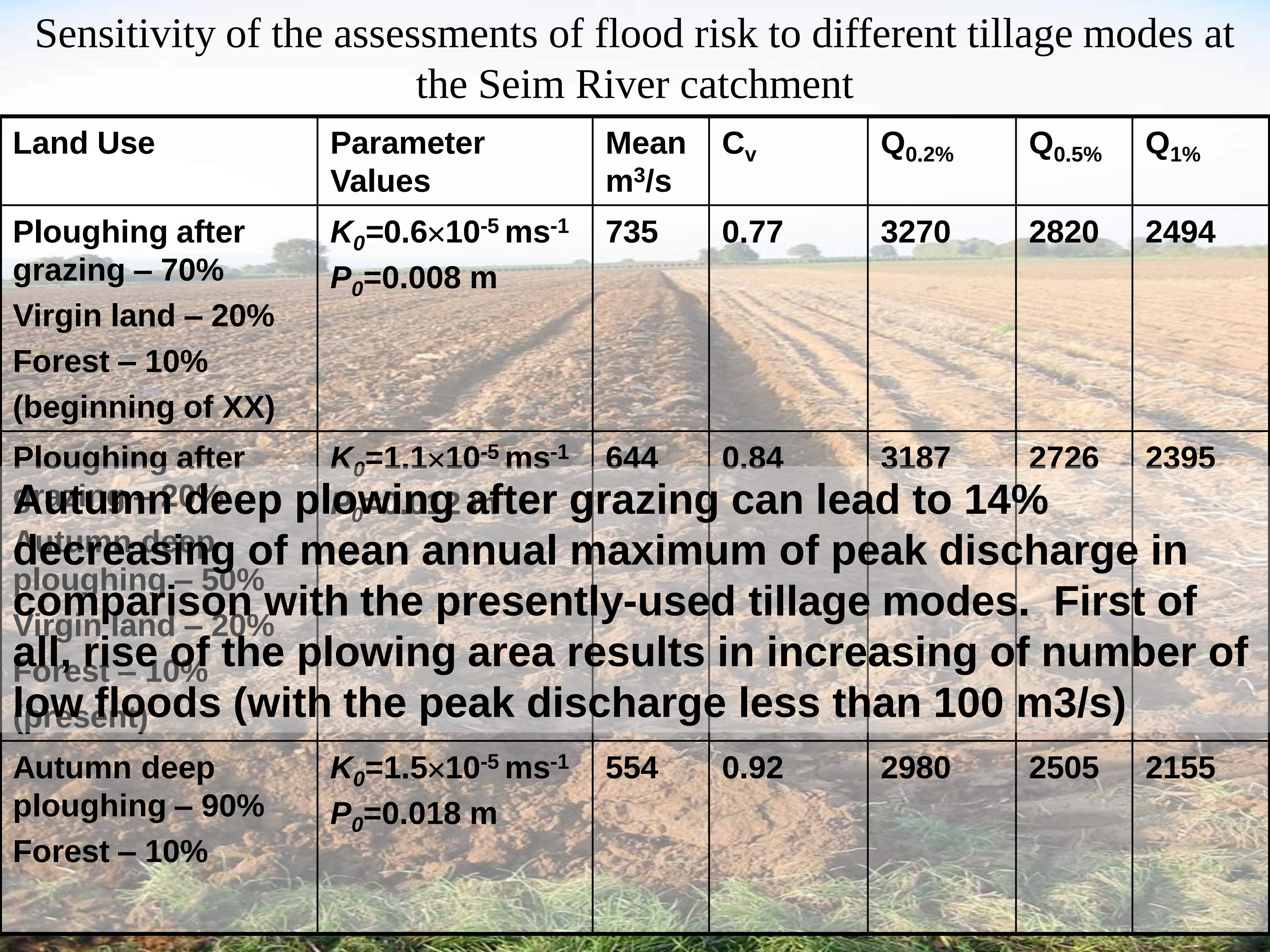
ic-stochastic approach

by the weather

select among the
d to generation of the
akes the dynamic-
tionally fast



Sensitivity of the assessments of flood risk to different tillage modes at the Seim River catchment



Land Use	**Parameter Values**	**Mean m^3/s**	**C_v**	**$Q_{0.2\%}$**	**$Q_{0.5\%}$**	**$Q_{1\%}$**
Ploughing after grazing – 70% **Virgin land – 20%** **Forest – 10%** **(beginning of XX)**	$K_0=0.6\times10^{-5}$ ms^{-1} $P_0=0.008$ m	**735**	**0.77**	**3270**	**2820**	**2494**
Ploughing after grazing – 20% **Autumn deep ploughing – 50%** **Virgin land – 20%** **Forest – 10%** **(present)**	$K_0=1.1\times10^{-5}$ ms^{-1} $P_0=0.012$ m	**644**	**0.84**	**3187**	**2726**	**2395**
Autumn deep ploughing – 90% **Forest – 10%**	$K_0=1.5\times10^{-5}$ ms^{-1} $P_0=0.018$ m	**554**	**0.92**	**2980**	**2505**	**2155**

Autumn deep plowing after grazing can lead to 14% decreasing of mean annual maximum of peak discharge in comparison with the presently-used tillage modes. First of all, rise of the plowing area results in increasing of number of low floods (with the peak discharge less than 100 m3/s)

“There are no such things as applied sciences, only applications of science”.

Louis Pasteur

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