Hydrological modelling and specific challenges

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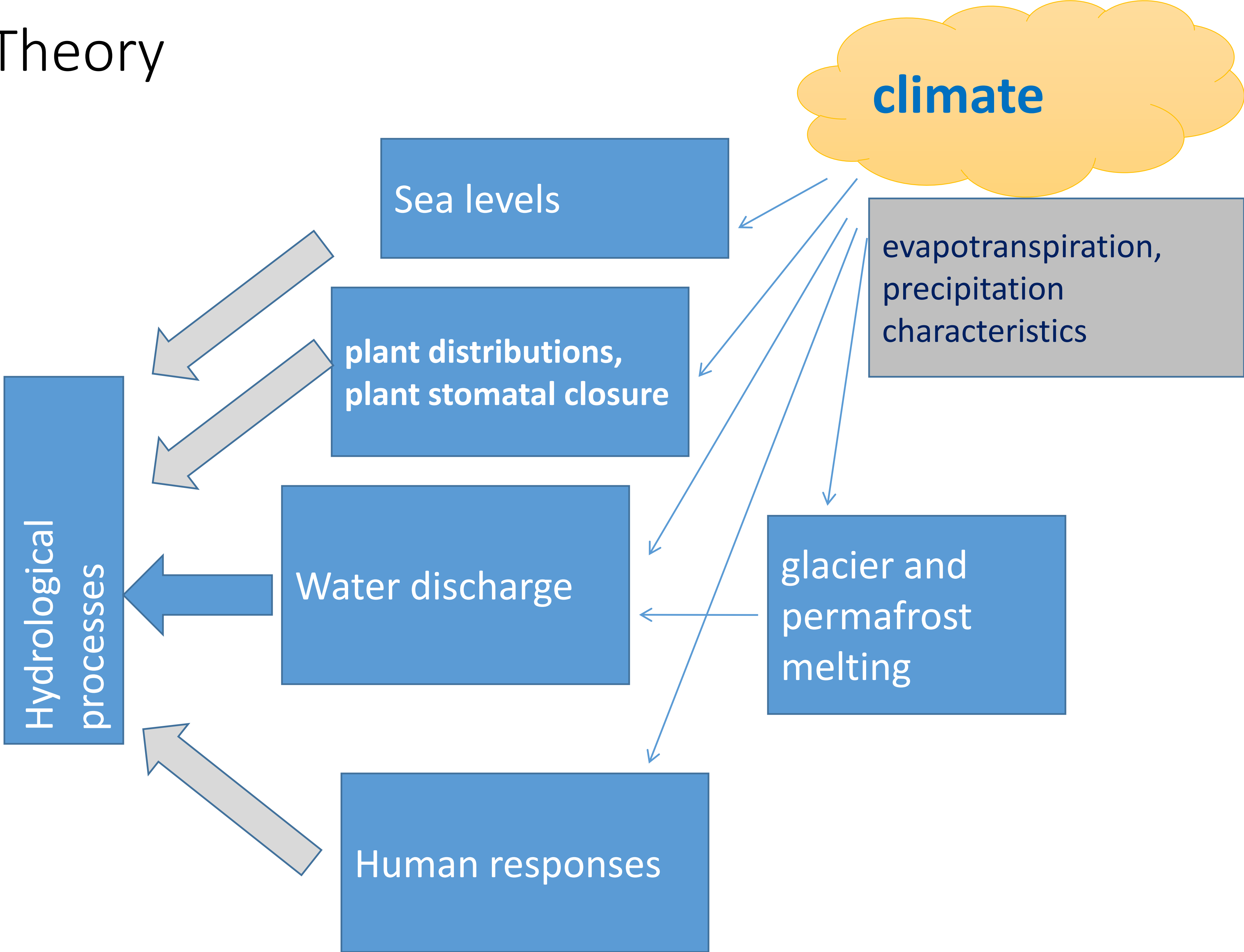
PHILOSOPHIES OF CHANGES

THEORY OF UNIFORMITY

THEORY OF CATASTROPHES

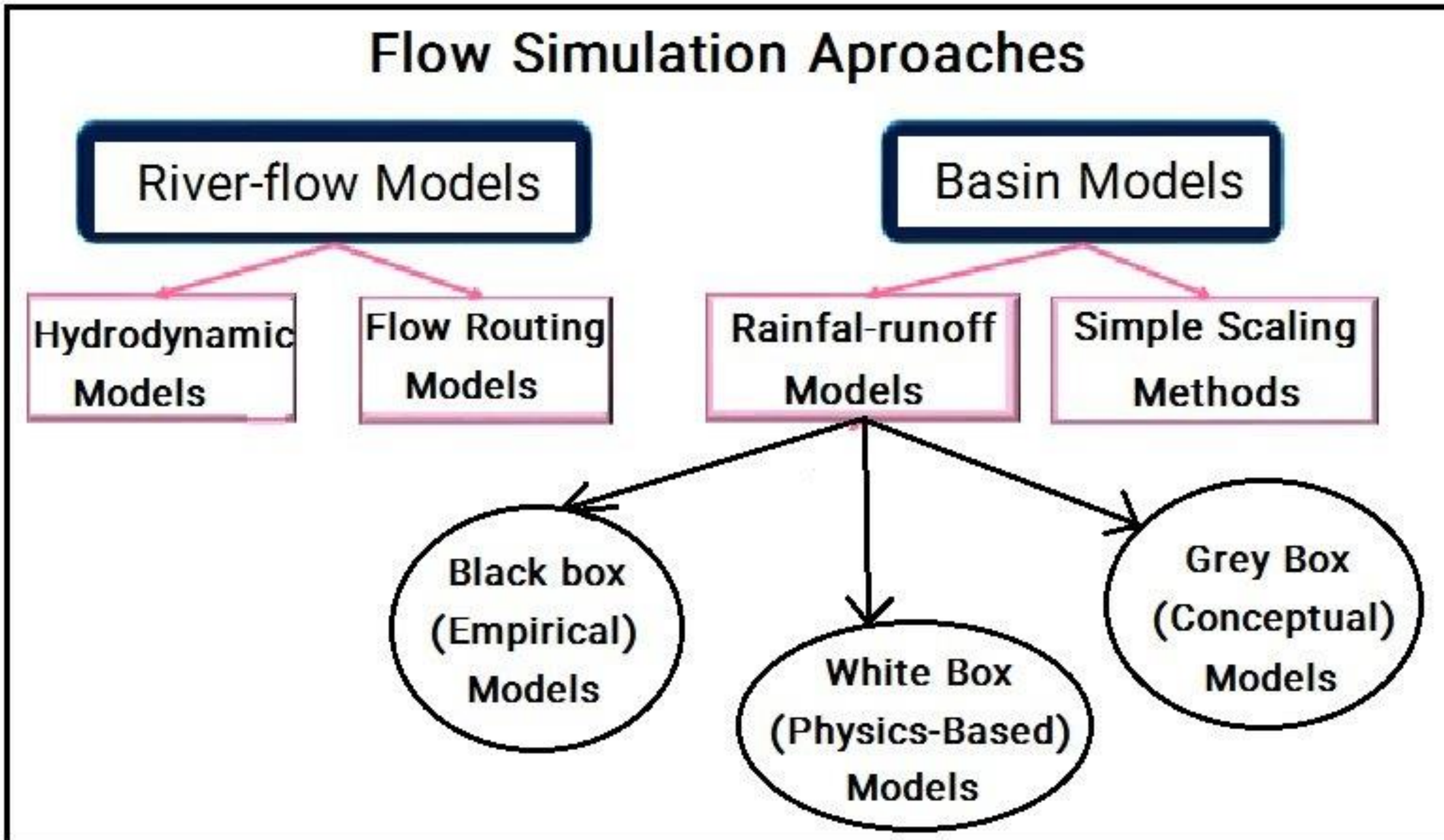
1. BASIC LAWS OF NATURE ARE TIME-INVARIANT
2. SIMILAR PROCESSES AND RATES PREVAILED IN THE PAST AS AT PRESENT
3. CHANGE TAKES PLACE GRADUALLY RATHER THEN SUDDENLY

Theory


climate
Sea levels
evapotranspiration,
precipitation
characteristics
plant distributions,
plant stomatal closure
Water discharge
glacier and
permafrost
melting
Hydrological
processes
Human responses

Main groups of models we will consider in the lecture:

1. Flow simulation
2. Erosion modelling
3. Hydrogeochemical modelling


Flow Simulation Aproaches
River-flow Models
Basin Models
Hydrodynamic Models
Flow Routing Models
Rainfal-runoff Models
Simple Scaling Methods
Black box (Empirical) Models
White Box (Physics-Based) Models
Grey Box (Conceptual) Models

Water runoff models

- 1. Empirical
- 2. Conceptual
- 3. Physical

	Empirical	**Conceptual**	**Physical**
Method	Non-linear relationship between inputs and outputs, black box concept	Simplified equations that represent water storage in catchment	Physical laws and equations based on real hydrologic responses
Strengths	Small number of parameters needed, can be more accurate, fast run time	Easy to calibrate, simple model structure	Incorporates spatial and temporal variability, very fine scale
Weaknesses	No connection between physical catchment, input data distortion	Does not consider spatial variability within catchment	Large number of parameters and calibration needed, site specific
Best Use	In ungauged watersheds, runoff is the only output needed	When computational time or data are limited.	Have great data availability on a small scale
Examples	Curve Number, Artificial Neural Networks[a]	HSPF[b], TOPMODEL[a], HBV[a], Stanford[a]	MIKE-SHE[a], KINEROS[c], VIC[a], PRMS[d]

The conceptual model HSPF schematic shows the Pervious Land segment module (PERLND) as an
assembly of multiple storage processes following the water balance equation.

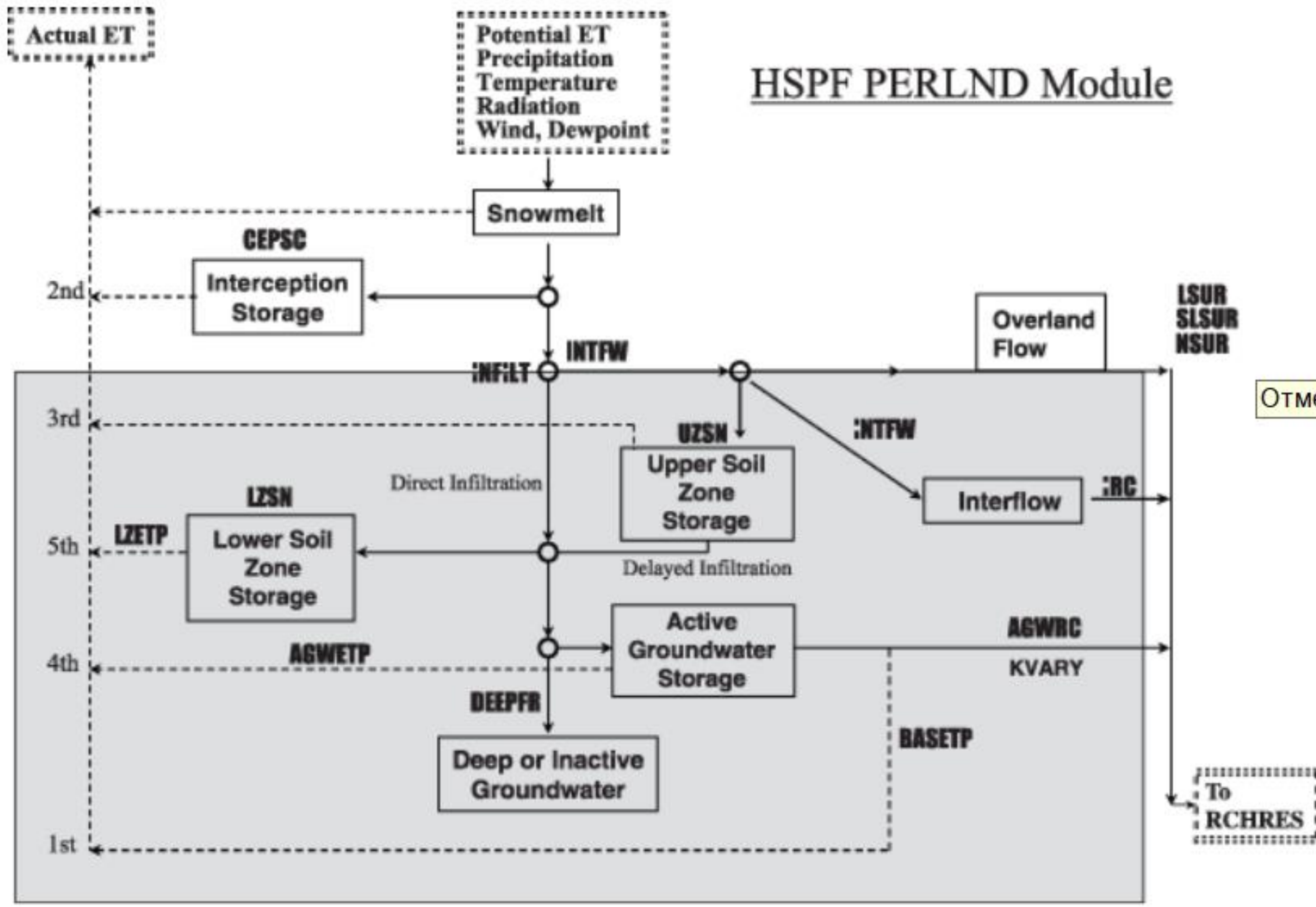
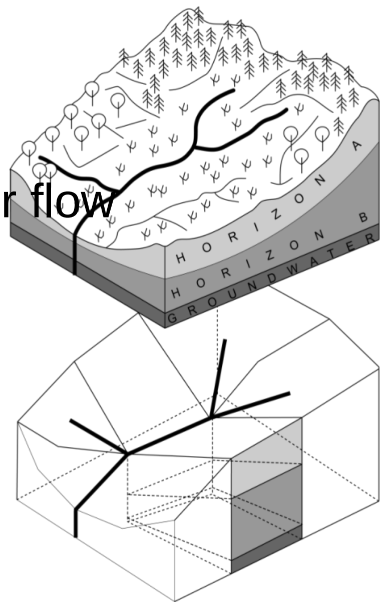


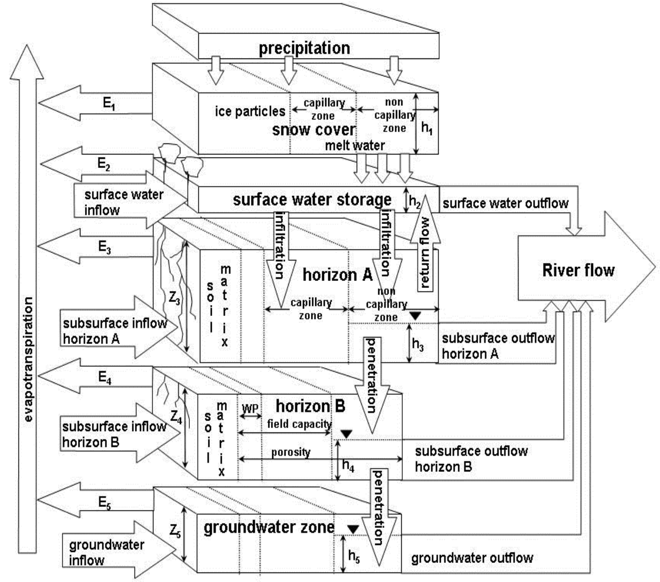
Image from (Atkins et al., 2005)

Physically-based semi-distributed model ECOMAG (ECOlogical Model for Applied Geophysics) (developed by Yury Motovilov)

Model description

snow accumulation, soil freezing, water infiltration , evapotranspiration, overland, subsurface, ground and river flow





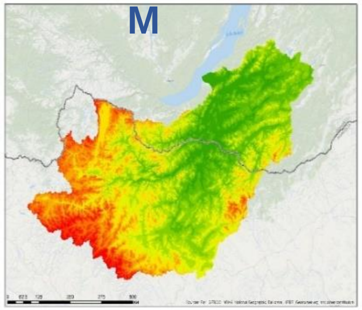
Model initial database

Input data: Daily timestep

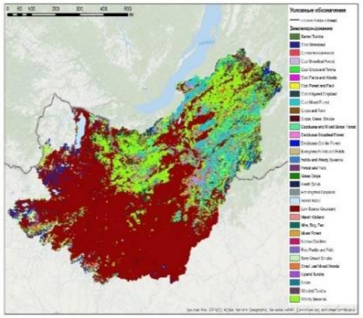
- Near-surface air temp.
- Prec. amount
- Humidity deficit

SPATIAL SCHEMATIZATION OF WATERS

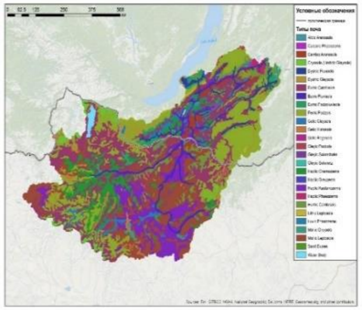
DEM

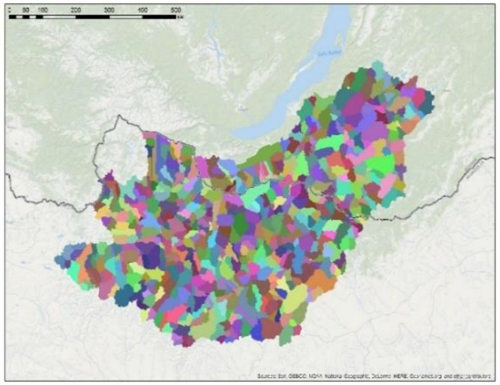


Landuse



Soil



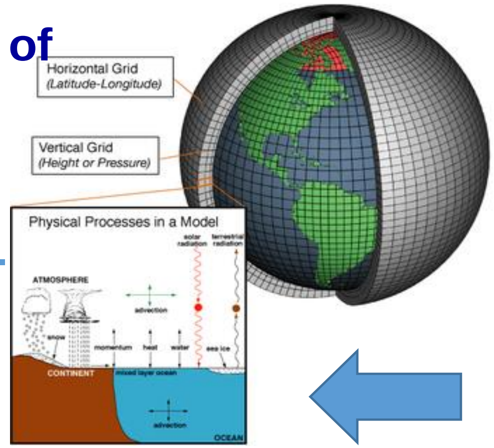


References:

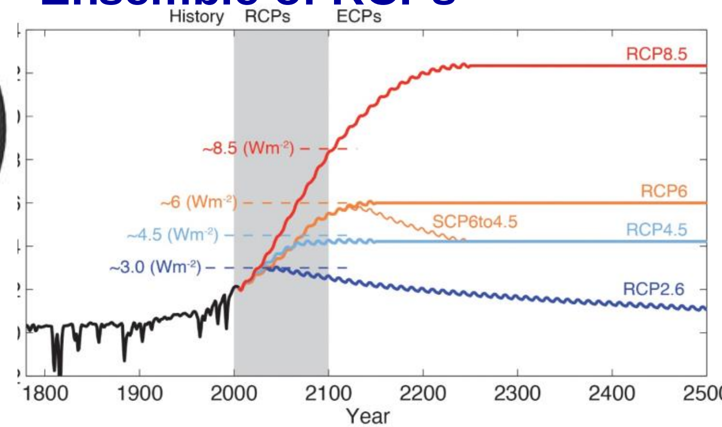
1. Motovilov Y., Gottschalk L., Engeland L., Rodhe A. Validation of a distributed hydrological model against spatial observation // Agricultural and Forest Meteorology. 1999. V. 98–99. P. 257–277.
2. Motovilov Yu.G. Hydrological Simulation of River Basins at Different Spatial Scales: 2. Test Results. Water Resources, 2016, Vol. 43, No. 5, pp. 743–753
3. Motovilov Yu.G. Hydrological Simulation of River Basins at Different Spatial Scales: 1. Generalization and Averaging Algorithms. Water Resources, 2016, Vol. 43, No. 3, pp. 429–437

Projections derived from hydrological models forced by the GCMs ensemble data

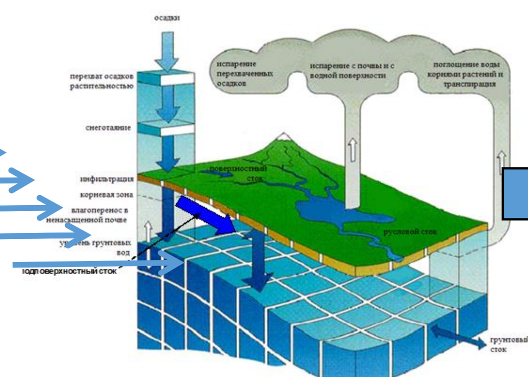
Ensemble of GCMs



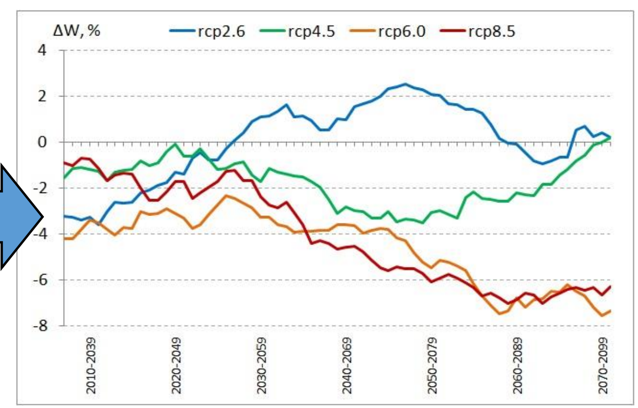
Ensemble of RCPs



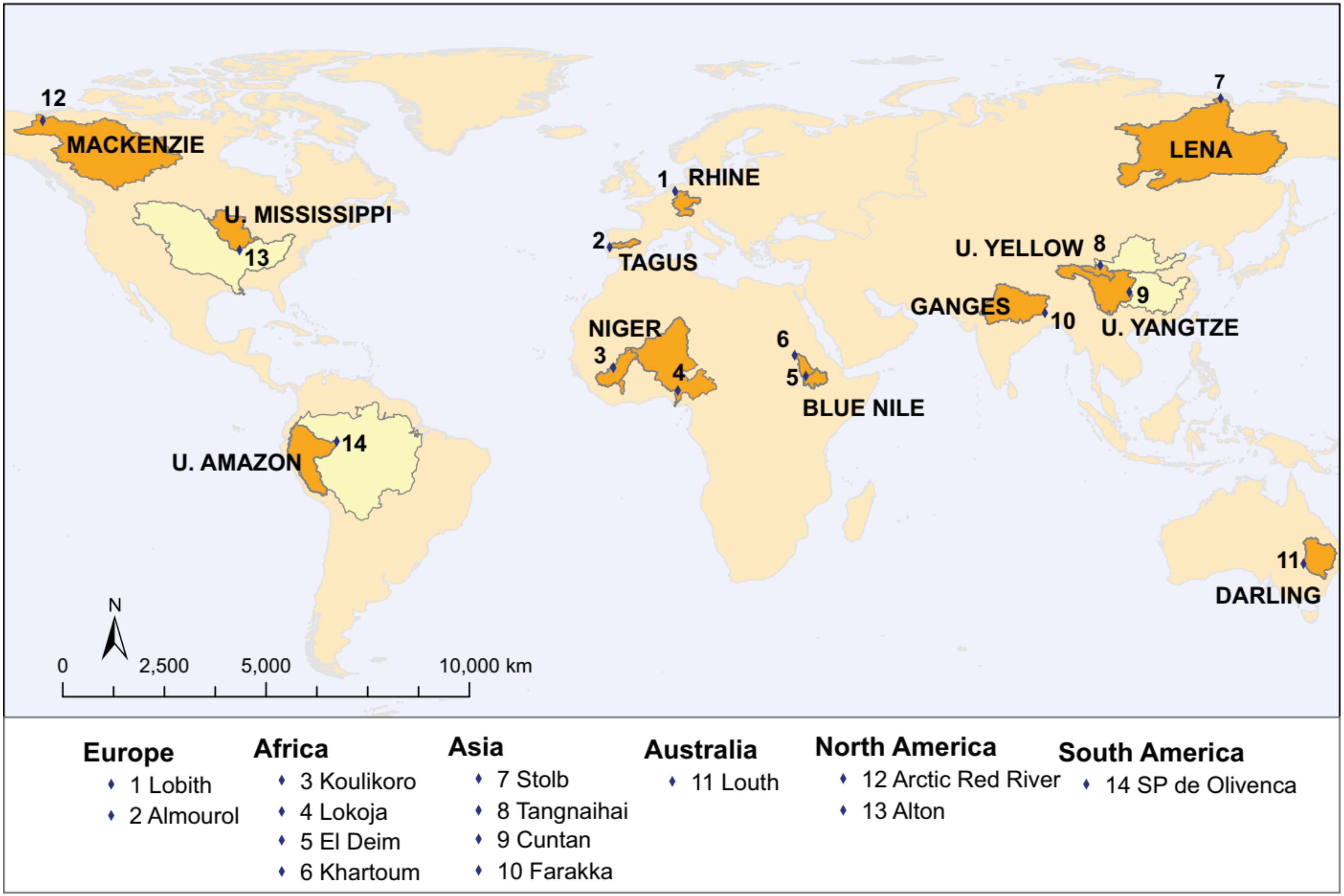
Ensemble of Hydrological Models (HMs)



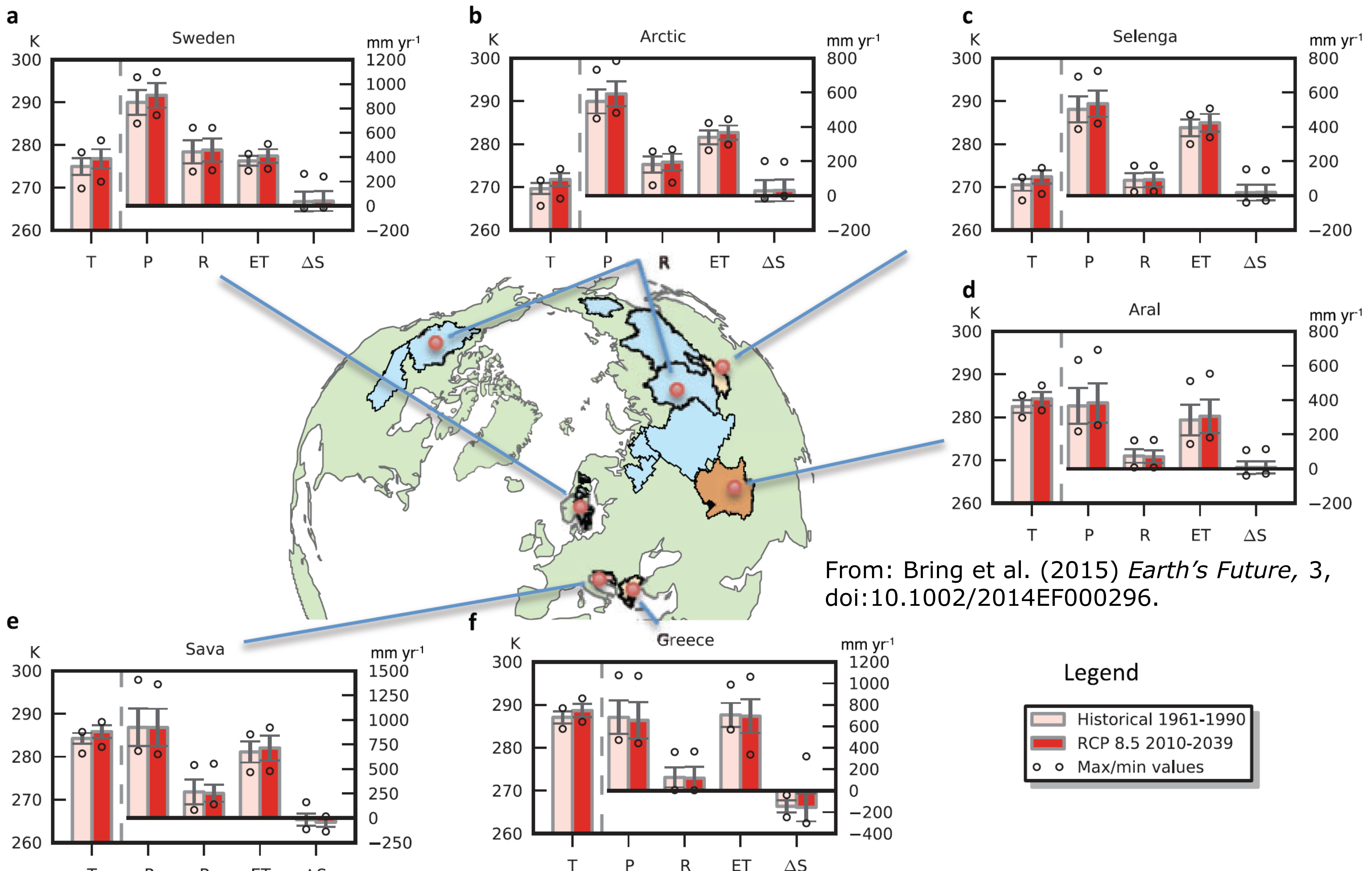
Ensemble of Hydrological Responses to Climate Change Impacts



Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)

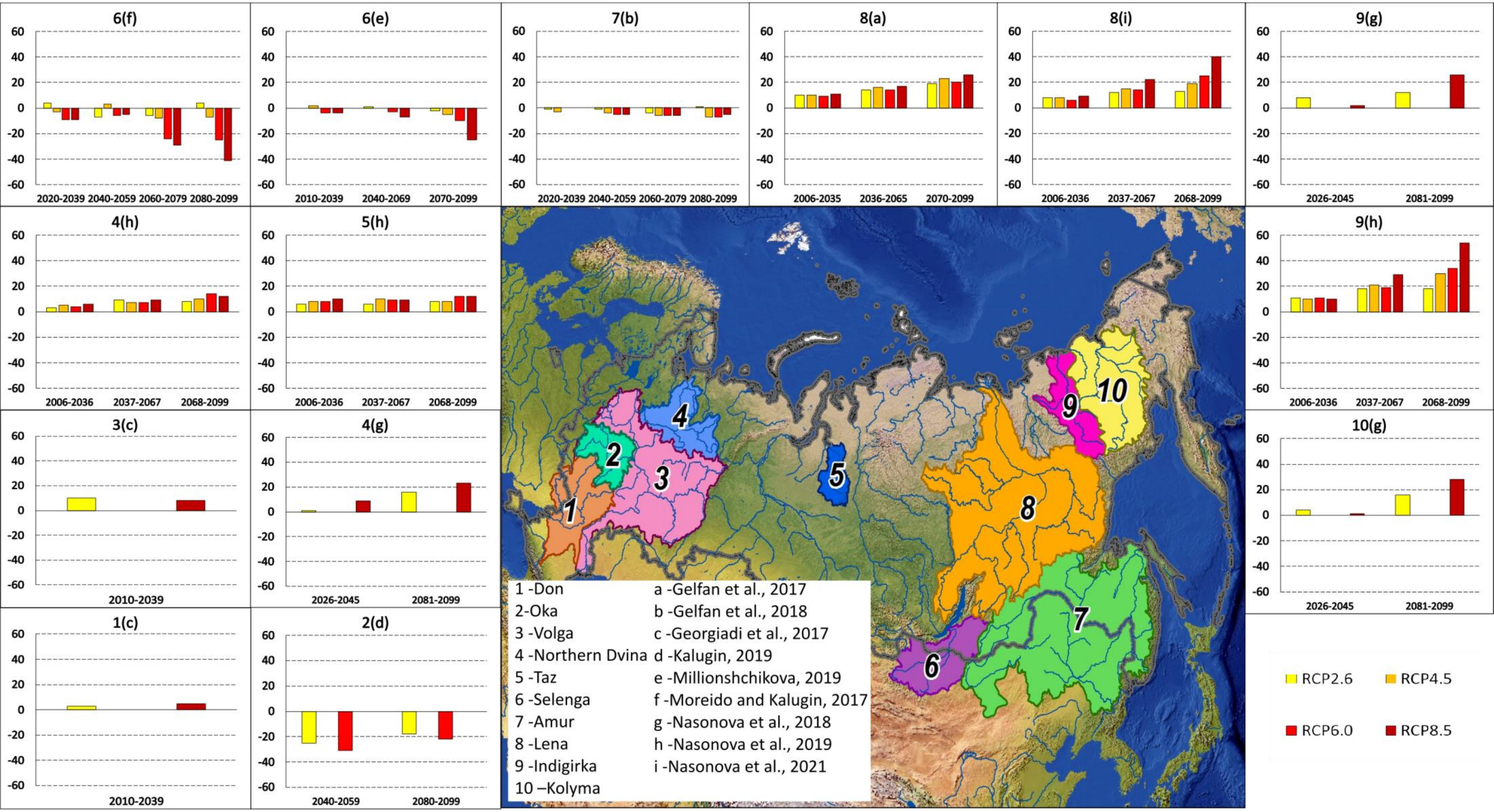


Northern hemisphere assessment



From: Bring et al. (2015) *Earth's Future,* 3, doi:10.1002/2014EF000296.

Mean annual runoff projections for the large Russian rivers in the 21th century under the different RCP-scenarios (HMs+GCMs ensemble experiments)



from Gelfan et al., 2022 (in press)

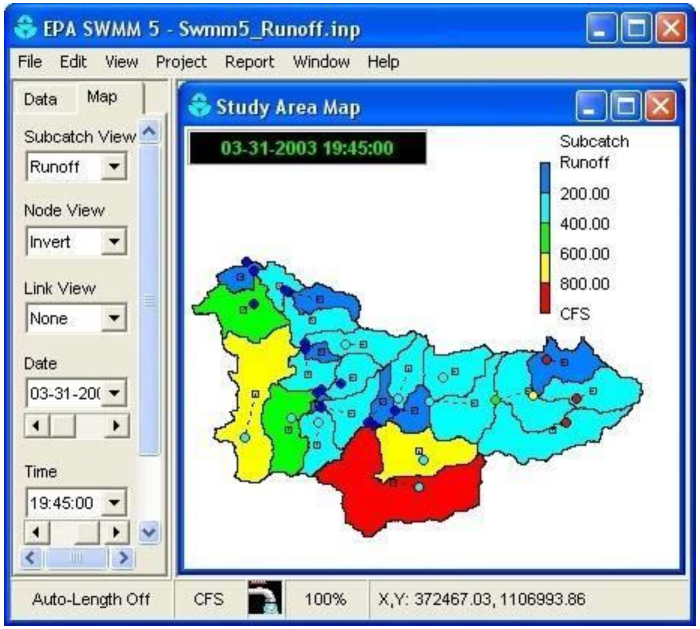
Storm Water Management Model

Distributed dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas

Developed in 1971 by US EPA

Includes 3 modules:

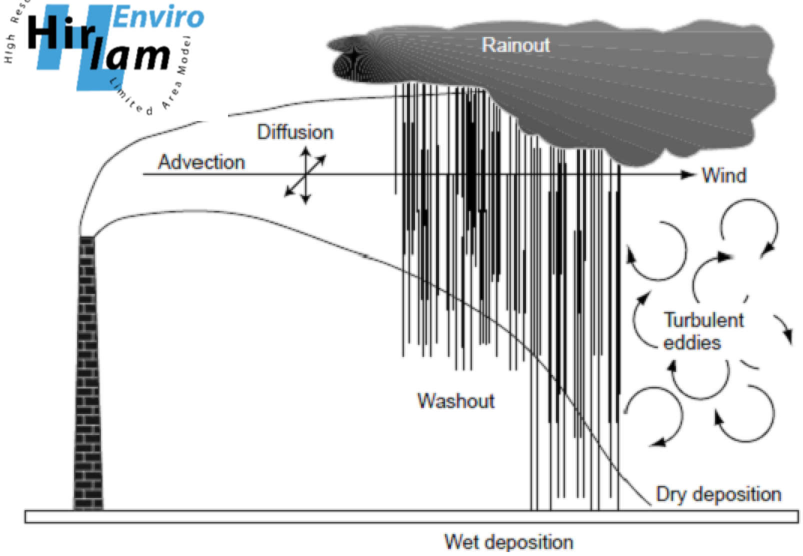
- Hydrology
- Hydraulics
- Water quality



Monitoring approach: Comparison of atmospheric deposition and point-source load from the Moscow River

Loading with point sources will be estimated based on Russian Federal Statistics data about input of toxic elements with wastewater discharge

Deposition rate will be estimated for the entire Moscow river based on Enviro-HIRLAM



Modeling approach: **Enviro-HIRLAM + SWMM**

To estimate non-point pollution loading in the Setun basin due to atmospheric deposition

Enviro-HIRLAM		**SWMM**
Meteorological output: rainfall, relative humidity, wind speed, temperature	→	**Meteorological input**: rainfall, relative humidity, wind speed, temperature
Atmospheric composition output: concentrations, wet/dry deposition, sedimentation	→	**Atmospheric deposition input**

Erosion models

MODELLING STUDY

- **There are many models available for soil erosion estimation:**
  - Empirical: USLE, USPED, RUSL2, RUSLE 3D, MUSLE etc.
  - Physically-based: WEPP, SWAT, SedNet, EPIC, GUEST, CREAMS, EUROSEM etc.
- **Distributed or physically-based models:**
  - Allow simulation of soil loss over time and normally include a hydrological components but
  - require big volume of input data and normally involve GIS interface
- **Empirical models:**
  - Simple structure and easy use, but
  - they are based on coefficients computed or calibrated on the basis of measurement and/or observation

UNIVERSAL SOIL LOSS EQUATION (USLE)

$$A = R \cdot K \cdot C \cdot LS \cdot P$$

Estimated soil loss per year [t ha^{-1} yr^{-1}]

R – rainfall erosivity factor [MJ mm h^{-1} ha^{-1} yr^{-1}]

K – soil erodibility factor [t h MJ^{-1} mm^{-1}]

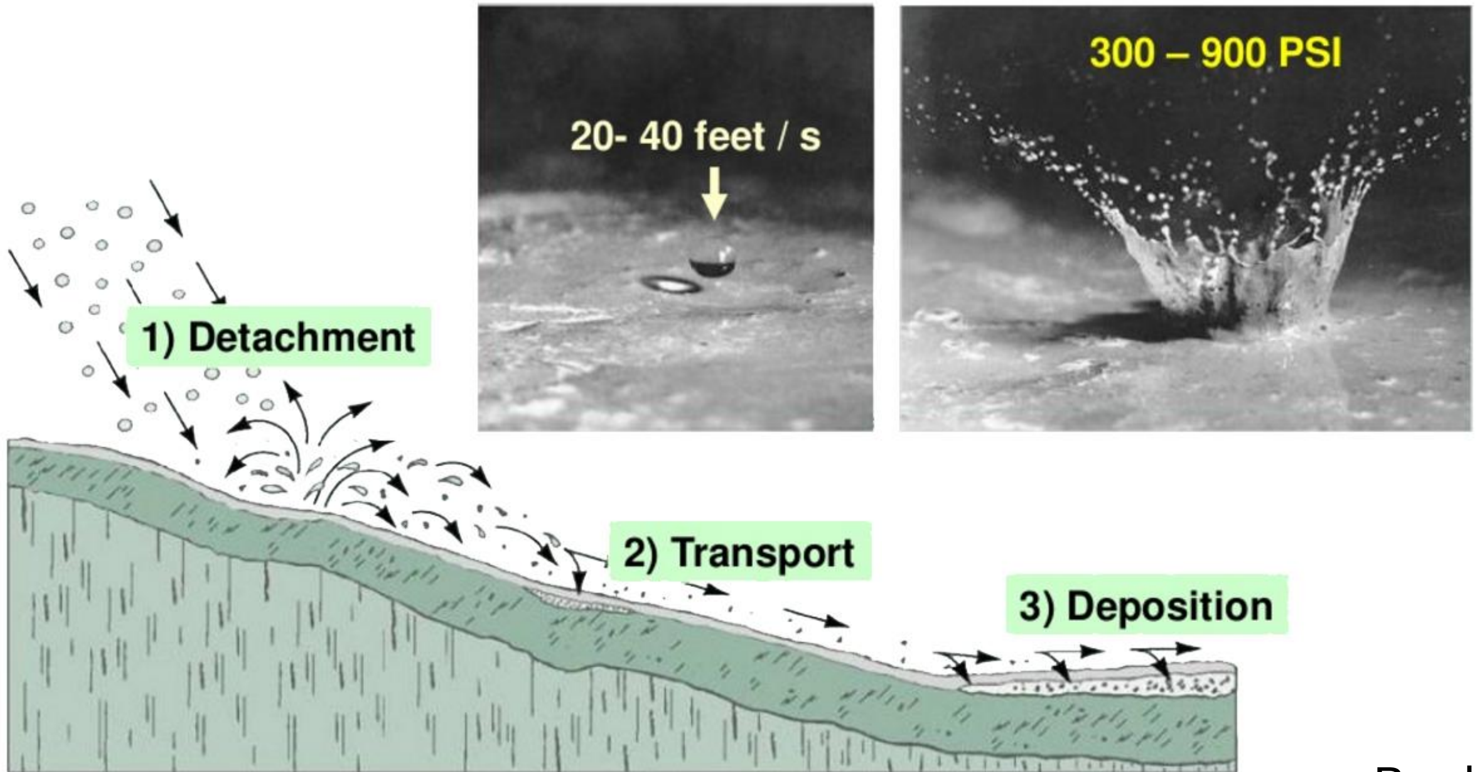
C – crop/cover and management factor [dimensionless]

P – conservation/support practice factor [dimensionless]

LS – the slope length and steepness factor (also known as topographic factor)

[dimensionless]

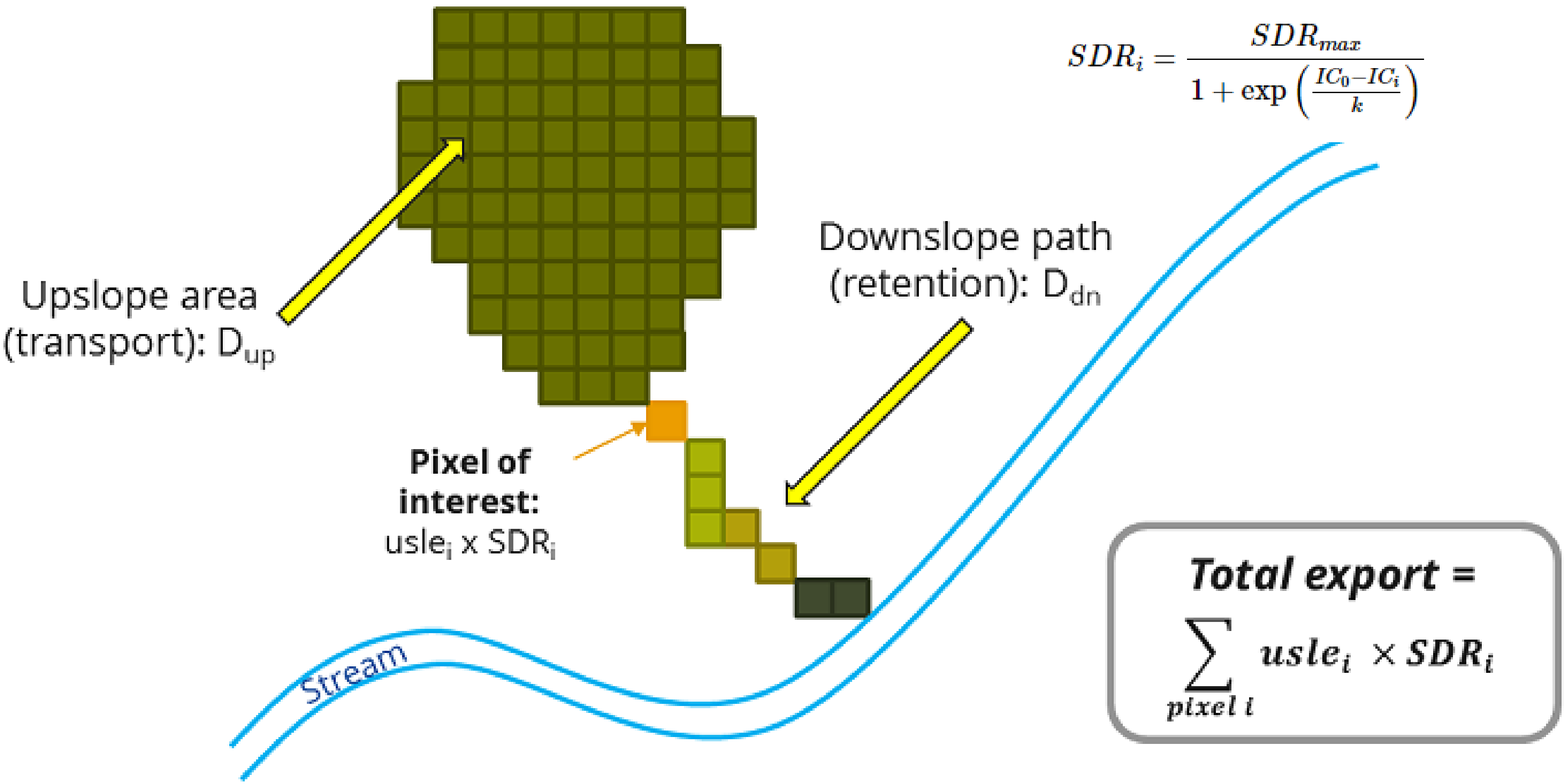
How USLE works?



Brady and Weil (2002)

UNIVERSAL SOIL LOSS EQUATION (USLE)

- Empirical model:
  - Analysis of observations
  - Seeks to characterize response from these data.
- Based on:
  - Rainfall pattern, soil type, topography, crop system and management practices.
- Predicts:
  - Long term average annual rate of erosion
- Subroutine in models such as:
  - SWRRB (Williams, 1975), EPIC (Williams et al., 1980), ANSWERS (Beasly et al., 1980), AGNPS (Young et al., 1989), USPED (Mitasova et al., 1996), SWAT (Neitsch et al., 2005)



$SDR_i = \frac{SDR_{max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k}\right)}$
Upslope area (transport): D_{up}
Downslope path (retention): D_{dn}
Pixel of interest: $usle_i \times SDR_i$
Stream
Total export = $\sum_{pixel\ i} usle_i \times SDR_i$

HOW?

RELATIOSHIP CURVES

$SDR = 0{,}627 \cdot SLP^{0{,}403}$

Slope, gradient, and relief-length ratio

[Williams, Berndt, 1977]

$SDR(\%) = C_{\text{почва}}/C_{\text{наносы}}$

Particle size and SDR

[Walling, 1983]

Drainage area (A) and SDR

$SDR = 0.42\ A^{-0.125}$

Vanoni (1975)

$SDR = 0.51\ A^{-0.11}$

USDA SCS (1979)

$log(SDR) = 1.7935 - 0.14191\ log\ (A)$

Renfro (1975)

Rainfall-runoff and SDR

$SDR = ((q_p / r_p) / (0.782845 + 0.217155\ Q / R))^{0.56}$

(Arnold, et al. 1996)

Watershed erosion modeling

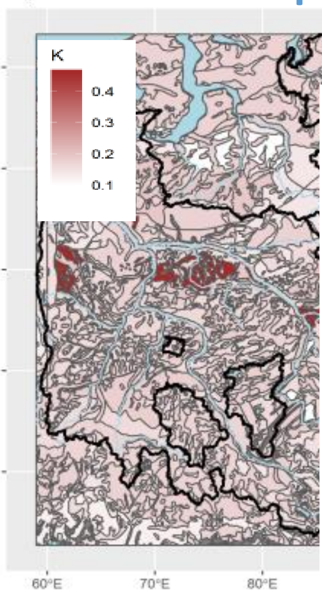
For estimation of watershed erosion was RUSLE applied for big boreal watersheds

A = R·K·LS·C

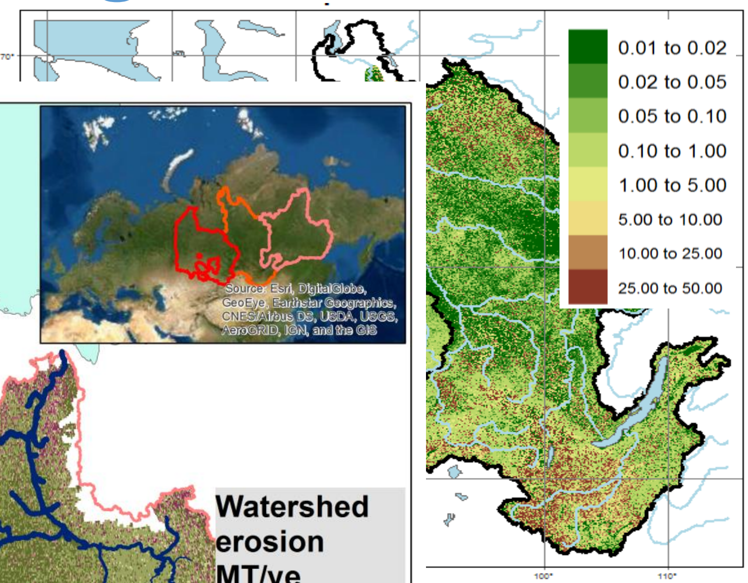
Factor	Issue	Resolution	Formula
R - Rainfall erosivity	Rainfall erosivity map (Panagos et al., 2017)	30 sec.	$R = \frac{(\sum_{i=1}^{n}(\sum_{r=1}^{k}(e_r \vartheta_r) I_{30})}{n}$ (Morgan, Nearing, 2011)
K - Soil erodibility factor	Soil map FAO (IUSS Working Group WRB, 2015)	30 sec.	$К = f_{csand} \times f_{cl-si} \times f_{orgc} \times f_{hisand}$ (Sharpley, Williams, 1990)
LS - Slope length (L) and steepness (S) factor	ЦМР GMETED 2010 (Danielson, Gesch, 2011)	30 sec.	$LS = (m+1)\left(\frac{U}{L_0}\right)^m \left(\frac{sin\beta}{S_0}\right)^n$ (Borrelli et al., 2017)
C - Cover and management factor	GlobCover 2009 Landcover map (Bontemps et al., 2011)	250 m	Empirical coefficients for each vegetation zones (Panagos et al., 2015) (Morgan, Nearing, 2011)

Mapping of RUSLE modeling

$$A = R \cdot K \cdot LS \cdot C$$

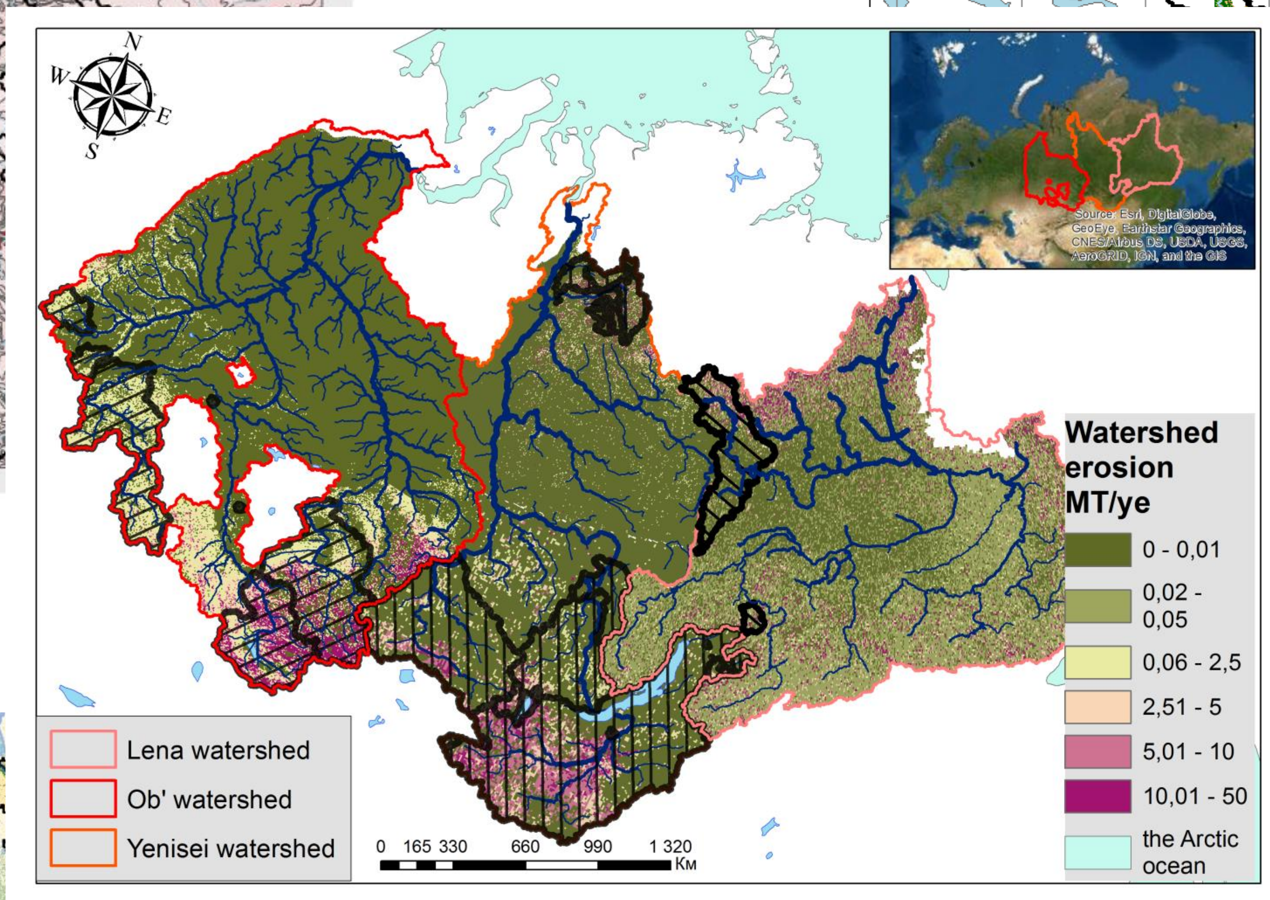


K factor

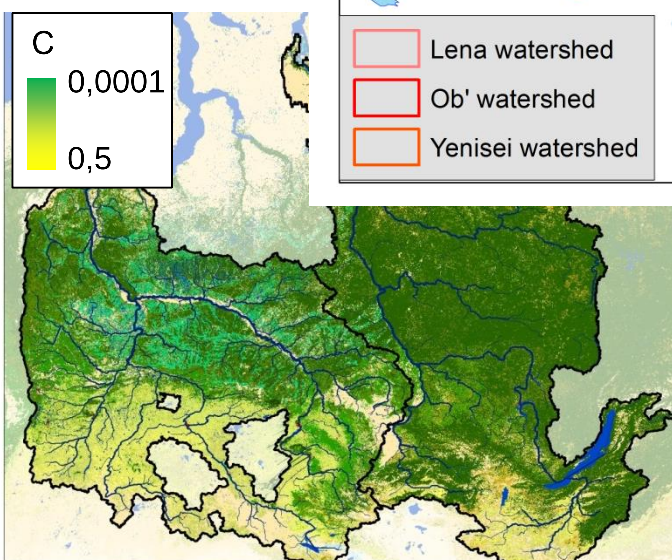


LS

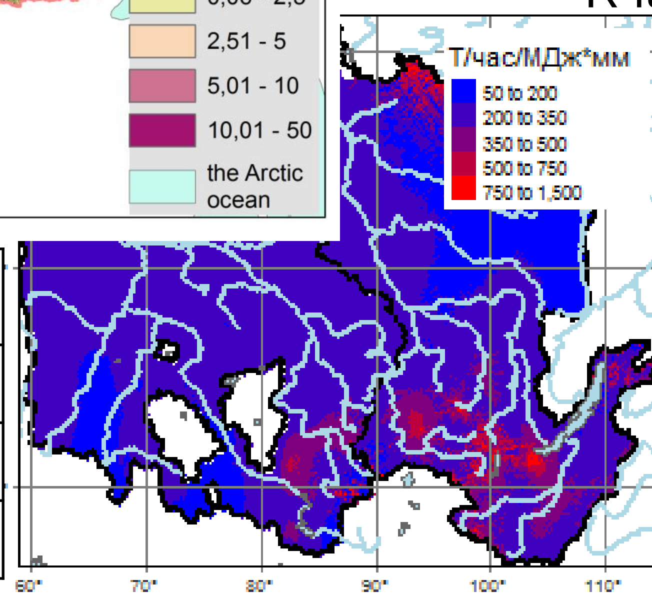
factor



C factor



R fa



Watershed	Mean er., t/ha /year	Sum. Er MT/year
Ob’	4,57	1250
Yenisei	1,22	315
Lena	3,09	762

Hydrogeochemical modeling

Model approach

- **Models of water quality**
  - Dimension (0-3D)
  - Phase & temperature
  - Chemical processes
    - Transport
    - Chem. thermodynamic
    - Complex

Visual MINTEQ 3.1
migration thermodynamic reactor model
Method – balance equations, minimization of Gibbs free energ
Author: Jon Petter Gustafsson, KTH, Dept. of Land and Water resources engineering, Stockholm, 2012

Thermodynamic models - Based on the calculation of the mass balance for substances that react. Do not require a detailed analysis of the equilibrium constants

11 Visual MINTEQ 3.0

The model is based on solving multicomponent problems of chemical equilibrium by calculating the systems of linear and nonlinear balance equations

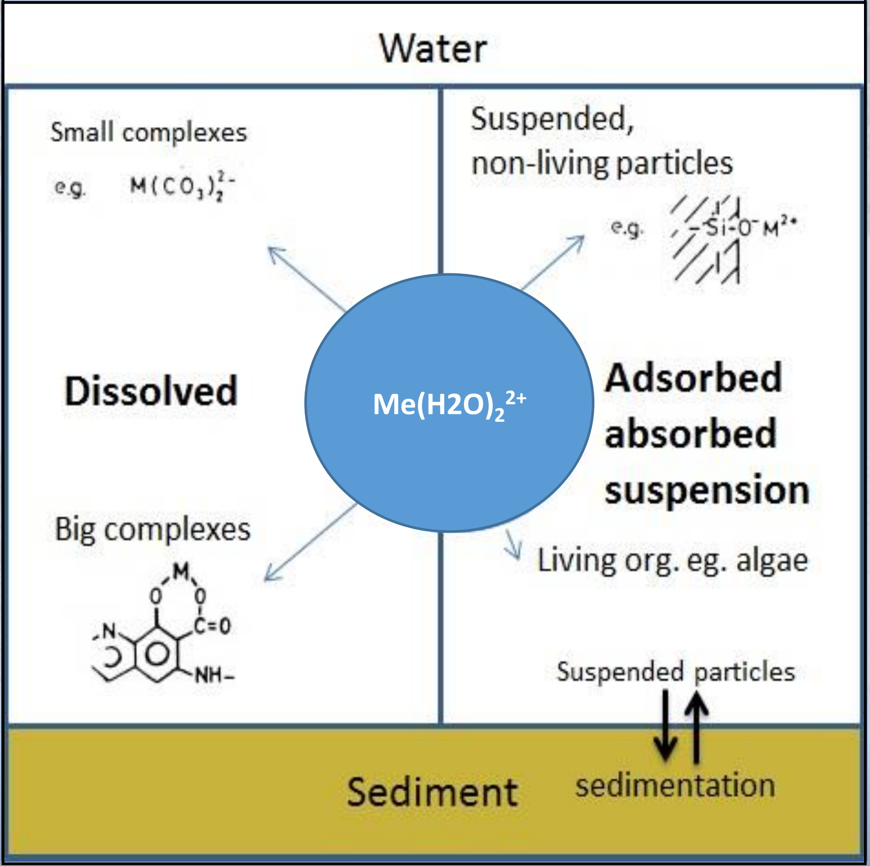
Mass balance equation:

$$Y_j = \sum a_{ij} C_i - T_j \qquad C_i = K_i' N X_j^{a_{ij}}$$

T_j – Total concentration
Y_j - the difference between the calculated total dissolved concentration of substance j and the known analytical total dissolved concentration of component j.
C_i – element concentration
a – stoichiometric coefficient
N- all elements concentration
X- element activity

Input data		
I	Water	T^0C, pH, CO_2
II	Geochemical background	Sediments composition, surface complexation
III	Element concentrations	Elements concentration, DOC

Main processes, represented in model *(Thorslund et al. 2016)*



12 Model calibration

Model worked with 25 problems

Part of the model	Parametr	Res	Cal1	Cal2	Cal3	Cal4
Organic complexation(SHM)	Fulvic acid concentration(p4)	75%	75%	75%	75%	100%
	Concentration of DOC in TOC(p3)	50%	50%	50%	75%	75%
Surface complexation	Migration layers (TFO/DLM) (p2)	1/1	1/1	2/1	2/1	2/1
Background	Redox potential(pE) (p1)	100%	75%	75%	75%	75%

Model verification

After calibration variant **Cal4** was chosen

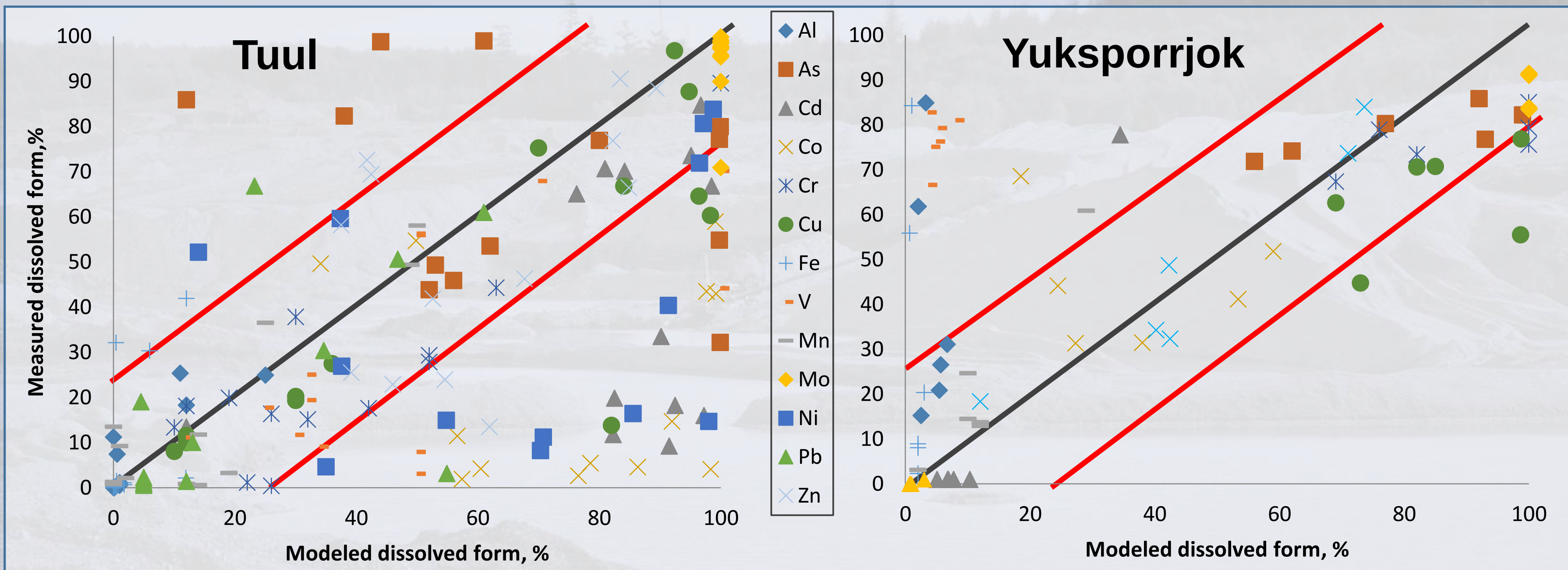
$$\Delta = \frac{(M_{mod} - M_{fact})}{M_{mod}} * 100$$

For each element, a calculation error was determined (Δ,%)

Object	Al	As	Cd	Co	Cr	Cu	Fe	V	Mn	Mo	Ni	Pb	Zn	Aver
p. Yuksporrjok	-11	-2	50	-52	11	21	-3	-154	-64	13	-	94	-8	-9
p. Modonkul	-20	12	57	20	64	27	-15	63	-44	-21	6	33	18	15
p. Tuul	-15	14	32	80	37	20	-11	30	-16	2	56	54	20	23

13 Model verification

Comparison of the measured and simulated results for the dissolved fraction



Based on the calibration results, the elements most accurately reproduced by the model were chosen(-25≤Δ≤25)

	-25≤Δ≤25
p.Yuksporrjok	Al,As,Cr,Cu,Fe,Mo,Zn
p.Modonkul	Al,As,Cu,Fe,Ni,Zn
p.Tuul	Al,As,Cu,Fe,Mn,Mo,Zn

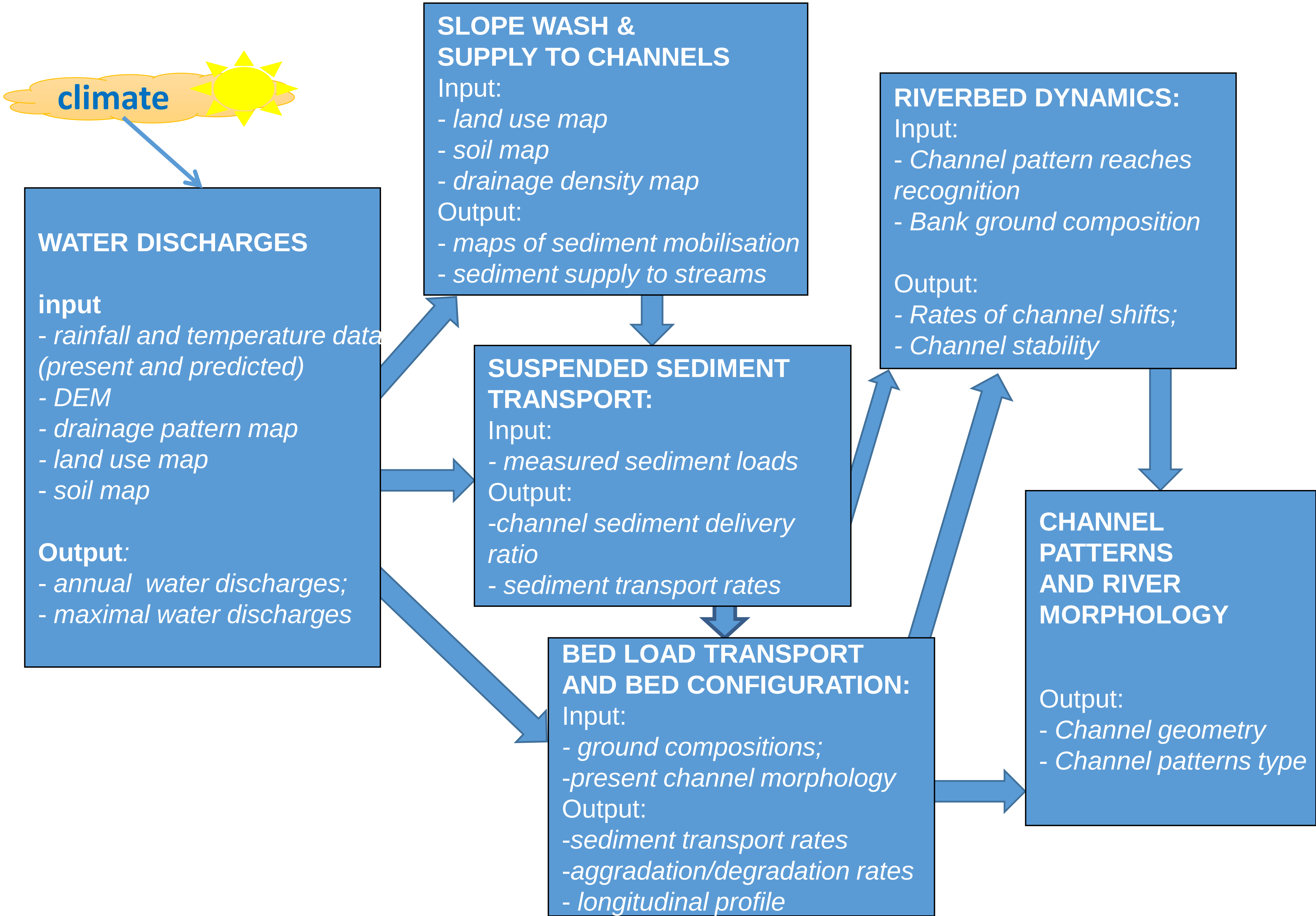
Al^{+3}, Fe^{+3}, Cu^{+2}, Zn^{+2}, As(V) и Mo(IV) were used in scenario calculations

The main problems of this method –qualitative properties of the metals themselves.

•SHM moldel / NICA-Donnan model

•Geochemical background composition

Conceptual diagram of the hydrological models flow



THANK YOU FOR YOUR ATTENTION!