HIGH-RESOLUTION LARGE-SCALE MODELING FRAMEWORK FOR A TRANSBOUNDARY WATERSHED: A CLIMATE CHANGE ASSESSMENT OF NUTRIENT LOADS AND POSSIBLE ENVIRONMENTAL CONSEQUENCES

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Start of the journey….

Nemunas River watershed area

Study area: Nemunas River Basin

Lies at 56^{o}15´-52^{o}45´ N and 22^{o}40´-28^{o}10´ E;
Total length of the river is 937 km;
Basin area: 97 928 km^{2};
Long-term mean flow 700 m^{3}/s .

Watershed is shared by:

Belarus (48%)
Lithuania (46%)
Poland (2.57%)
Russian Federation Kaliningrad oblast (3.34%)
Latvia (0.09%)


Bloom-filled Baltic. Image by ESA

Why do we care?

Unhealthy State of the Baltic Sea → HELCOM
Baltic Sea Action Plan (BSAP) →
Nutrient Reduction Scheme →
Maximum Allowable Inputs (MAI) of nutrients →
Country-Allocated Reduction Targets (CART)

- progress towards the national targets for input of nutrients achieved by 2014 is insufficient (Svendsen et al., 2018);
- the Maximum Allowable Inputs are calculated under the assumption that the Baltic Sea environmental conditions are in a biogeochemical and physical steady-state (HELCOM, 2018);
- adaptation to climate change is a central issue for the planning and implementation of measures to reduce nutrient inputs, as well as for adjusting the level of nutrient input reductions to ensure protection of the Baltic Sea marine environment;

Clear task

We want to:

- Assess the entire watershed;
- Water balance of the entire watershed;
- Calculate flows;
- Nutrient loads;
- Point source pollution;
- Diffused pollution;
- Nutrient retention;
- Sediment dynamics;
- Climate change;
- Assess BMPs;
- LU change;
  - Anything else?

… lets be original…

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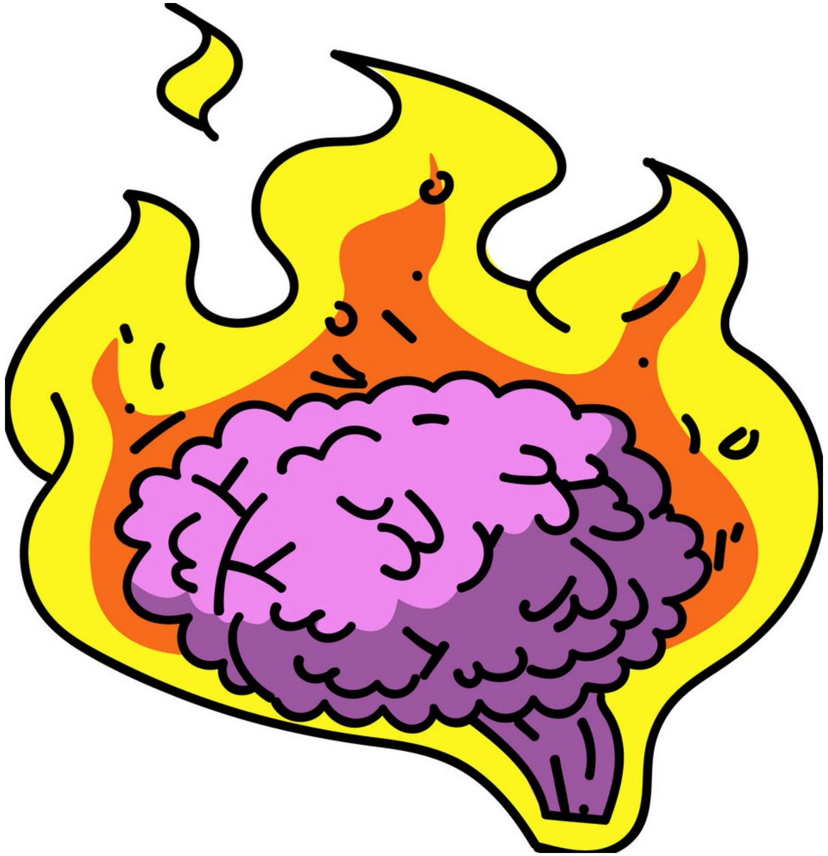
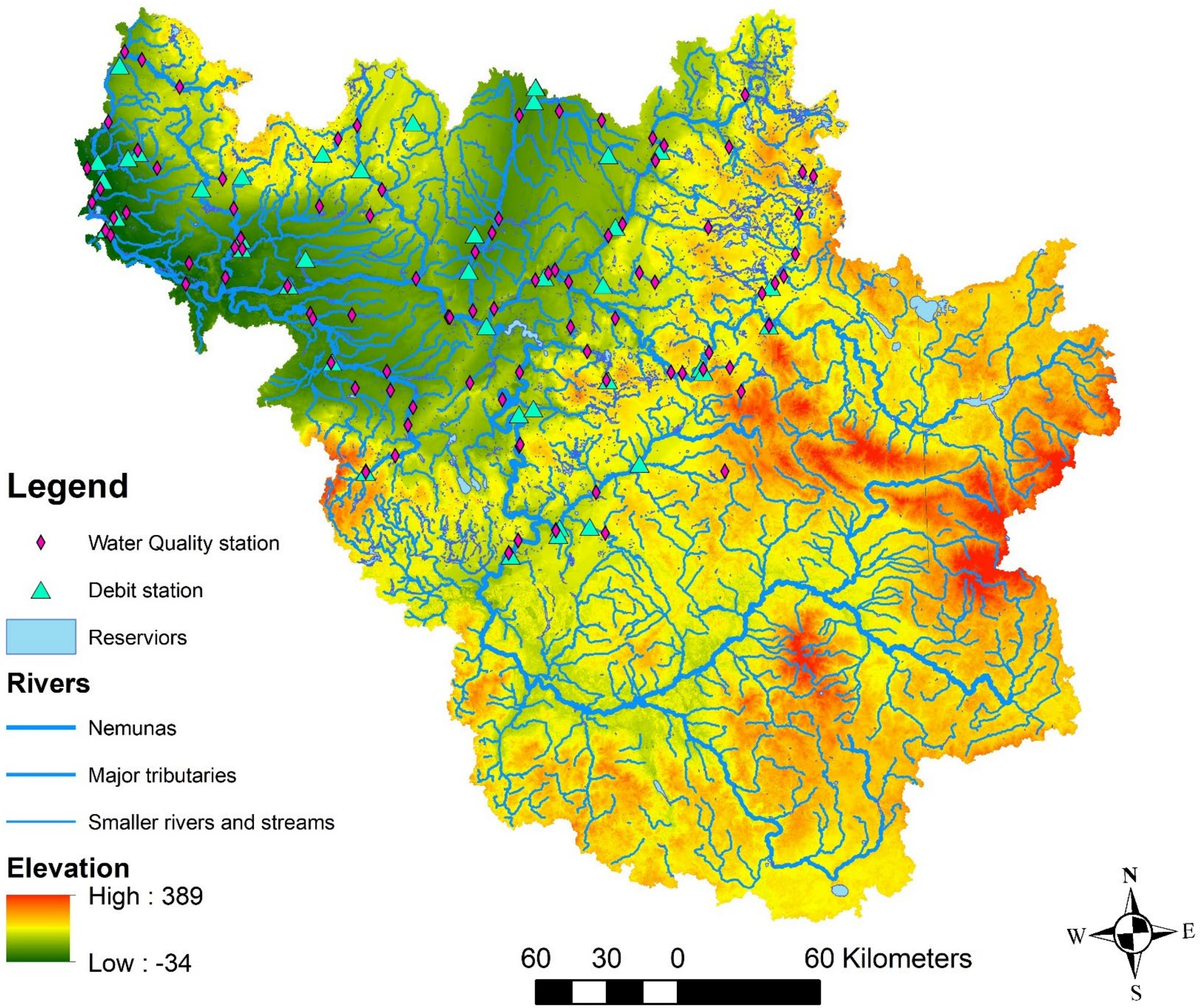


Quest for data



Not that bad… in Lithuania;

- Mostly national datasets from LT;
- Global datasets from other countries.

Digital Elevation Model:

- LT: 5x5 m (resampled to 35x35);
- Other: 35x35 m

Soil

- LT: 1:10 000 (National DB);
- Other: FAO + correction from national soil surveys;

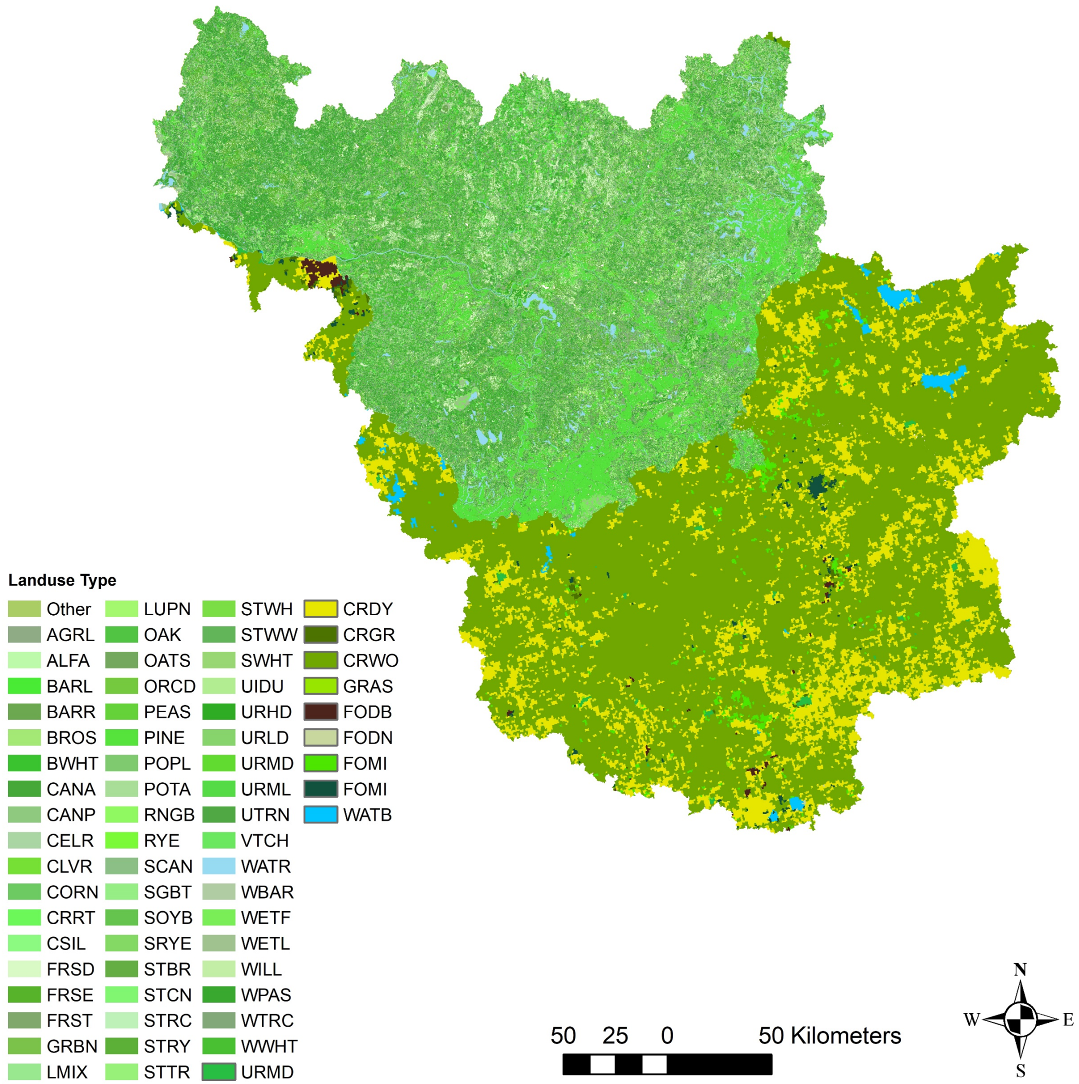
Landuse:

- LT: combination of National cadaster datasets;
- Other: Corine, Satellite imagery, Open Access database.

Observations:

- LT: Hydrometeorological surveys;
- Other: statistical yearbooks, forums, old documents.

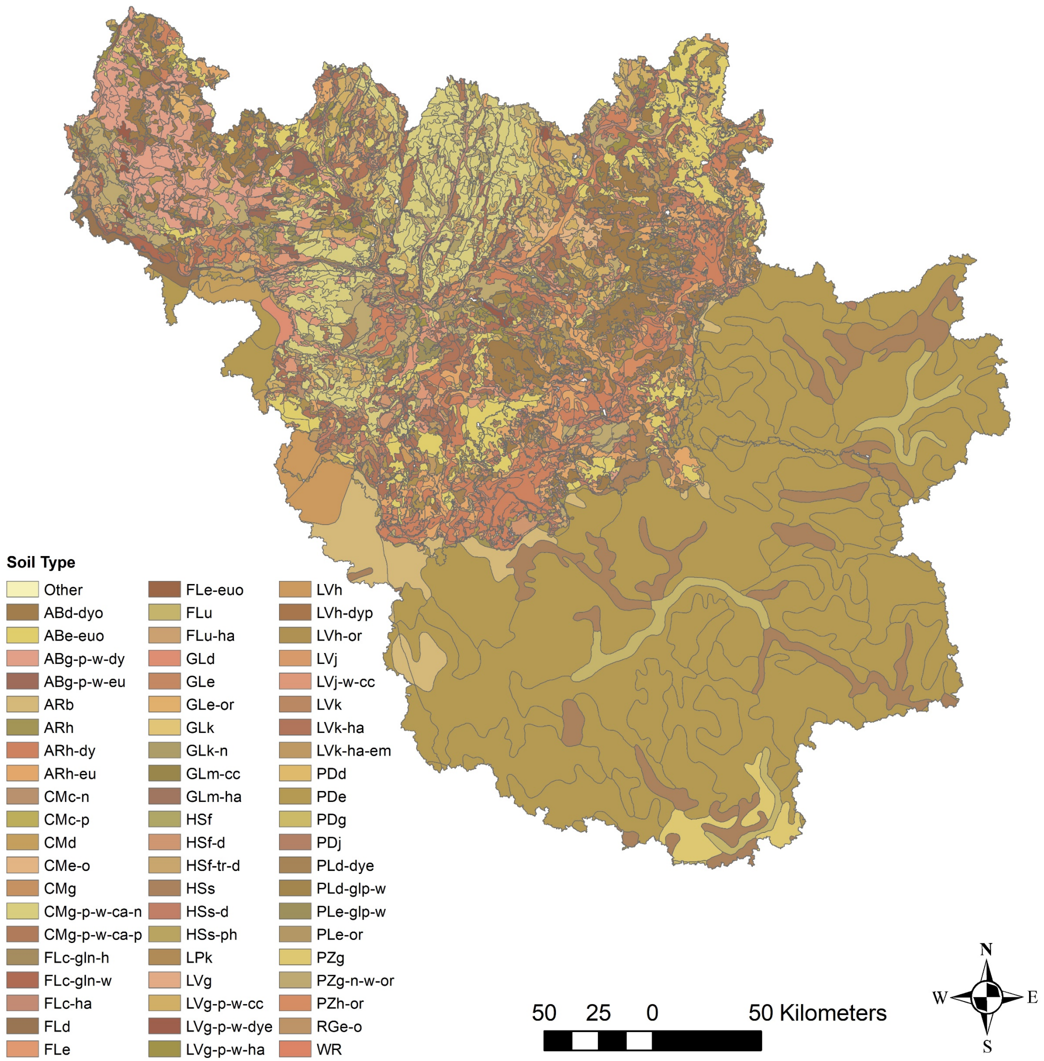
Landuse



	Landuse type	Percentage of the total watershed area	Landuse code
1	Cropland/woodland mosaic	38.65	CRWO
2	Dryland cropland and pasture	9.67	CRDY
3	Winter Pasture	9.64	WPAS
4	Pine	6.13	PINE
5	Agricultural - General	4.45	AGRL
6	Forest-Deciduous	3.56	FRST
7	Forest-Evergreen	3.09	FRSD
8	Winter Wheat	2.73	WWHT
9	Poplar	2.68	POPL
10	Range-Brush	1.68	RNGB

Simplified map of Landuse in the study area

Soil



	Soil type	Percentage of the total watershed area	Soil code
1	Eutric Podzoluvisols	43.65	PDe
2	Terric Histosols	8.63	HSs
3	Haplic Arenosols	8.45	ARh
4	Gleyic Luvisols	5.79	LVg
5	Haplic Luvisols	4.21	LVh
6	Gleyic Cambisols	3.88	CMg
7	Eutric Leptosol	2.39	LPe
8	Gleyic Podzols	2.36	PDg
9	Cambic Arenosols	2.28	ARb
10	Gleyic Arenosols	2.01	ARg

Simplified map of Soil in the study area

Lets start to build a model… and be original!

- Physically meaningful subbasins (thinking in “objects”):
  - Large/significant waterbody;
  - Settlement/city (Urban);
  - Monitoring stations;
  - Dams;
  - Landscape feature (unit ☺).

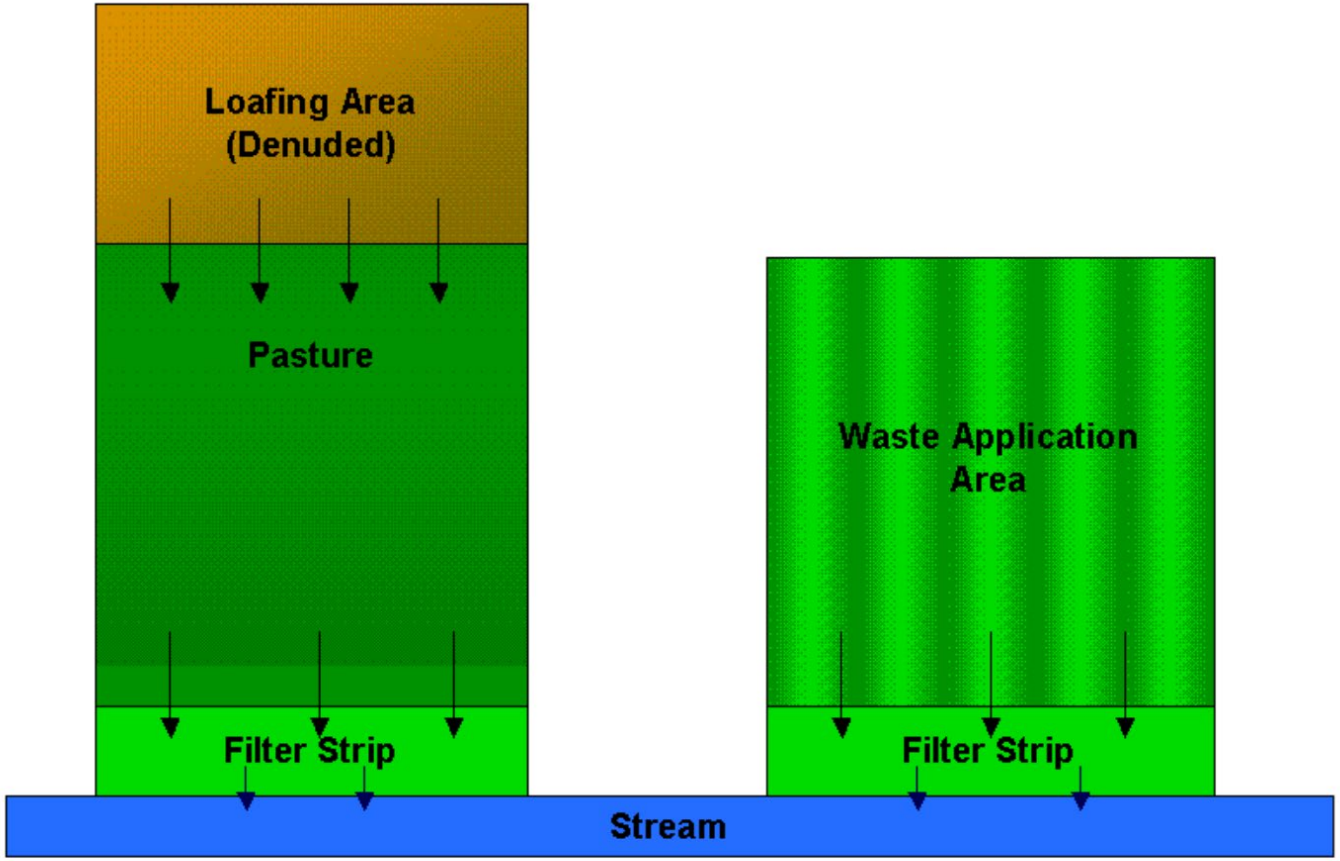
- Physically more accurate routing:
  - hillslope discretization

- Physically more accurate channel representation:
  - channel dimension correction
  - channelized/unchannelized flow

- No HRU simplification, everything is accounted in the HRU classification

A question I often hear.... *What is Hillslope Discretization?*

SWAT I/O Documentation, Appendix B.2



Hillslope discretization in SWAT2012 (Arnold et. al. 2012)

- Controlled by FLOW_OVN parameter in fig file
- Urban subbasins (completely channelized);
- Agricultural subbasins (partly channelized);
- Pond/reservoir subbasins (completely channelized);
- Forest/buffer subbasins (unchannelized);
- Stream and forest subbasins (partly channelized);
- Channel subbasins (completely channelized).

The setup

Number of subbasins: >10 000

Number of HRUs: >1 000 000

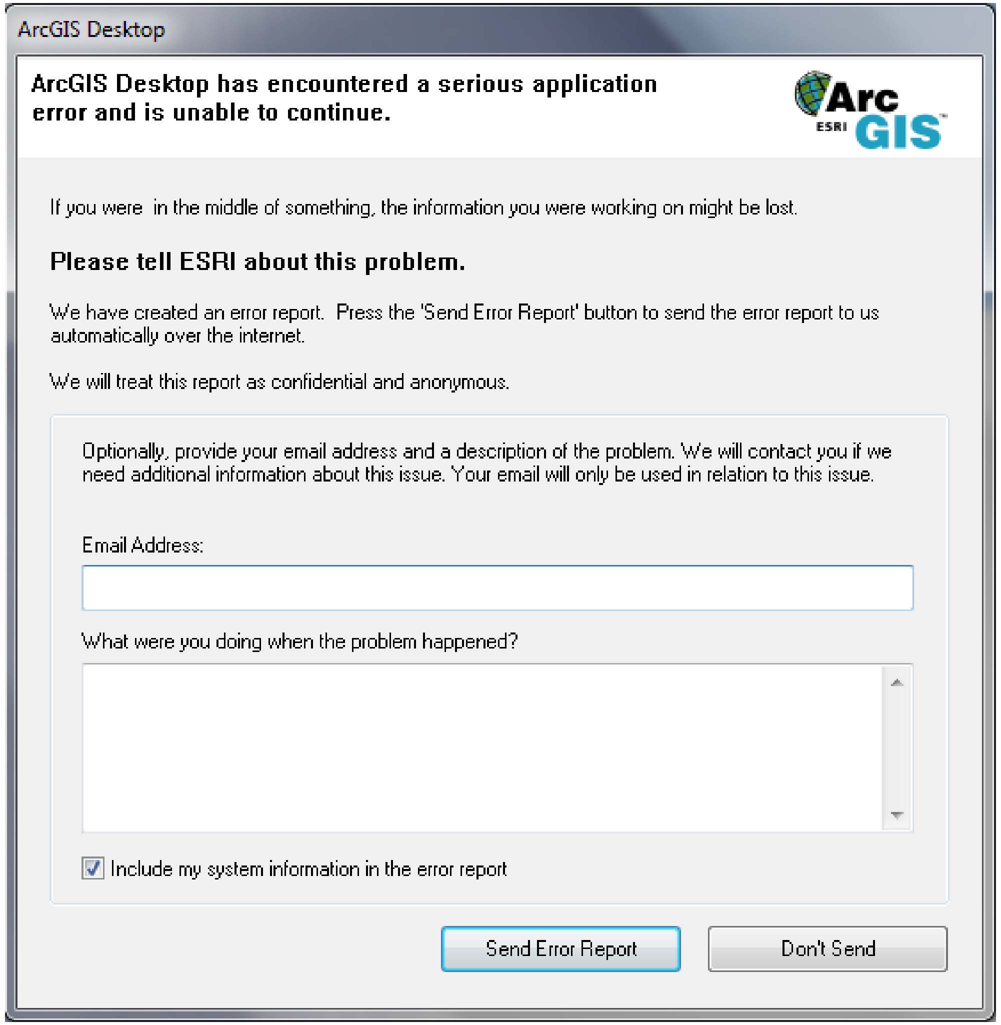
Model runtime:

The setup

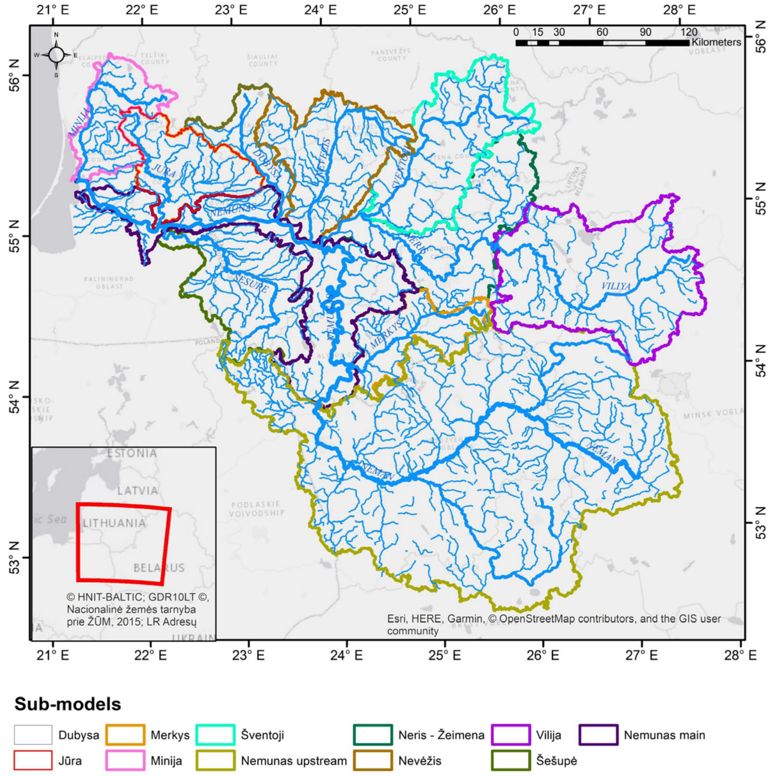
Number of subbasins: >10 000

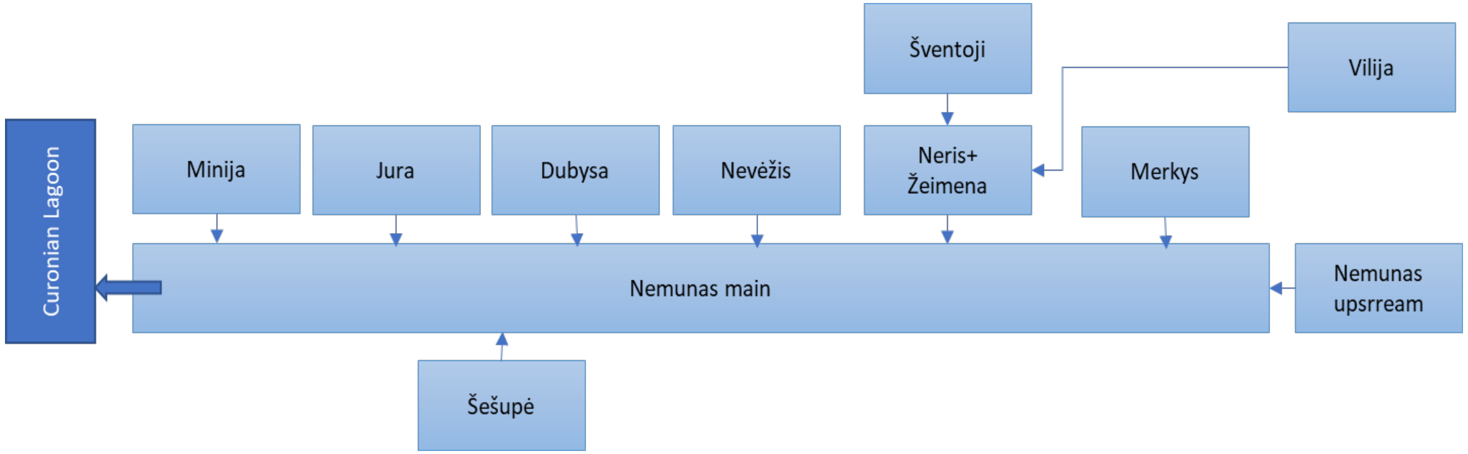
Number of HRUs: >1 000 000

Model runtime: I do not know ☺



Rethinking the setup...





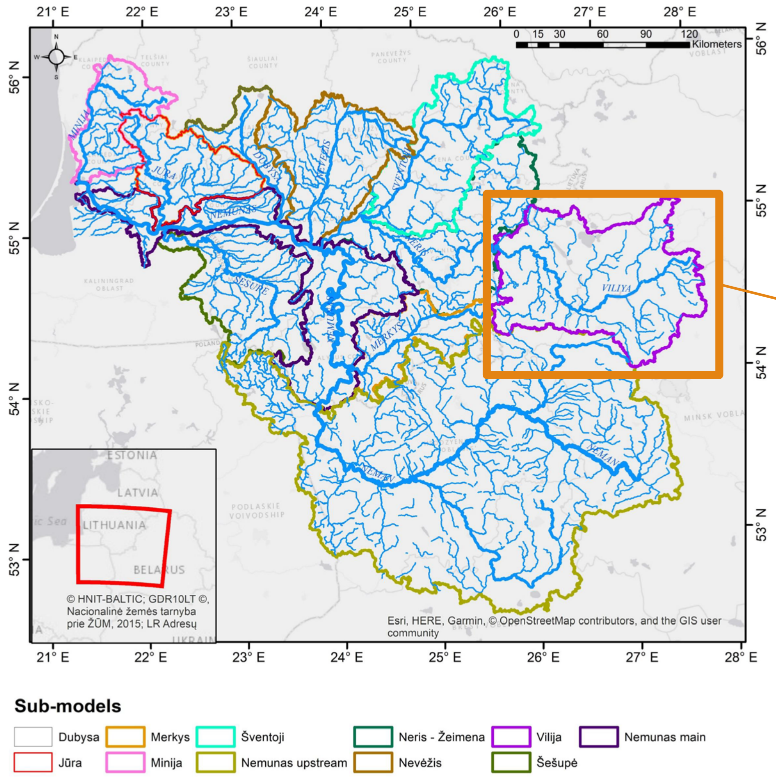
Interconnected sub-models (downstream area receives all the information from upstream);

Upstream subbasins are independent;

Interconnected sub-models:

- 1 sub-model in the Belarus territory of river Neris, which is called *Vilija* in Belarus;
- 2 transboundary watersheds: *Šešupė* (Pl, RU, LT) and *Nemunas upstream* (PL, BY);
- 7 sub-models with more than 95% or entirely situated in the territory of Lithuania (*Minija, Jūra, Dubysa, Nevėžis, Šventoji, Neris Žeimena, Merkys*);
- 1 sub-model, which is the *Nemunas main branch*, which discharges into the Curonian Lagoon.

Model setup



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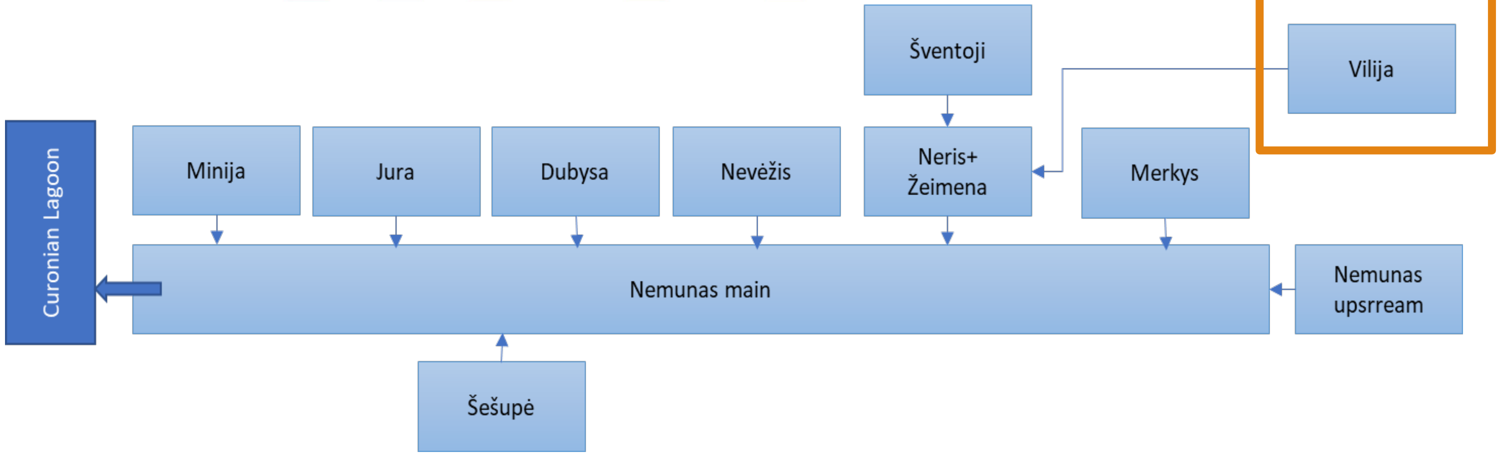

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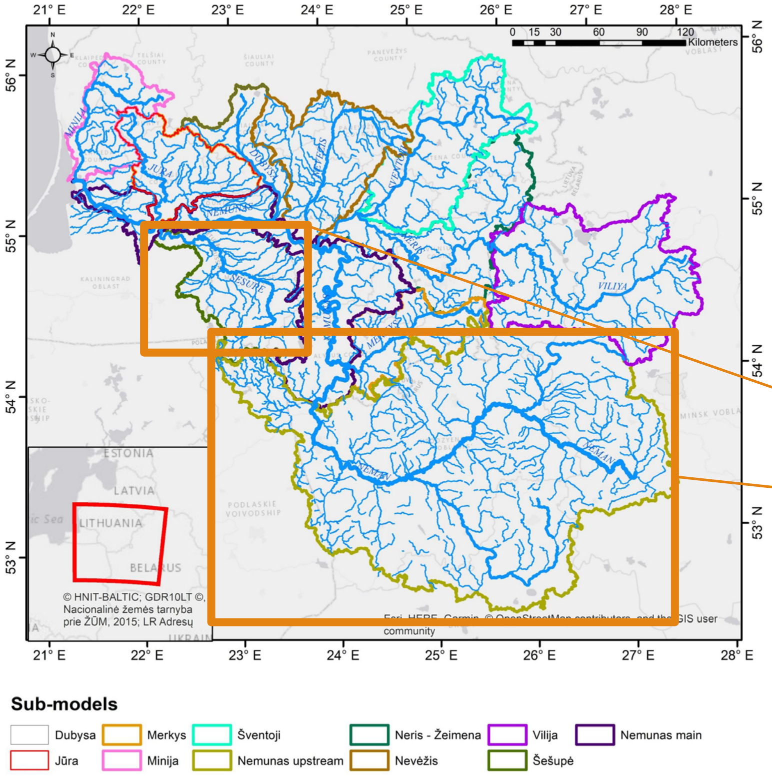

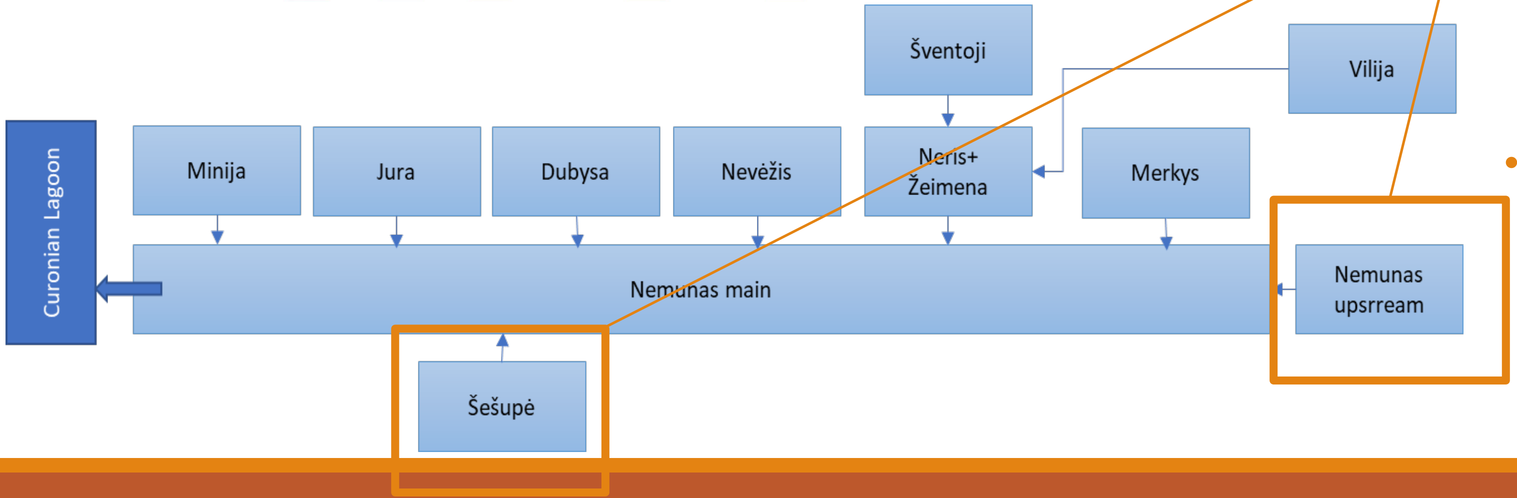

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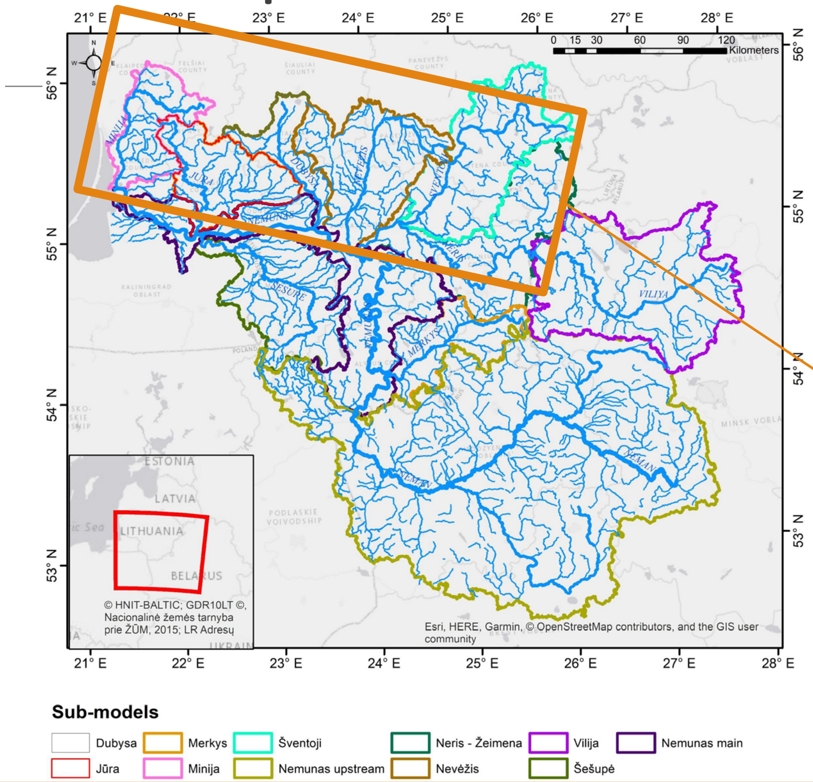

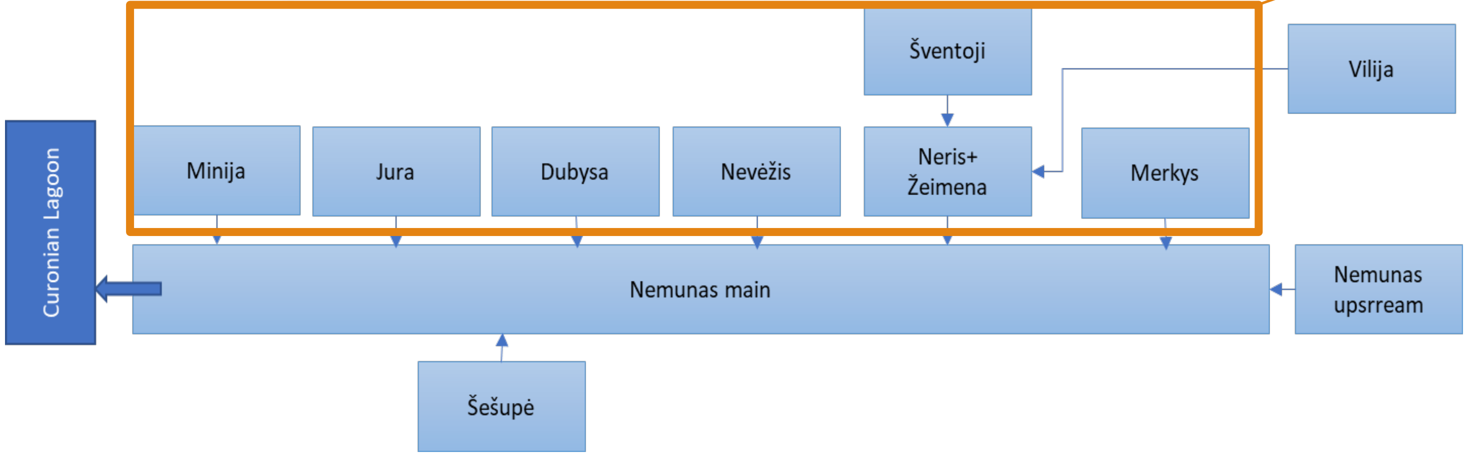

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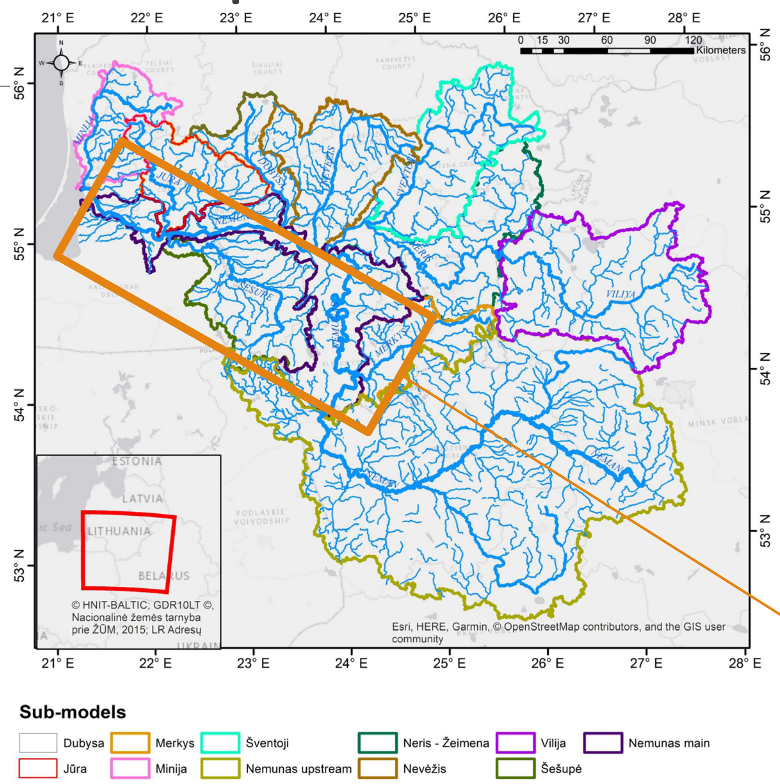

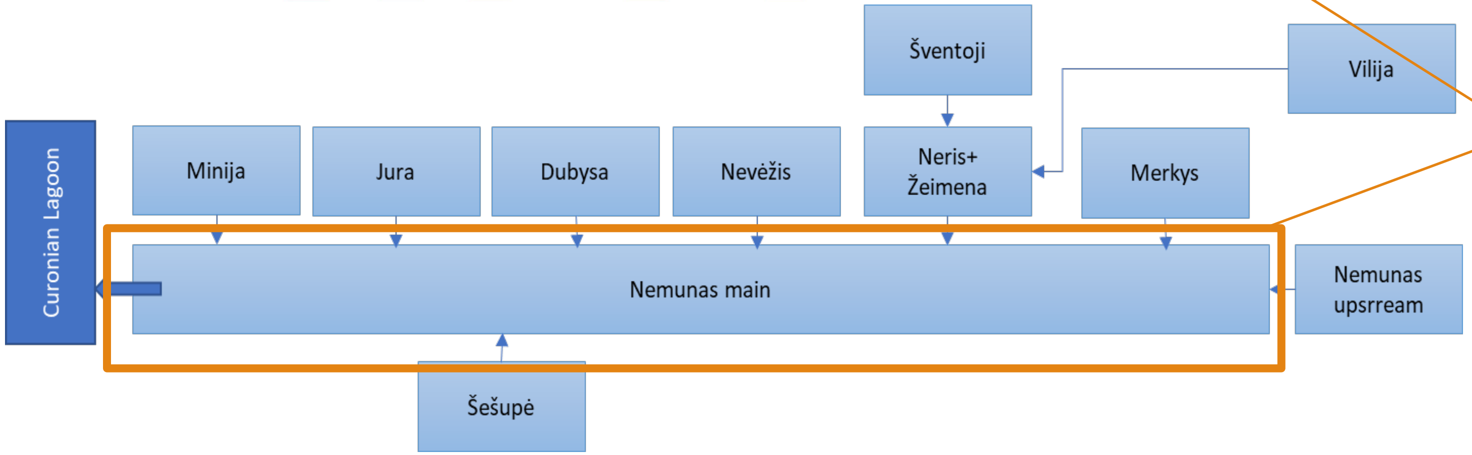

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No standard tools available for hillslope discretization!

✓ Crated custom Matlab scripts;

✓ Use the flexibility of custom scripts to define HRUs differently:

- Include the administrative grid

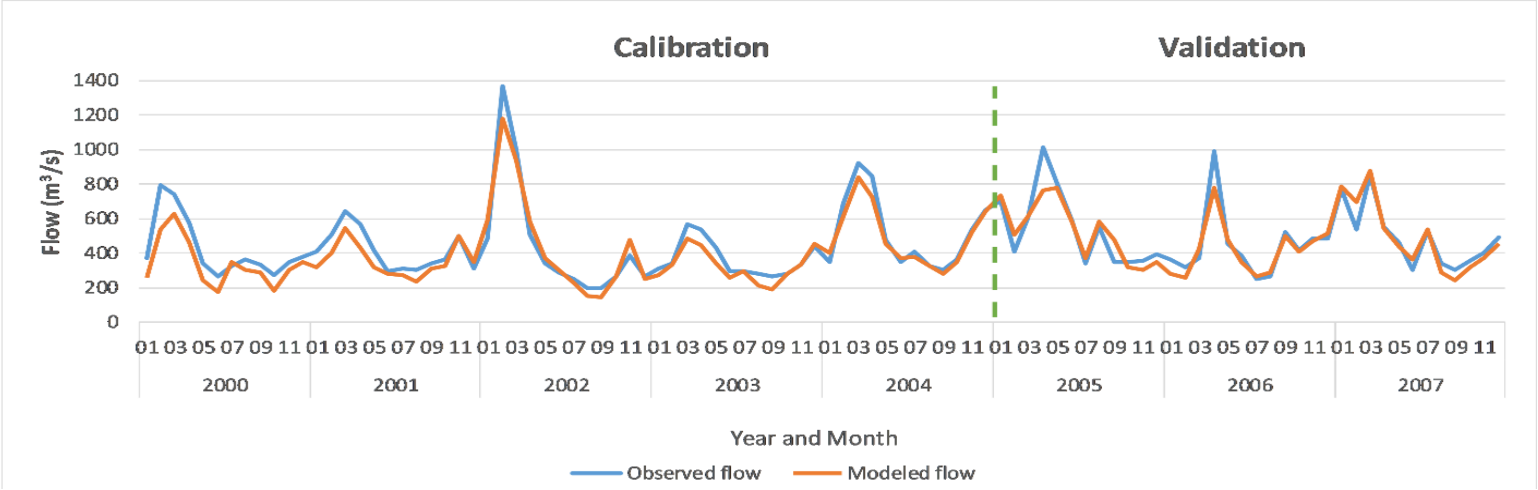
- Reason: many public datasets are available on an administrative unit level!
  - Used for soft calibration;
  - Used to define diffused pollution loads;

- Input data simplification has to be used for practical purposes

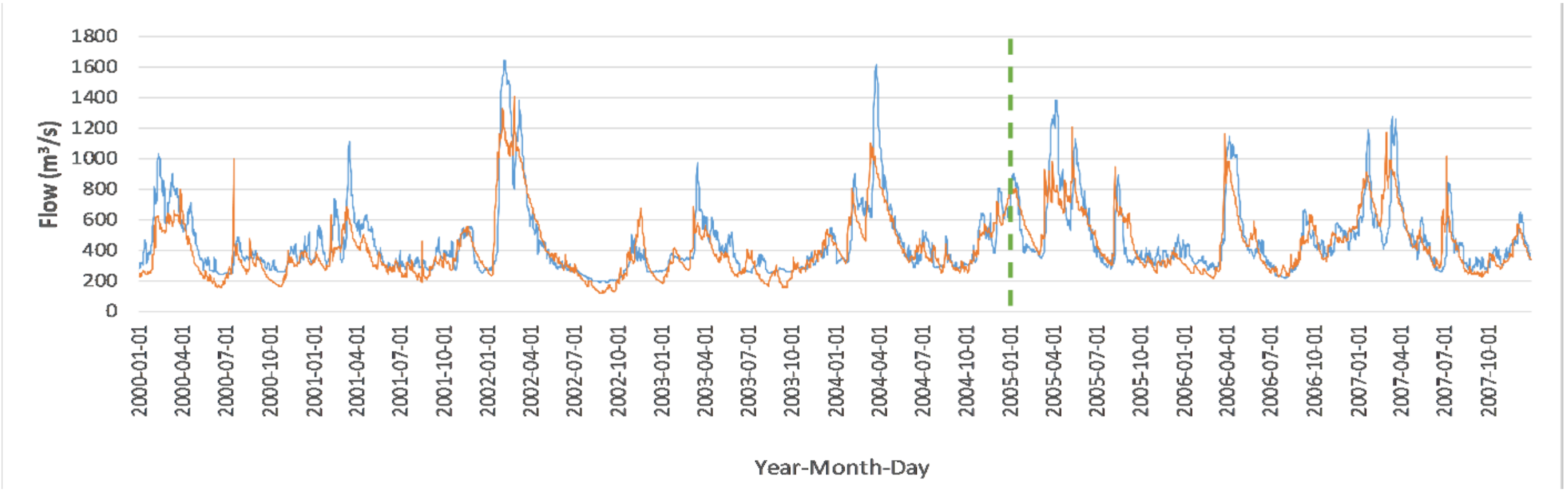
→ Reduces the number of HRUs 8k-25k per submodel.

→ Even higher resolution model setups exist for BMP and other possible applications.

Monthly comparison of modeled and monitored flow



Daily comparison of modeled and monitored flow



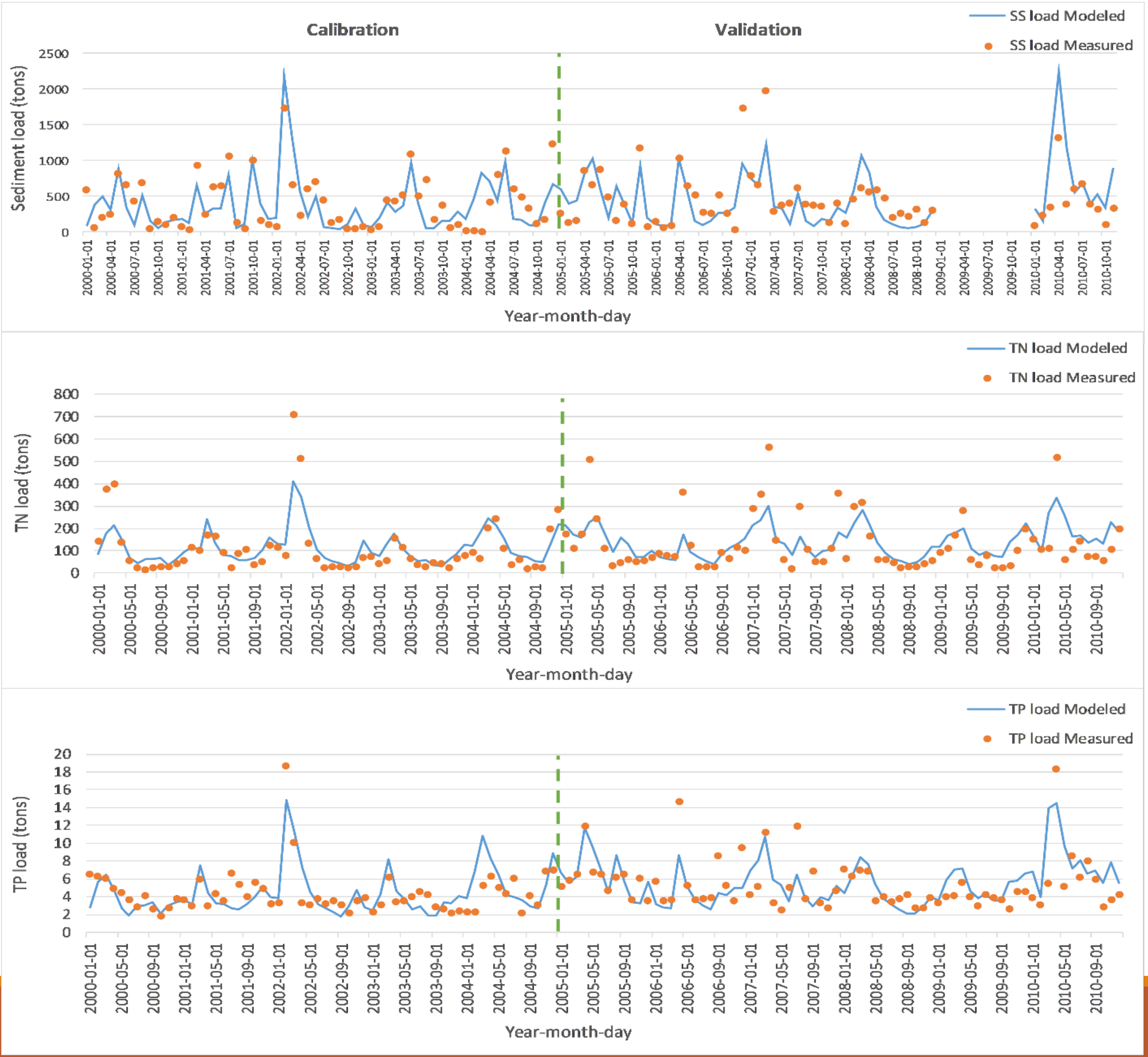
Monthly (top) and Daily (bottom) flow calibration and validation example for Nemunas River (at Smalininkai station)

How to calibrate the (sub)models?

Automatic calibration takes too long – minimum 15 days for 500 simulations with 5 parameters (1 iteration for 1 sub-model).

✓ Manual calibration (with some automated functions):

- Soft (yearly values of yield, pcp, other);
- Monthly timestep (flow);
- Daily timestep (flow);
- Daily timestep (WQ);
- 22 flow rate stations;
- 18 water quality stations;
- 5 years warm-up period;
- Combination of wet and dry years;
- Sensitive parameters only (~20).



Model performance evaluation

R^2 - Coefficient of determination;
NS - Nash–Sutcliffe model efficiency coefficient;
PBIAS - Percent bias.

Daily Sediment load (top) and TN load (middle) and TP load (bottom) calibration and validation example for Nemunas River (at Smalininkai station)

Model performance by sub-model

Nr	Sub-model	Country	Flow R^2	Flow NS	Flow PBIAS	TN R^2	TN NS	TN PBIAS	TP R^2	TP NS	TP PBIAS	Sediment load R^2	Sediment load NS	Sediment load PBIAS
1	Vilija	BY	0.80	0.83	-6.09	0.71	0.61	-0.54	0.55	0.52	-6.45	0.44	0.46	-8.39
			0.79	0.76	2.03	0.53	0.56	10.83	0.50	0.48	5.30	0.55	0.44	-15.30
2	Nemunas upstream	BY, PL	0.75	0.81	5.05	0.69	0.61	-12.40	0.63	0.65	9.70	0.54	0.56	25.30
			0.71	0.79	-4.00	0.67	0.59	-10.80	0.65	0.69	5.89	0.55	0.58	23.65
3	Šešupė	RU, PL, LT	0.87	0.75	-1.87	0.65	0.64	4.66	0.62	0.58	3.80	0.58	0.49	-11.32
			0.86	0.77	-4.62	0.68	0.65	13.88	0.68	0.55	3.84	0.50	0.54	6.82
4	Neris-Žeimena	LT	0.83	0.73	8.36	0.75	0.61	18.41	0.62	0.64	3.58	0.61	0.54	-1.21
			0.81	0.70	11.30	0.69	0.59	16.50	0.64	0.63	4.26	0.62	0.58	-1.71
5	Šventoji	LT	0.74	0.72	1.91	0.66	0.66	-2.88	0.42	0.40	2.35	0.63	0.55	18.83
			0.72	0.70	2.50	0.66	0.65	1.24	0.47	0.45	-9.82	0.59	0.55	24.18
6	Merkys	LT, BY	0.76	0.74	2.76	0.66	0.63	-1.32	0.58	0.55	0.37	0.64	0.62	2.73
			0.66	0.65	-5.90	0.56	0.58	-6.80	0.55	0.54	-1.80	0.59	0.57	0.80
7	Nevėžis	LT	0.74	0.73	-9.58	0.58	0.56	3.99	0.60	0.59	-0.38	0.65	0.59	26.68
			0.74	0.74	0.74	0.74	0.68	14.05	0.60	0.58	7.68	0.60	0.50	24.75
8	Dubysa	LT	0.81	0.80	1.02	0.67	0.65	-3.81	0.56	0.59	0.73	0.62	0.58	-3.33
			0.81	0.79	1.03	0.65	0.65	-2.89	0.57	0.55	1.90	0.63	0.60	0.25
9	Jura	LT	0.78	0.77	-3.83	0.61	0.55	-5.55	0.67	0.69	-10.37	0.62	0.58	-16.03
			0.80	0.81	10.11	0.59	0.54	14.68	0.60	0.57	-5.50	0.59	0.55	-2.08
10	Minija	LT	0.75	0.72	9.80	0.85	0.80	−11.0	0.45	0.40	−11.2	0.60	0.54	14.60
			0.70	0.68	7.10	0.63	0.62	−9.3	0.46	0.45	1.80	0.56	0.53	−11.6
11	Nemunas main channel	LT	0.82	0.77	2.72	0.66	0.61	-2.79	0.67	0.58	-2.61	0.56	0.58	16.26
			0.77	0.73	3.73	0.67	0.60	-1.04	0.57	0.58	-2.82	0.59	0.60	12.03

Performance (calibration/validation)

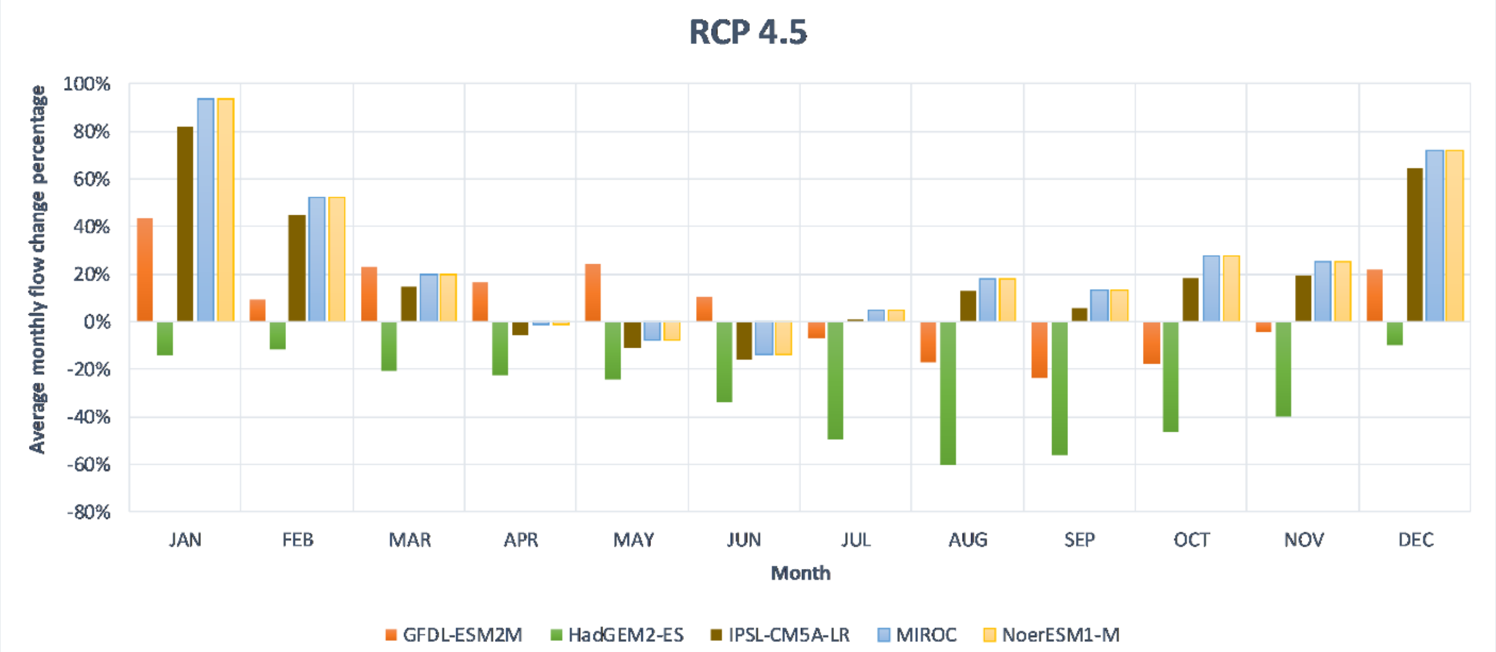
Very good
Good
Satisfactory

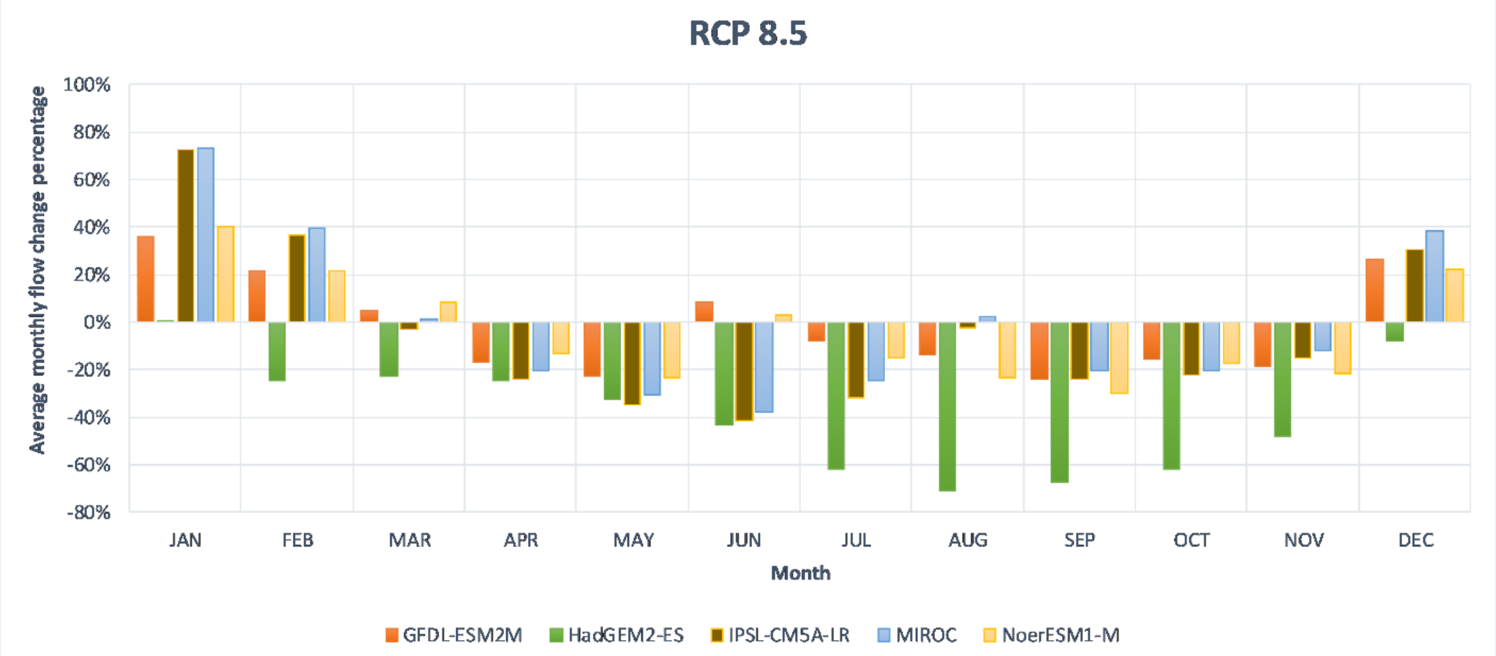
According to performance evaluation criteria for recommended statistical performance measures for watershed-scale models by Moriasi et al., 2015.

Scenario setup

- **5 general circulation models (GCM)**; data prepared using the CCT **;**
- **2 Representative Concentration Pathways (RCP)**: Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) RCP4.5 and RCP8.5, “business as usual” conditions;
- **2 periods** + baseline: Short term [2040-2050], Long term [2090-2099], Baseline scenario [2000-2010];
- Land management, point sources, diffused pollution loads → no change;
- **110** projection model runs + 1 baseline (11 runs);

Model abbreviation (GCM)	Name	Institute
GFDL-ESM2M	Global Coupled Carbon–Climate Earth System Models; Modular Ocean Model	NOAA/Geophysical Fluid Dynamics Laboratory
HadGEM2-ES	Hadley Global Environment Model 2 - Earth System	Met Office Hadley Center
IPSL-CM5A-LR	Institut Pierre Simon Laplace - Earth System Model for the 5th IPCC report: Low resolution	L'Institute Pierre-Simon Laplace
MIROC	Model for Interdisciplinary Research on Climate	AORI, NIES and JAMSTEC
NorESM1-M	Norwegian Earth System Model 1 - medium resolution	Norwegian Climate Center





Differences in projections: why the results so different?

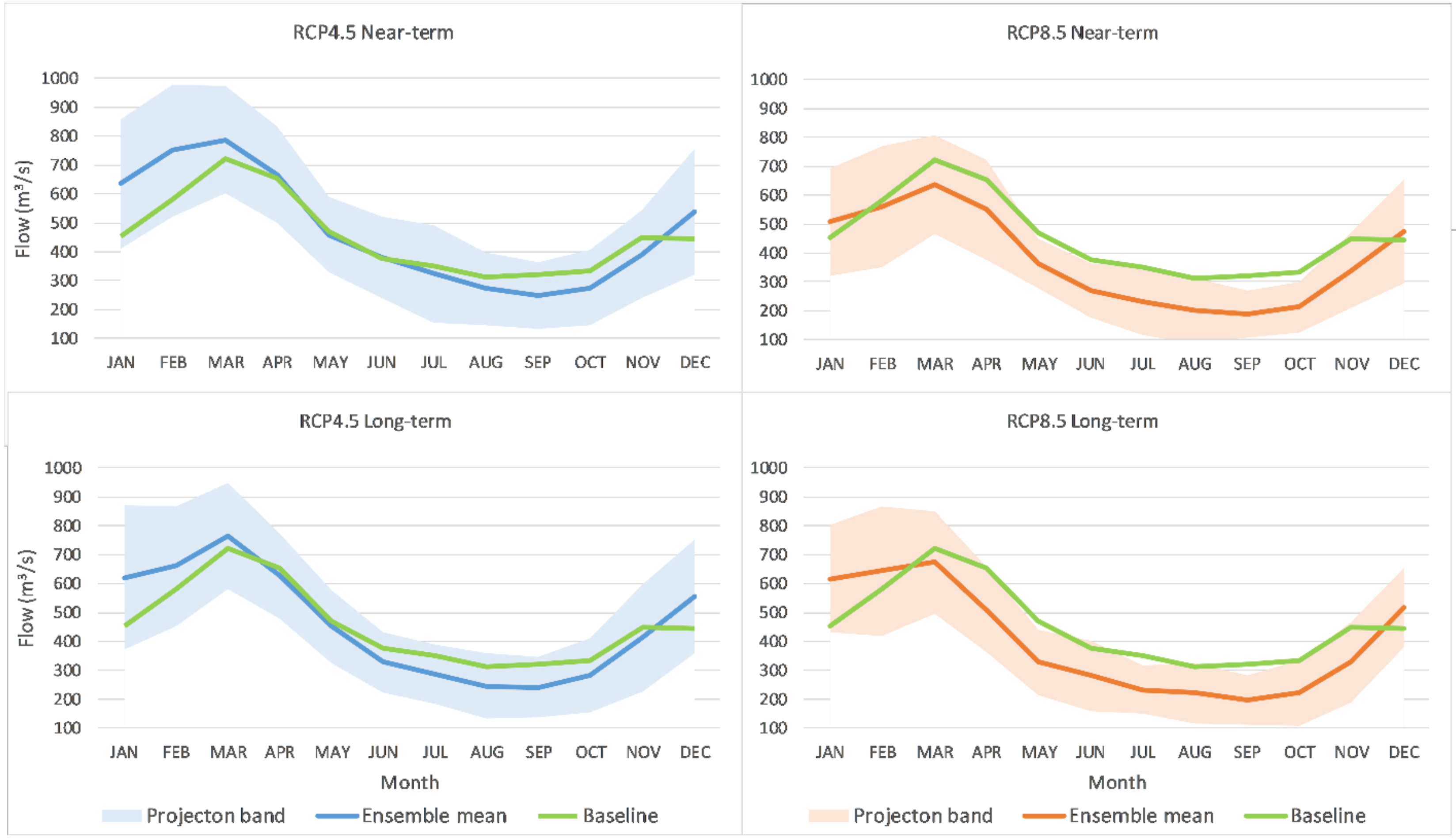
Uncertainty due to variations in climate model initial conditions or model parameterisations;

Prediction band added:

- can be judged as the variation in the prediction data

Difference in the average monthly flow for used GCMs under the conditions
of RCP4.5 (top) and RCP8.5 (bottom) compared to the baseline scenario for Nemunas River

Monthly flow projection



Interseasonal projected flow at the Nemunas – Smalininkai station, compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

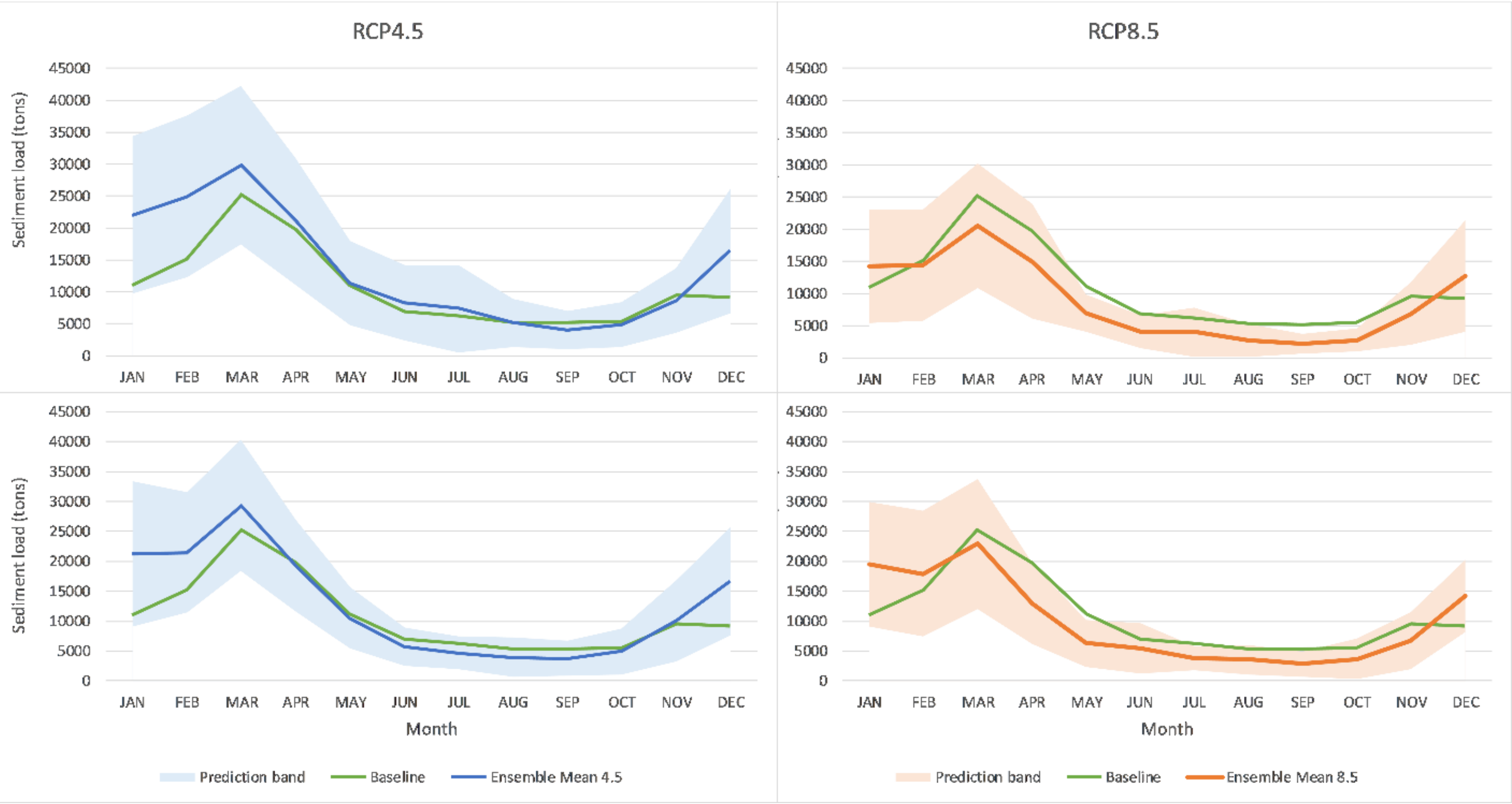
RCP4.5:

- Increased flows in all winter months under the RCP4.5 near- and long-term;

RCP8.5:

- near-term an increase only in December (+10%) and January (+6.5%);
- long-term (December: +22%, January: +44.5%, February: +18.9%).
- Reduction of flow in the spring to fall seasons in the RCP8.5.
- Likely explanation: reduced precipitation in warmer season, increased temperatures and extended vegetation season;

Sediment load projection



Interseasonal projected sediment load at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

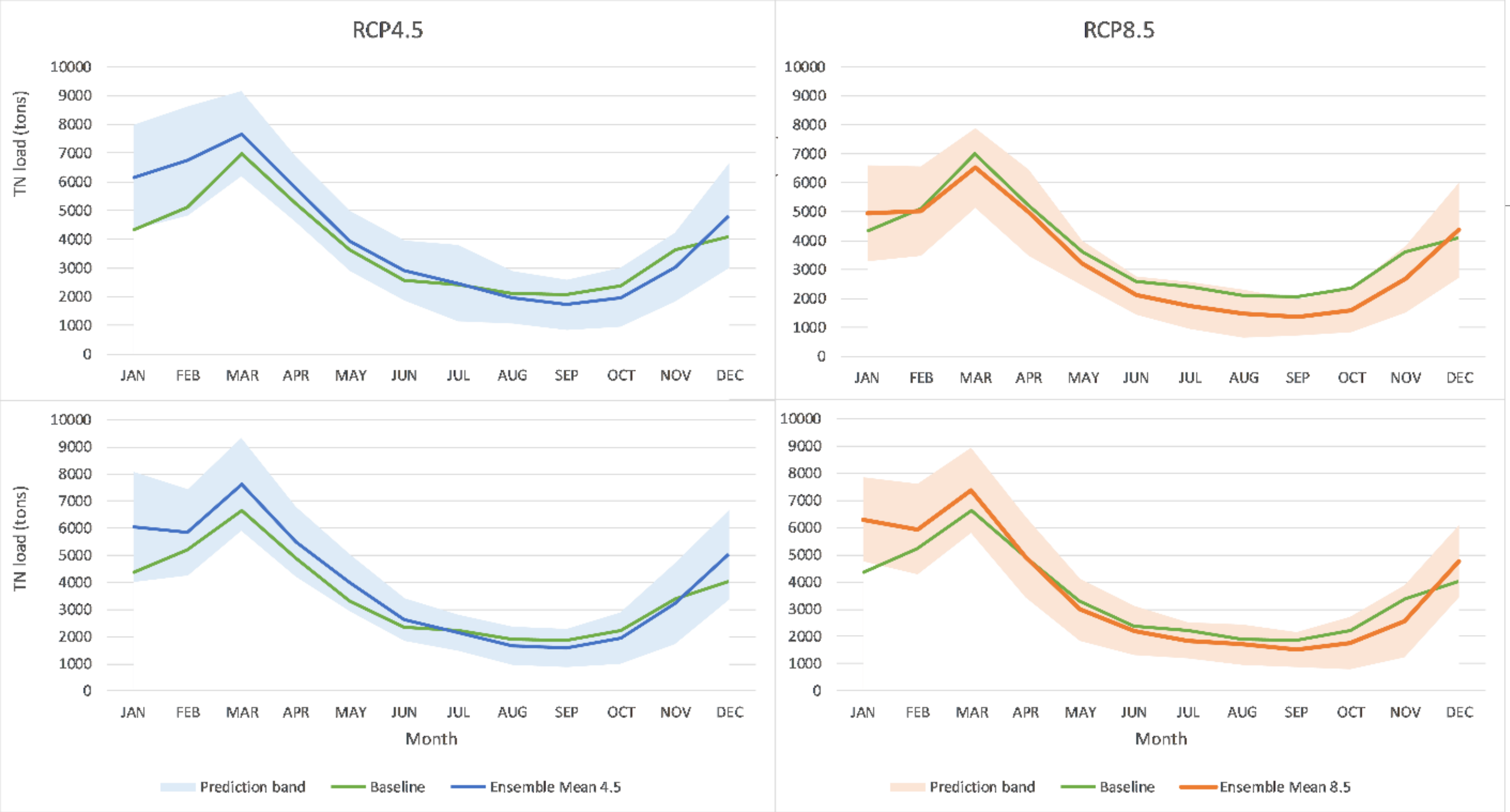
RCP4.5:

- near-term ensemble mean is two-fold higher in winter (December to February) and 20% in early spring (March to April);
- long-term period: 93% increase in January-February, and up to 16% in March-April;

RCP8.5:

- projected ensemble mean falls much lower than the baseline;
- up to 20% decrease in March until November;
- Likely explanation: lower snow cover in the winter months.

Nutrient load projection : TN



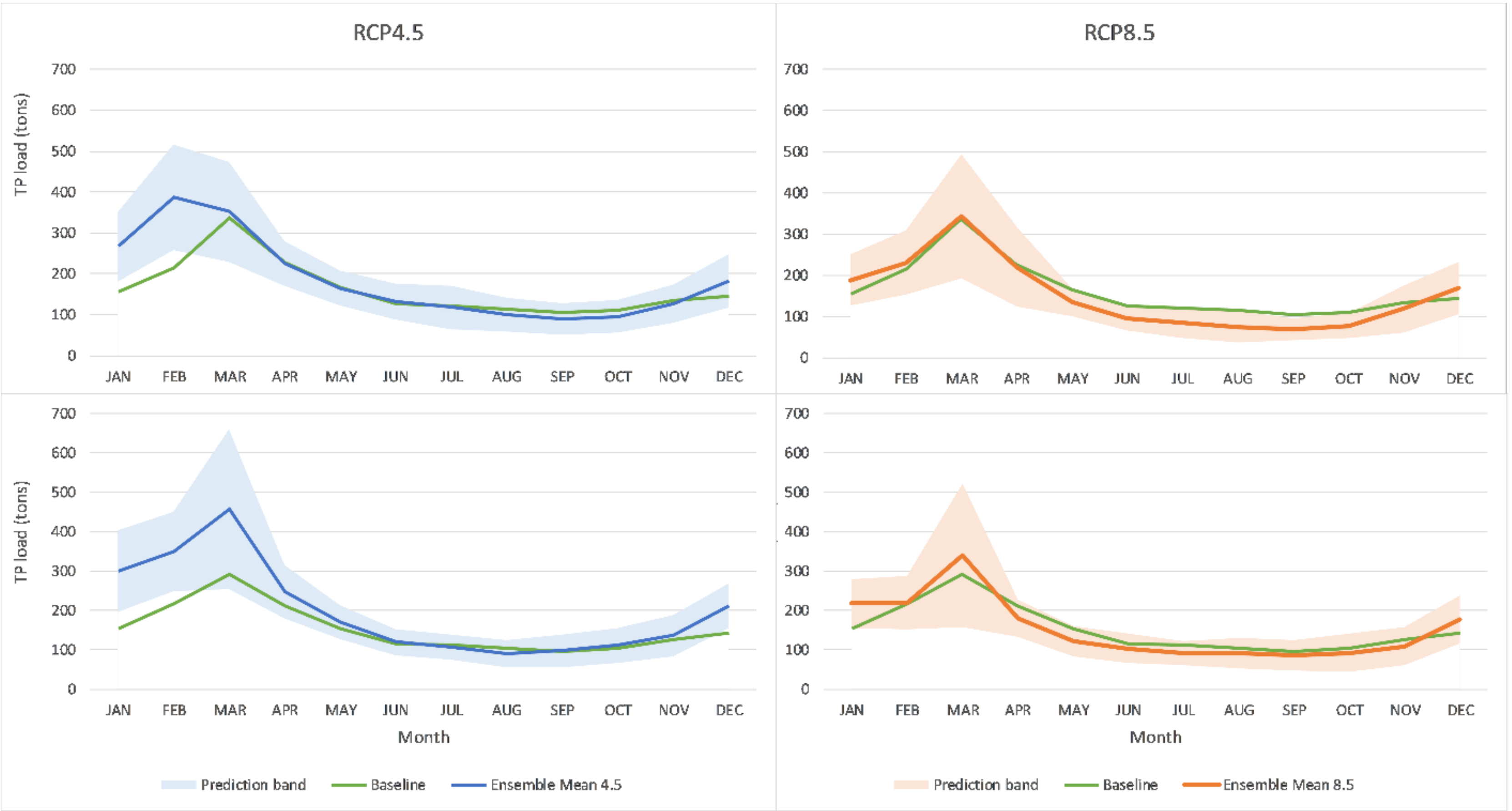
Interseasonal projected TN load at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

TN delivery is projected to change insignificantly;

Slight decrease of the ensemble mean compared to the baseline in the near-term RCP8.5 scenario for summer-fall months (by 27%);

Outcome: use of nutrient reduction and retention measures would still be necessary if Lithuania aims to comply with the Baltic Sea Action Plan and reduce the nutrient loads to the Maximum Allowable Inputs levels

Nutrient load projection : TP



Interseasonal projected TP load at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

RCP4.5:

- Significant change in the winter and early spring season: from December to March (especially in the long-term: up to 62% increase).

RCP8.5:

- TP loads do not change substantially.

Likely explanation: higher erosion in the winter months; PO_4 contribution to streamflow from the groundwater.

To sum up…

Average annual changes (%) compared to the baseline for the Nemunas river

	Short-term		***Long-term***	
	4.5	***8.5***	***4.5***	***8.5***
Flow	5.62	-12.17	10.40	-9.96
Sediments	23.74	-16.95	32.08	-8.05
TN	8.81	-8.41	15.00	1.85
TP	20.39	-0.63	33.80	-0.13

To sum up…

Average annual changes (%) compared to the baseline for the Nemunas river

	Short-term		***Long-term***	
	4.5	***8.5***	***4.5***	***8.5***
Flow	5.62	-12.17	10.40	-9.96
Sediments	23.74	-16.95	32.08	-8.05
TN	8.81	-8.41	15.00	1.85
TP	20.39	-0.63	33.80	-0.13

So what?

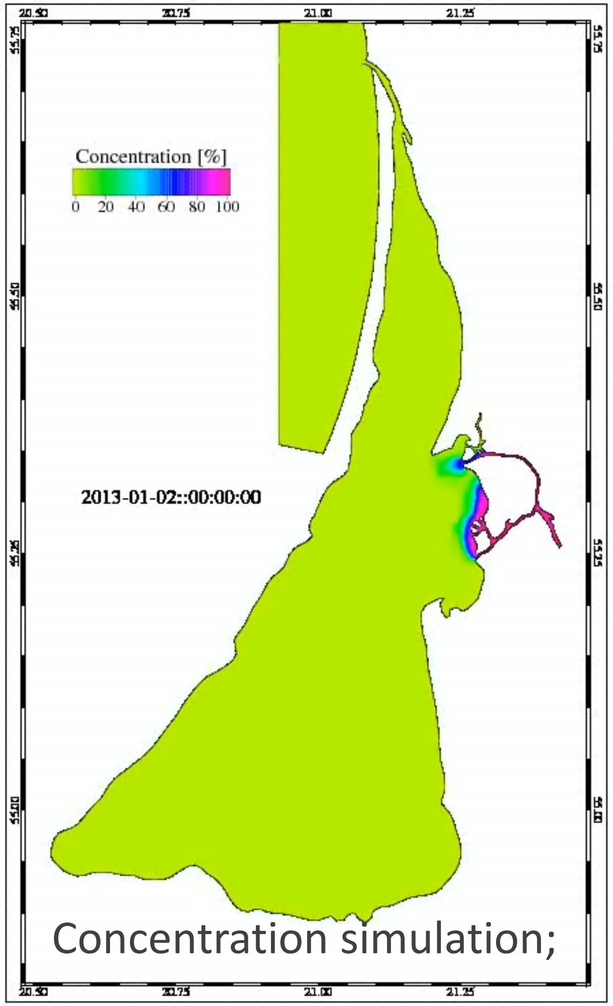
Change in the Curonian lagoons' hydrodynamics

3D hydrodynamic model (SHYFEM) of the Curonian Lagoon with an ecological module;

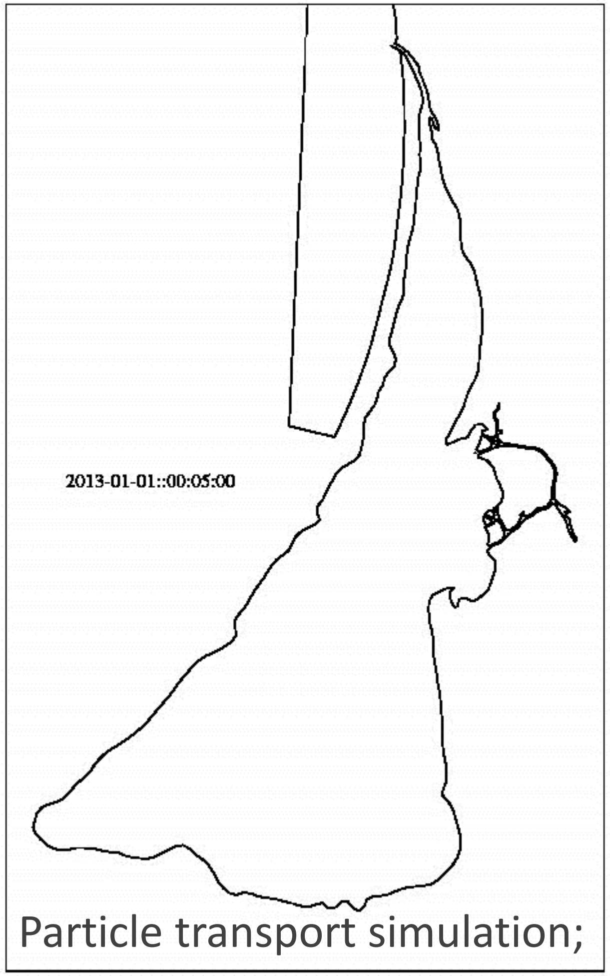
Possible changes in Water Residence Times (WRT)

- Even higher WRT in Summer;
  - Easily stratified lagoon;
  - N gets consumed very rapidly;
  - Possible P release..
    - → party time for cyanobacteria!

- Even lower WRT in Winter
  - Increased nutrient export to the Baltic sea;
  - Influence Ice Formation;
    - → No Ice fishing for me ☹



Concentration simulation;



Particle transport simulation;

Possible ecological changes

Average annual changes (%)
compared to the baseline for the Nemunas river

	Short-term		Long-term	
	4.5	**8.5**	**4.5**	**8.5**
Flow	5.62	-12.17	10.40	-9.96
Sediments	23.74	-16.95	32.08	-8.05
TN	8.81	-8.41	15.00	1.85
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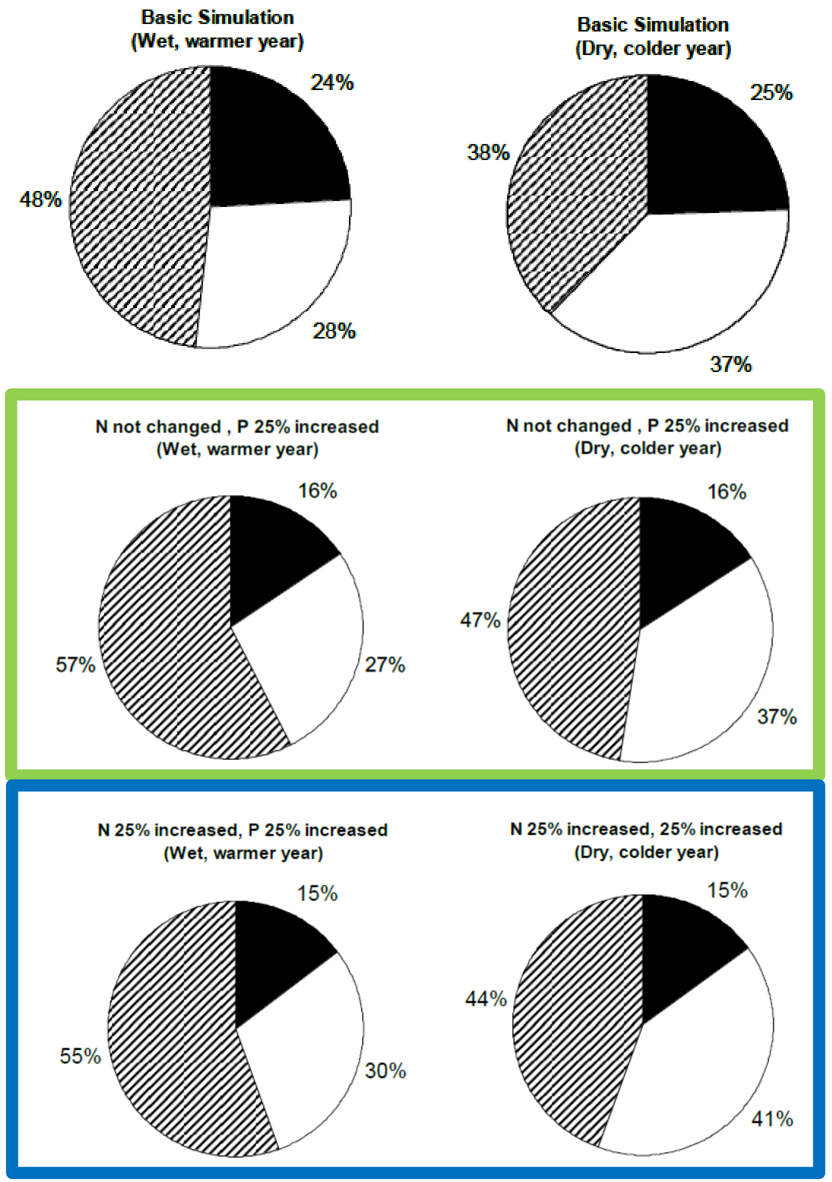

■ O.P.A. □ Diatoms ▨ Cyanobacteria

Ertürk A. et al. (2015) Linking Carbon-Nitrogen-Phosphorus Cycle and Foodweb Models of an Estuarine Lagoon Ecosystem

Conclusions

Climate change effects:

- ✓ Variability among the GCMs is high;
- ✓ The possible interseasonal changes in all scenarios suggests an increase in mid to late-winter water delivery to the Curonian Lagoon, and a possible decrease in summer;
  - ✓ Might result in higher nutrient delivery to the Baltic Sea during winter;
  - ✓ Might result in more cyanobacteria blooms;
  - ✓ Target the nutrient retention measures which work best in the cold season.

Model setup:

- ✓ Be creative .. ☺

Thank you

Btw: we are looking for a PhD students…

And also: I will be looking for a post-doc ;)

Thank you

Questions?

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