Dramatic water-level fluctuations in lakes under intense human impact: modelling the effect of vegetation, climate and hydrogeology

Marko Vainu

Institute of Ecology at Tallinn University, Uus-Sadama 5, Tallinn, Estonia, 10120, e-mail mvainu@tlu.ee

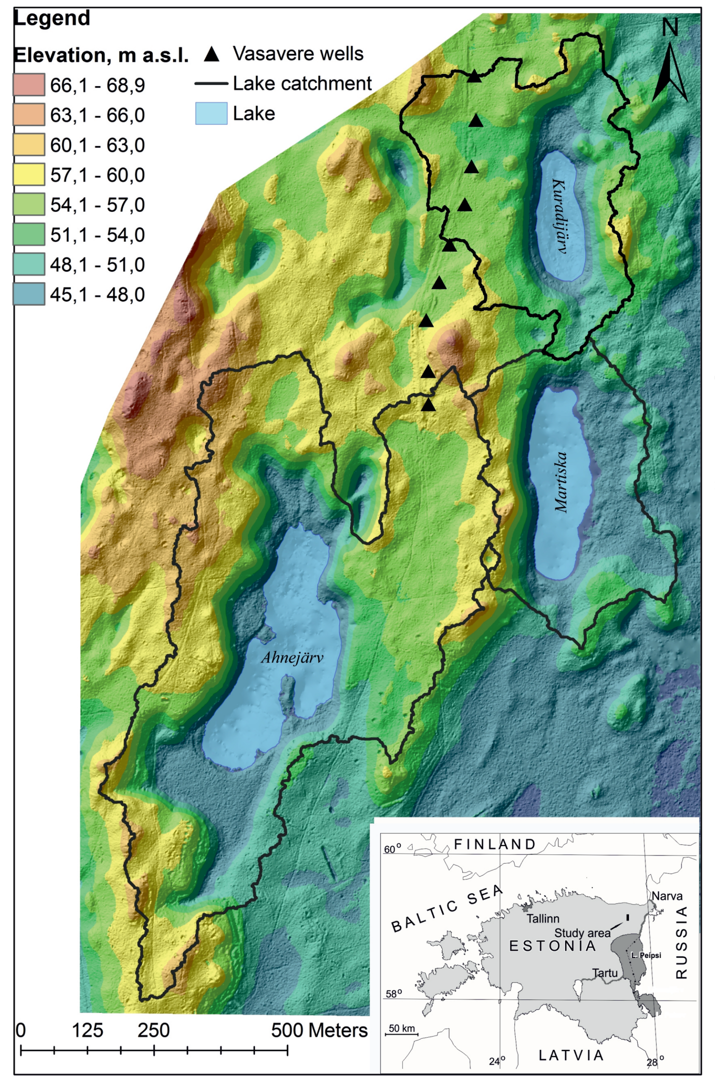
General aims

To reveal the possible causes of recent dramatic water-level changes in three small Estonian lakes and to assess the importance of the causes during different time periods with a new lumped lake water-balance model.

Previously the rapid decrease and the consequent rapid increase of the lakes' water levels have been explained solely by the effect of groundwater abstraction - its initiation, increase and decrease in pumping rates.

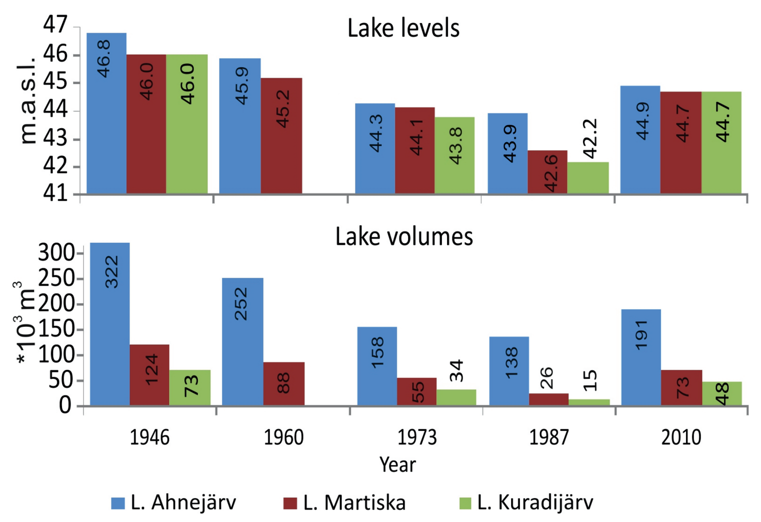
Study area

Three small closed-basin lakes in NE Estonia were under study.



	Lake Ahnejärv	Lake Martiska	Lake Kuradijärv
Surface area (ha)	5.7	3.1	1.7
Volume (m^3)	191 000	73 000	48 000
Mean depth (m)	3.3	2.3	2.8
Max. depth (m)	9.0	8.2	7.7
Catchment area (ha)	44.5	14.3	16.3

The lakes have suffered dramatic water-level fluctuations during the last half-century.

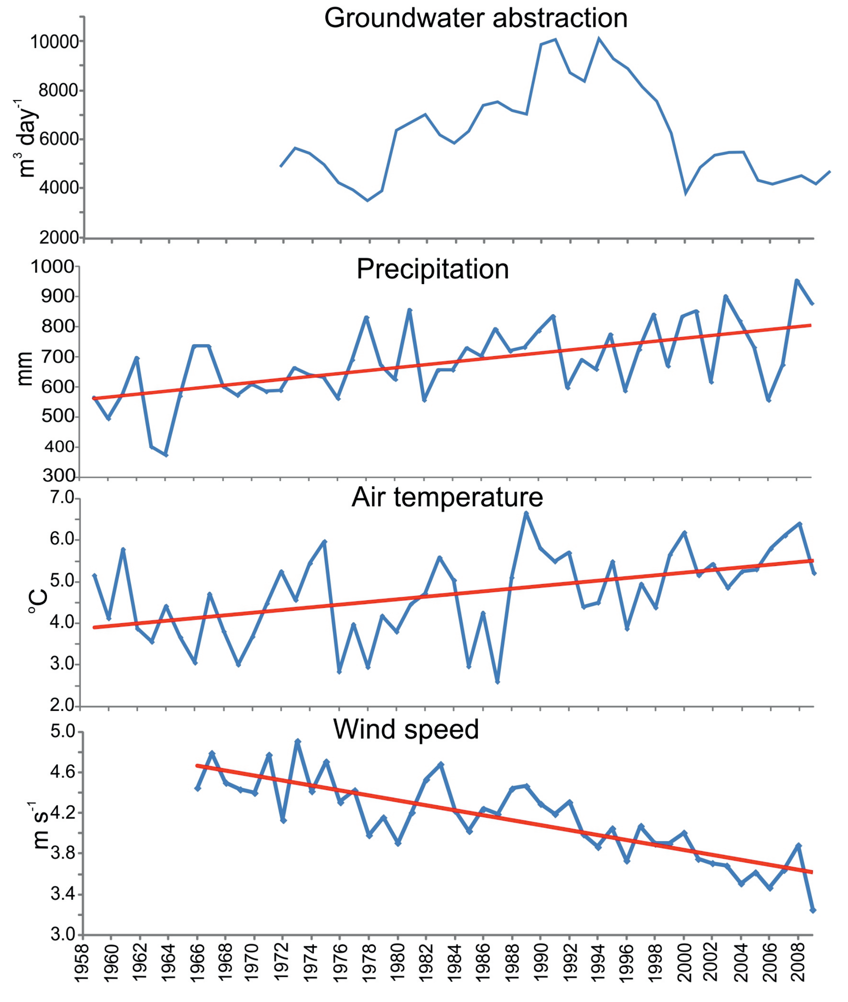


What has happened?

a) **Vegetation**: Lake catchments were unforested in 1946 because of a huge wildfire during World War II. By 1960 the catchments had been uniformly reforested with pine trees and have remained that way until the present day.

b) **Hydrogeology**: In 1972 groundwater abstraction wells were built close to the lakes to provide drinking water to a nearby city. Groundwater abstraction rates have varied considerably in time.

c) **Climate**: Local climate has changed significantly in the region since the beginning of the 1960s.



Research questions

Considering the data known about the lakes and their environmental setting three research questions and more precise simulation scenarios were posed:

1) **The effect of vegetation:** Could the lake water-level drop in the 1950s have been caused by a significant vegetation change on lake catchments?

Scenario: "What would happen with the lakes' water levels if their catchments were covered with moor vegetation in the 2000s?".

This analogy-based design had to be set, because sufficient meteorological data from the 1960s was missing.

2) **The effect of hydrogeology:** Could the inter-lake differences in water-level recovery have been caused by a dissimilar change in the hydrogeological setting of the lakes after 1987?

Scenario: ""How high would the lakes' water levels have been in 1987 if just meteorological parameters had differed in the 1980s and 2000s and the hydrogeological setting of the lakes had not changed?"

3) **The effect of climate:** Could the lake water levels have been higher in the end of 2010s than in the 1970s due to a climatic shift towards moister conditions?

Scenario: „How large were the atmospherically affected lake water-balance component amounts in the 1970s and in the 2000s?"

Methods

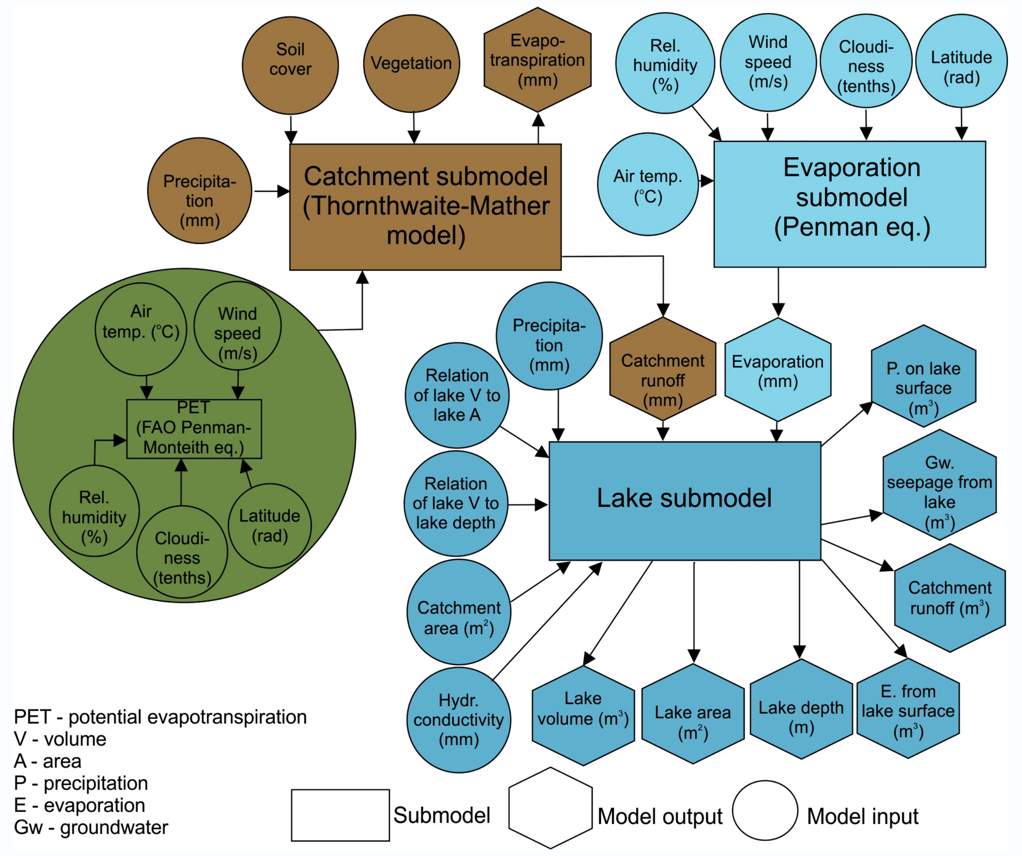
Lake water-balance modelling

The amount of water in a lake can be calculated with lake water-balance equation

$$\Delta V = P_l + R + G_i - D - E - G_o$$

where ΔV is the change in lake volume during the time period under consideration, P_l - precipitation on lake surface, R - runoff from the catchment, G_i - seepage from groundwater, D - surface water discharge, E - evaporation from lake surface and G_o - seepage into groundwater.

A new deterministic lumped *MS Excel*-based water balance model was compiled, calibrated and used for the simulations.



The model:

- Is suitable for closed-basin lakes.
- Uses the basic lake water-balance equation according to monthly climatic, geo-graphic and hydrological input data.
- Works with a monthly time-step.
- Is run until lake volume reaches an equilibrium, which corresponds to the input data.

Results

1) The effect of vegetation

If the lake catchments had been unforested in the 2000s lower evapotranspiration rates would have produced 16% higher catchment runoff than when forested with conifers. It would have risen the water level of the lakes from 0.5 to ca. 1 m for 2010.

Year 2010	Lake Ahnejärv		Lake Martiska		Lake Kuradijärv	
	Conifers	Moor	Conifers	Moor	Conifers	Moor
Annual runoff (mm)	370	430	370	430	370	430
Lake volume (m^3)	191 000	227 000	73 000	82 000	48 000	64 000
Lake level (m a.s.l.)	**44.9**	**45.4**	**44.7**	**45.1**	**44.7**	**45.5**

The inter-lake variations can be explained by different catchment area to lake area ratios and by lakes' differing bathymetry.

The vegetation change would notably alter present catchment runoff that would be expressed in lake water volume and level rise. Thus, the increase in runoff of the resulted magnitude would not fully cover the changes observed from 1946 to 1960.

2) The effect of hydrogeological setting

If the hydrogeological setting of the lakes had been the same in 1987 as in 2010 then, according to the simulation results, the water level of L. Ahnejärv would have been ca. 0.5 m lower in 1987 than it actually was and the water levels of L. Martiska and L. Kuradjärv ca. 1.5 m higher.

Year 1987	Lake Ahnejärv		Lake Martiska		Lake Kuradijärv	
	Actual	Modelled	Actual	Modelled	Actual	Modelled
Lake volume (m^3)	138 000	118 000	26 000	52 000	15 000	30 000
Lake area (ha)	4.9	4.6	1.3	2.5	0.9	1.4
Lake level (m a.s.l.)	**43.9**	**43.4**	**42.6**	**43.9**	**42.2**	**43.5**

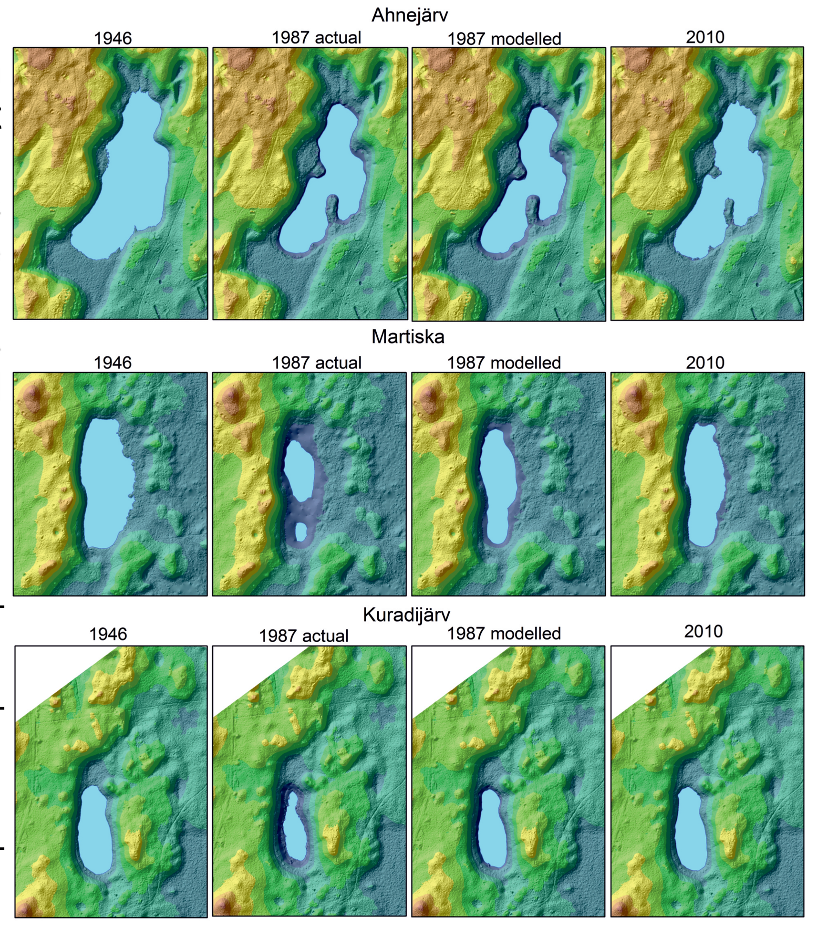
The role of hydrogeological change in lake water-level restoration has not been alike for the lakes.

For L. Martiska and L. Kuradjärv it has contributed, together with local climate change, to water-level rise.

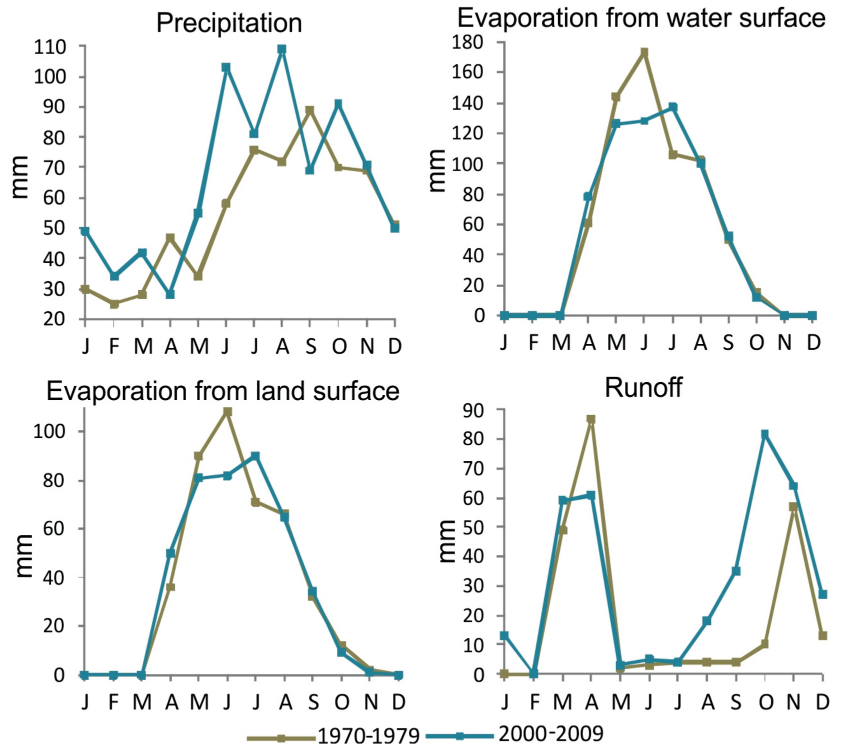
For L. Ahnejärv, on the contrary, it has reduced the positive effect of local climate change.

Change in lake water levels from 1987 to 2010 under different forcing factors

	Only hydrogeology (m)	Only climate (m)	Actual (m)
L. Ahnejärv	-0.5	+1.5	+1.0
L. Martiska	+1.3	+0.8	+2.1
L. Kuradijärv	+1.3	+1.2	+2.5



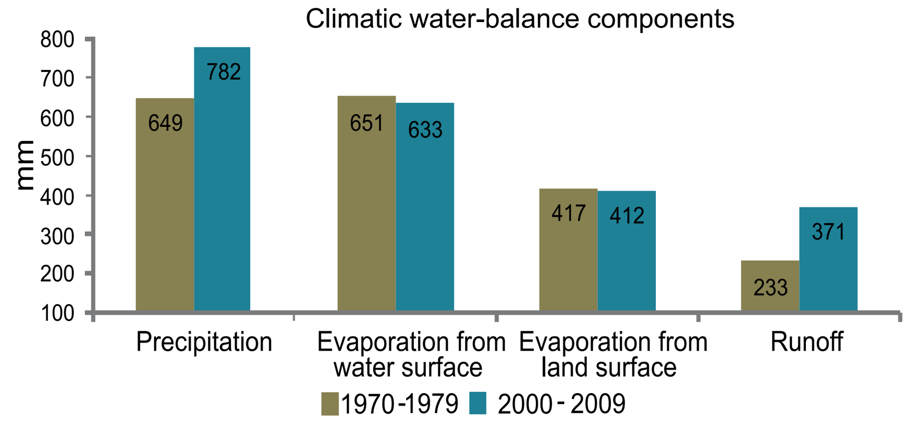
3) The effect of climate



Increasing precipitation and decreasing wind speed caused, according to the simulation results, more water input to the lake in the 2000s than in the 1970s, both through increased direct precipitation to lake surface and catchment runoff.

Evaporation rate, on the other hand, decreased even though average air temperature rose also.

As more water entered the lakes in 2000s than in the 1970s, it is local climate change that probably explains the higher lake levels in 2010 compared to 1973 when groundwater abstraction rates had been similar.



Answers to the research questions

1) **Vegetation change was likely an important, but not the only factor between 1946 and 1960.**

Vegetation change on lake catchments is an important factor in the formation of the water body of a lake. Large scale changes in catchment vegetation may cause notable changes in the water levels of a lake. But in the case of the studied lakes it can not fully explain the observed water-level changes.

2) **The differences in lake water-level recovery between 1987 and 2010 are likely explained by varying changes in the lakes' hydrogeological setting.**

A uniform groundwater-related activity in the vicinity of closely situated lakes can have an opposite effect on their hydrogeological setting, causing their water levels to change dissimilarly.

3) **Local climate change likely caused the difference in lake water levels between 1973 and 2010.**

Local relatively short term climate change can have a significant effect on the water level of small closed-basin lakes. Specifically, climate moistening can mitigate the negative effect of groundwater abstraction.

Scientific significance of the study

Although concentrating on three specific lakes in a specific region, the results indicate the complexity of universal factors influencing the amount of water stored in a lake. Therefore it emphasises the importance of taking the factors into consideration in lake research and management all around the world.

Acknowledgements

The study was financed by the Estonian target-financed project Sf0280016s07.

Participation in the EGU 2012 conference was financed by the Estonian Doctoral School of Earth Sciences and Ecology.