Review of 'Simulating carbon fluxes in boreal catchments: WSFS-Vemala model development and key insights '

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Reviewer 1:

Overall, this is a well-written paper that describes an important modelling advance. While the model has been designed for Finnish conditions, the findings of this paper will be useful to a broad range of researches including those working with catchment or regional scale modelling, those interested in aquatic carbon cycling and climate issues as well as applied researchers having a responsibility to support decision makers. The authors present a regional / national scale model of aquatic carbon production, transport and loss. To the best of my knowledge, this is the first model to attempt such national scale simulations with such a high degree of process fidelity.
One of the key strengths of this model is that it tracks the production, transport, transformation and loss of both total inorganic carbon (TIC) and total organic carbon (TOC).

Answer: We thank Reviewer 1 for the positive feedback on the manuscript and for acknowledging its clarity, novelty and relevance to the readers of Hydrology and Earth System Sciences. The changes to the manuscript have now been described under each response to the comments from the reviewer as tracked changes.

I do have a number of reservations about this paper that I hope the authors will have the opportunity to address in a revised version.
The authors present their model as a tool for simulating total organic carbon and total inorganic carbon. This is appropriate for boreal conditions where there is typically very little particulate organic carbon and the underlying geology for the most part precludes high levels of particulate inorganic carbon (e.g., carbonate –derived rocks).

Answer: Thank you for highlighting the relevance of this model formulations under boreal conditions. In Finnish and other boreal catchments, particulate inorganic carbon is typically very low because carbonate rocks are rare and bedrock is dominated by silicate lithologies (Kortelainen et al., 2006 https://link.springer.com/article/10.1007/s00027-006-0833-6). Therefore, TIC can reasonably be assumed to represent dissolved inorganic carbon.

In contrast, the dominance of organic carbon in boreal inland waters is primarily controlled by land cover and climate rather than geology. Extensive peatlands and wetlands, organic-rich soils, and cold and humid climatic conditions promote the production, mobilisation, and export of dissolved organic carbon. As a result, DOC constitutes the dominant fraction of total organic carbon in boreal rivers and lakes. For example, Mattsson et al. (2005 https://link.springer.com/article/10.1007/s10533-005-6897-x) showed that, on average, 94% of TOC in Finnish rivers occurs in dissolved form.

We will explicitly add these details to the introduction in the revised version of the manuscript to clarify the applicability of this model under boreal conditions. We will also add in the discussion the limitation of the model applications to low particulate inorganic and organic carbon concentrations.
We have added details through the text to clarify the applicability of the model:
Ln 46-48: In boreal rivers and lakes, DOC constitutes the dominant fraction of total organic carbon (TOC). Mattsson et al. (2005) reported that, on average, 94% of TOC in Finnish rivers occurs in a dissolved form.

Extensive peatlands, forested catchments, and cold and humid climatic conditions promote the mobilisation and export of organic carbon, resulting in humic and DOC-rich waters.
Ln59-61: Boreal catchments in Finland are characterised by silicate lithologies or non-carbonate bedrocks (Kortelainen et al., 2006) leading to inorganic carbon being mostly dissolved and low buffer capacity of the freshwater (low alkalinity and pH) that enhances the availability of dissolved CO2 for evasion (Tranvik et al., 2009).
Ln 232-233: The resultant alkalinity definition in this model can be expressed in terms of TIC and TOC as we consider the total C fully dissolved in Finnish waters as (Eq. (5)):
Ln682-683: This model is especially relevant in boreal catchments where TIC and TOC are mostly under a dissolved form.

I suggest the authors either refer to dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) throughout (as they seem to be doing from statements made on line 154), or note that in the environment for which this model has been developed, only a small fraction of the total aquatic carbon is in a particulate form. Using DOC instead of TOC could also make more clear the separation between soil organic carbon and organic carbon in the aquatic phase.
Answer: Thank you for this helpful suggestion. We agree that the use of DOC and DIC terminology can improve conceptual clarity, especially regarding the distinction between soil organic carbon and aquatic carbon pools. In our case, we use TOC and TIC because these are the forms in which long-term and spatially consistent observations are available for model development, calibration, and validation in Finland. We will add to the manuscript the link between non-carbonate bedrocks and low particulate inorganic carbon leading to the fact that most of the inorganic carbon in the water is under a dissolved form.
Ln 156: "TIC is assumed fully dissolved and thus is representing DIC."
Ln 289: "TOC and TIC are measured on unfiltered samples in Finland, while DOC and DIC are very rarely sampled."
We have clarified the use of TIC and TOC in the model by adding these sentences to the manuscript:

Ln59-61 Boreal catchments in Finland are characterised by silicate lithologies or non-carbonate bedrocks (Kortelainen et al., 2006) leading to inorganic carbon being mostly dissolved and low buffer capacity of the freshwater (low alkalinity and pH) that enhances the availability of dissolved CO2 for evasion (Tranvik et al., 2009).
Ln 184-186: DOC loads simulated by the TOC terrestrial model are calibrated against TOC observations in inland waters. TOC is mostly under a dissolved form (Mattsson et al., 2005) in Finnish rivers. Therefore, TOC is assumed to be fully dissolved and represents DOC in Vemala
Ln 189 TIC is assumed fully dissolved and thus is representing DIC.
Ln 232-233: The resultant alkalinity definition in this model can be expressed in terms of TIC and TOC as we consider the total carbon fully dissolved in Finnish boreal waters as (Eq. (5)):

As the authors present their work as a new contribution to our ability to model aquatic carbon, I suggest deleting information about N and P simulations (e.g., Table 3). Either that or provide a rationale for why nitrogen and phosphorus simulation results should be included in this study.

Answer: Thank you for this suggestion to focus the manuscript on carbon alone. The rationale for the presentation of nutrients results is linked to the application of the biogeochemical model concept in the aquatic ecosystem. The strength of the biogeochemical model is to simulate concurrently nutrients and carbon processes as they are combined through algal growth and mineralisation processes (sensitivity analysis 5.5 lines 569-575). We could add this rationale to the paragraph 2.3 Aquatic biogeochemical submodel. Presenting only TIC and TOC results would omit the strength of the model to simulate processes based on physical, chemical and biological reactions and how TIC and TOC are integrated with nutrients, and algal and bacterial growth. We believe this integration of nutrients and carbon is crucial in our work regarding the Water Framework Directive and the link between carbon and eutrophication.
We reformulated the description of WSFS-Vemala and added a sentence to the discussion.

Ln 204-206 The Vemala biogeochemical submodel (Korppoo et al., 2017) simulating the co-impact of nitrogen and phosphorus on algal growth and therefore eutrophication, was developed to couple organic carbon to inorganic carbon processes and simulate total carbon cycling.
Ln 665-667: WSFS-Vemala through its biogeochemical sub-model links nutrients to phytoplankton growth and carbon cycling in inland waters to further study these fundamental links between eutrophication and GHG emissions.

My biggest concerns about this paper arise from statements made on lines 134 and lines 153-157. On line 134, the authors state that “SOC and DIC can be mineralized into DIC that is simulated as a loss from the system to the air”. Paraphrasing lines 153-157, they appear to state that alkalinity is a proxy for TIC which in turn includes CO2, HCO3- and CO3_2-.
I would be grateful if the authors could clarify whether or not they are using the regression on line 156 to estimate the sum of CO2, HCO3- and CO3_2-. If they are doing so, I would appreciate a stronger motivation for the decision.

Answer: Thank you for this comment to clarify the model structure. The TOC terrestrial model is only used for the simulation of terrestrial loading of TOC and includes mineralisation in soils, however DIC storage in the soil is not explicitly simulated in this model version nor are CO_2 emissions from soil. The simulation of the TIC terrestrial loading that uses equation on ln156, and is related to alkalinity, is separate from the TOC loading model. This model simulates TIC as a bulk pool but does not simulate the carbonate speciation (CO_2, HCO_3^-, CO_3^{2-}) in the terrestrial ecosystem separately. The carbonate speciation is calculated only in the aquatic environment for the simulation of carbon emissions from the aquatic ecosystem and requires alkalinity, TIC and TOC for calculation of pH. To our understanding, geology through rock weathering is the main characteristic explaining the variation of TIC loading to surface waters. It is unclear to us what proportion of TIC leaching is explained by mineralisation in organic soils. A representation of national scale TIC and TOC concentrations in the aquatic environment (figure 1), shows that high TOC concentrations in Northern Finland (catchments number 36-67) are associated with low TIC concentrations. Northern catchments are till dominated catchments, which is a low source of alkalinity while southern catchments (5-30) are characterised by an increased proportion of clay and bedrock which are a higher source of alkalinity (Korkka-Niemi (2001)). Based on this assumption that rock weathering is the predominant process leaching TIC to surface waters, we built a model accordingly using geology and alkalinity as a proxy for TIC. Alkalinity simulations were also required in the aquatic ecosystem to calculate pH and simulate carbonate speciation and thus CO2 emissions.

Lines 145~~35~~-149~~37~~ should be modified to reflect the fact that DIC storage is not simulated explicitly in the TOC terrestrial model, only SOC and DOC dynamics (mineralisation, dissociation, storage and leaching) are simulated in the soil:
‘There are ~~three~~ two C storages in the soil – SOC and~~,~~ DOC ~~and DIC~~ linked to soil types and land uses. Inputs to the model are annual litter fall and initial C storage in soil. Interactions among these pools are as follows:

- SOC can be disassociated into DOC, and vice versa.
- SOC and DOC can be mineralized ~~into DIC that is simulated as a loss from the system to the air.~~
- DOC leaches with the subsurface runoff and baseflow.’

We have removed the terms of DIC from the TOC sub-model as it is not explicitly simulated in this sub-model to avoid confusion between the TIC and TOC terrestrial sub-models:
Ln 153-160: The model represents two C storages in the soil: SOC and DOC. These pools are defined separately for different soil types and land use classes. The main inputs to the model are annual litter fall and the initial C storage in soil. Carbon exchanges between the SOC and DOC pools are represented through the following processes:
- SOC can be disassociated into DOC, and DOC can be reassimilated into SOC.
- Both SOC and DOC can be mineralized

- DOC is transported from soil to water through subsurface runoff and baseflow.

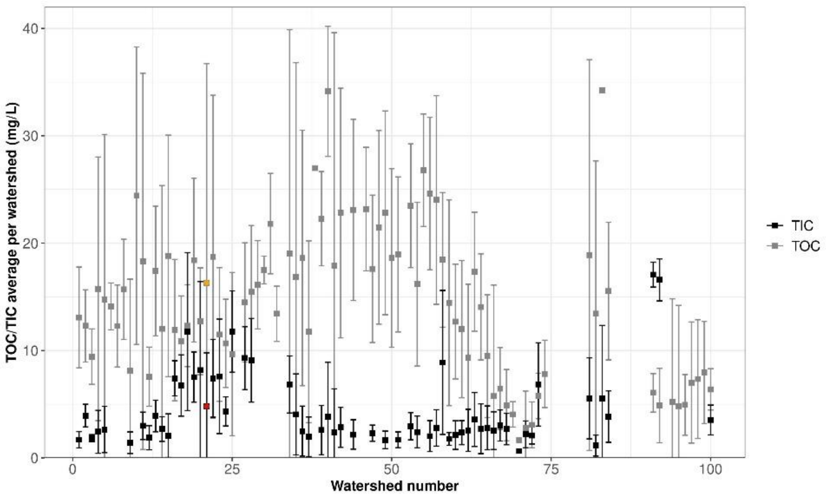


Figure 1: Average TIC and TOC concentrations in Finnish main catchments (VESLA database, Syke).

My second concern about lines 134 and 153-157 is that they seem to state that terrestrial DIC is modelled twice, once as a breakdown product of SOC and / or TOC (line 134) and once as an empirical soil-related property (lines 153-157). Why? Doing so seems to violate a carbon mass balance as the DIC produced through mineralization leaves the system to contribute to atmospheric warming while the regression takes no explicit account of terrestrial carbon mineralization. This really needs a better explanation and justification.

Answer: Thank you for this comment. There are historical reasons why TOC leaching is simulated separately from TIC leaching in Vemala. The Vemala model was originally developed to provide national-scale estimates of TOC loading and concentrations for the implementation of the Water Framework Directive (WFD). In Finnish waters, changes in TOC concentrations are known to contribute to brownification, which has ecological effects on inland water systems. When the model was first created (around 2018), TIC leaching was not considered a key output variable.
TIC leaching has since been integrated into Vemala as a separate sub-model for at least two main reasons:

1. *The TOC module in Vemala does not simulate weathering processes in rocks and mineral soils. It only represents mineralization, which accounts for only part of the processes that generate TIC in soils.*
2. *The national scale observed TIC dataset is very small. However, the approach must rely on variables with national coverage for the development of the model at the national scale. Alkalinity is well correlated with TIC and is supported by comprehensive monitoring data across Finland.*

In the future, the terrestrial TOC model could be coupled more tightly with the TIC model to simulate mineralisation processes and greenhouse gas emissions from land.
We added these sentences to the manuscript in order to distinguish between the TIC and TOC terrestrial models:
Ln 591-594: Vemala must rely on variables with national coverage for its development at the national scale, however observed TIC dataset (VESLA, Syke) is very limited. Thus, alkalinity that is well correlated with TIC and is supported by comprehensive monitoring data across Finland is a good proxy to simulate TIC in Finland.
Ln 598-601: In our model, TIC input loading is associated with rock weathering using alkalinity and soil types rather than accounting for mineralisation of organic carbon in the soil. TIC load from bedrock and clay soils is higher than from coarse soils (sand and silt) as analysed from well waters in Finland (Korkka-Niemi, 2001).
Ln 607-608: Point sources of TIC are not included in this model nor is the mineralisation process producing DIC in the soil at this stage of the model development.

Ln 611-612: In the future, the terrestrial TOC model could be coupled more tightly with the TIC model to simulate mineralisation processes and greenhouse gas emissions from land areas.
Ln 691-693: Future development efforts for Vemala model should aim at linking the TOC and TIC terrestrial submodels to represent TIC leaching from rock weathering and mineralisation in soils as well as CO2 emissions from land areas.

From the text on lines 225-230, it appears that the authors calibrated to loads. This is poor practice for demonstrating the skill of a biogeochemical model. Any calibration that does a reasonable job of reproducing the observed flow has a high probability of generating misleadingly high Nash Sutcliffe Efficiencies. Please consider either recalibrating to concentrations or present performance statistics based on modelled and observed concentations.

Answer: Thank you for this important methodological comment. We agree that calibrating and evaluating biogeochemical models solely based on loads can be misleading, as loads are strongly controlled by discharge and may result in artificially high performance metrics such as NSE. In the WSFS-Vemala framework, calibration is not based on loads alone. The automatic calibration uses a modification of the direct search Hooke–Jeeves optimisation algorithm (Huttunen et al., 2016, https://link.springer.com/article/10.1007/s10666-015-9470-6) and considers both loads and concentrations during parameter optimisation.

To address this concern more explicitly, we will revise the manuscript to include performance statistics based on observed and modelled concentrations in the lake in addition to loads in the rivers. This will allow a more robust evaluation of model skill that is less dominated by discharge and better reflects biogeochemical process representation in lake systems. We will also clarify the distinction between calibration strategy and performance evaluation in the Methods and Results sections. Section 4.2.2 Water quality Tuusulanjärvi will be updated with the description of r^2 and PBIAS results in Tuusulanjärvi.
We have added Table 4 as well as the description of the table in the results section of the manuscript:
Ln 269-270: The Vemala calibration process used a modification of the direct search Hooke-Jeeves optimisation algorithm as described in Huttunen et al. (2016) and considers both loads and concentrations during parameter optimisation.
Ln 275-277: . To evaluate the performance of the model in terms of concentrations the coefficient of determination for linear regression (R^2, Krause et al., 2005) and the percent bias (PBIAS, Gupta et al., 1999) were calculated.
Ln 396-399 Vemala performed well in terms of TOC daily loads at the Vantaanjoki outlet observation point, with a NSE of 0.65 for the calibration period (2004-2023), and 0.79 for the validation period (1990-2003) (Table 3), as well as for the simulation of TOC daily concentrations (r2=0.89 for both periods and pBIAS between 7 and 16%, Table 4 and Fig. 6).
Ln440-441: The alkalinity daily concentrations were well simulated compared to the observations (r2=0.93-0.99); however alkalinity was overestimated in the validation period (pBIAS between -16 and -28%) in Vantaanjoki and Tuusulanjärvi (Table 4).
Ln 443-445: . TIC daily concentrations showed a strong correspondence with the observations (r2=0.88-0.99 for both periods), however TIC concentrations were underestimated in both periods (pBIAS between 17 and 33%, Table 4 and Fig. 6).
Ln 483-485: The concentrations in Tuusulanjärvi are well simulated with r2 higher than 0.90 for all variables (Table 4), although some variables are underestimated like TIC (pBIAS between 17 and 25%) and TOC (pBIAS between 18 and 24%) (Table 4 and Fig.8).

Table 4: The model performance statistics (r2, n = number of observations and pBIAS) for carbon and nutrient concentrations, alkalinity and pH at Tuusulanjärvi and Vantaanjoki outlets (Vantaanjoki 4,2 6040) during the calibration (2004-2023) and validation (1990-2003) periods. Variables include total organic carbon (TOC, mgC L-1), total inorganic carbon (TIC, mgC L-1), alkalinity (Alk, mmol L-1), pH, total phosphorus (TP, µg L-1) and total nitrogen (TN, mg L-1).

Observation point	Period	TOC (mg L^{-1})		TIC (mg L^{-1})		Alk (mmol L^{-1})		pH		TP (µg L^{-1})		TN (mg L^{-1})	
		r^2	pBIAS	r^2	pBIAS	r^2	pBIAS	r^2	pBIAS	r^2	pBIAS	r^2	pBIAS
Tuusulanjärvi	1990-2003	0.93, n=28	18	0.99, n=9	25	0.99, n=169	-16	0.99, n=180	-6	0.91, n=202	-2	0.92, n=169	12
	2004-2023	0.98, n=47	24	0.98, n=4	17	0.98, n=209	-4	0.99 n=219	-4	0.90, n=265	5	0.93, n=209	10
Vantaanjoki 4,2 6040	1990-2003	0.89, n=193	7	0.95, n=12	17	0.93, n=197	-28	0.99 n=249	-3	0.86, n=252	-1	0.87, n=252	28
	2004-2023	0.89 n=242	16	0.88, n=199	33	0.93, n=241	2	0.99 n=436	-5	0.86, n=435	-0.5	0.89, n=436	25

Minor questions

L108 – how is soil temperature include in the model ? are measured time series used or is soil temperature simulated in some manner?

Answer: Soil temperature is simulated within an unpublished soil frost simulation model developed in late 1990-ties in the WSFS system. The model is based on simulation of the energy flux between air, snow and soil layers. It calculates the snow thermal conductivity, soil thermal conductivity and soil specific heat. The model simulates distribution of the energy flux - how much energy is used:

1) to freeze or melt the soil frost

2) to decrease or increase the soil temperature for the soil layers.

The Figure 2 below illustrates the soil temperature simulation for example at the 3rd level sub-catchment for years 2019-2020. The model is able to represent two quite different winter soil temperatures – snowy 2018/2019 and mild 2019/2020.

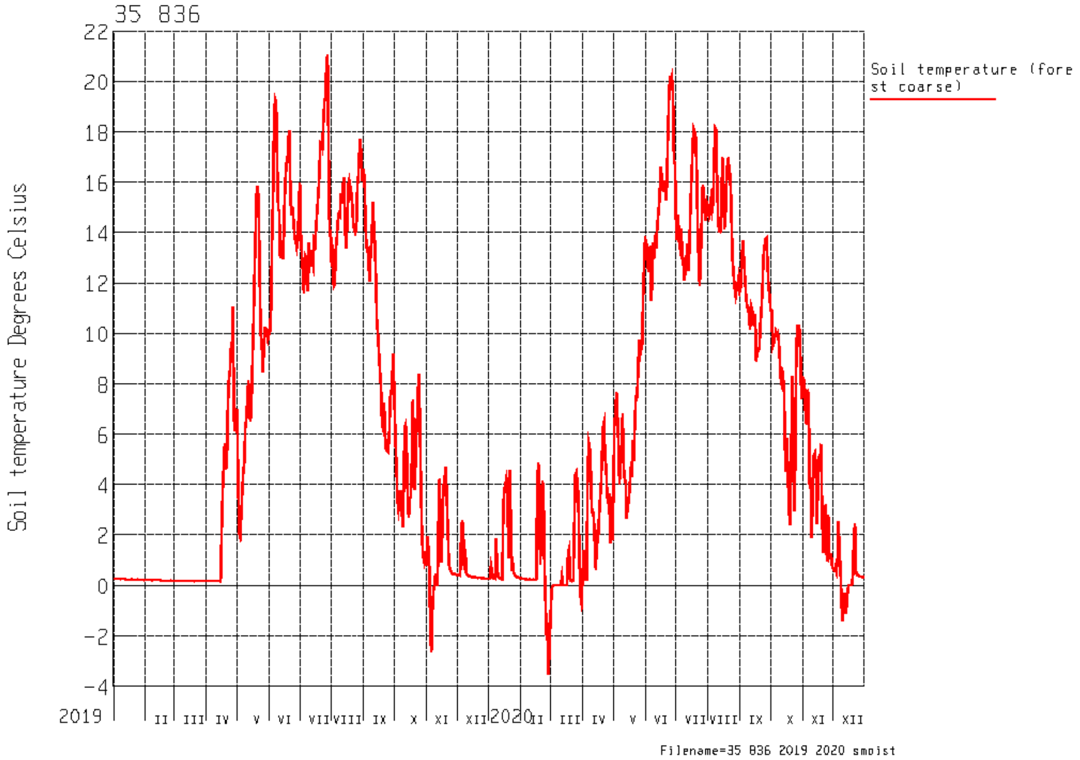


Figure 2. Soil temperature simulation for one 3rd level sub-catchment for years 2019-2020.

We have added the following sentence to the manuscript:

Ln 183-184 Soil temperature is simulated based on simulation of the energy flux between air, snow and soil layers, and distribution of energy to freeze the soil frost or to change soil temperature in the soil layers.

L112-115 – Please provide some additional description of the Vemala conceptual model. After reading this text multiple times, it is still not entirely clear to me how the model represents the landscape. Is a watershed built up of “small brook catchments” or is some other approach used? I presume the model is semi-distributed as opposed to grid based? Having this type of background information would be quite useful to other modelers attempting to work at the same scale as Vemala.

Answer: Thank you for this comment. An example of a map including 3rd level and small (4th level) brook sub-catchments can be added to supplementary materials for clarity. The model is semi-distributed and a better overall description of WSFS-Vemala system should be added below the 2 Model description section.
Over the whole Finland there are about 200 000 sub-catchments which are the simulation units of the model. These sub-catchments of Vemala represent an additional (4th) level of detail, created as a subdivision of the existing 3rd level sub-catchments dataset (https://metadata.ymparisto.fi/dataset/{44394B13-85D7-4998-BD06-8ADC77C7455C}). In Vantaanjoki, there are 48 3rd level sub-catchments split into 989 small (4th level) brook catchments of average size 148ha, excluding lake catchments.
Vemala simulates 40 different land-use/soil type combinations based on national soil and land cover datasets (Lilja et al. 2009 https://urn.fi/URN:ISBN:978-952-487-252-2; Syke 2012 : https://metadata.ymparisto.fi/dataset/{66D9A881-EE3C-42AD-9416-014EA6B84D23}). Runoff is simulated separately for each combination at the 3rd level subcatchment scale (Kolhinen et al., 2026 https://doi.org/10.1016/j.jhydrol.2025.134650) and then used at the small brook subcatchment scale.

We added a more detailed description of the model to the Model description section and a figure in the Appendix (Fig. A1):
Ln 113-120: A semi-distributed process-based hydrological model (WSFS: Watershed Simulation and Forecasting System; Kolhinen et al., 2026), is included in Vemala (Fig. 1). The spatial simulation unit in runoff simulations is a sub-catchment, called third level sub-catchment, with a mean size of 60 km^2 (Catchment area dataset, Syke, Fig. A1). For surface water routing and water quality simulations, these sub-catchments are divided into a fourth level of detail (Fig. A1) to take into account the variation of characteristics affecting hydrology and nutrient and carbon loading. Small brook or fourth level sub-catchments are defined by a river width greater than 2m (Metadata: Shoreline10 from Syke and National Land Survey of Finland, NLS). The median size of the catchments in Vemala is 0.8km^2 with 80% of the catchments smaller than 2km^2 (WSFS-Vemala dataset, Syke).

Ln 124-127; Vemala simulates 40 different land-use/soil type combinations based on national soil and land cover datasets (Finnish Soil Database, Natural Resources Institute Finland & Geological Survey of Finland, 2023 and Corine land cover 2018 dataset, Syke 2018).

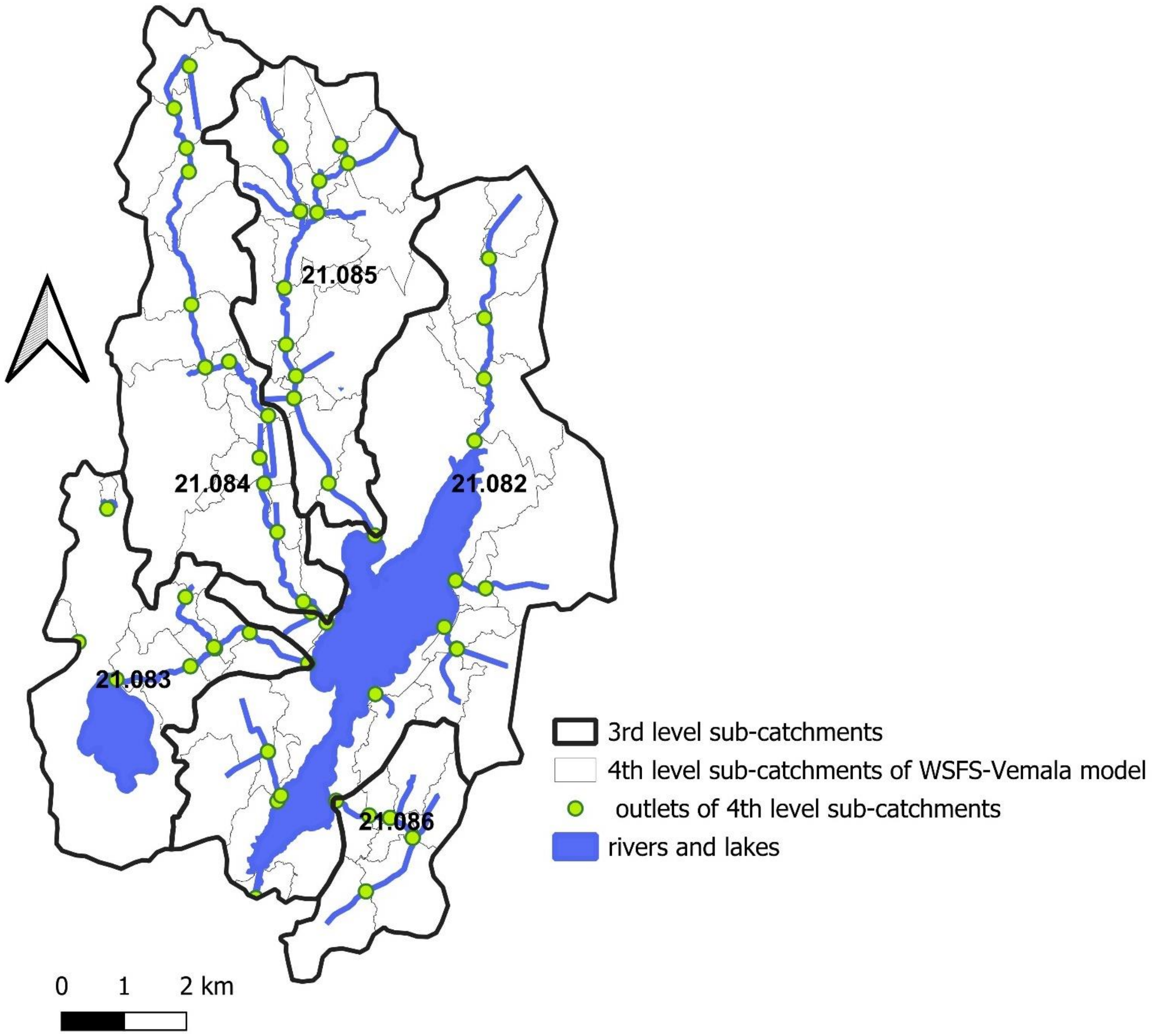


Figure A1: 3rd and 4th level sub-catchments including rivers and lakes (blue) and the outlets of the 4th level sub-catchments (green dots) describing the river routing in Tuusulanjärvi catchment. (Source: WSFS-Vemala, Syke).

L125 – Again, some more detail about the model structure would be appreciated. The authors note that carbon concentrations change with depth in both peat and mineral soils. Is this phenomenon represented in Vemala through different carbon contents in the unsaturated soil layer and groundwater layer?

Answer: Carbon content is related to the depth according to the following equation adopted from Wen et al. 2019 (https://hess.copernicus.org/articles/24/945/2020/):

$$C_d(z) = C_0 e^{\left(-\frac{z}{coef}\right)}$$

where C_d is SOC at z, the depth below the surface; C_0 is the SOC level at the ground level and coef reflects the decline with depth, set here to a value of 0.3 for mineral soils. For peat soils coef=1.0 determining that there is no decline of SOC with depth. Thus, simulated SOC content is different in unsaturated soil layer and groundwater layer for mineral soils.

We have added a more detailed description of the TOC terrestrial model in the model description section and in Appendix B:

Ln 172-175:Methodology of the calculation of the initial C content in agricultural soils is given in Appendix B and is based on field parcel data from soil laboratory Viljavuuspalvelu oy which contains soil organic matter

(SOM) class (vm - low, m – medium, rm –rich, erm – very rich, mm – mull, Tm – peat soil). Initial C content in mineral forest soils is based on Finnish multisource national forest inventory data (Mäkisara et al., 2016). Simulated initial C content decreases exponentially with the soil layer depth in mineral soils (Wen et al. 2019), whereas in peat soils carbon content is constant with depth.

Appendix B

Calculation of the initial C content in soils

The C content calculation is performed at the national scale since the WSFS-Vemala TOC model is applied at this scale. The C content calculation in mineral agricultural soils is based on field parcel data from Soil testing laboratory Viljavuuspalvelu oy which contains soil organic matter (SOM) class (vm - low, m – medium, rm –rich, erm – very rich, mm – mull, Tm – peat soil). Only the 5 first classes are for mineral soil and were used in creating C content for mineral soils. Only 40% of fields have observations, so the mean C content for 3rd level subcatchments for clay or for coarse soils was extrapolated based only on 40% of observed data.

Table B1. Soil organic matter classes according to soil type(mineral/organic) and soil organic matter percentage (Lemola et al. 2018)

Organic matter, %	Organic matter class	Symbol
< 3	low	vm
3-5,9	medium	m
6-11,9	rich	rm
12-19,9	very rich	erm
20-39,9	mull	Mm
> 40	peat soil	Tm

The methodology was as follow:

1) the mean SOM content in % for the top soil for each class was obtained from LUKE report (Lemola et al., 2018, see the Table B1)

2) the area of agricultural clay soils and coarse soils for each 3rd level subcatchment was estimated,

3) the mean SOM content for clay and coarse soils separately was estimated, and then weighted mean SOM content for 3rd level subcatchments was estimated,

4) SOM content 1000 kg ha-1 is calculated using bulk density of the mineral soils and SOM content,

5) it is assumed that SOM content in the 0-1 m deep soil (Mg ha-1) is decreasing exponentially with the layer depth. The van Bemmelen factor of 0.58 was used to convert SOM data to SOC. Corresponding values for Vantaanjoki catchment are 180-200 Mg C/ha.

L132- How are annual litter inputs added to the system? Are inputs prorated across every day of the year or is another approach used?

Answer: The daily litter fall inputs are calculated from annual litter fall and are added to the soils during autumn months.

A sentence has been added to the Model description section:

Ln 177-179: Annual litter fall data for forests is obtained from PREBAS model results for 16x16m grids for all Finland, and is added to the soils in Vemala TOC model as daily input during autumn months.

L135 – I presume TOC produced in the leaching zone can percolate vertically to groundwater?

Answer: Yes, it should be added to the manuscript that TOC produced in the unsaturated layer is percolated to the groundwater layer by percolated water, which is simulated in the hydrological model for each land use/soil texture class separately. Percolation of TOC is an important component of TOC balance in groundwater layer as it is one of the processes increasing TOC content in the groundwater layer, in contrast to the unsaturated soil layer, where litter fall is increasing OC content annually. However, simulation of *percolation of TOC has caused also challenges in different soil textures, especially for coarse soils, where percolation is high due to the high hydraulic conductivity. In such soil DOC storage can be quickly emptied during the intensive snow melt or heavy autumn rainfall periods, when there are high amounts of percolation. In such cases the model simulated very low river TOC concentrations due to the probably overestimated TOC percolation. Further discussion and developments are needed to better simulate TOC percolation in different soil textures in more realistic way.*

A sentence has been added to the Model description section:

Ln 163-165: DOC produced in the unsaturated layer is percolated to the groundwater layer. Percolation is simulated in the hydrological model for each combination of land use/soil type class separately.

L145-148 – please provide numeric soil organic matter (SOM) levels for the SOM classification presented here; this information could be in the Supplementary Information

Answer: The C content calculation is performed at the national scale since the WSFS-Vemala TOC model is applied at this scale. The C content calculation in mineral agricultural soils is based on field parcel data from Soil testing laboratory Viljavuuspalvelu oy which contains soil organic matter (SOM) class (vm - low, m – medium, rm –rich, erm – very rich, mm – mull, Tm – peat soil). Only the 5 first classes are for mineral soil and was used in creating C content for mineral soils. Only 40% of fields have observations, so the mean C content for 3rd level subcatchments for clay or for coarse soils was extrapolated based only on 40% of observed data.

Table 2. *Soil organic matter classes according to soil type (mineral/organic) and soil organic matter percentage.*

Orgaaninen aines, % ***Organic matter, %***	**Multavuusluokka** ***Organic matter class***	**Lyhenne** ***Symbol***
< 3	vähämultainen *low*	vm
3–5,9	multava *medium*	m
6–11,9	runsasmultainen *rich*	rm
12–19,9	erittäin runsasmultainen *very rich*	erm
20–39,9	multamaa *mull*	Mm
> 40	turvemaa *peat soil*	Tm

The methodology was as follow:

1) the mean SOM content in % for the top soil for each class was obtained from LUKE report (Lemola et al., 2018, see the Table 2)

2) the area of agricultural clay soils and coarse soils for each 3rd level subcatchment was estimated,

3) the mean SOM content for clay and coarse soils separately was estimated, and then weighted mean SOM content for 3rd level subcatchments was estimated,

4) SOM content 1000 kg ha^{-1} is calculated using bulk density of the mineral soils and SOM content,

5) it is assumed that SOM content in the 0-1 m deep soil (1000 kg ha^{-1}) is decreasing exponentially with the layer depth. Figure shows the national scale estimates of the OC content in the Finnish agricultural soils used as initial OC inputs to the Vemala TOC model. Corresponding values for Vantaanjoki catchment are 180-200 kg C/ha. This information can be added to the Supplementary material.

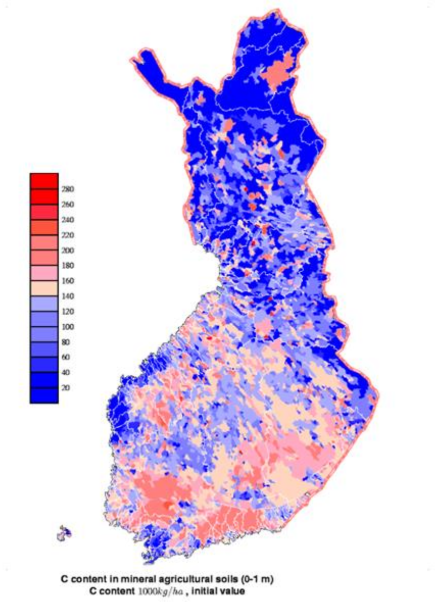


Figure. Initial value of OC content in a) mineral agricultural soils (0-1 m) based on SOM class data (WSFS-Vemala)

Appendix B has been added to the manuscript.

L156 – how were the values in Table 2 obtained? Are they directly from Korka-Niemi (2001) or did the authors do the calibration themselves?

Answer: The title of Table 2 should be updated stating the definition of the mean of the alkalinity per soil type as provided by Korkka-Niemi (2001) and rephrasing the sentence: "The range of alkalinities per soil types was defined from Korkka-Niemi (2001) measurements of well waters in Finland using the mean values per soil type with a range of ±20% (Table 2)." to "The range of alkalinities per soil types was defined using the mean values measured by Korkka-Niemi (2001) from well waters in Finland and a variation of ±20% from the mean values." The terrestrial loading of alkalinity was then calibrated within this range per soil type using the alkalinity observations available in the aquatic ecosystem.

The sentence has been modified in the manuscript:

Ln 191-193 The range of alkalinities per soil types was defined using the mean values measured by Korkka-Niemi (2001) from well waters in Finland and a variation of ±20% from the mean values (Table 1).

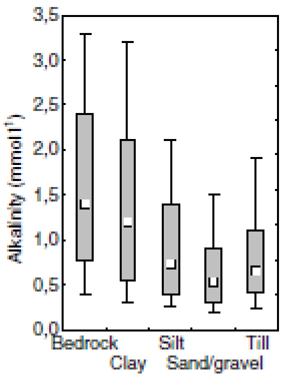


Figure from Korkka-Niemi (2001).

L165 – presumably a triprotic model is being used for DOC dissociation? Please identify which one. From statements made later in the manuscript, I presume it is the model of Hruska et al. (2003 https://pubmed.ncbi.nlm.nih.gov/12775041/)?

Answer: The triptotic model used for the DOC dissociation refers to Hruska et al., 2003 work. A reference to Hruska et al., (2003) should be added to ln 165. Hruska's model is described in more details on ln 181 but a reference should be added earlier in the manuscript.
The reference to Hruska's paper has been added to the sentence:
Ln 206-208: The new state variables are TIC, alkalinity and pH. TIC represents the sum of three fractions (CO2, HCO3-, CO32-), TOC the sum of four fractions (DOCH3, DOCH2-, DOCH2- and DOC3-; Hruska et al., 2003), and pH the hydrogen ions H+ (Eq. (4)):

L172 – phytoplankton settling in one of a number of processes that can lead to TOC sedimentation. Geochemical coagulation may be important in some circumstances. If phytoplankton settling in the only TOC process simulated in Vemala, please note that it may not be the only process operating in reality.

Answer: Thank you for this comment. A sentence should be added in the manuscript that although phytoplankton settling is the only TOC process in the model feeding the sediments with TOC, it is not the only process occurring in the environment. The importance of iron in TOC sedimentation has been recognised in Finland (Heikkinen et al., 2022 https://doi.org/10.1016/j.scitotenv.2021.150256*) and should be further studied before being added to the model at a later stage.*
A sentence has been added to the Model description section:
Ln 215-216: Other processes linked to DOC sedimentation are omitted from the model at this point.

Equations 3, 5 – please consider different left hand side terms for equations 3 and 5. It is a bit confusing to have them both described as "Alk" (I know there is the subscript "n" in equation 3 but that does not help terribly much)

Answer: In equation 3 we defined the alkalinity load per soil type. The text describing the equation should be amended to add the term load to the alkalinity in ln 154 as well as the units used. Equation 5 describes the total alkalinity in the water as a concentration, units in mmol L-1, should be added to the ln 189.
The alkalinity terms have been clarified:
Ln 188-191: The alkalinity load per soil type (Alkn,load, mol d-1) is calibrated with runoff from each soil type (qrn) in the catchment area (Eq. (3)):

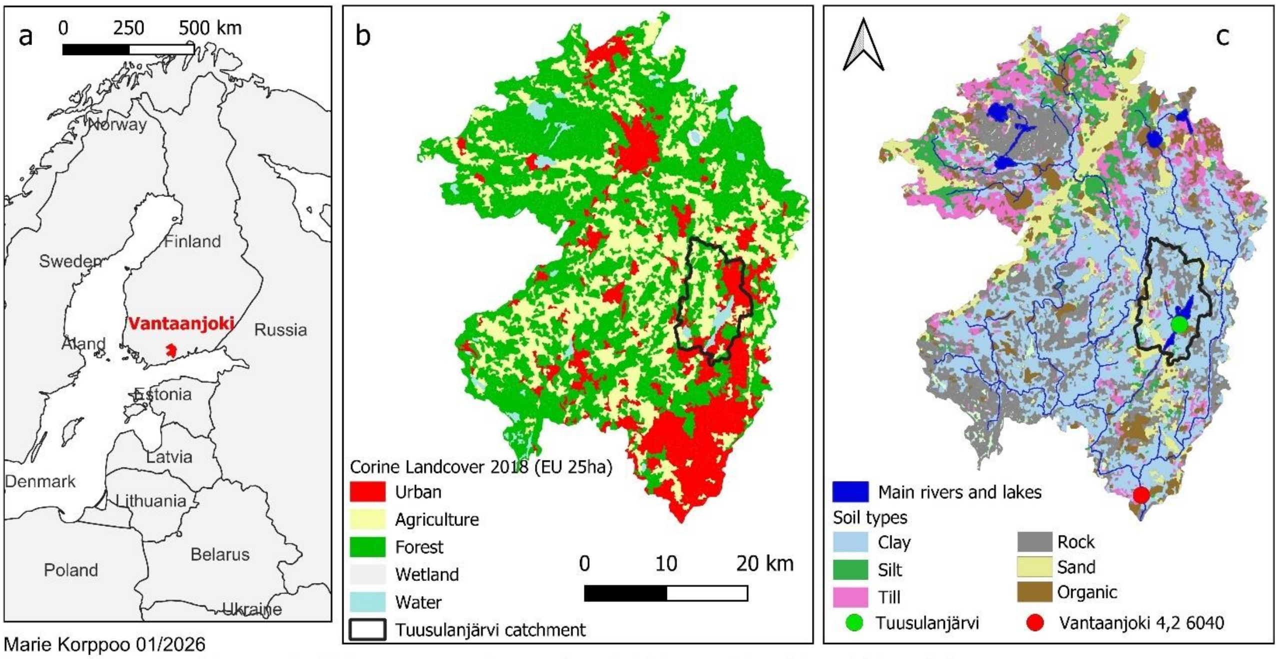
$$Alk_{n,load} = \gamma_n * qr_n^{\varepsilon_n} \qquad (3)$$

with γn and εn the alkalinity coefficients for each soil type (n).

Ln 234-236: With α_1 and α_2 the respective proportion of HCO_3^- and CO_3^{2-} ions in TIC (mmol L^{-1}) and β1, β2 and β3 the respective proportion of $DOCH_2^-$, $DOCH^{2-}$ and DOC^{3-} ions in TOC (mmol L^{-1}). OH^- (mmol L^{-1}) and H^+ (mmol L^{-1}) are the concentrations of hydroxide ions and protons and Alk refers to alkalinity (mmol L^{-1}).

Figures 3 b and c should be bigger if they are to be useful

Answer: We agree with this statement. We tried to limit the number/size of the figures in the manuscript. We can provide larger maps for the final article or add more detailed maps including 3rd level and 4th level subcatchments in the supplementary materials for added clarity.
We rearranged Figure 3 and it became figure 2 to increase the size of Figure 2b and 2c



Marie Korppoo 01/2026
Source: b- Corine Land Cover - Finnish Environment Institute (Syke), LUKE, MAVI, LIVI, DVV, EU, NLS 01/2017
Source: c- Soil types: Geological Survey of Finland (GTK) and Natural Resources Institute Finland (LUKE)

Figure 2: a- Vantaanjoki catchment in red in the European map; b- land cover (Corine Land Cover, 2018) in Vantaanjoki catchment; c- soil types in Vantaanjoki catchment

Lines 295-300 – please provide more detail as to how flows at the Tuusulanjarvi outflow were estimated.
Figure 4 – consider a separate plot for the Tuusulanjarvi outflow

Answer: The outflow of Tuusulanjärvi is regulated and observed. We can modify Figure 4b to present observed outflow.

We changed Figure 4b to present the observed outflow.

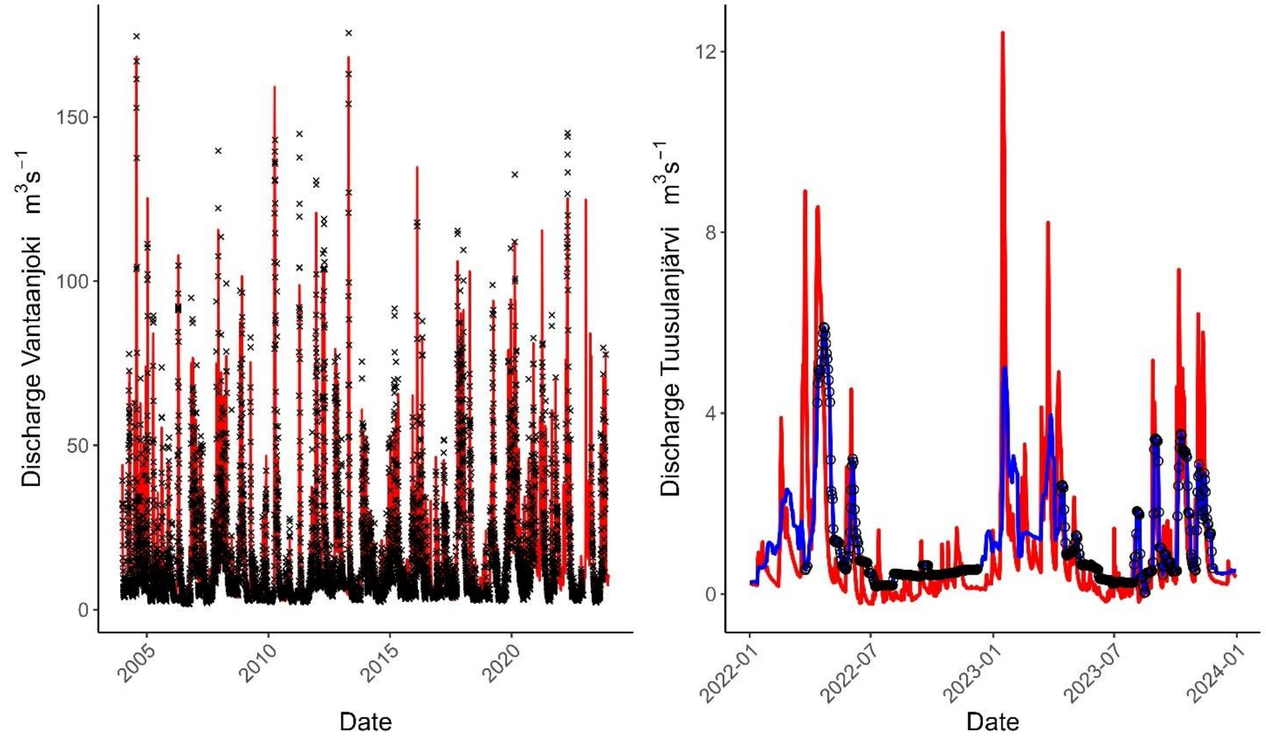


Figure 4. a- Simulated (red line) and observed (black cross) discharges at Vantaanjoki outlet for calibration period 2004 – 2023. B- Simulated inflow (red line). Observed outflow (black circle) and simulated outflow (blue line) of Tuusulanjärvi for calibration period 2022 – 2023.

Table 3 – please present NSE for concentrations, not loads in all cases.

Answer: We can provide the statistical analysis for concentrations rather than for loads for all points. Table 4 has been added to the manuscript as well as the description of the results in the results' section.

Line 485 – could the authors present any connection to PREBAS here? Is PREBAS simulating higher litter fall inputs over the study period and could tis account for the increase in DOC? I would appreciate it if the authors could also comment on peat soil drainage as a factor behind increasing TOC. I was under the impression there was little or no new drainage of Finnish peat soils?

Answer: Results of the forest growth model PREBAS were available for Vemala TOC modelling only for period 2017-2025, and for future scenarios. Therefore, literature values were used for the long-term tree biomass increase estimates for the Vemala TOC modelling. Main reference for that is Lehtonen and Heikkinen, 2016 (https://cdnsciencepub.com/doi/10.1139/cjfr-2015-0171). According to the Yasso07 model simulations there is about a 10% increase in total litter fall input to the soils. This information and reference can be added to the manuscript.

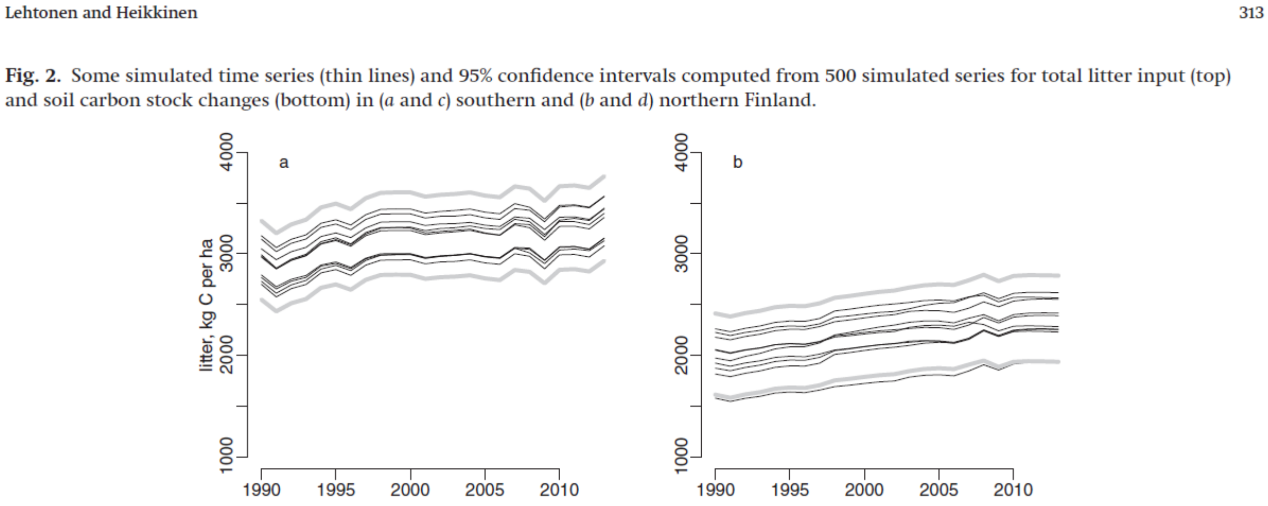

Lehtonen and Heikkinen 313

Fig. 2. Some simulated time series (thin lines) and 95% confidence intervals computed from 500 simulated series for total litter input (top) and soil carbon stock changes (bottom) in (*a* and *c*) southern and (*b* and *d*) northern Finland.

We agree with Reviewer 1 that there is practically no new peatland drainage performed in Finland. However, remedial drainage is still performed, and peatlands are managed for forest harvesting, which contribute to increased TOC leaching. We believe that already performed peatland drainage has possibly long-term effect on increasing TOC trends. Peatland drainage is causing higher concentrations in receiving streams compared to undrained peatlands, and possibly steeper increases over past decades from drained than undrained peatlands (Nieminen et al. 2021, https://www.sciencedirect.com/science/article/pii/S0048969721002163). This study is among the first which indicated that peatland drainage may have a long-term legacy effect on TOC concentrations. The results of this study also supported earlier findings in that the increase in forest cover and biomass ("greening effect") that has occurred in northern areas during the last decades may have contributed to increasing TOC trends.
Finer et al. 2021, (https://www.sciencedirect.com/science/article/pii/S0048969720376294) is writing – 'drainage for forestry has been shown to contribute to the increasing trends of OC and N fluxes in large river basins (Asmala et al., 2019; Räike et al., 2020). Drainage increases decomposition of surface peat and mineralization of organic matter as well as soil erosion, and therefore also the export of elements in both dissolved and particulate forms (Ahtiainen and Huttunen, 1999). These drainage impacts

have been suggested to last – or even increase – over several decades after drainage (Nieminen et al., 2017, 2018).'
Some sentences summarizing the peatland drainage effect on TOC increasing trend and references can be added to the manuscript.
Few sentences have been added to the manuscript to explain the increase in TOC leaching:
Ln 567-573: According to Räike et al. (2024), the main reasons for increasing trends of TOC transport to waterbodies are decrease in acid sulphate deposition, increase in temperature, runoff, tree biomass and management of drained peatlands. According to the Yasso07 model simulations, total litter fall input to the forest soils has increased by about 10% since 1990's (Lehtonen and Heikkinen, 2016). Although, there is practically no new peatland drainage being carried out in Finland; remedial drainage is still conducted, and previously drained peatlands continue to be managed for forestry, both of which contribute to increased TOC leaching. Already performed peatland drainage has possibly a long-term effect on increasing TOC trends (Nieminen et al., 2021).

Line 495 – What are the consequences, if any, of simulating alkalinity as a conservative tracer? It seems to imply that there will be no evasion of CO2 to the atmosphere but perhaps I misunderstand.

Answer: Even though alkalinity is simulated as a tracer, the TIC concentrations are not and are affected by CO2 evasion to the atmosphere as well as mineralisation of TOC and primary production in the water column. Alkalinity is used to calibrate the terrestrial loading of TIC to the river/lake network and for the simulation of pH in relation with TIC and TOC. The definition of pH then leads to the calculation of the part of TIC that is dissolved as CO2 in the water and thus available for exchange with the atmosphere. Processes like photosynthesis, mineralisation, nitrification and denitrification in the water column affect alkalinity (e.g. Marescaux et al., 2020, https://doi.org/10.5194/hess-24-2379-2020) and thus would affect the pH simulations in the water. The importance of these processes on the overall alkalinity model would however be limited with findings from Marescaux et al. (2020) showing a contribution to alkalinity export from instream processes of less than 4%. At this stage of the model development, it is thus justified to simulate Alkalinity in the river network as a tracer.
This explanation has been added to the manuscript:
Ln 587-593: The importance of these processes on the overall alkalinity model would however be limited with findings from Marescaux et al. (2020) showing a contribution to alkalinity export from instream processes of less than 4%. At this stage of the model development, it is thus justified to simulate alkalinity in the river network as a tracer. Vemala must rely on variables with national coverage for its development at the national scale, however observed TIC dataset (VESLA, Syke) is very limited. Thus, alkalinity that is well correlated with TIC and is supported by comprehensive monitoring data across Finland is a good proxy to simulate TIC in Finland.

Figure A3 – In my opinion, Figure A3 is more convincing than Figure 7, why not switch these figures between the main text and SI?

Answer: We would have liked to present both figures in the main text but for conciseness we placed the Figure A3 in the supplement. Figure 7 was needed for the validation of the lake processes and subsequent lake carbon budget discussed in the manuscript. Both figures could be kept in the main section of the manuscript.
Figure A3 has been moved to the main text as Figure 8

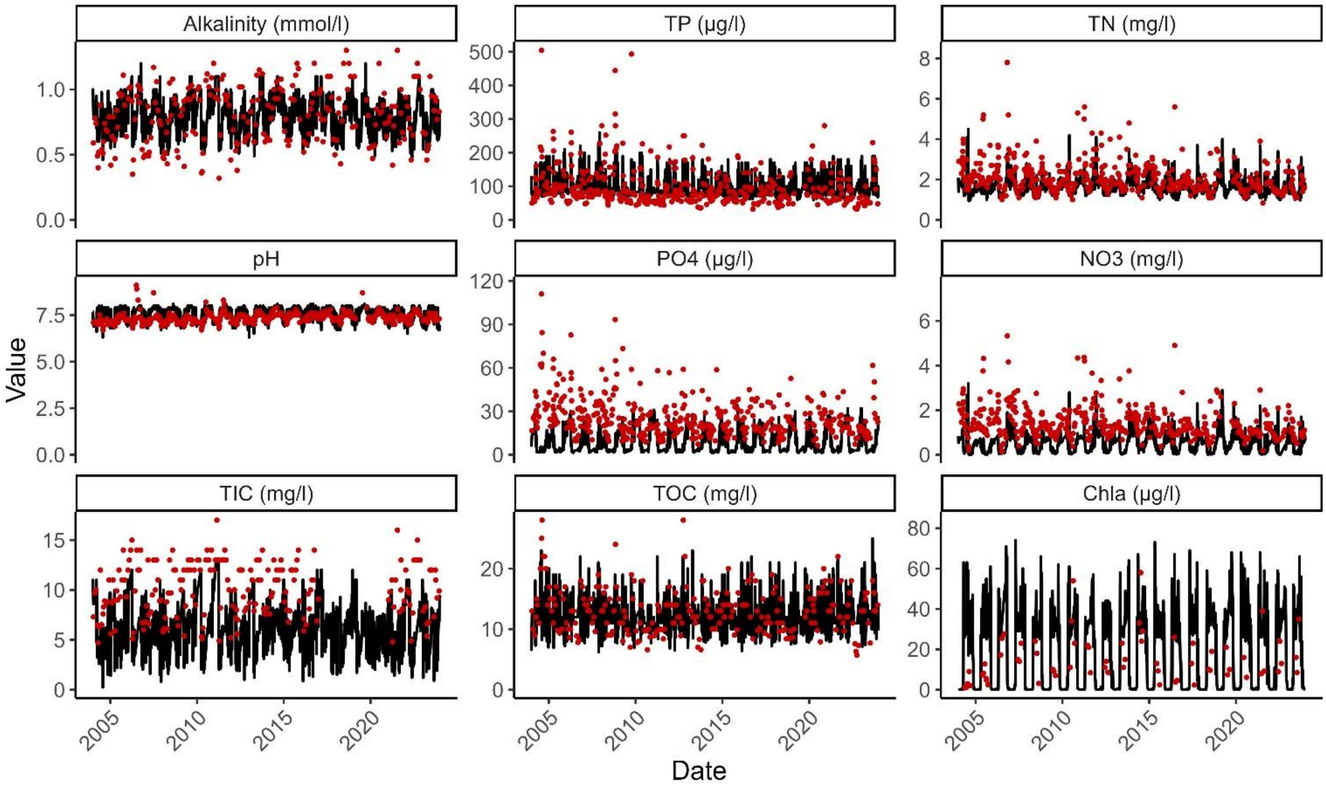


Figure 8: Water quality in Vantaanjoki 4.2 6040 over the period 2004-2023 with observations (red dots) and simulations (black line) for alkalinity (mmol L^{-1}), pH, total inorganic carbon (TIC, mg L^{-1}), total phosphorus (TP, µg L^{-1}), phosphate (PO_4, µg L^{-1}), total organic carbon (TOC, mg L^{-1}), total nitrogen (TN, mg L^{-1}), nitrate (NO_3, mg L^{-1}) and phytoplankton (Chla, µg L^{-1}).

Citation: https://doi.org/10.5194/egusphere-2025-3255-RC1

Review of 'Simulating carbon fluxes in boreal catchments: WSFS-Vemala model development and key insights '

Marie Korppoo[1], Inese Huttunen[1], Markus Huttunen[1], Maiju Narikka[1], Jari Silander[2], Tom Jilbert[3], Martin Forsius[4], Pirkko Kortelainen[4], Niina Kotamäki[5], Cintia Uvo[5,6], Anna-Kaisa Ronkanen[5]

Reviewer 2:

This work quantitatively predicts the dynamics of carbon flux at the scale of the river-lake aquatic ecosystem. The Vemala model was integrated into a hydrological model to simulate carbon flux driven by water flows. The evidence strongly supports their conclusions, and the findings hold great potential for providing new insights into the carbon cycle in river-lake systems.

Answer: We thank reviewer 2 for the positive comment.

The reviewers only raised minor concerns for the authors to consider in the revised version:

1. Details regarding observation data collection are insufficient, such as the methods for collecting water/soil samples and measuring target parameters.

Answer: Thank you for this comment. We agree that the description of observational data should be clarified in the manuscript. The WSFS-Vemala model is developed and applied using long-term hydrological and water quality observations from national monitoring programmes maintained by the Finnish Environment Institute (Syke). Discharge data are obtained from the HYDRO dataset, which consists of continuous flow measurements from gauging stations across Finland. Water quality data, including total organic carbon, total inorganic carbon, alkalinity, pH, nitrogen, and phosphorus, are obtained from the VESLA dataset, which is based on routine grab sampling and laboratory analyses following standardized national protocols. Sampling frequency typically ranges from monthly to seasonal, depending on site and variable.

These observational datasets are used for model calibration and validation at the national scale. In addition, the targeted sampling campaign conducted in 2023 at Lake Tuusulanjärvi was used to support this study particularly. The sampling procedures and analytical methods for these measurements are described in detail in lines 290–292.

We will revise the Methods section accordingly to improve the clarity of the observational data description. As the current Methods section is already relatively long and detailed, we will also reconsider its overall structure and assess whether some technical details can be moved to Supplementary Materials. This will allow us to keep the main manuscript focused while still providing full methodological transparency. At the same time, we will ensure that all essential information regarding the observational datasets, sampling approaches, and analytical methods is clearly described in the main text.
The Monitoring data section has been modified:

Ln 323-329: The WSFS-Vemala model is developed and applied using long-term hydrological and water quality observations from national monitoring programmes maintained by the Finnish Environment Institute (Syke). Discharge data are obtained from the HYDRO dataset (Syke), which consists of continuous flow measurements from gauging stations across Finland. Water quality data, including total organic carbon, total inorganic carbon, alkalinity, pH, nitrogen, phosphorus and phytoplankton are obtained from the VESLA dataset (Syke), which is based on routine grab sampling and laboratory analyses following standardized national protocols. Sampling frequency typically ranges from monthly to seasonal, depending on site and variable.

And the references to the dataset have been added to the reference list:
HYDRO dataset / Syke, https://metadata.ymparisto.fi/dataset/%7B86FC3188-6796-4C79-AC58-8DBC7B568827%7D

VESLA dataset / Syke, https://ckan.ymparisto.fi/dataset/%7BB1444E19-0F36-49F5-A849-01A3D2083A11%7D

2. Only a single reference is provided for Eqs. 13–14 in the text. Additional references should be added to solidify the selection of coefficients.

Answer: Observations from the Vesla data management system of the Finnish Environment Institute (Syke) have been used. A reference to the database will be added to these equations.
A reference has been added to the equation:
Ln 340: (VESLA dataset, Syke).

3. Time series plots comparing simulated and observed TOC/TIC are missing in Sections 4.1.2–4.1.3, which undermines the validity of the NSE values presented in Table 3.

Answer: We agree that a reference to the appropriate figure already in the manuscript presenting TIC/TOC time series at the outlet of Vantaanjoki (suppl figure 3) is missing from this section 4.1.2. and 4.1.3. We will revise it accordingly.

Figure 8 has been added to the main part of the text.

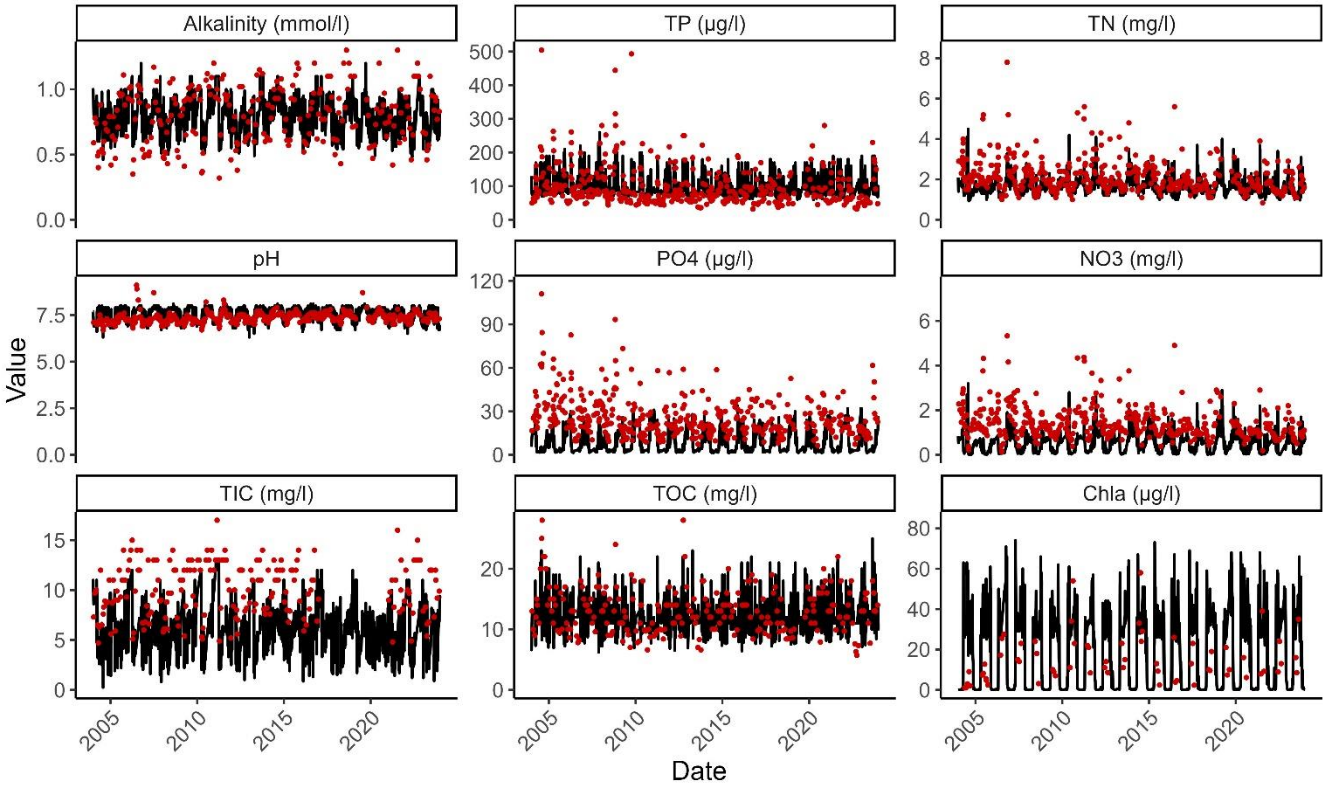


Figure 8: Water quality in Vantaanjoki 4.2 6040 over the period 2004-2023 with observations (red dots) and simulations (black line) for alkalinity (mmol L^{-1}), pH, total inorganic carbon (TIC, mg L^{-1}), total phosphorus (TP, µg L^{-1}), phosphate (PO_4, µg L^{-1}), total organic carbon (TOC, mg L^{-1}), total nitrogen (TN, mg L^{-1}), nitrate (NO_3, mg L^{-1}) and phytoplankton (Chla, µg L^{-1}).

4. The limitations of the modeling approach require further discussion, such as the underlying assumptions of the dozens of sub-models.

Answer: We agree that clarifying the assumptions and limitations is important. In the revised manuscript, we will discuss the need for further development of the model towards a combined inorganic/organic carbon soil model to take into account mineralisation in the soil as a source of inorganic carbon. Presently, the model simulates the inorganic carbon loading associated with rock weathering using alkalinity and soil types rather than accounting also for mineralisation of organic carbon in the soil. This model is seen as a first step towards a more integrated inorganic and organic carbon terrestrial model capable to simulate GHG from soils and TIC leaching from mineralisation and rock weathering. The lack of TIC data available for model development is the reason for the development of a separate TIC terrestrial sub-model. The strength of this sub-model is to use alkalinity data available at the national scale. Another limitation of the model is its applicability to areas dominated by carbonate soils. In boreal environments with rare carbonate soils, most of TIC and TOC are under a dissolved form. For the application of this model in carbonate soils, sedimentation processes of carbon should be added to the model.

The aim of this modelling approach is not a single lake but national scale modelling of TIC and TOC loading to the aquatic environment and to the Baltic Sea and to provide GHG from aquatic environments to be *added to national estimates of GHG. We therefore focused our modelling development to the most important processes affecting TIC and TOC in boreal environments at the Finnish scale.*

We have added details on the model structure as well as justified the model's limitations through the text using the comments of reviewer 1. We have also added more specific limitations in the conclusion of the manuscript to better define the possible applications of this model as well as the future developments needed.

Ln 681-682: This model is especially relevant in boreal catchments where TIC and TOC are mostly under a dissolved form.

Ln 690-692: Future development efforts for Vemala model should aim at linking the TOC and TIC terrestrial sub-models to represent TIC leaching from rock weathering and mineralisation in soils as well as CO_2 emissions from land.

Citation: https://doi.org/10.5194/egusphere-2025-3255-RC2