

Climate change impacts on dissolved organic carbon and total suspended solids in Alpine streams and rivers

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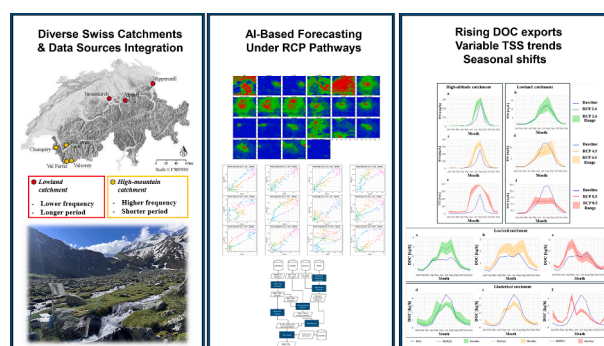
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HIGHLIGHTS

- Machine learning predicts DOC and TSS across Alpine catchments.
- DOC exports projected to rise ~50 % in high-mountain and ~15 % in lowland.
- TSS increases in glacierised basins but decreases in most lowland streams.
- Seasonal DOC load peaks shift earlier under future climate scenarios.
- Discharge is the dominant driver of DOC change, not land cover.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is altering hydrology, land cover, and biogeochemistry in Alpine river systems, yet predictive understanding of dissolved organic carbon (DOC) and total suspended solids (TSS), across glacierised and lowland catchments remains limited. This knowledge gap constrains our ability to forecast impacts on carbon cycling and sediment management. We present a data-driven predictive model for Swiss streams from diverse catchments, spanning glacierised high-mountain basins to lowland agricultural and forested systems. The machine learning framework incorporates discharge, water quality, and land use and land cover changes to predict DOC and TSS, with high accuracy (RMSE=14% of standard deviation for DOC) following validation of the best performing algorithm. While its reliance on routinely measured parameters makes it adaptable for near real-time forecasting, the model was designed for climate change scenario analysis. Projections indicate that by 2090, under RCP8.5, DOC exports will rise by ~50% in high-mountain catchments and ~15% in lowland systems, primarily driven by discharge, not by land cover change. TSS responses vary seasonally and by catchment, with increases in many glacierised basins and decreases in most lowland streams. Seasonal DOC load peaks are projected to occur earlier in the year. By harmonising diverse datasets and quantifying site-specific climate,

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hydrology and land cover interactions, this approach provides a tool for managing carbon and sediment fluxes in rapidly changing Alpine environments.

1. Introduction

Understanding the role of dissolved organic carbon (DOC) within the aquatic carbon cycle is fundamental for quantifying terrestrial–aquatic linkages and predicting how carbon storage and release will evolve under climate and land-use change. DOC is an important intermediary in the carbon cycle (Mattsson et al., 2005). Recent decades have seen an increase in DOC export from soils to inland waters (i.e., “browning”) in boreal-subarctic regions and parts of North America and Europe (Bouchard 1997; Freeman et al. 2001; Hejzlar et al. 2003; Hongve et al. 2004; Liu et al. 2022; Stoddard et al. 2003). This “browning” trend has major ecological and biogeochemical implications, as DOC regulates light availability, microbial respiration, and nutrient dynamics in receiving waters (Fabre et al. 2020).

Several potential drivers for this increase have been suggested, including higher temperatures leading to increased DOC leaching (Freeman et al. 2001; Liu et al. 2022; Rind et al. 1990) and greater runoff (Ledesma et al. 2012). In addition to climate-related factors, long-term declines in acid deposition have increased the solubility and mobility of organic matter, and changes in vegetation cover and microbial activity can enhance DOC production and transport by altering soil organic matter decomposition rates and water flow pathways (Evans et al. 2005; Hruška et al. 2009; Monteith et al. 2007). Large-scale analyses also show that DOC export dynamics are tightly coupled to soil nutrient status and the soil C:N ratio, which serves as a strong predictor of riverine DOC flux across diverse biomes (Aitkenhead and McDowell 2000); another strong predictor of DOC fluxes is basin slope (Ludwig et al. 1996), with steeper slopes typically present in mountainous catchments.

Mountain glaciers worldwide are shrinking due to global warming (Milner et al. 2017), leading to increased vegetation cover (Rumpf et al. 2022) and significant changes in runoff patterns. Glacier runoff carries sediments and DOC; therefore, such changes are anticipated to affect the biogeochemistry of glacier-fed streams. DOC concentrations have been predicted to increase with glacier retreat in some settings (Milner et al. 2017). Recent global-scale modelling work further supports that deglaciation and changing hydrological connectivity are likely to amplify terrestrial DOC export to rivers and coastal waters in coming decades (Nakhavali et al. 2024b). However, limited research has analysed the drivers of DOC export from glacierised catchments (Hood and Scott 2008; Tockner et al. 2002).

The concentration of total suspended solids (TSS) can also affect DOC concentrations through mechanisms such as DOC adsorption (Aufdenkampe et al. 2001). TSS exhibits remarkable spatial and temporal variation and is influenced by runoff, lithology, rainfall patterns, vegetation cover and basin size (Meybeck et al. 2003), all of which affect erosion. Sediment fluxes, as summarised by Zhang et al. (2022b), have been increasing in most cold regions of the world over recent decades, including the Swiss Alps, and further variations in TSS are expected (Moragoda and Cohen 2020), with different land uses and altered runoff regimes causing changes in erosion patterns. Glacierised catchments are anticipated to see a continuous increase in sediment transport, followed by a shift to precipitation-dependent regimes when deglaciation passes a critical point (Zhang et al. 2022b). Projected TSS changes remain highly uncertain also because sediment trapping by reservoirs and run-of-river dams can substantially attenuate TSS export. Dam presence, operation schedules, and sediment management practices can decouple upstream sediment production from downstream transport, leading to over- or underestimation of future sediment fluxes if not explicitly considered (Vörösmarty et al. 2003; Zhang and She 2021). Although a few studies have assessed past trends and future projections in Arctic regions, predictions for glacierised catchments in the European Alps are limited.

This gap is particularly important, as global assessments of riverine carbon fluxes often identify that the largest uncertainties are found in high-latitude and alpine systems (Fabre et al. 2020; Li et al. 2017). Furthermore, a comparison of projected DOC and TSS changes for high-altitude European Alps catchments and lower-altitude catchments within the same region is currently missing.

The amount of carbon exported from terrestrial ecosystems to inland waters is crucial to improve understanding of the global carbon cycle (Battin et al. 2009; Regnier et al. 2013), and recent research is helping to overcome modelling uncertainties and inconsistencies (Liu et al. 2024). Nevertheless, the scarcity of high-resolution, long-term empirical data often leaves process-based models as the primary tool to quantify the magnitude and temporal evolution of DOC flux from soil to rivers at regional and global scales. Mechanistic, process-based models are typically based on comprehensive but complex conceptualisations of the system, making them time- and data-intensive to build and difficult to validate at a local scale. Advanced terrestrial–aquatic coupled models, such as the NICE-BGC system, have demonstrated skill in simulating interannual variations in carbon fluxes across river networks by linking hydrological, biogeochemical, and vegetation processes (Nakayama 2020). Some empirical modelling approaches have been proposed (Boix Canadell et al. 2019; Underwood et al. 2023), leveraging rare datasets with high temporal resolution, while data-driven models for TSS prediction are more common (Bayram et al. 2014) and can be attempted using satellite sensing (Isidro et al. 2018) based on the reflectance properties of sediments. However, the applicability to small rivers is limited by the spatial resolution of non-commercial satellite data (e.g., 10 m x 10 m at best for Sentinel-2). These limitations underline the need for models built from in situ measurements, which resolve fine-scale hydrological variability in small headwater systems.

Based on these premises, this study assesses whether long-term changes in DOC and TSS concentrations can be modelled accurately in multiple streams spanning diverse high-mountain and lowland catchments. Advancements in machine learning, along with demonstrated success in water quality applications (Wai et al. 2022; Zhu et al. 2022), highlight the potential for reliable predictive modelling when sufficiently large datasets are available. The goal of this study was to integrate two large historical datasets from high-mountain and lowland streams to develop a machine learning model capable of predicting DOC and TSS. In Switzerland, various water quality monitoring programs have collected substantial data from a wide range of catchments (Fig. 1), including high-mountain and partially glacierised regions, as well as pre-alpine and lowland areas. Harmonising such datasets and predicting DOC and TSS based on, among others, catchment features and discharge (Q), provided opportunities to understand how DOC and TSS in different streams and rivers may respond to the predicted land use and land cover (LULC) and climate change. Whenever possible based on data temporal frequency, hysteresis analysis was completed first, to understand the relationships between hydrology, DOC and TSS and to inform model design. The final model, which proved to be a *k*-nearest neighbour model, was informed by comprehensive data analysis and, for the high-mountain streams, hysteresis analysis of DOC-Q and TSS-Q patterns. Balancing data collection duration and temporal resolution was required due to the different properties of the two monitoring programmes. Developing such models and unpacking the complex interrelationships among predictors allowed us to quantify how future TSS and DOC concentrations and exports would be impacted by LULC and climate variations, under low (RCP2.6), intermediate (RCP4.5) or high (RCP8.5) emission scenarios.

2. Methods

Fig. 2 presents the methodological framework of this study, which is described in greater detail in the subsequent sections and in the Supplementary Material. Data were compiled from multiple sources (Section 2.1) and pre-processed for various analyses (Section 2.2). Beyond generating specific insights, this process also enabled the identification of the subset of catchments and processed data suitable for model development (Section 2.3) and scenario analysis (Section 2.4).

2.1. Data collection and pre-processing

This study encompasses several catchments in high-altitude and lowland areas of Switzerland (Supplementary Table S14) for a total of 16 stream stations selected for model development following data pre-processing and analysis (Section 2.2.1). The four high-altitude catchments cover a broad range of elevations (1191m–2161 m) and LULCs (dominated by bedrock and loose sediments), with varying glacier coverage (0–18 %), and smaller areas of pastures and forest. The five lowland streams drain a wider range of catchment areas, from 0–1 km²

for the three Alpthal sub-catchments to over 74 km² for the Appenzell station AP. They are dominated by different LULCs, broadly classified as pastures and forests, with NE also including a large proportion of agricultural land. Urban areas do not exceed 2 %. The average annual discharge is $\leq 1 \text{ m}^3/\text{s}$ for all streams aside from VAD (2.3 m³/s) and AP (3.1 m³/s). Average annual DOC is substantially higher for most lowland streams, while annual TSS varies greatly among sites (2–153 mg/L) and is usually higher for high-mountain streams.

The four high-mountain catchments, each with three monitoring stations, are monitored by the METALP monitoring network (<http://metalp.epfl.ch/>). High-frequency sensor data from the METALP stream monitoring network were accessed for the high-mountain streams. All data for the lowland catchments were taken from the Swiss National River Monitoring and Survey Programme (NADUF) data portal (BAFU 2024). Details about the methods of historical data collection and data pre-processing are provided in Supplementary Methods. Spatial data, such as LULC over different periods, as well as geology for the entire Swiss territory, were accessed through the SWECO25 dataset, a raster database at 25 m resolution (Külling et al. 2024). Details on the collection of original datasets and processing of

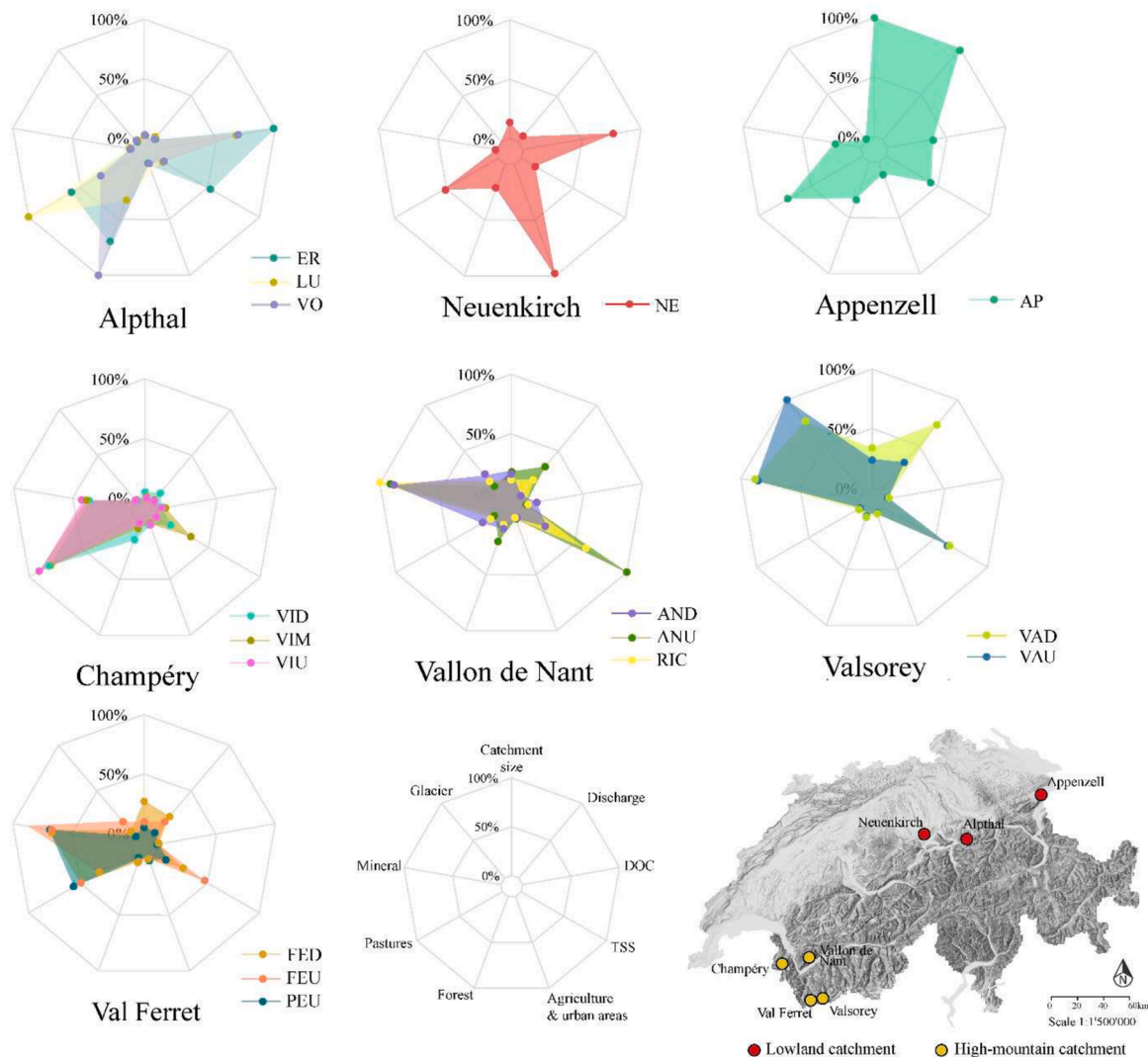


Fig. 1. – Locations and key properties of monitored catchments. In each spider plot legend, the codes of the different monitoring sites for that catchment (e.g., ER, LU and VO for Alpthal) are displayed along with their individual properties. Spider plots show LULC, average DOC, TSS, and discharge for each catchment. Values are normalized (0–100 %) based on maximum dataset values. High-mountain streams in south-west of Switzerland (marked in red) have higher TSS and lower DOC on average. Lowland streams in the northern part of Switzerland (marked in yellow) have more forest and pastures. LULC categories and spatial features are detailed in Methods and Supplementary Tables S1–S8.

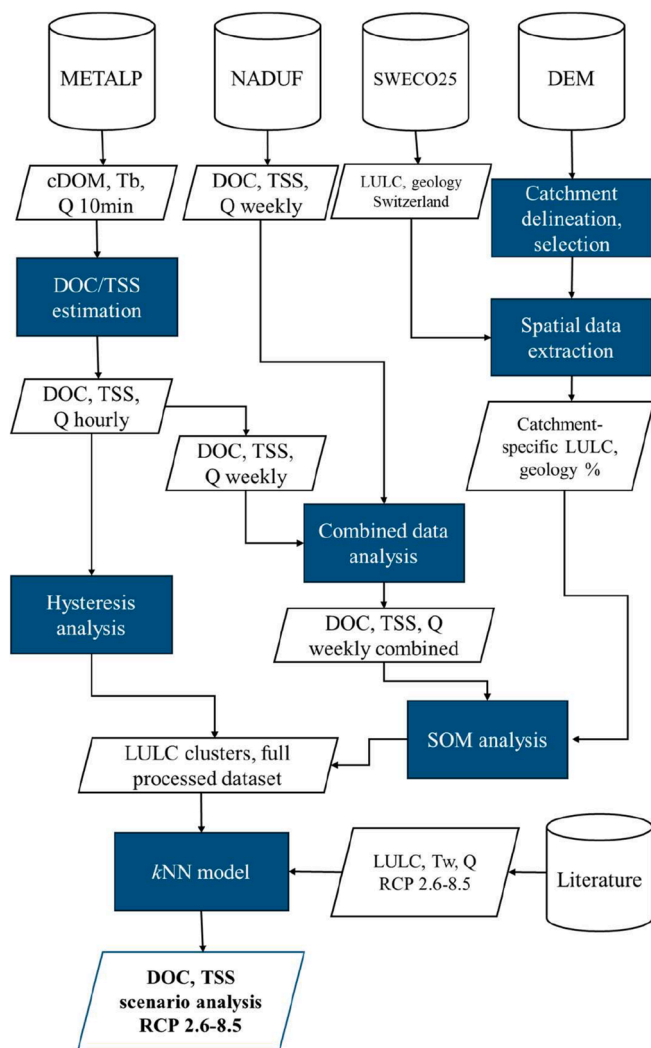


Fig. 2. – Workflow summary, combining spatial datasets, long-term monitoring time series, and hydrological projections. The procedure included delineation of catchments, extraction of land cover and geological variables, harmonisation of high-frequency and low-frequency water quality data, and selection of the stations suitable for model development. This process ensured that only sites with consistent discharge records, reliable spatial data, and robust DOC and TSS estimates were retained for analysis and scenario simulations.

output rasters are available in Külling et al. (2024).

2.2. Data analysis

2.2.1. Spatial data extraction and analysis

SWEQ25 raster layers, which specifically included one layer per individual LULC/geology class indicating presence (1) or absence (0) for that class, were downloaded and imported into QGIS (version 3.28.15). In order to delineate each catchment for feature extraction, a 25 m resolution Digital Elevation Model (DEM) was downloaded from the Federal Office of Topography (Swisstopo 2024) for the entire Swiss territory, with additional 2 m resolution DEM for the areas covering the smaller catchments. These were also imported in QGIS, and the Strahler stream order (Strahler 1957) was generated accordingly. Next, based on geographical coordinates of the monitoring stations, the Upslope Area function was applied to generate raster layers of the related catchment areas. To automate the process of extracting the percentages of LULC and geology cover from each raster layer (i.e. 72 LULC layers for three time periods plus 30 geology layers, making it 246 layers) for each catchment, an algorithm was developed in the R environment (RStudio

2023.06.1 Build 524) for this purpose. Some catchments were excluded because their drainage area could not be delineated accurately at 2 m resolution or because spatial processing was computationally infeasible. Many of the very large basins also contain lakes, dams, or wastewater inputs, which would complicate interpretation of DOC and TSS responses to land cover and hydrology. The final set therefore represents the stations for which spatial features could be extracted reliably and for which water quality can be related to catchment characteristics without major confounding factors. A total of 11 METALP stations and 5 NADUF stations were retained for modelling, as shown in Table S14 and in Fig. 1.

2.2.2. DOC and TSS estimation and analysis

The analysis consisted of four main steps: (1) estimating DOC and TSS from surrogate sensor variables, (2) harmonising time series across programmes, (3) exploring seasonal and discharge-related patterns, and (4) reducing the number of LULC classes for modelling. High-frequency sensors deployed in high-mountain catchments monitored only surrogate parameters for DOC and TSS, namely chromophoric dissolved organic matter (CDOM) and turbidity. Optical CDOM sensor interference compensation was applied following established procedures (Daraei et al. 2024; Downing et al. 2012), excluding correction for inner filtering effects, which were negligible due to the very low DOC concentrations. Regression models were then developed to estimate TSS from turbidity and DOC from CDOM for the high-mountain stations. Further methodological details and results are provided in the Supplementary Material, including in Supplementary Figures S1-S38. Across most models and catchments, R^2 values exceeded 0.7.

The resulting 10-minute time series of DOC and TSS, as well as discharge, were first aggregated into hourly frequencies for various analyses. This included box plots with monthly data to assess seasonal patterns and time delays between DOC, discharge, and TSS for each station. Cross-correlations between DOC and TSS and all other laboratory results parameters were analysed for both high-mountain and lowland catchments using Self-Organising Maps (Kohonen 1998), through algorithms developed in the R environment (RStudio 2023.06.1 Build 524). In this case, for temporal consistency, the METALP dataset was converted to a weekly time frequency. Box plot analysis was repeated with the merged NADUF/METALP weekly dataset. An additional analysis of DOC and TSS relationships with discharge was completed by applying the concentration-discharge (C-Q) analysis as in Gómez-Gener et al. (2021). Self-Organising Maps were also used to visually assess correlations between DOC and TSS, and other water quality/spatial features across all stations (Figures S39-S40). Analysis of LULC classes through Self-Organising Maps allowed clustering into broader categories based on their cross-correlations, description, significant presence in any catchment, and cross-correlations with DOC or TSS. These were classified as (1) agricultural/urban, (2) pastures, (3) forests, (4) mineral/unproductive, and (5) glaciers and were used for model development (Fig. 2). A list of LULC classes included in each of these final categories, as well as their respective percentage summaries, is provided in Supplementary Material (Tables S6-S8).

2.2.3. Hysteresis analysis

Hysteresis analysis was performed, to examine how DOC and TSS in streams respond to changes in discharge over time and whether there are any lag effects or asymmetries in this relationship. Different classes of concentration-discharge plots are described in Williams (1989). Clockwise cycles typically indicate early exhaustion of the solute from the soil and a local source, while anticlockwise patterns may point to early dilution followed by subsurface contributions or more distant sources. Average daily patterns for different months and seasons were plotted for all locations. For each specific hour of the day, all corresponding DOC, discharge, and TSS data points in the dataset for each station, at that particular hour and in that particular month or season, were identified and averaged. This was repeated for all 24 h, and DOC-Q and TSS-Q

scatterplots were created accordingly, with points connected chronologically through arrows. While hysteresis analyses are traditionally performed to measure the response to specific rainfall events, in this context most of the annual discharge occurs on regular daily cycles during snowmelt (or ice melt). Therefore, averaging as described here was deemed a reasonable method to assess DOC and TSS response to typical discharge events at these locations, despite the high variability (Supplementary Results SR3). A previous rainfall-related hysteresis assessment performed in two of our catchments (Wagnon et al. 2021) resulted in similar hysteresis properties to those obtained with our approach. For the station-specific month with the highest average discharge, we calculated the Flushing Index (FI) as proposed by Vaughan et al. (2017), and a particular version of the Hysteresis Index (HI) proposed by Lloyd et al. (2016), both adapted to an average monthly analysis rather than storm-specific analysis. The former mainly quantifies the chemo-dynamic response, while the latter summarises the magnitude and direction features of the hysteresis loop (Liu et al. 2021). FI can be defined as:

$$FI = C_{Qpeak,norm} - C_{Qinitial,norm} \quad (1)$$

Where $C_{Qpeak,norm}$ and $C_{Qinitial,norm}$ are the normalised DOC or TSS concentrations at the point of peak discharge and of lowest discharge Q , respectively. HI on the other hand, is defined as:

$$HI_{Qi} = C_{RL,Qi} - C_{FL,Qi} \quad (2)$$

Where HI_{Qi} is the index at percentile i of Q , $C_{RL,Qi}$ is the chemical value (e.g. DOC or TSS concentrations) on the rising limb at percentile i of Q and $C_{FL,Qi}$ is the chemical value at the equivalent point in discharge on the falling limb. The same normalisation and integration procedures as in Lloyd et al. (2016) were applied, reiterating that HI was calculated on the average hourly DOC- Q and TSS- Q over the course of the month with highest discharge, and not on an individual storm.

Most of this hysteresis analysis was performed using dedicated algorithms developed in the R environment (RStudio 2023.06.1 Build 524). This analysis was possible only for the high-mountain METALP catchments due to the required higher data frequency. The findings would reveal insights on relationships between discharge and water quality and help processing the most suitable dataset for model development (Fig. 2).

2.3. Model development

2.3.1. Data preparation

To prepare the final dataset for model development, time series of all potential predictors were created. For some spatial variables, such as geology layers, catchment slope, and area, a fixed value for all time steps was applied. For LULC data, these were based on three surveys over three decades. The specific year of aerial image collection for each catchment was extracted from FSO (2021), and linear interpolation was applied among the three retrieval years for the rest of the time series. Linear interpolation was considered appropriate given the relatively minor changes observed between consecutive retrievals, the short time intervals separating them, and the absence of evidence suggesting any systematic nonlinear trends. Time-series data, whose length varied by monitoring station according to historical data availability, were scaled between 0 and 1 and log-transformed for DOC, TSS, and discharge.

2.3.2. Best model identification

Different machine learning models were developed and tested, with performance evaluated using Root Mean Squared Error (RMSE) and visual inspection of predictions. Tested models included simple linear regression, random forest, k -nearest neighbour, linear support vector machine (LSVM), lasso and ridge regression, and elastic net regression. This covered a range of models with distinct advantages and limitations. Linear models, that is as linear, lasso, ridge, and elastic net regressions

and LSVM, are easy to interpret, computationally efficient, and effective for high-dimensional data with linear relationships, but they struggle with non-linear dynamics, require assumptions about data distribution, and may be sensitive to multicollinearity or outliers. Tree-based models, such as random forest, handle non-linear relationships, are robust to outliers, and provide feature importance, but are computationally intensive and less interpretable. K -nearest neighbour can also be computationally intensive and sensitive to its hyperparameters, but is intuitive, captures local patterns in the data, and is effective for non-linear relationships (Breiman 2001; Cortes and Vapnik 1995; Cover and Hart 1967; James et al. 2013; Kuhn 2013).

A 10-fold cross-validation was applied. The best-performing model was selected and used for further analysis for both DOC and TSS as target variables. This model was a k -nearest neighbour model with $k = 10$. K -nearest neighbour is a non-parametric algorithm that predicts the output of interest based on the outputs of its k closest neighbours in the feature space and has been applied to similar water quality prediction problems (Dong et al. 2024; St-Hilaire et al. 2012). In this application, neighbours are defined as time steps in the merged dataset with characteristics similar to those of the day of simulation. These characteristics, called attributes, are potential predictors of DOC and TSS, such as discharge or specific LULCs. The algorithm calculates the Euclidean distance between the input data point and all other points in the dataset as below:

$$d = \sqrt{\sum_{i=1}^n (x_i - y_i)^2} \quad (3)$$

where x_i and y_i are the values of the i th predictor (e.g. discharge, a specific LULC) for the input point and a given data point, with n being the number of input variables. As mentioned above, all input variables were normalised, thus avoiding biases due to different data ranges when applying Eq. (1). Such distance d is calculated for all time steps in the historical dataset; the algorithm then selects the $k = 10$ closest points based on these distances (i.e. the nearest neighbours) and retrieves their corresponding DOC and TSS values. The prediction is, in turn, the average of the DOC and TSS values of these k neighbours. Equal weights for all k neighbours were assigned for this application, though weighted averages can also be used. Model accuracy is discussed in detail in Supplementary Results SR4, showing in particular how RMSE for the k -nearest neighbour model was only about 14 % of the variability in the DOC data. We assessed the sensitivity of each key predictor (whose list is presented in Fig. 3) by quantifying the change in model RMSE when each variable was omitted from model development and validation (Figure SR1). Water temperature emerged as the most influential predictor; however, its relative variation under the projected future scenarios is smaller than that of discharge. Consequently, predicted DOC concentrations are expected to more closely track changes in discharge. In contrast, TSS exhibited a comparatively minor effect on DOC predictions. When considering DOC exports, which are directly dependent on discharge projections, the importance of discharge is further amplified. Models were developed in the R environment (RStudio 2023.06.1 Build 524) using packages such as “neuralnet” and “caret”.

2.4. Scenario analysis

To evaluate potential future changes in DOC and TSS, projected variations in the model predictors were compiled and used in scenario analyses. LULC predictions were mainly sourced from Bütikofer et al. (2024). The developed LULC maps for future time periods and two Representative Concentration Pathways (RCP 4.5 and RCP 8.5) were downloaded and processed in QGIS. A hypothetical RCP2.6 scenario was approximated by taking the RCP4.5 predictions for the mid-century time horizon. A similar spatial feature extraction code to that developed for the original LULC determination was implemented to determine catchment-specific LULC projections and predicted changes from the latest observations (Table S9). Seasonal changes in mean water

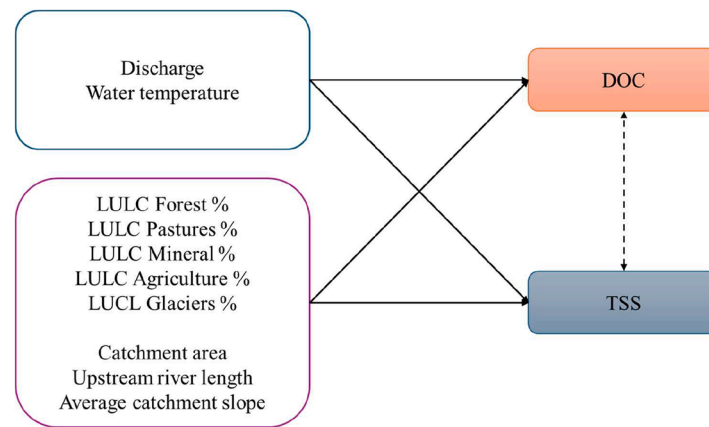


Fig. 3. – Final set of processed predictors used in the DOC and TSS models. The blue box indicates high-frequency temporal variables, while the purple box denotes catchment-specific spatial predictors that exhibit limited/no temporal variability.

temperature and discharge for RCP 2.6, RCP 4.5, and RCP 8.5 relied on estimations from Michel et al. (2022) for similar Swiss Plateau and Alpine catchments. The variability range derived by clustering all the high-mountain (used for METALP) and Swiss Plateau (used for NADUF) lowland site results was applied to our predictions, to cover catchment-specific variation. Glacier mass loss and the consequent hydrological response are the focus of much research (Huss and Hock 2018; Kneib et al. 2020). Relative glacier volume changes for RCP 2.6, RCP 4.5, and RCP 8.5 were extracted from Zekollari et al. (2019). Runoff predictions from the Global Glacier Evolution Model (GloGEM) (Huss and Hock 2015) for the specific glaciers within the catchments of this study were extracted. The most and least conservative global circulation models, based on prediction output analysis, were used to determine the uncertainty range, representing a plausible best-case to worst-case scenario. These runoff predictions were used to refine discharge predictions for the streams in the glacierised catchments (Tables S10–S13). Although other relevant studies exist (Muelchi et al. 2021; Price et al. 2015), they provided less applicable information for our catchments. These variables together represent the dominant drivers of future DOC and TSS dynamics. Land use and land cover affect organic matter sources and erosion, while discharge, temperature, and glacier mass changes influence mobilisation and transport processes. Combining these predictor projections allows direct simulation of changes in DOC and TSS concentrations and exports under each RCP.

All of the above resulted in a set of season-specific, and catchment-specific, predictions of changes in discharge, water temperature, and LULC for RCP 2.6, RCP 4.5, and RCP 8.5, along with associated uncertainty ranges determined by the different global circulation models or as reported in the original studies that supplied the input predictions. For each monitoring station in our final dataset, synthetic 30-year time series were created by repeating the existing data according to their available time period (e.g., a station with 6 years of data was repeated 5 times). This created equally long time series for all 16 catchments. The best-performing model was run with both the original and the RCP-modified input time series. For the RCP-modified scenarios, a Monte Carlo approach was used ($n = 5000$) to perturb the relevant inputs within the determined uncertainty ranges. Outputs were averaged by month over the entire 30-years of generated predictions so that seasonal changes could be assessed. This was performed for both DOC and TSS concentrations, as well as DOC load, estimated by multiplying DOC concentration by average weekly discharge. This was in turn used to estimate the predicted annual DOC export changes for each catchment. Monthly DOC loads were averaged throughout the year, and the annual DOC export analysed and visualised for all catchments, across the different RCPs considered (Supplementary Figure S62). This analysis was also performed in R and took approximately 25 h for DOC and TSS

combined, considering $n = 5000$ and three RCP scenarios. The model's performance was limited to assessing monthly median, rather than mean, TSS (Supplementary Results SR4). This limitation of the TSS model likely resulted in an underestimation of actual annual exports, as high sediment loads often arise from episodic extreme weather or hydrological events (Zhang et al. 2022b), whose future changes are difficult to simulate and remain poorly understood. Nevertheless, accurately predicting monthly medians was considered valuable for assessing seasonal TSS changes under future conditions.

3. Results

3.1. Seasonal and spatial patterns of discharge, DOC, TSS, and land cover change

Across the 12 high-mountain stations, discharge generally peaked in June, except for glacier-dominated catchments where summer icemelt caused a larger July peak. DOC concentrations typically peaked earlier, in April, at the onset of snowmelt, though contributing limited export due to low discharge. TSS peaks occurred later, around August, aligning with summer melt or rainfall events. Glacier-influenced catchments showed clear seasonal TSS patterns, whereas non-glacier sites like Champéry exhibited irregular, rainfall-driven extremes. Similar behaviour was observed in lowland catchments, which lacked clear seasonality for discharge and TSS but typically showed higher summer DOC concentrations. DOC levels were markedly lower in high-mountain (<0.5 mg/L) than in lowland (2–10 mg/L) sites, while discharge magnitudes mainly reflected catchment size. Occasional high TSS peaks (>1000 mg/L) occurred in both datasets.

Self-organising map analysis confirmed expected clusters for nutrients and ionic variables in the lowland dataset but showed no correlation between discharge, DOC, or TSS and other variables. In the combined dataset, lower DOC corresponded to steeper slopes, greater glacier coverage, and more mineral land cover, indicating intertwined catchment characteristics rather than simple causal drivers, reinforcing the need for machine learning modelling.

Land use trends showed modest agricultural and urban expansion (2–3 %) in lowland catchments and a shift from pastures to forests in several sites. In contrast, all high-mountain catchments experienced significant glacier loss (e.g. up to 50 % in Val Ferret) between 1995 and 2016, with projections indicating near-total loss by century's end. Concentration–discharge analysis (Gómez-Gener et al. 2021) indicated predominant chemostasis across catchments, with hourly hysteresis patterns better capturing short-term melt dynamics (Supplementary Results 2).

3.2. Hysteresis analysis

Hysteresis analysis (Liu et al. 2021; Williams 1989), which examines looping patterns between variables during rising and falling limbs of the hydrograph, was performed for DOC and TSS for the high-altitude streams. This analysis is crucial to understand temporal dynamics and source-sink relationships of organic carbon and sediments, particularly under varying hydrological conditions. The insights gained inform the prediction models for DOC and TSS, leveraging strong correlations and complex patterns with discharge.

TSS consistently exhibited a positive correlation with discharge during seasons with higher concentrations, particularly in summer and, to a lesser extent, autumn, when discernible patterns emerged (Supplementary Figures S41–S44). In summer, a positive clockwise hysteresis (e.g., in the streams of Valsorey and Val Ferret, Fig. 4a) potentially indicated allochthonous material mobilised from areas close to the stream. This persisted into autumn (e.g., Fig. 4b for Valsorey), for most sites. The amplitude of the hysteresis loop increased with the temporal

lag between discharge and concentration peaks and varied by stream and season.

In spring, when the first DOC peaks are recorded, there was a clear positive correlation with discharge at all sites (Supplementary Figures S45–S48). The four streams showing evidence of more local sources (clockwise loops – e.g. Fig. 4c) are either the most upstream sites of their respective catchments or streams draining smaller catchments. In summer, as concentrations decreased, the correlations became less defined except for the glacier-fed streams in Valsorey and the most upstream stream site in the mildly glacierised Vallon de Nant. For most of such sites, DOC concentrations are typically very low and relatively stable during the summer months, explaining the limited daily fluctuations, which however occur regularly and consistently. These sites switched to a relatively evident, anticlockwise, negative correlation (e.g. Fig. 4d), suggesting source limitation during such periods of large, glacier melting-related discharge.

Hysteresis Index (HI) (Lloyd et al. 2016) and Flushing Index (FI) (Vaughan et al. 2017), averaged over the month with the highest Q,

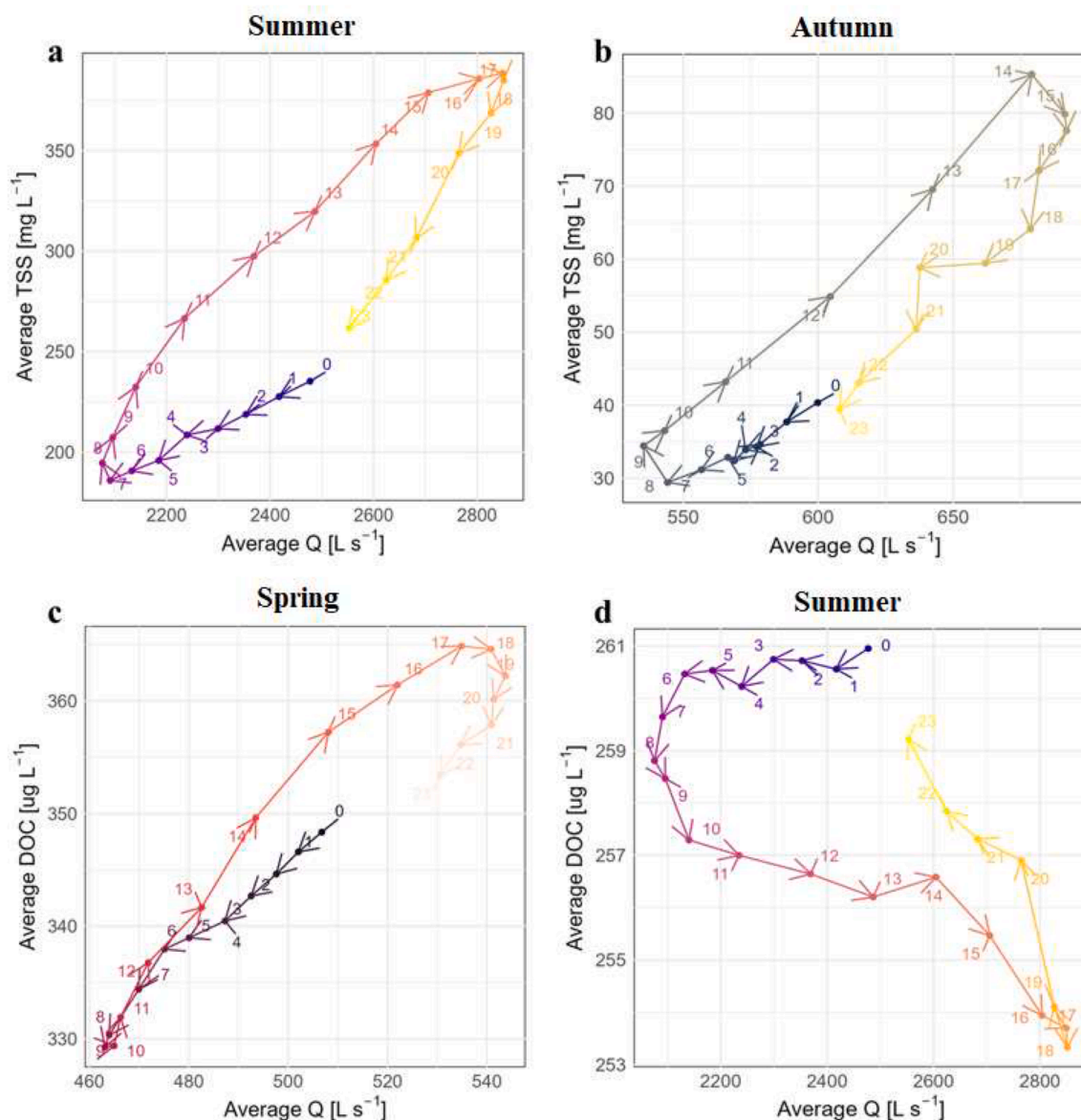


Fig. 4. – Hourly average discharge (Q) [L/s] versus Total Suspended Solids (TSS) [mg/L] for summer (Jun-Jul-Aug, a) and autumn (Sep-Oct-Nov, b), and hourly average Q [L/s] versus Dissolved Organic Carbon (DOC) [μg/L] for spring (Mar-Apr-May, c) and summer (Jun-Jul-Aug, d) in the stream of the most glacierised catchment, VAU. Numbers indicate the hour of the day. The arrows show the temporal progression through the day, illustrating diurnal variations in TSS and DOC in response to changes in discharge. Standard deviations are reported in tabular format in Supplementary Results SR3.

were calculated (Fig. 5). Counterclockwise loops (i.e. $HI < 0$, peak Q preceding peak solute) were more prevalent for DOC than TSS, although HI is mostly weak to moderate (-0.5 to -0.2). Some of these loops, especially for glacier-fed streams, were accompanied by a very negative (< -0.9) FI . This suggests a relatively distant but limited DOC source, that is insufficient to cope with large discharge, indicating source limitation during specific high-discharge summer months (i.e., July). For these and other partially glacierised catchment sites, both HI (> 0.7) and FI (0.1 – 0.6) switched to positive values for TSS hysteresis. This indicates a relatively large, allochthonous and proximal source causing TSS to peak before discharge and making these systems transport-limited. Sites from non-glacierised catchments often had low FI (mostly $< |0.4|$) for both TSS and DOC hysteresis, accompanied by large HI ($> |0.4|$). This indicates that while the difference between base- and peak-flow concentration was small overall, concentrations varied greatly throughout the day in response to changes in discharge. Thus, defining such systems as chemostatic may underestimate the complexity of hydrology-water quality interactions. Overall, this analysis provided insights into the relationships between hydrology, DOC, and TSS in high-mountain streams, aiding model development and interpretation.

3.3. Projected changes in DOC and TSS

Relationships between DOC, TSS, and discharge derived from data

and hysteresis analysis supported model development and enabled projections of DOC and TSS based on site- and season-specific variations in LULC, discharge, and water temperature under different RCPs. These projections were generated using a k -nearest neighbour model, trained and validated on historical data from all sites and identified as the best-performing model among those tested (Section 4.3 and Supplementary Material SR4).

DOC projections for lowland catchments showed similar patterns, with generally flatter, smaller peaks in summer but higher concentrations in spring and autumn (Supplementary Figures S54–S56). This smoothing of seasonal peaks becomes more pronounced under more extreme RCPs. Streams in high-mountain catchments at lower elevations either produced similar seasonal shifts (e.g. Vallon de Nant streams), or site-specific responses (e.g. for the Champéry catchment). High-mountain streams in higher-altitude catchments (e.g. Val Ferret) are expected to show more consistent reductions in DOC throughout the year. The most glacierised catchment, Valsorey, shows significant decreases in DOC, except for a small increase at the downstream location in winter. Unlike other high-mountain catchments, the decreases in Valsorey increase with RCP severity. These changes align with hysteresis analysis. In glacier-fed streams like Valsorey, during peak discharge in summer, there is a negative DOC- Q correlation due to dilution. With glaciers shrinking and peak discharge predicted to occur earlier (Supplementary Figures S57–S59), the currently higher spring DOC

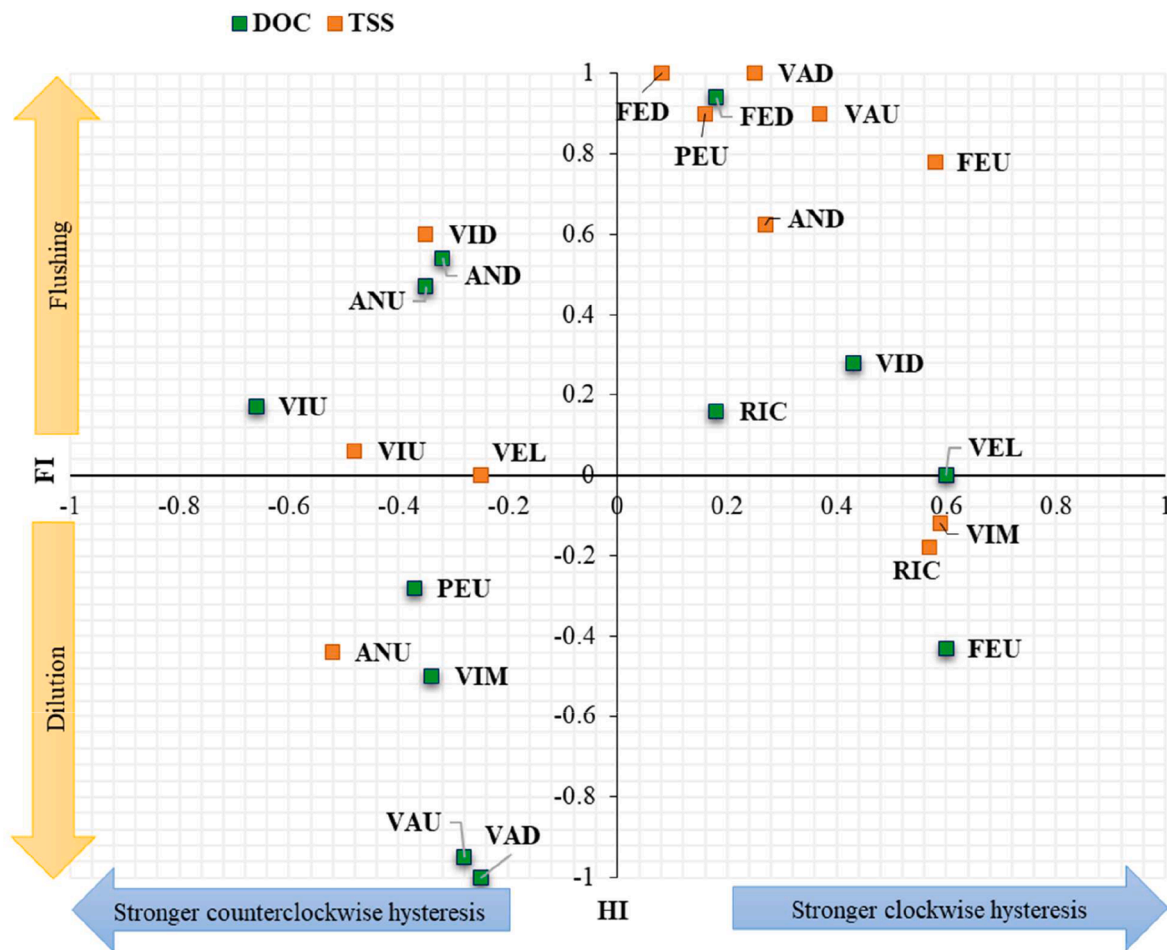


Fig. 5. – Flushing Index (FI – y axis) and Hysteresis Index (HI – x axis) for DOC- Q (green) and TSS- Q (orange) hysteresis loops, averaged for the month with the highest discharge (Q) (July for VAD and VAU, June for all other sites). Positive HI values indicate clockwise hysteresis loops, while negative values indicate anticlockwise loops, with values closer to ± 1 representing "fatter" loops and thus stronger hysteresis [49]. FI values near 1 suggest strong positive correlation between Q and solute, indicating system flushing (transport limitation), while values near -1 indicate dilution (source limitation). FI values close to zero may suggest chemostasis, although solute variations might still be present and quantified through HI . DOC and TSS dynamics in each site for each catchment are shown, highlighting variability in hydrological and biogeochemical responses. VEL station was included in the hysteresis analysis but excluded from the model development.

concentrations will reduce through dilution due to higher discharge. Overall, most high-mountain streams are predicted to experience a decrease in DOC concentration, particularly within the most glacierised catchments, due to anticipated discharge increases and the source-limited nature of these environments.

While future discharge patterns are quite consistent across all streams, increases for all seasons except summer, and autumn for lowland catchments, the DOC response varies greatly, reflecting the complexity of relationships and the model's capacity to capture catchment-specific interactions among land cover, hydrology, and biogeochemistry.

Predicted seasonal changes in DOC load are more informative for overall DOC export. These were calculated by multiplying predicted DOC concentrations with predicted discharges (Supplementary Figures S60-S62). In lowland catchments, higher DOC loads can be expected in spring, with minimal variations in autumn and winter (e.g., Figs. 6a-6c). In summer, more conservative RCPs predict increases in DOC loads, whereas under RCP8.5 scenario these loads are more likely to decrease. Most high-mountain streams also show higher DOC loads in winter and spring, with many higher-altitude sites expecting peak DOC loads earlier in the year, especially under RCP8.5. For example, in Valsorey the peak DOC load shifts from July to May (Fig. 6d-6f). This transition occurs under RCP8.5, whereas under RCP2.6 and RCP4.5 the summer peak mainly decreases. Streams in partially glacierised catchments consistently show decreases in their summer peaks, with larger drops in catchments currently more glacierised.

When examining overall annual DOC exports (Fig. 7, Supplementary Figure S63), high-mountain catchments show an increasing trend with more extreme RCPs, although responses under RCP2.6 are diverse, especially for Valsorey. In lowland catchments, despite export increases up to 40 % under RCP2.6 and RCP4.5, a decline is evident under RCP8.5, about 10–25 %. This decline is largely attributed to expected discharge variations, used in simulations (Tables S10-S13), and consistent with previous findings (Michel et al. 2022), which show annual discharge peaking under RCP4.5 in lowland catchments. Comparatively, for the

high-mountain catchments, despite significant changes (e.g., over 100 % average increase for the sites at the lower elevation Champéry catchment), their streams' DOC export will still be just a fraction of those from lowland catchments, particularly the Alpthal catchments. This is likely due to the dominance of unproductive land covers (e.g., minerals, bare rocks) in high-mountain catchments, which contribute less DOC than forests or pastures. Despite a predicted “greening” of some of the analysed high-altitude catchments, with up to 10 % more forest cover under RCP8.5, the extent of forests and pastures will remain much larger in lowland catchments.

Median monthly TSS is expected to decline in most lowland streams (e.g., Figs. 8b-8d-8f) under RCP8.5, with Neuenkirch as an exception (Supplementary Figures S64-S66). Some high-mountain streams showed similar predicted changes, for instance expecting lower summer concentrations and slightly higher TSS for the rest of the year. However, other high-mountain streams (i.e. the majority of the Champéry and Val Ferret sites) are predicted to experience substantial increases, particularly in summer (e.g., Fig. 8a-8c-8e).

4. Discussion

4.1. Current and future DOC export trends

This research, through meticulous data harmonisation, advanced processing, and the development of machine learning models, has enabled the simultaneous analysis of current and future DOC export across a diverse range of high-mountain and lowland catchments. Data show that streams in high-mountain catchments, which are less affected by human activity and dominated by unproductive land cover, currently export only $<1 \text{ g C m}^{-2} \text{ yr}^{-1}$. The Champéry catchment, consistent with previous findings (Boix Canadell et al. 2019), is the high-altitude catchment whose streams have the highest exports. Conversely, lowland catchments, with higher proportions of pastures, forests, or agricultural land, have current DOC exports between 3 and $9 \text{ g C m}^{-2} \text{ yr}^{-1}$. Such high variability has been noted in other studies. For instance, Creed

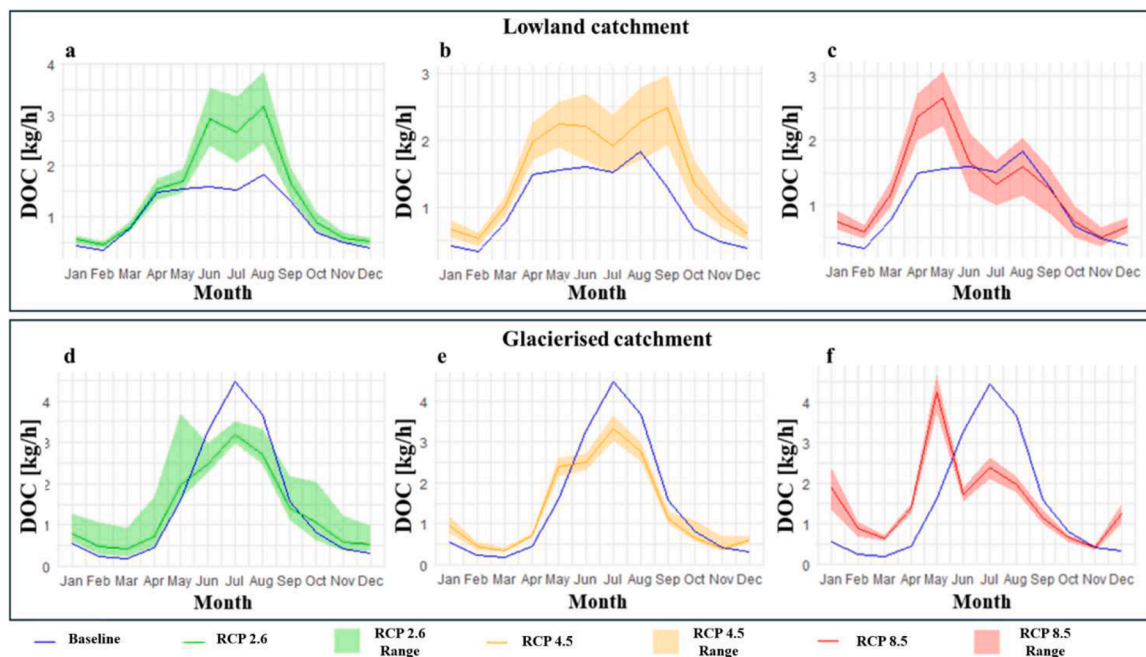


Fig. 6. - Predicted DOC loads, generated using a k -nearest neighbour model with 5000 iterations, under different RCPs for lowland (a-c) and glacierised (d-f) catchments. a-c, Lowland catchment at VO with DOC predictions for RCP2.6 (a), RCP4.5 (b), and RCP8.5 (c). d-f, Glacierised catchment at VAD with DOC predictions for RCP2.6 (d), RCP4.5 (e), and RCP8.5 (f). The blue lines represent the baseline scenario with unchanged inputs. Shaded areas represent the uncertainty range for each RCP scenario: green for RCP2.6, yellow for RCP4.5, and red for RCP8.5. DOC concentrations typically peak in summer, with higher peaks and shifts to earlier months under more extreme RCPs.

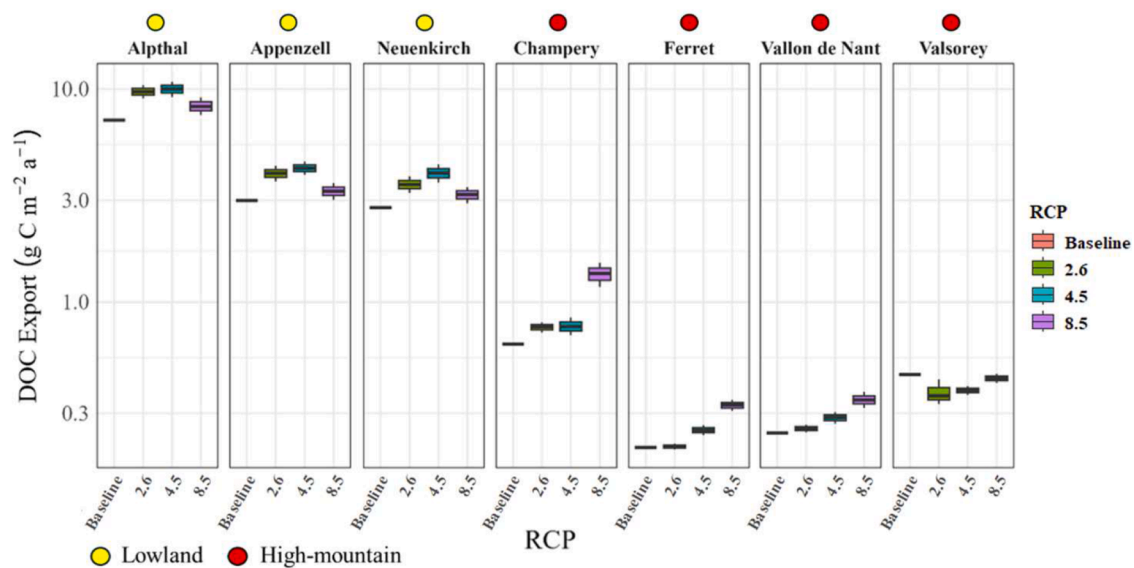


Fig. 7. – Annual stream DOC export for Baseline, RCP2.6, RCP4.5, and RCP8.5 scenarios, including uncertainty ranges, averaged per catchment. Boxplots represent DOC export in $\text{g C m}^{-2} \text{a}^{-1}$ for each catchment: Alpthal, Appenzell, Champéry, Ferret, Neuenkirch, Vallon de Nant, and Valsorey. Baseline scenario assumes unchanged inputs. Model developed using k -nearest neighbour with 5000 iterations. The y-axis is in logarithmic scale.

et al. (2008) recorded highly variable average annual DOC export among 33 experimental headwater catchments in forested regions on glaciated landscapes, ranging from 0.9 to $13.7 \text{ g C m}^{-2} \text{yr}^{-1}$. In a study of catchments in North America draining to the Atlantic Ocean, the mean annual DOC flux (± 1 standard deviation) over 1980–2008 was $2.37 \pm 0.60 \text{ Tg C yr}^{-1}$ (Tian et al. 2015), which, given the overall area of $870,000 \text{ km}^2$, corresponds to $2.72 \pm 0.69 \text{ g C m}^{-2} \text{yr}^{-1}$. For high-mountain streams, a study from the Rocky Mountains reported a comparable estimate of $0.96 \text{ g C m}^{-2} \text{yr}^{-1}$ (Pacific et al. 2010), while studies of glacierised catchments in Alaska (Hood and Scott 2008) reported much higher DOC estimates (approx. $5 \text{ g C m}^{-2} \text{yr}^{-1}$ for 25 % glacier coverage, similar to Valsorey) likely due to the much higher runoff from Alaskan glaciers. Overall, our estimates are within the same order of magnitude as previous findings, and they share large catchment-specific variability, indicating that differences in LULC and climate can substantially affect DOC export, and highlighting the need for machine learning models that can unpack such complexity.

The projections for stream DOC export in high-mountain catchments reveal a significant upward trend. On average, these catchments are expected to experience a 50 % increase in DOC export under RCP8.5, whereas lowland catchments show a smaller 15 % rise, which decreases from a peak under RCP4.5 consistent with decreasing discharge. These findings align with previous studies that highlight the impact of climate change on DOC dynamics. For example, Clair et al. (1999) projected a 14 % increase in DOC export in Canadian basins under a doubled CO_2 scenario (similar to RCP8.5), while Hejzlar et al. (2003) estimated a 7 % rise in DOM concentration for a mid-altitude European catchment and Seitzinger et al. (2010) simulated a global DOC export increase of 3 % in a shorter timeframe (2000–2050) using the former Millennium Ecosystem Assessment scenarios. Similarly, Zhang et al. (2022a) attributed a 25 % increase in DOC delivery to European rivers over the past century mainly to climate change, and historical data from some UK peat catchments reported a near-doubling of DOC export over 30 years (Worrall and Burt 2004). A recent study modelled a 17 % increase in DOC leaching into rivers worldwide (Nakhavali et al. 2024a), with Fabre et al. (2025) recently estimating that large rivers bound by cold catchments will see an above-average DOC export increase of up to 55 % for RCP8.5, in line with our results. This growing body of evidence indicates a consistent global trend, climate change is likely to drive substantial increases in DOC export, particularly from high-mountain catchments,

with implications for carbon cycling and aquatic ecosystem health.

4.2. Drivers of DOC change

Our projections indicate that DOC export is predominantly influenced by changes in discharge, highlighting the critical role of hydrology as a primary driver of both current and future DOC dynamics. Increased runoff is a key factor in elevated DOC leaching rates (Clair et al. 1999; Gommet et al. 2022), particularly in wetter regions. For example, de Wit et al. (2016) demonstrated up to a 30 % increase in soil DOC mobilisation with a 10 % rise in rainfall across Scandinavian freshwater sources, underscoring the strong linkage between "climate wetting" and carbon cycling. Our findings corroborate these patterns, with the Alpthal catchments exhibiting the highest DOC exports due to their exceptional precipitation levels, up to twice that of other lowland catchments, and hydrological systems dominated by fast runoff flow paths (von Freyberg et al. 2018). The humid conditions and limited storage capacity in these catchments amplify DOC transport, further reinforcing the relationship between precipitation and export rates (Botter et al. 2019). In contrast, temperature-induced changes in DOC concentrations or exports are comparatively minor, as noted in studies such as Gommet et al. (2022). This consistent evidence across studies, in line with ours, emphasises the dominant role of hydrological processes, particularly discharge variability, as the primary driver of DOC export changes under future climate scenarios.

Higher discharge consistently led to increased DOC export, because changes in discharge are proportionally much larger than those in DOC concentration. However, the relationship between discharge and DOC concentration is highly variable, influenced by transport- vs. source-limitation that depends on catchment characteristics and seasonality. Our results, derived from high-frequency data and hysteresis analysis, reveal that most lower-altitude sub-catchments exhibit flushing behaviour during peak discharge, characterised by high FI values and a positive correlation between runoff and DOC (Fig. 5), consistent with findings from lowland European catchments (Haaland et al. 2024). In contrast, glacierised catchments with much larger peak discharges often show source-limited behaviour, marked by negative FI values and dilution, particularly during summer (e.g. Fig. 4). This seasonal variability aligns with previous studies, such as Hood and Scott (2008), who observed DOC increases during snowmelt followed by summer dilution

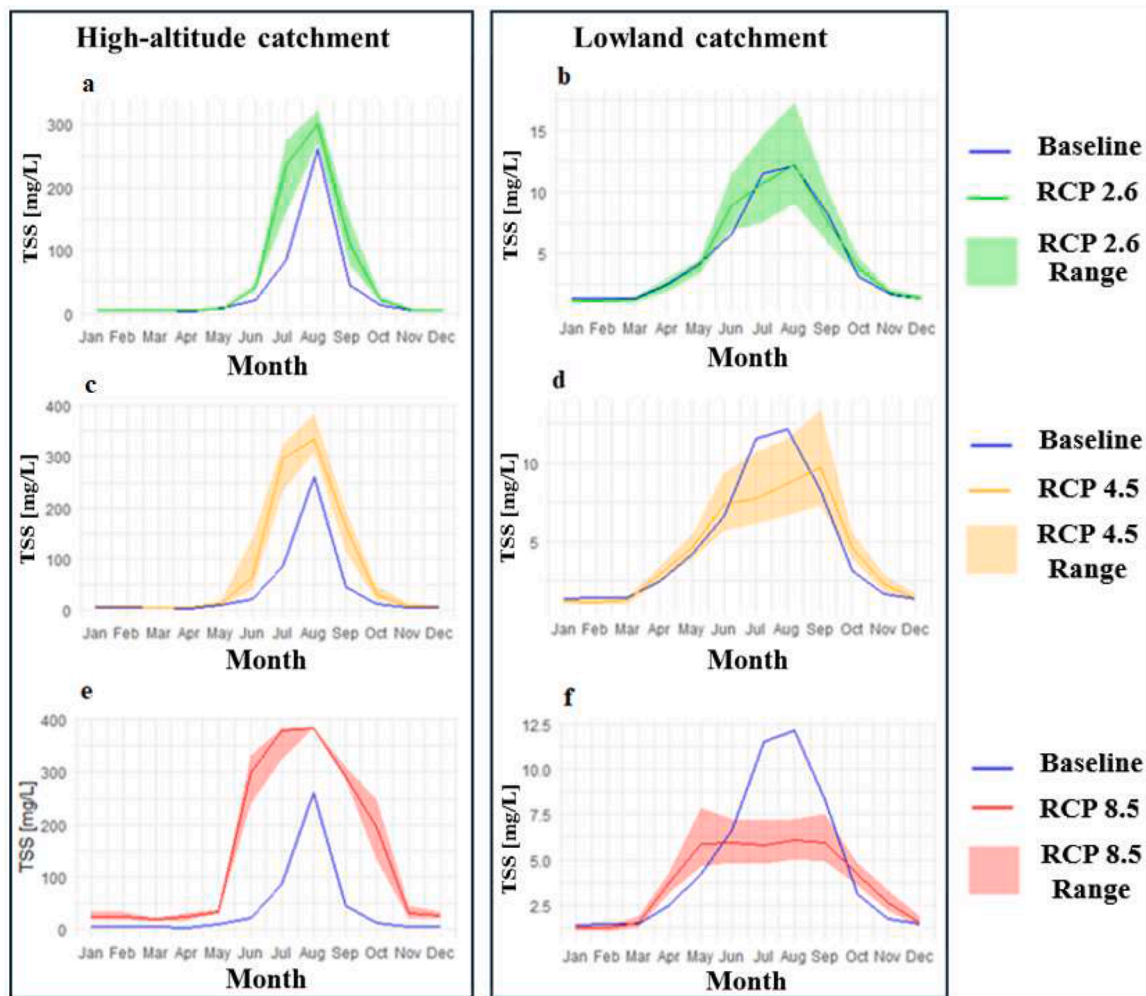


Fig. 8. - Predicted median monthly TSS concentrations, generated using a k-nearest neighbour model with 5000 iterations, under different RCPs for lowland (a-f) catchments. a-c, Lowland catchment at FEU with TSS predictions for RCP2.6 (a), RCP4.5 (c), and RCP8.5 (e). d-f, Lowland catchment at LU with TSS predictions for RCP2.6 (b), RCP4.5 (d), and RCP8.5 (f). The blue lines represent the baseline scenario with unchanged inputs. Shaded areas represent the uncertainty range for each RCP scenario: green for RCP2.6, yellow for RCP4.5, and red for RCP8.5. TSS concentrations typically peak in summer, with variations in peak magnitude and timing under more extreme RCPs.

in Arctic rivers, and Boyer et al. (1997), who reported similar patterns in alpine catchments. The prevalence of transport limitation in lower-altitude catchments aligns with studies of forested catchments in Vermont (Sebestyen et al. 2008) and other regions, where chemostasis and transport-limited behaviour dominate (Gómez-Gener et al. 2021). Seasonal shifts, particularly in glacier-fed systems, further emphasise the dynamic interplay between hydrological and biogeochemical processes. Overall, our findings reinforce the dominant role of transport limitation in lower-altitude catchments and source limitation in most glacierised systems during peak discharge, providing a nuanced understanding of DOC export dynamics across diverse hydrological regimes.

In addition to discharge and, to a lesser extent, water temperature, our model was also sensitive to existing and future LULC. However, the influence of LULC appears to be context dependent and relatively minor compared to hydrological drivers. Previous research shows contrasting results on the effects that land use may have on DOC exports and concentrations. For instance, model predictions by Nakhavali et al. (2024a) concluded that LULC change has limited impact on global DOC leaching changes, while the conversion of agricultural land to forest in the South Atlantic Bight region was identified as a major factor reducing DOC export (Tian et al. 2015). In our study, Neuenkirch is the only catchment with a notable extent of agricultural land, but the predicted LULC changes under RCP8.5 (approximately a 5 % decrease in agricultural

land replaced by forest, Table S9) are minor relative to the anticipated changes in discharge. Similarly, while wetland proportion has been shown to significantly influence DOC export in forested headwater catchments on glaciated landscapes (Creed et al. 2008), the limited presence of wetlands in our catchments reduces their impact on future DOC dynamics. Overall, while LULC changes may play a localised role in shaping DOC export, their influence in our study catchments is overshadowed by the dominant effects of discharge. This emphasises the need to prioritise hydrological variables when modelling and managing DOC export under future climate scenarios.

The only significant and common trend in the LULC projections for our catchments that has profound implications for DOC dynamics is glacier cover loss. The Valsorey catchment has the highest glacier cover (>18 %), and is predicted to almost completely disappear by 2090 under RCP8.5. The Val Ferret and Vallon de Nant catchments, with smaller glacier coverage (1–6 %), are expected to undergo complete deglaciation. Stream DOC exports in these catchments, while remaining modest, are projected to increase, driven primarily by higher runoff (particularly in winter and spring) which offsets slightly reduced DOC concentrations throughout much of the year. The lower DOC concentrations suggest that glaciers may be more significant sources of DOC than the mineral surfaces and unproductive land covers expected to replace them. While previous studies hypothesised an increase in DOC concentration with

the retreat of glaciers (Hood and Scott 2008; Milner et al. 2017), and others underscored the importance of glacier DOC release for forthcoming assessments of the global carbon cycle (Li et al. 2018), our seemingly contrasting results are based on the assumption that glaciers will be mainly replaced by unproductive land cover, with only minor proportions replaced by forests. Nonetheless, the predicted reductions in DOC concentrations are minor and season specific. Overall, DOC export is expected to rise under RCP8.5 toward the end of the century, largely driven by increased discharge. These findings highlight the pivotal role of hydrological changes, primarily driven by glacier retreat, in shaping DOC export dynamics.

4.3. Variable TSS predictions

As summarised by Zhang et al. (2022b), the limited availability of long-term field observations, such as sediment-yield and its driving factors, poses a significant challenge for sediment-yield modelling in cold regions. This study addressed this gap by analysing and modelling data from two extensive datasets to estimate long-term changes in TSS. Predictions show highly variable seasonal median changes, with annual median TSS generally increasing in high-mountain streams, particularly in Val Ferret, and decreasing in most lowland streams. However, the analysis does not fully capture the dynamics of extreme TSS peaks, which are expected to change substantially under future scenarios.

The variability of our findings aligns with related studies. For instance, Moragoda and Cohen (2020) predict an increase in sediment flux under an RCP8.5 scenario that cause an 11 % increase in mean global river discharge. For glacierised catchments, Milner et al. (2017) describe a complex trajectory, sediment yields initially increase due to meltwater and the exposure of unconsolidated glacial sediments, followed by a decline as glacial runoff diminishes and erosion decreases. This is consistent with the review by Zhang et al. (2022b), which points to an initial increase in sediment yield driven by meltwater and more frequent rainfall extremes for glacierised basins, followed by a decrease past the “sediment peak” due to declining glacier mass and meltwater below a critical point.

Our results, even under RCP8.5, primarily reflect the increase in runoff driven by glacier melt. However, a scenario considering post glacier-melt conditions, and the associated runoff reduction was not tested. Consequently, the observed increases in stream TSS for most glacierised catchments align with findings from previous studies. The smaller-than-expected predicted variation in TSS for the Valsorey sites compared to Val Ferret aligns with earlier research on the same sites, which reported no clear correlation between glacial influence and turbidity data (Kneib et al. 2020). This suggests that more complex interrelationships among changes in LULC, discharge, and water temperature may have been captured by the model, leading to predictions that may appear counterintuitive when evaluating single variables in isolation. Furthermore, while changes in TSS (not included in the DOC model) directly influence DOC concentrations by affecting light penetration and, subsequently, primary production, these processes contribute proportionally much less to DOC leaching compared to discharge-driven mechanisms. This is consistent with our model results and sensitivity analysis (Figure SR1, Supplementary Results 4), and the broader literature, emphasising the dominant role of hydrological changes over secondary drivers in shaping DOC export dynamics.

In conclusion, glacier retreat and hydrological changes are the primary drivers of predicted increases in monthly median TSS for high-mountain streams, and decreases for lowland streams. The model's ability to provide stream-specific predictions, particularly by accounting for varying LULC changes across sites, underscores its complexity. This approach reveals the relationships between TSS, water quality, and catchment features, capturing site-specific dynamics that reflect the interplay of glacial influence, discharge patterns, and local land use variations.

4.4. Implications

To the best of our knowledge, this study is the first to analyse a wide range of Alpine streams to predict future changes in DOC and TSS with a machine learning model supported by a harmonised dataset. For both high-mountain and lowland Alpine streams, we predicted increased DOC export, especially for more extreme RCPs. DOC is a major contributor to the net heterotrophy of inland waters by providing a key carbon and energy source for microbial respiration (Battin et al. 2008), leading to significant CO₂ production, which is therefore expected to increase further. This is consistent with the review from Marx et al. (2017), who showed that DOC export and processing in headwater streams are closely coupled to hydrological connectivity and runoff dynamics, making these systems major yet often underrepresented sources of CO₂ outgassing at the global scale. Poulter et al. (2025) further confirm this by highlighting that inland water outgassing of CO₂ and CH₄ remains highly uncertain, largely due to limited observational data and challenges in scaling estimates across diverse aquatic systems. Previous studies estimated that global lateral carbon flux is of comparable magnitude to the net carbon sink of global terrestrial ecosystems (Regnier et al. 2022). The carbon fraction that is not buried or recycled back to the atmosphere will reach the oceans, partly contributing to the trophic status of marine waters (Dai et al. 2022). Increasing DOC exports would exacerbate these effects. DOC peaks will often occur earlier in the year, causing phenological seasonality shifts.

TSS is predicted to increase overall in high-mountain Alpine streams, causing more loss of storage volume for connected reservoirs, especially those producing hydropower. Using global datasets of dams and reservoir characteristics, Vörösmarty et al. (2003) estimated that large reservoirs collectively trap about 26 % to 30 % of the global annual river sediment flux, with local efficiencies of individual reservoirs often exceeding 80–90 %, depending on storage capacity and inflow. As such the annual rate of loss in the storage capacity of the world's reservoirs was estimated at 0.5–1.0 % already two decades ago (Dams 2000), with recent assessments pointing to higher (>1.5 %) averages (Minocha and Hossain 2025). Based on our predictions, sedimentation will increase at faster rates in such catchments, leading to multifaceted water-energy supply issues. Conversely, median monthly TSS is expected to decrease for most lowland streams. An increase in gross primary production (GPP), with decreased turbidity has been reported (Trentman et al. 2022), suggesting that turbidity mediates of stream metabolism. Higher GPP typically implies healthier river ecosystems and better water quality, and contributes to carbon sequestration. Hence, while increase in DOC may lead to increased respiration, this could be partly counterbalanced in lowland streams by an increase in GPP.

4.5. Limitations and outlook

The applied machine learning model accurately predicted DOC concentration variations in Swiss streams draining diverse catchments. While the primary application of this model (and the TSS model) was long-term scenario analysis, its high accuracy and reliance on slowly changing parameters, that is LULC, and regularly monitored parameters (e.g., water temperature and discharge), makes it suitable for now-casting DOC at these locations. The model could be further refined by improving the correlation between stream cDOM and DOC for high-mountain catchments as more data becomes available, and by applying it to additional catchments to enhance validation and expand the training dataset, including a broader range of land use and land cover configurations. For the scenario analysis, due to computational time required (approx. 24 h), the model iterations were limited to 5000. Increasing the number of iterations would likely yield larger and more robust uncertainty ranges for the projections. However, based on comparisons with runs using fewer iterations, the average projections are expected to remain similar.

Importantly, although water reservoirs and their storage capacities

are influenced by variations in TSS, the dynamics of TSS are, in turn, strongly governed by the presence of such artificial storage systems. While the present analysis focused on catchments without these structures (Section 2.2.1), future work incorporating reservoir-affected catchments will require careful evaluation of how current and projected storage capacities and operational regimes influence both TSS and DOC.

5. Conclusions

This study provides a comprehensive assessment of current and projected DOC and TSS dynamics across diverse Alpine catchments using a machine learning framework. Hydrological changes, particularly glacier retreat and altered discharge regimes, were identified as the principal drivers of future DOC and TSS fluxes, outweighing the influence of land use and temperature variations. The combined scenario analysis showed that land use and land cover changes primarily affect DOC sources, while discharge, water temperature and glacier mass changes control mobilisation and transport. High-mountain catchments are projected to experience substantial increases in DOC export (~50 % under RCP8.5), with earlier seasonal peaks, whereas TSS displays strong catchment specific and season specific responses. These results have important implications for carbon cycling, aquatic ecosystem functioning, and reservoir management.

Model limitations include the reliance on available high-frequency data and constrained scenario iterations, which may underestimate uncertainty. Future work should expand model validation across additional catchments, refine relationships between glacier dynamics and DOC mobilisation, and incorporate extreme hydrological events to improve predictive capacity and support adaptive water resource management strategies under climate change.

Data availability

Some of the processed input data are available in the Supplementary Information, with all the METALP, NADUF, and SWECO25 raw input data freely available online. The full code, and the pre-processed datasets are available at https://github.com/RIVER-EPFL/Bertone_CC_DOC_TSS.

Author contributions

T.I.B. and E.B. conceived and designed the study. E.B. and N.D. collected and pre-processed the data. E.B. conducted the data analysis and model development with assistance from N.D. E.B. wrote the manuscript with significant assistance and comments from N.D. and T.I.B. E.B. created all figures, N.D. created Fig. 1. All authors read, contributed to, and approved the final manuscript.

CRedit authorship contribution statement

Edoardo Bertone: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicola Deluigi:** Writing – review & editing, Visualization, Supervision, Software, Resources, Conceptualization. **Tom Ian Battin:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2025.125232.

Data availability

Most raw data freely available online. Some processed data available in Supplementary Material. Link to full codes provided in manuscript

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