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Modelling Subarctic watershed dissolved organic carbon response to hydroclimatic regime

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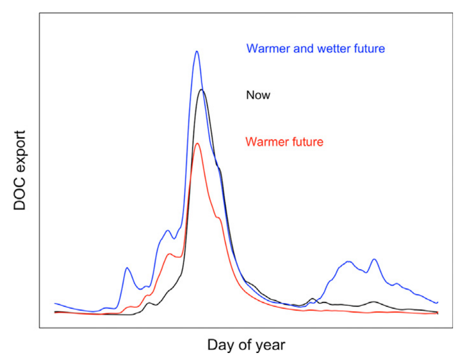
HIGHLIGHTS

- Streamflow and DOC patterns modelled in a complex subarctic catchment for different hydroclimate regimes.
- Model calibration captured temporal variability in stream DOC export.
- Warmer climate increases water residence time, increases DOC concentrations, but decreases DOC export.
- Warmer and wetter climate yields higher DOC export and runoff due to increased catchment connectivity.
- Shift to a combined nival and pluvial streamflow regime is predicted to increase winter DOC export.

GRAPHICAL ABSTRACT



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ABSTRACT

Shifts in hydroclimatic regimes associated with global climate change may impact freshwater availability and quality. In high latitudes of the northern hemisphere, where vast quantities of carbon are stored terrestrially, explaining landscape-scale carbon (C) budgets and associated pollutant transfer is necessary for understanding the impact of changing hydroclimatic regimes. We used a dynamic modelling approach to simulate streamflow, DOC concentration, and DOC export in a northern Canadian catchment that has undergone notable climate warming, and will continue to for the remainder of this century. The Integrated Catchment model for Carbon (INCA-C) was successfully calibrated to a multi-year period (2012–2016) that represents a range in hydrologic conditions. The model was subsequently run over 30-year periods representing baseline and two future climate scenarios. Average discharge is predicted to decrease under an elevated temperature scenario (22–27 % of baseline) but increase (116–175 % of baseline) under an elevated temperature and precipitation scenario. In the latter scenario the nival hydroclimatic regime is expected to shift to a combined nival and pluvial regime. Average DOC flux over 30 years is predicted to decrease (24–27 % of baseline) under the elevated temperature scenario, as higher DOC concentrations are offset by lower runoff. Under the elevated temperature and precipitation scenario, results suggest an increase in carbon export of 64–81 % above baseline. These increases are attributed to greater connectivity of the catchment. The largest increase in DOC export is expected to occur in early winter. These predicted changes in DOC export, particularly under a climate that is warmer and wetter could be part of larger ecosystem change and warrant additional monitoring efforts in the region.

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1. Introduction

The potential for shifts in hydroclimatic regimes is an important consideration given global climate change. These shifts may impact freshwater availability, both in magnitude and timing, as well as surface water quality. Shifts in hydroclimatic regimes may also affect the landscape-scale carbon (C) budget, which may manifest through altered patterns of catchment dissolved organic carbon (DOC) export, and pollutant transfer (e.g. Hudson et al., 2003; Oni et al., 2012). Many factors, however, including temperature (Clair et al., 1999), runoff amount and flow pathways (Evans et al., 2005; Walvoord and Striegl, 2007), elevated atmospheric CO_2 (Clair et al., 1999; Freeman et al., 2004; Evans et al., 2005), sea-salt deposition (de Wit et al., 2016a), and acid deposition (Evans et al., 2005; Monteith et al., 2007) have been linked to surface water DOC dynamics. These factors vary with regional hydroclimate and the local landscape, and high-quality long-term datasets are often used to disentangle the effect of different drivers.

Increasing trends in DOC concentration over the last few decades in catchments of northern Europe (Freeman et al., 2001; Evans et al., 2006; Monteith et al., 2014) and eastern North America (Monteith et al., 2007; Oni et al., 2014) have been reported. Increases in DOC concentration, however, have not been universally associated with increasing flux, indicating that runoff amount also plays a critical role (Eimers et al., 2008; Oni et al., 2012). Many of these observations fall in regions with a long history of elevated acidic deposition associated with industrialization, where long-term hydrochemical monitoring networks are extant (e.g. Monteith et al., 2007). In these and other regions, DOC export has been shown to change in response to hydroclimatic regime and other landscape-scale drivers (Clair et al., 1999; Striegl et al., 2005; Futter et al., 2009; Ledesma et al., 2012; Noacco et al., 2019). Notably, wetter climate has been linked to browning of surface waters for a range of catchment types in Fennoscandia (de Wit et al., 2016b).

Catchment-scale models can play a valuable role in understanding these patterns. These models provide the opportunity to predict long-term response where observational data are more limited, allow for exploration of future response to changing conditions, and also make it possible to investigate individual drivers including land use, precipitation and temperature, among others. Some earlier models of DOC behaviour included process-based aquatic (Hanson et al., 2004) and watershed (Boyer et al., 1996) models, and statistical models of watershed behaviour (McClelland et al., 2007). With a growing interest in landscape carbon storage and aquatic carbon export, a variety of different tools have been developed and used to simulate DOC dynamics across a range of domains in recent years. This includes different biogeochemical watershed models (Futter et al., 2007; Rawlins et al., 2021) and biogeochemical modules for hydrological models (Du et al., 2020).

In Subarctic North America, which has experienced some of the highest rates of warming globally, reduced DOC export during the warm summer months has been associated with a changing hydroclimatic regime as flow path lengths and residence times increase (Striegl et al., 2005). The Northwest Territories (NT), in northern Canada, is projected to undergo significant climatic change during the remainder of this century (GNT, 2008), beyond those increases in temperature and precipitation documented to date (De Beer et al., 2016). Changes to the hydroclimatic regime, for example through changing precipitation phase or amount, and warming induced changes to water yield are an important consideration in this region where seasonal surface water DOC fluxes have been linked to catchment runoff regime (Spence et al., 2015). The extent of permafrost loss with warming across the Subarctic is a function of many factors (Swindles et al., 2015). This loss will influence DOC concentrations and loads because they depend on the subsurface hydrological connectivity, deeper groundwater flow paths and landscape heterogeneity that permafrost state controls (Petrone et al., 2006; Benoy et al., 2007; Buffam et al., 2007; Laudon et al., 2011). This introduces uncertainty into small catchment response to a changing climate; however, process-based catchment models can be used to illustrate the linkages between hydrological behaviour and C dynamics.

The potential for changes to surface water C concentrations and fluxes in northern catchments is an important consideration for water quality. Northern catchments have a history of anthropogenic landscape disturbance, including mining, in addition to changes in climate (Webster et al., 2015). In this study, we use a dynamic modelling approach to understand and predict long-term changes in DOC dynamics in a northern catchment expected to undergo notable climate change over the coming decades. Using the Integrated Catchment model for Carbon (INCA-C), which combines soil and stream C processes (Futter et al., 2007), we modelled the behaviour of a small Subarctic Canadian Shield catchment. The objectives of this study were to: 1) apply INCA-C using a manual calibration approach to simulate catchment DOC export, and 2) forecast future catchment DOC response under different hydroclimatic regimes. Using these exercises to link landscape-scale factors to DOC export, we illustrate how DOC dynamics in Subarctic catchments may change in the near future in northern Canada. This work is important in this region where there is concern about DOC associated co-transport of metals deposited to the landscape through mining operations in the region.

2. Materials and methods

2.1. Site description

The Baker Creek catchment is located in Canada's NT on the northern side of Great Slave Lake near the city of Yellowknife (Spence and Hedstrom, 2021; Fig. 1). The catchment (155 km^2) is located approximately 30 km northwest of and downwind of (predominant wind direction is from SE to NW: Galloway et al., 2018) historic mining activities (e.g. Giant Mine) which are a source of atmospheric deposition of metals (Bromstad et al., 2017). High concentrations of bioavailable arsenic (As) and mercury (Hg) in whitefish (Cott et al., 2016), elevated sediment As and other metal concentrations (Jasiak et al., 2021; Leclerc et al., 2021) and high concentrations of total dissolved solids and heavy metals in downstream locations (GNT, 2017) have all been reported in the Giant Mine airshed. The major land cover in the catchment is exposed bedrock, which occupies 40 % of the total area. Open water (23 %), largely as lakes of varying sizes, forest (21 %), and wetlands and peatlands (16 % combined) (Spence and Hedstrom, 2018) are also common. Organic soil depths in these low lying areas range from less than one m to more than 10 m (Spence and Hedstrom, 2018). Mineral soils typical of forested areas are derived from sandy till and glaciofluvial deposits (Spence et al., 2010).

The catchment experiences very long and cold winters with an average daily temperature in January of −24 °C and short, cool summers with an average daily July temperature of 17 °C. The average annual precipitation in the catchment is 249 mm, of which 36 % falls as snow. Precipitation in the catchment typically falls as rain from May to September and snow from October to April. The Baker Creek catchment upstream of the Water Survey of Canada gauge (07SB013) at the outlet of Lower Martin Lake was the focus of this study (Lower Martin). Streamflow from the catchment is dominated by snowmelt in spring. Additionally, given heterogeneity of the catchment and available monitoring data, three sub-catchments (Duckfish Lake, Lake 690, and Vital Narrows; Fig. 1) with different physical features and hydrological behaviour (Table 1) were used to inform the modelling.

2.2. Data sources and processing

Most of the data collected in the catchment to date have been previously published as a dataset (Spence and Hedstrom, 2018), which is used extensively here (details below). Data processing, data visualization, and statistical analyses were all performed using R: A Language and Environment for Statistical Computing, 2017 (R Core Team, 2020); version 3.6.3).

2.2.1. Topography and land cover

Elevation data were collected on August 21, 2007, using Light Detection and Ranging (LiDAR) with methods described in Spence and Hedstrom (2018). Land cover data were derived from SPOT5 MS satellite images

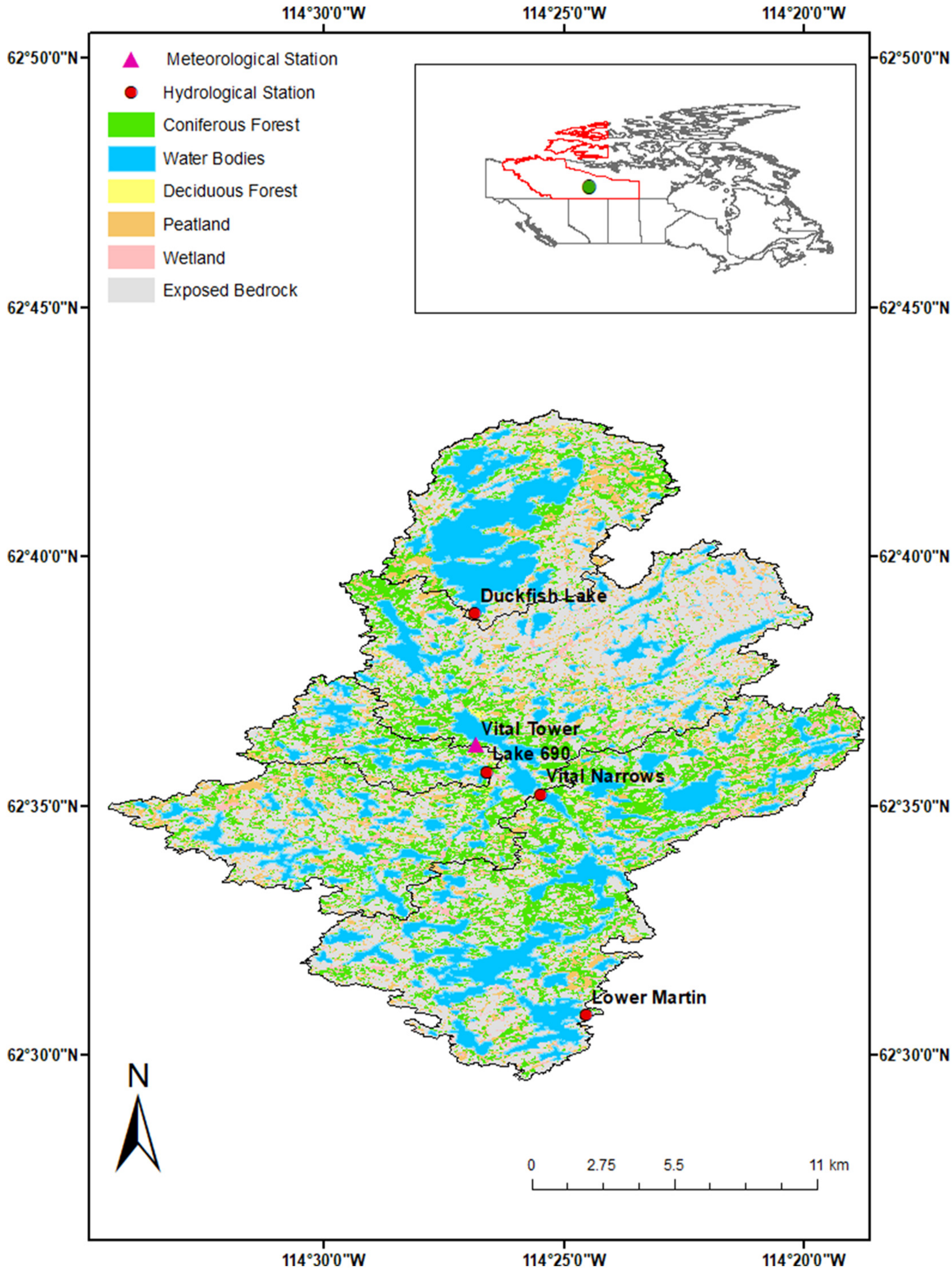

Fig. 1. Map of the Baker Creek catchment (above the Lower Martin lake outflow) and three sub-catchments (Duckfish Lake, Lake 690, Vital Narrows) used in this study. Land cover and locations of meteorological and hydrometeorological stations are shown (Projection: NAD 1983, UTM 11N). The Northwest Territories are outlined in red in the inset map, with the location of the Baker Creek catchment denoted by the green circle.

collected on May 24, 2008 and June 20, 2009. The images were classified into land cover using a maximum likelihood of supervised classification of a composite image of the two satellite images. The Normalized Difference Vegetation Index and all four multispectral bands were used as input (Spence and Hedstrom, 2018). Both land cover and elevation data have a 10 m resolution.

2.2.2. Hydrometeorology

Temperature and precipitation data from the Vital upland climate tower (VT) (Fig. 1) for 2005–2016 were obtained from Spence and Hedstrom (2018). Regional temperature and precipitation data were obtained from the Meteorological Service of Canada Yellowknife A climate stations (YKA: stations 1706 (1955–2013) and 51058 (2013–2019); http://www.climate.weather.gc.ca) using the R data retrieval package ‘weathercan’ (LaZerte and Albers, 2018). At VT, temperature data were obtained with a Vaisala HMP45C thermohygrometer, and rainfall data were collected with a Texas Instruments TE-525M tipping bucket rain gauge (Spence and Hedstrom, 2018). The VT station operates from approximately early April until November annually. For VT temperature and rainfall, half-hourly data were converted into daily values. Gaps in the data were infilled by

Table 1
Catchment characteristics for the Baker Creek catchment (Lower Martin), and three sub-catchments (Spence and Hedstrom, 2018).

Name	Catchment area (km^2)	Land cover (%)				Average annual runoff (mm)
		Surface water	Forest	Wetland	Bedrock	
Lake 690	9	21	25	15	39	115
Duckfish	25	34	17	16	33	40
Vital Narrows	102	22	19	16	43	108
Lower Martin	155	23	21	16	40	49

linear regression using data from YKA, which lies ~5 km from the southern end of the catchment. For the winter period outside of normal tipping bucket operation at VT, rainfall amounts for days with an average temperature above zero degrees were also estimated as above, assuming precipitation under these conditions falls as rain. When winter period data were missing in both stations, they were infilled using the predictive mean matching method (package: 'imputeTS'; function 'mice'; Moritz and Bartz-Beielstein, 2017). Daily snowfall accumulation during the period when rainfall gauges were not in operation was estimated by interpolation, according to the snow water equivalent (SWE) amount measured in April (Spence and Hedstrom, 2018). For the period between the snow survey and tipping gauge activation each year, precipitation as snowfall at VT was estimated using snowfall amount observed at YKA. Total daily precipitation at VT was taken as the sum of these rainfall and snowfall reconstructions.

Hydrological data at the outlet of Lower Martin Lake collected by WSC (1983–2017) was retrieved from https://wateroffice.ec.gc.ca/search/historical_e.html. Warm-season discharge data for the three sub-catchments (Duckfish Lake (2009–2016), Lake 690 (2008–2016), and Vital Narrows (2005–2016)) operated by the Science and Technology Branch of Environment and Climate Change Canada, were available from Spence and Hedstrom (2018).

2.2.3. Organic carbon

Water samples for DOC analysis (n = 64) were collected downstream of the outlet of Lower Martin Lake approximately biweekly during the open-water season (~May–September) of 2012–2016 by the Government of the Northwest Territories Water Resource Division. These samples represent a wide range (70 %) of the discharge conditions (0–2.8 m s^{-1}) during this period, only missing peak flows (approaching 4.1 m s^{-1}) in 2012. For two other sites, Lake 690 (n = 12; 2012–2014) and Vital Narrows (n = 6, 2015–2016), grab samples were also collected during the open-water season. These water samples were filtered to 0.45 μm and analyzed for DOC using infrared combustion (method: SM5310:B; detection limit 0.5 mg L^{-1}) at the Taiga Environmental Laboratory, NT. Additionally, DOC was sampled at Duckfish Lake in the summer of 2019 and analyzed by Shimadzu Total Organic Carbon combustion analyzer at the Environmental Geochemistry Laboratory (University of Waterloo, method detection limit 0.3 mg L^{-1}) and used to inform this study.

2.3. Modelling approach

A coupled model framework using PERSiST and INCA-C was used in this research (Fig. 2). PERSiST is a semi-distributed hydrological model designed for modelling rainfall-runoff patterns for the INtegrated CAtchment (INCA) family of models (Futter et al., 2014). Input data for PERSiST consists of daily temperature and precipitation (Futter et al., 2014; de Wit et al., 2016a). PERSiST has been used across catchment scales from small headwater boreal systems in Sweden, to moderate-sized temperate catchments in Norway (Couture et al., 2014) and the UK (Futter et al., 2014), as well as in large sub-tropical catchments like the upper Ganga and Brahmaputra (Futter et al., 2015). PERSiST is used to generate a time-series of daily Hydrologically Effective Rainfall (HER) and Soil Moisture Deficit (SMD) for use in INCA. PERSiST calculates HER as precipitation minus the sum of evapotranspiration and interception. PERSiST model version 1.6.4 was used in this study.

The INCA-C model is based on the Integrated Catchment Model for Nitrogen, developed in Europe with the aim of understanding catchment nutrient budgets (Whitehead et al., 1998). The model integrates hydroclimatic processes with terrestrial components and simulates DOC fluxes (Futter et al., 2007; Oni et al., 2012) at daily time steps. It incorporates information about in-soil C processes, surface water processes, and landscape-scale water movement and is described in detail in Futter et al. (2007) and Ledesma et al. (2012). Briefly, the model represents the transfer of organic C between terrestrial and surface water environments, with the ability to represent sub-catchment behaviour as part of model parameterization (Futter et al., 2007). The terrestrial part of the model was represented using three land cover classes (bare rock, forest, wetland). Processes include litter breakdown, organic carbon sorption/desorption, and mineralization. Forest and wetland classes are represented using an upper

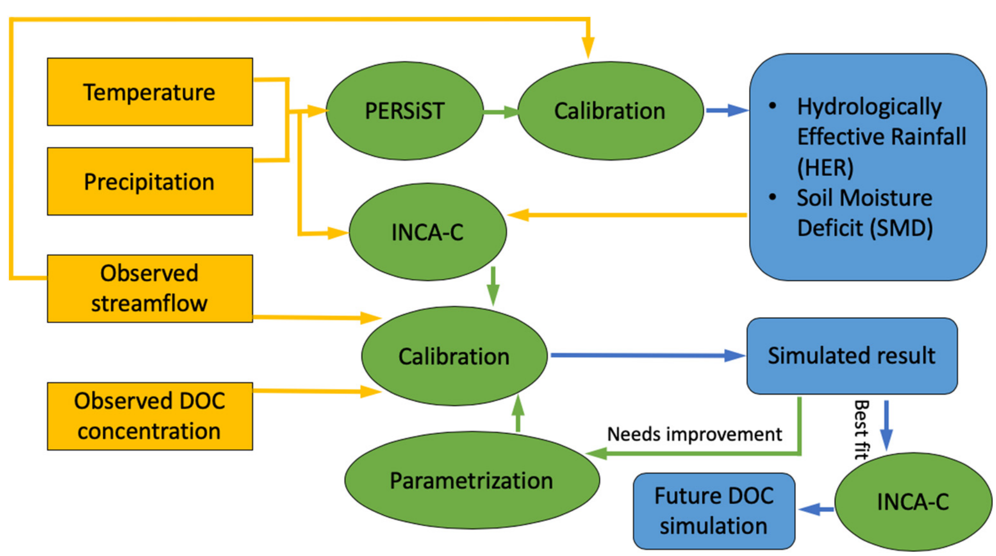

Fig. 2. Flowchart of the modelling approach (gold rectangles represent inputs, green ovals represent methodological steps, and blue rounded boxes represent output). Note: Daily temperature and precipitation data from the Vital upland tower station was used as input for PERSiST. Output from PERSiST (SMD and HER) were used as input for INCA-C. PERSiST was calibrated using streamflow data. INCA-C was calibrated using streamflow and available observed DOC concentration data from the Baker Creek sampling sites.

organic-rich soil compartment (high DOC), and a lower mineral soil compartment (low DOC) (Ledesma et al., 2012). Water can flow through these compartments, or above the land surface (e.g. saturation excess overland flow), and to the stream.

The surface water environment (stream) is modelled as a single stream reach or a branched stream network. Surface water biogeochemical processes in INCA-C include sedimentation, transformation of potential dissolved carbon to DOC, DOC mineralization, photosynthesis, and diffusion of DIC to the atmosphere (see details in Futter et al., 2007; Ledesma et al., 2012). The model is run using daily HER and SMD as inputs and operates at a daily time step. Although the most robust record of observations is available at Lower Martin, this study used the new branching version of INCA-C (Version: Branching_INCA-C_v2.0.0_BETA_14) to model the more diverse behaviour in Baker Creek sub-catchments. The 2012–2016 period, spanning a wide range in streamflow conditions from moderately wet to extremely dry, was used for model calibration, as this period featured the most complete data record, including DOC observations, meteorological data, and streamflow records for Baker Creek (Lower Martin) and sub-catchments. All annual results (observed and scenario) are summarized on a September 1–August 31 hydrological year.

2.4. Model calibration

2.4.1. PERSiST

The PERSiST model calibration strategy followed the steps described by Futter et al. (2014). The model was first calibrated manually using daily discharge data spanning the period where both DOC and discharge observations were available (2012–2016). The main focus of the manual calibration was to get appropriate water balance parameters by calibrating the water routing matrix. To simulate discharge, PERSiST was parameterized to allow water to move quickly with low water loss by evapotranspiration; much of the water was routed via the faster layer to streamflow. A quasi-nested approach to manual calibration was used, where headwater catchments (Duckfish and Lake 690) were calibrated first. Influential parameters were updated iteratively when a better-simulated result than the previous starting point was obtained. At each iteration, model performance was evaluated using coefficient of determination (R^2), Nash-Sutcliffe efficiency (NS), Log Nash Sutcliffe efficiency (Log (NS)), the absolute proportional difference (AD) and the ratio of variances of modelled and observed values (Var) as goodness-of-fit metrics for the five-year calibration period. After obtaining a satisfactory fit for these records, the downstream stations at Vital Narrows and Lower Martin were calibrated using the same approach. This parameter set from manual calibration, was used in Monte Carlo (MC) analysis to explore parameter space and generate an ensemble of behavioral parameter sets. Tolerance windows for sensitive parameters (Table S1) were set as ± 25 % of the values obtained through manual calibration. The MC analysis gave one best-performing parameter set from each iteration. The best-performing parameter set from all iterations was identified by checking goodness-of-fit metrics and this was used to generate a single SMD and HER input set for INCA-C.

2.4.2. INCA-C

The INCA-C model was calibrated manually using daily discharge and DOC observations for four sub-catchments (Duckfish Lake, Lake 690, Vital Narrows, and the outlet of Lower Martin Lake). Again, a quasi-nested approach was used, however, the Lower Martin outlet was the focus of our INCA-C modelling as this site had a robust record of DOC observations. Vital Narrows and Lake 690 had only sparser observations for some years during the calibration period. Observations were not available at Duckfish in the calibration period; however, an observation for 2019 (52 mg L^{-1}) and visual observations of darker colour of water in downstream reaches when this sub-catchment is hydrologically connected (C. Spence, pers. comm.), suggest an important source of DOC. Collectively, the observations at Duckfish Lake, Lake 690, and Vital Narrows were used to guide model parameterization and to ensure that the model was able to capture spatial variability in DOC within the study catchment.

The initial focus of manual calibration was streamflow, to achieve similar or better performance than obtained from PERSiST. After calibrating for streamflow, the in-soil parameters governing C processes (e.g. C input, transformation) were calibrated to model DOC concentration. Model performance for both discharge and DOC simulations for the calibration period was evaluated using goodness of fit metrics (R^2, NS, Log (NS), AD, and Var). In addition to evaluating model predictions of discharge and DOC concentration, the manual calibration was also evaluated for the behaviour of potential DOC (in the direct runoff layer) and DOC (in organic and mineral layer) pools. In instances where the calibration did not yield relatively constant pools (which leads to unstable forecast simulations), further calibration was performed. While MC analysis was also explored as a follow up to manual calibration in an effort to further improve calibration performance (as described above for PERSiST), this step did not yield simulations that both improved on manual calibration performance and maintained stable C pools necessary for meaningful simulations. Thus, the manual calibration was used for scenario analysis.

2.5. Hydroclimatic scenarios

Future catchment behaviour was simulated by running PERSiST and INCA-C for three 30-year scenarios, one of which represents baseline conditions, and two possible future scenarios. Daily temperature and precipitation for input to PERSiST were generated using the package CoSMoS (Papalexiou et al., 2021), which is used to extend or generate time-series data by preserving the probability distribution and linear autocorrelation structure. The baseline (reference) scenario was generated using the data record for VT, extended to 30 years. Future scenarios for a warmer (elevated temperature) and a warmer and wetter climate (elevated temperature and precipitation) were also generated using this method (nominally 2066–2095). Given that any increase in precipitation will not occur in the absence of a temperature increase in this northern region where climate warming is pronounced, no precipitation-only scenario was modelled as it would not yield a plausible outcome. To derive the future climate scenarios, it was assumed that temperature and precipitation increased linearly according to the trends for the region ($+0.52$ °C per decade, $+6.5$ % precipitation per decade) reported by De Beer et al. (2016). Note that this approach does not account for seasonal changes in precipitation amount (which remain uncertain) or temperature patterns that may occur as the regional climate changes (e.g. De Beer et al., 2016), but does account for phase changes associated with changing temperature, by partitioning precipitation phase according to daily average temperature (with 0 °C used as threshold for partitioning between snow and rain).

Simulated total annual discharge amount and projected total annual precipitation were used to calculate annual runoff ratios under baseline and future scenarios. Annual C fluxes (g m^{-2} d^{-1}) under baseline, elevated temperature, and elevated temperature and precipitation scenarios were calculated as the sum of daily fluxes, which were estimated as the product of simulated daily DOC concentration and flow divided by catchment area. Uncertainty was explored using 90 % confidence interval values and 5th percentile (Q5) and 95th percentile (Q95) values were calculated for average discharge, DOC concentration, and DOC flux.

3. Results

3.1. Model calibration

INCA-C simulations yielded a good fit between observed and simulated discharge (Fig. 3, Table 2). The calibration did an adequate job of reproducing discharge peaks, providing calibration performance similar to PERSiST (Table S2). Simulations of peak flows were reasonably strong at Duckfish Lake, Vital Narrows, and Lower Martin but somewhat weaker at Lake 690 (Table 2). Variance ratios were closest to 1.0 for Duckfish (with a shorter observational record) and Lower Martin, but discharge amount for these stations was overestimated, owing in part to overestimation of peak discharge during spring freshet and baseflow in dry years (Fig. 3). Overall, it

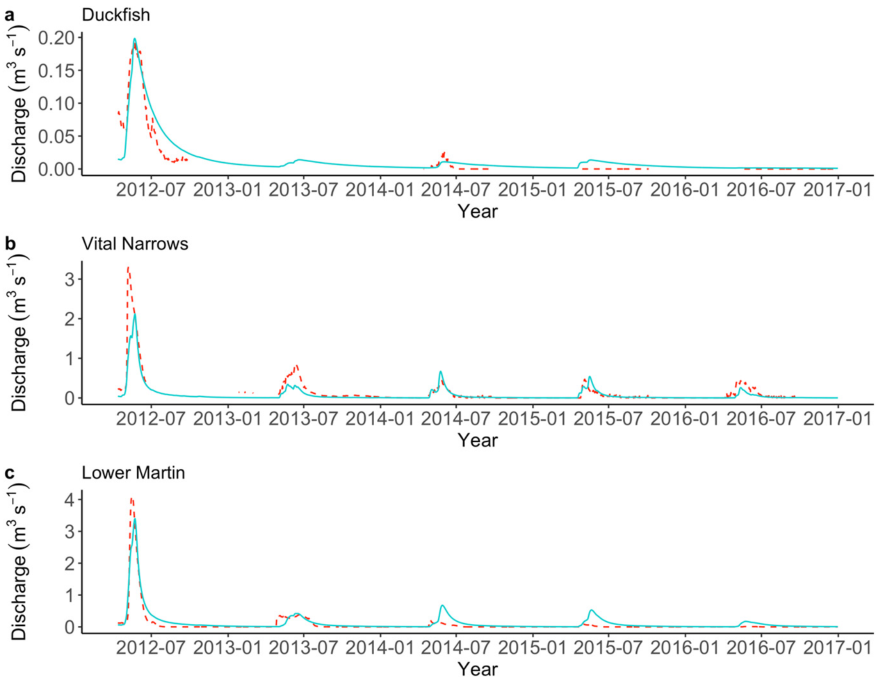

Fig. 3. INCA-C simulated (blue) and observed (dashed red) discharge ($m^3\ s^{-1}$) at Duckfish (a), Vital Narrows (b), and Lower Martin (c) (2012–2016).

was possible to reasonably capture different hydrological behaviors such as peak flow in spring, and variation in discharge amount in wet and dry years, including hydrological drought after 2012, using INCA-C. It is worth noting, however that the strength of the predictions varied according to the station of interest and goodness-of-fit metrics. Baker Creek at Duckfish Lake for example, was difficult to model robustly as the model did not successfully represent its intermittent flow.

INCA-C was able to provide a reasonable simulation of DOC dynamics at Lower Martin (Fig. 4a), during the calibration period representing extremely dry to moderately wet conditions, although model performance varied interannually. Low R^2 for DOC concentration at both Vital Narrows (0.31) and Lower Martin (0.19) were reported, and DOC concentration was underestimated at Lower Martin (AD: −0.32). The calibration did an adequate job of reproducing DOC peaks with the Var (~1) at Lower Martin. The best model fit for Lower Martin DOC concentration was observed in dry years (2014 and 2015); both high and low DOC concentrations were captured. At Duckfish Lake, observed DOC concentration in the post-drought period was high (52 mg L^{-1} in 2019). Together, this suggests that the connectivity of Duckfish Lake can be important for downstream DOC patterns in Baker Creek. Investigation of weekly C fluxes (2012–2016; Fig. 4b) for Lower Martin shows evidence that DOC flux can be both underestimated and overestimated at times during the calibration period. Except for few observations in 2013 and 2014, the overall tendency was for DOC flux to be overestimated (Fig. 4b), despite DOC concentrations being underpredicted overall (Fig. 4a). The overestimated DOC flux is largely a consequence of discharge overestimation, particularly during 2014 and 2015 (Fig. 3c).

Table 2
INCA-C manual calibration of discharge in four stations in the Baker Creek catchment, using five goodness-of-fit metrics including the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NS), Log Nash-Sutcliffe efficiency (Log (NS)), the variance ratio (Var) and the absolute proportional difference (AD).

Sub-catchment	R^2	NS	Log(NS)	Var	AD
Lake 690	0.60	0.59	0.50	0.60	−0.04
Duckfish	0.86	0.84	−0.11	0.96	0.62
Vital Narrows	0.82	0.74	0.67	0.43	−1.24
Lower Martin	0.86	0.85	−0.89	0.79	0.57

Discharge was a major control on annual DOC export in the Baker Creek catchment. Flow weighted mean DOC export at Lower Martin was 0.36 g $m^{-2}\ yr^{-1}$ in a wet year (2012) and 0.05 g $m^{-2}\ yr^{-1}$ on average in dry years (2013–2016). High DOC export in 2012 and low export in dry years shows the importance of hydrological connectivity with C rich sources for C export. This is further explained by the connectivity of Duckfish Lake to the lower reaches. In 2012, Duckfish Lake was connected to lower reaches for a prolonged period when DOC concentrations remained elevated; however, in dry years surface flow from Duckfish Lake (Fig. 3) was short-lived (2014) or did not occur (2015, 2016). Without flow from Duckfish Lake (16 % of catchment area), which available observations suggest features higher DOC, concentrations at Lower Martin decreased more rapidly on the falling limb of the hydrograph (e.g. 2015, 2016; Fig. 4a).

3.2. Climate change effects on future catchment behaviour

3.2.1. Discharge

Simulated average annual discharge under baseline, elevated temperature, and elevated temperature and precipitation scenarios revealed important differences (Fig. 5). The predicted average discharge under the baseline scenario at Duckfish Lake is 0.04 $m^3\ s^{-1}$, Vital Narrows is 0.22 $m^3\ s^{-1}$, and Lower Martin is 0.37 $m^3\ s^{-1}$ (Table 3). The average discharge is predicted to decrease under elevated temperature and increase under elevated temperature and precipitation scenarios (Table 3).

Interannual flows are predicted to be highly variable, with simulated average annual discharge for Duckfish (9×10^{-3}–0.1 $m^3\ s^{-1}$), Vital Narrows (0.01–0.4 $m^3\ s^{-1}$), and Lower Martin (0.03–0.7 $m^3\ s^{-1}$) spanning more than an order of magnitude (Table 3). Wide ranging wet and dry conditions have been observed for the Lower Martin catchment during the operation of the WSC gauge (Fig. S1). Under the elevated temperature scenario, average annual discharge at Duckfish, Vital Narrows, and Lower Martin demonstrated an absolute decline relative to the baseline. Under the elevated temperature and precipitation scenario, average annual discharge is predicted to increase by 175 %, 122 %, and 116 %, for Duckfish, Vital Narrows, and Lower Martin, respectively. Compared to the baseline condition, we found that annual discharge under the elevated temperature scenario was less variable, but was more variable under the elevated temperature and precipitation scenario (Fig. 5, Table 3). The predicted average annual runoff ratio under the baseline scenario at Duckfish Lake is 0.17,

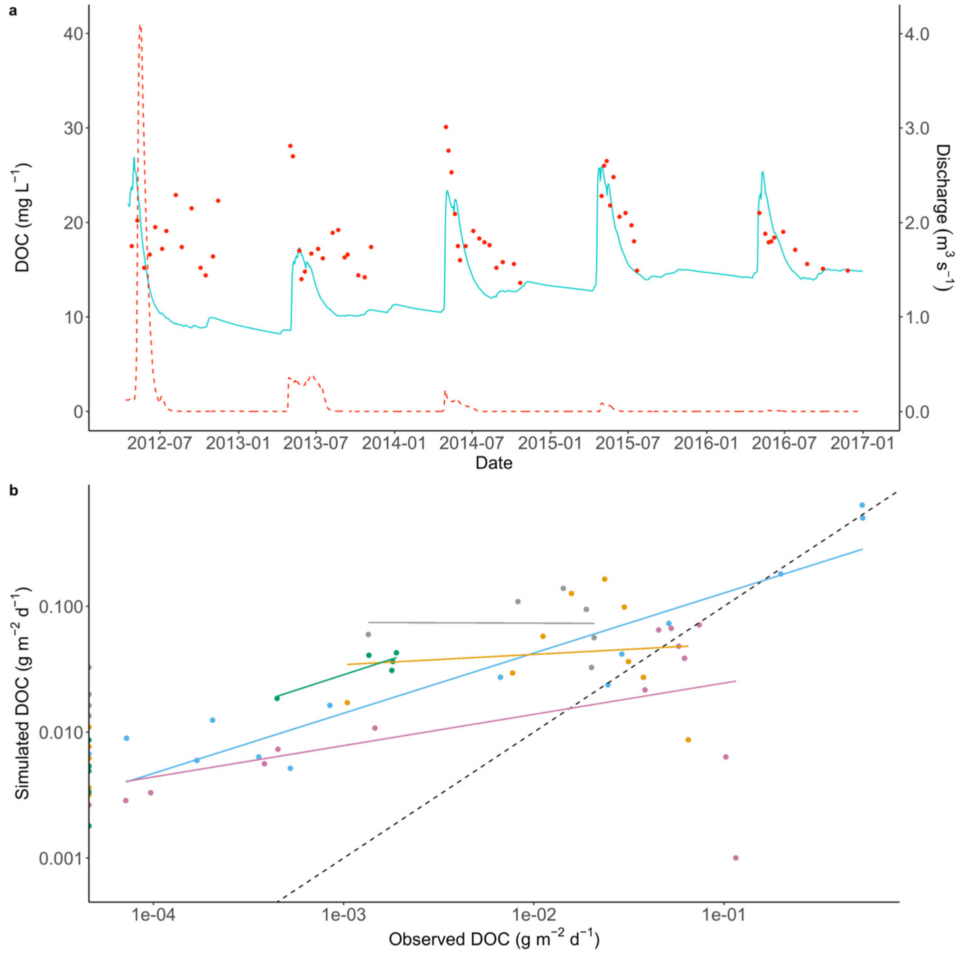

Fig. 4. INCA-C (a) simulated (blue line) and observed DOC (red circles), and discharge (red dashed line), and (b) simulated and observed weekly DOC flux at Lower Martin (2012–2016), with coloured points and lines representing individual years (blue: 2012, pink: 2013, orange: 2014, grey: 2015, green: 2016). The coloured lines in (b) represent a regression line of the observations in a given year, and the 1:1 line (dashed black) is also shown.

Vital Narrows is 0.24, and Lower Martin is 0.26. This is predicted to decrease notably under elevated temperature (Duckfish: 0.13, Vital Narrows: 0.18, Lower Martin: 0.19) and increase under elevated temperature and precipitation scenarios (Duckfish: 0.35, Vital Narrows: 0.37, Lower Martin: 0.40).

At Lower Martin, under the elevated temperature scenario average daily discharge is predicted to increase in March and April and decrease from May to November (Fig. 6). Under the elevated temperature and precipitation scenario, average daily discharge and Q95 values of average daily discharge were simulated to increase throughout the year, although the magnitude of increase varies seasonally (Fig. 6). Under this scenario, a pronounced secondary peak of discharge in late fall and early winter was predicted. The average daily rainfall (Fig. S2) is projected to increase under the elevated temperature scenario from March to Mid-May and from Mid-October through November whereas snowfall during these periods would decrease (no change in total precipitation). Under the elevated temperature and precipitation scenario, both rainfall and snowfall were simulated to increase with the shift in the highest rainfall peak from July to September (Fig. S2). In this scenario, higher rainfall amounts in fall are the likely driver of the secondary discharge peak from September to November (Fig. 6).

3.2.2. Dissolved organic carbon

INCA-C simulated average annual DOC concentration for the baseline, elevated temperature, and elevated temperature and precipitation scenarios revealed key differences (Fig. 5). The simulated annual average DOC concentrations at Duckfish (15–31 mg L^{-1}), Vital Narrows (5–12 mg L^{-1}), and Lower Martin (7–15 mg L^{-1}) under the baseline scenario were highly variable, however Duckfish DOC concentrations were characteristically higher. This reflects a parameterization approach needed to align with observations of higher DOC waters for this sub-catchment.

Under the elevated temperature scenario, annual average DOC concentrations at Duckfish (14–36 mg L^{-1}), Vital Narrows (4–12 mg L^{-1}), and Lower Martin (6–15 mg L^{-1}) were similar to the baseline scenario. Under the elevated temperature and precipitation scenario, annual average DOC concentrations at Duckfish (8–19 mg L^{-1}), Vital Narrows (4–8 mg L^{-1}), and Lower Martin (6–12 mg L^{-1}) demonstrated an absolute decline relative to baseline conditions.

Simulations of DOC export from the Baker Creek catchment under baseline, elevated temperature, and elevated temperature and precipitation scenarios illustrated potential changes in C dynamics (Table 3). The average DOC export under the baseline scenario at Duckfish is 1.10 g m^{-2} yr^{-1}, Vital Narrows is 0.90 g m^{-2} yr^{-1}, and Lower Martin is 2.51 g m^{-2} yr^{-1}. Exports are projected to decrease (Duckfish: 0.80 g m^{-2} yr^{-1}; Vital Narrows: 0.67 g m^{-2} yr^{-1}; Lower Martin: 1.89 g m^{-2} yr^{-1}) under the elevated temperature scenario compared to the baseline scenario (Table 3). Under conditions of elevated temperature and precipitation, however, DOC export is projected to increase (Duckfish: 2.00 g m^{-2} yr^{-1}; Vital Narrows: 1.48 g m^{-2} yr^{-1}; Lower Martin: 4.19 g m^{-2} yr^{-1}). At Lower Martin, the average daily and Q95 DOC exports were modelled to increase from March to May and October to December under the elevated temperature and precipitation scenario (Fig. 7). In contrast, for the elevated temperature scenario, DOC export was predicted to increase in April and decrease in May and June.

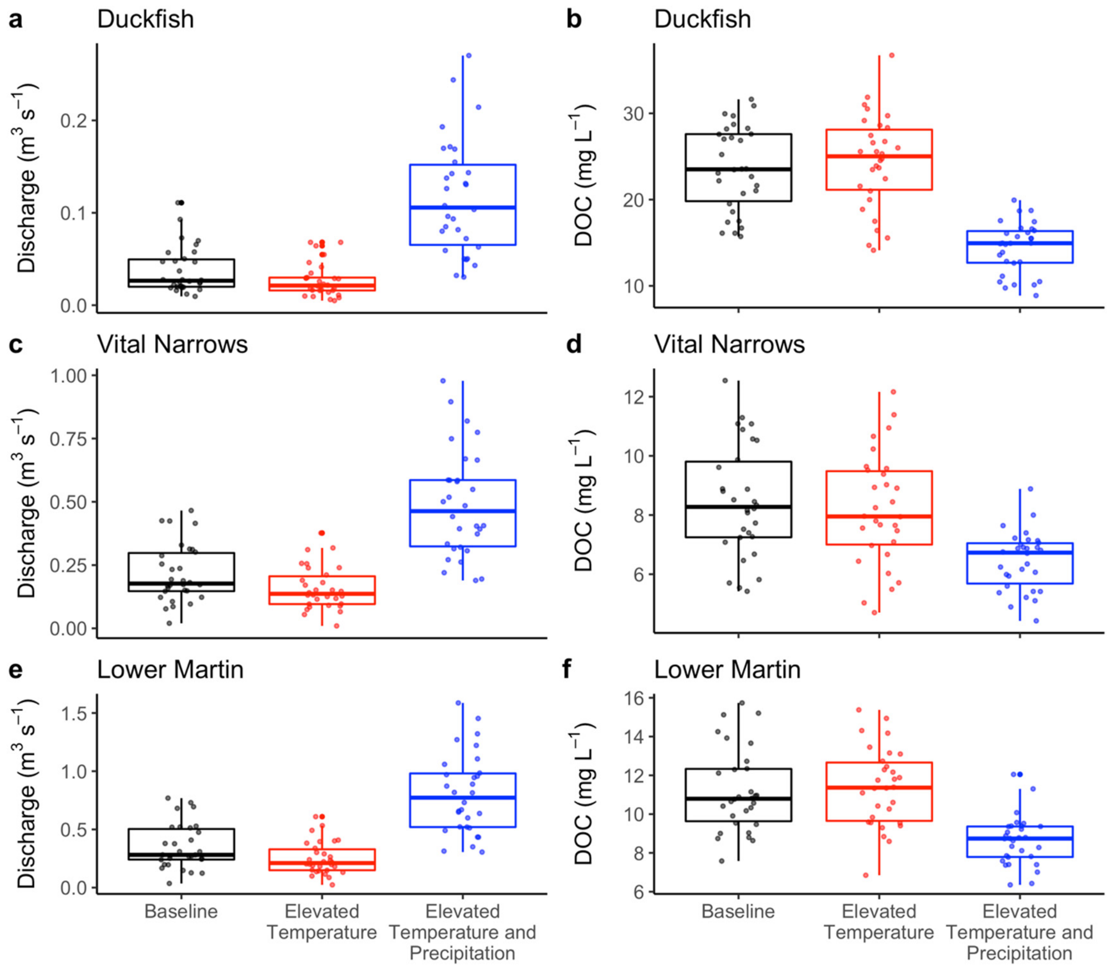

Fig. 5. Boxplot showing INCA-C simulated average annual discharge (m^3 s^{-1}) and DOC concentration (mg L^{-1}) for 30-year baseline (black), elevated temperature (red), and elevated temperature and precipitation (blue) scenarios at Duckfish (a, b), Vital Narrows (c, d), and Lower Martin (e, f). Points shown represent individual year averages simulated for each scenario. Note the difference in y-axis scales across panels in each column.

4. Discussion

Baker Creek exhibits diverse hydrological behaviour and despite a complex catchment with a multitude of connections and disconnections between water bodies (Phillips et al., 2011), overall catchment behaviour during the calibration period was well captured through our modelling. There was a tendency, however, for the models to overestimate the flow and underestimate concentration in certain years. While these challenges with respect to simulations of discharge are not unexpected given the relative simplicity of hydrological process representation in these models, this approach has provided a basis through with to explore the behaviour of the catchment. Here we explore model performance and limitations, and use the model representation of the catchment to predict and understand long-term hydroclimatic behaviour on the Baker Creek catchment. These future scenarios are likewise used to illustrate potential changes in carbon export as the climate warms and wets.

4.1. Model performance and limitations

This modelling approach proved successful in simulating inter- and intra-annual discharge patterns in Baker Creek and its sub-catchments. Among the four sub-catchments, INCA-C reasonably captured discharge (2012–2016) in three locations (Duckfish Lake, Vital Narrows, and Lower Martin). During this period, high flow years with high precipitation (e.g. 2012) were better captured. During dry periods when discharge from Duckfish was transient or absent, however, the model was not able to

Table 3
INCA-C model projected average discharge (m^3 s^{-1}) and DOC flux (g m^{-2} yr^{-1}) with 90 % confidence interval range (in parentheses) under baseline, elevated temperature, and elevated temperature and precipitation scenarios. Change in discharge and DOC export (% change from baseline) at Duckfish Lake, Vital Narrows, and Lower Martin is also known.

Catchment	Parameter	Baseline	Elevated temperature		Elevated temperature and precipitation	
		Average	Average	Change	Average	Change
Duckfish	Discharge	0.04 (0.03, 0.05)	0.03 (0.02, 0.04)	−25 (−33, −22)	0.11 (0.09, 0.13)	175 (160, 200)
	DOC flux	1.1 (0.9, 1.3)	0.8 (0.6, 1.1)	−27 (−33, −15)	2 (1.7, 2.3)	81 (76, 88)
Vital Narrows	Discharge	0.22 (0.18, 0.26)	0.17 (0.13, 0.20)	−22 (−27, −23)	0.49 (0.43, 0.55)	122 (111, 138)
	DOC flux	0.90 (0.74, 1.05)	0.67 (0.54, 0.80)	−25 (−27, −23)	1.48 (1.28, 1.68)	64 (60, 73)
Lower Martin	Discharge	0.37 (0.30, 0.43)	0.27 (0.21, 0.32)	−27 (−30, −25)	0.8 (0.70, 0.90)	116 (109, 133)
	DOC flux	2.51 (2.10, 2.91)	1.89 (1.55, 2.22)	−24 (−26, −23)	4.19 (3.66, 4.72)	67 (62, 74)

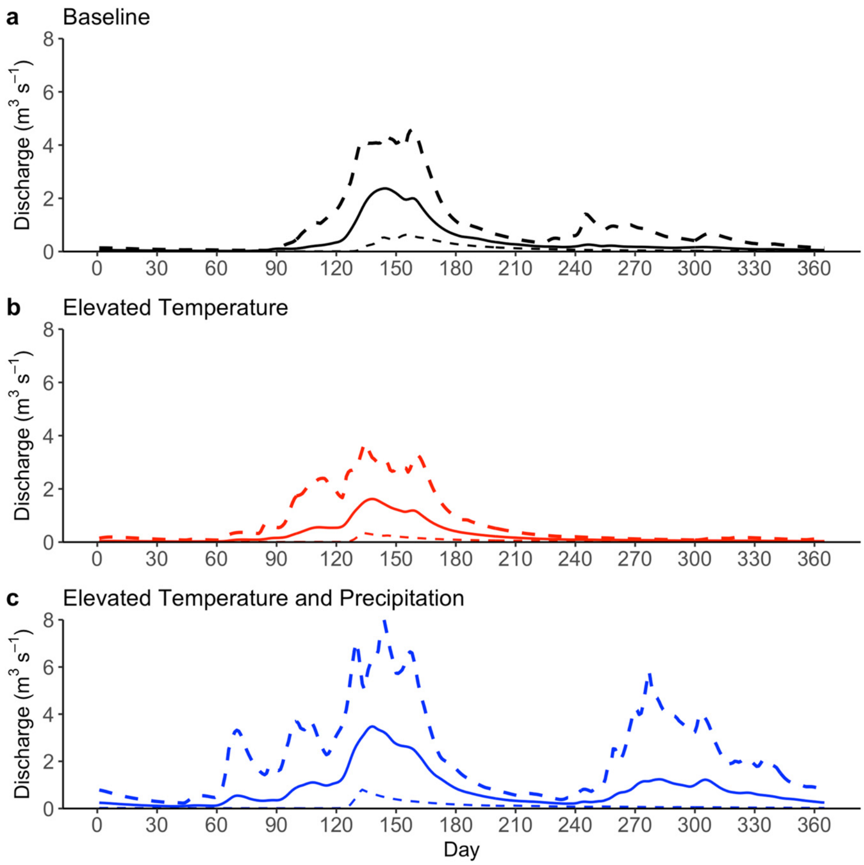

Fig. 6. Average (solid line), Q5 (thin dashed line), and Q95 (thick dashed line) daily discharge over 30 years under (a) baseline, (b) elevated temperature, and (c) elevated temperature and precipitation scenarios at Lower Martin.

represent these hydrologically disconnected periods and consequently baseflow was overestimated, although the timing of peak flow simulation was good. The model captured variability in flow magnitude, but discharge amounts were both underestimated (Lake 690 and Vital Narrows) and overestimated (Duckfish and Lower Martin). Some of the challenges to capturing the streamflow dynamics include the heterogeneity of the lake distribution among sub-catchments and widespread beaver activities (Spence and Hedstrom, 2018) that both alter flowpaths and lead to transient changes in stream network connectivity that are not represented with the semi-distributed structure of INCA-C.

Patterns of DOC concentrations were not captured as well as discharge by the model, but nonetheless described the overall behaviour for Lower Martin ($R^2 = 0.19$, Var $= 0.96$). In a larger domain model of DOC behaviour for rivers draining into the Arctic, DOC concentration has also been shown to be difficult to capture, and predictions of seasonal concentrations can be overestimated by a factor of two (Rawlins et al., 2021). Limited DOC observations for the sub-catchments made it difficult to meaningfully assess model performance at these locations, but we were able to represent expected differences in DOC concentration for different sub-catchments. While performance was not as strong as reported for other INCA-C applications in northern catchments (de Wit et al., 2016a, 2016b; Ledesma et al., 2012; Oni et al., 2012; Oni et al., 2014), this may be attributed in part to the challenge of capturing timing of flows from different sub-catchments with contrasting DOC concentrations. Overall, DOC concentrations are not well linked to discharge magnitude at Lower Martin. For instance, during wet periods when Duckfish is connected, it is expected to deliver high DOC waters to downstream reaches. Thus, it is necessary to accurately represent both the magnitude and timing of flow, as well as the DOC concentrations in these waters, to effectively represent the larger catchment. In drier years when the contributing area is smaller, the data clearly show the absence of higher DOC concentration water in the receding limb of the hydrograph, and this is better captured in the model simulations. Given the importance of accurate discharge simulation to simulation of DOC concentration, improvements to the model structure that improve representation of hydrological behaviour (e.g. through better representation of lake fill and spill processes), could enhance the ability of the model to represent DOC patterns.

We also note that due to extreme seasonality and long periods of ice cover in the region, DOC observations were not available during these periods, so this can contribute to uncertainty around our predictions of annual DOC fluxes. During these winter low flow periods, our simulations suggested low DOC concentrations, consistent with Rawlins et al. (2021) model representation of larger rivers in northern North America. During the winter period when DOC concentrations at Lower Martin are predicted to be low, flows from the catchment are typically very low (or zero). Given this, winter is not typically a period of notable DOC export, but may become one with increased temperatures and precipitation amounts. This presents an opportunity to further evaluate and potentially refine our model application in the future. We should also acknowledge the potential for equifinality. Previous modelling applications have highlighted over-parameterization and compensatory behaviour in parameter space as reasons for equifinality (Beven and Binley, 1992; Futter et al., 2007). While our focus here is on the manual calibration results, it is possible given a large number of parameters available in the model that alternate parameter sets could yield similar model performance, although the MC analysis suggests this is not likely.

4.2. Catchment hydroclimatic behaviour

Simulations under an elevated temperature scenario suggested a decrease in average annual discharge for Baker Creek. Decreased average annual discharge has also been predicted for Subarctic catchments in northern

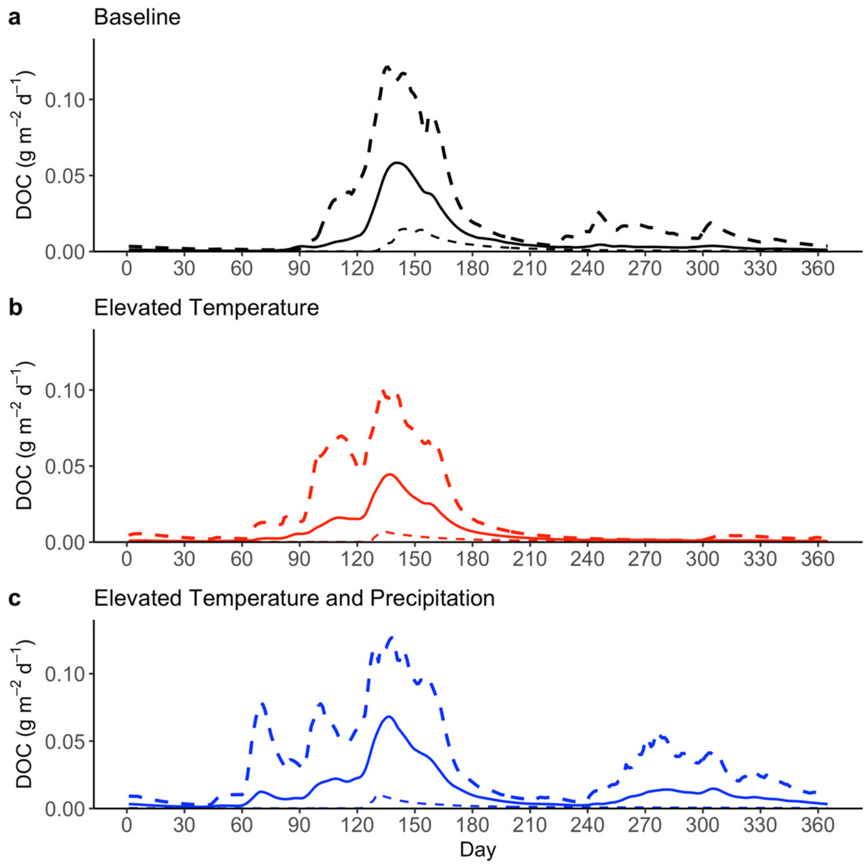

Fig. 7. Average daily DOC export (g m^{-2} day^{-1}), Q5 (thin dashed line), and Q95 (thick dashed line) over 30 years under baseline (a), elevated temperature (b), and elevated temperature and precipitation (c) scenario at Lower Martin.

Fennoscandia (Lotsari et al., 2010). At Baker Creek, lower discharge under the elevated temperature scenario was associated with runoff ratio decreases of more than 20 % (Duckfish Lake: −23.5 %; Vital Narrows: −25 %; Lower Martin: −27 %). Daily discharge in early spring is predicted to increase under warmer conditions that prompt earlier snowmelt, while a decrease in discharge during the remainder of the year is due to higher evapotranspiration, which aligns with findings across the circumpolar north (Vihma et al., 2016). Moreover, increasing evapotranspiration has the potential to decrease the contribution of discharge from upstream lakes such as Duckfish, which ultimately limits the active stream network and lowers contributing area (Phillips et al., 2011; Spence et al., 2010). Residence time of lakes in the catchment was also predicted to increase (Table S3).

Under the elevated temperature and precipitation scenario, the net effect is a wetting of the catchment, promoting increased discharge. This parallels observations for other Subarctic catchments such as in northern Sweden (Andréasson et al., 2004). The increase in precipitation and temperature in the catchment affects hydrological drivers such as runoff contributing area, effective precipitation, active stream networks, permafrost thaw, hydrological storage, and baseflow (Connon et al., 2014; Phillips et al., 2011; Spence et al., 2010; Morse et al., 2016). In Baker Creek, a projected increase in discharge under the elevated temperature and precipitation scenario is linked with projected increase in runoff ratio (Duckfish Lake: increased by 106 %; Vital Narrows: increased by 54 %; Lower Martin: increased by 54 %), which we attribute to higher precipitation and increasing connectivity of the catchment. In Baker Creek or other Subarctic catchments where permafrost is an important feature, INCA-C may underestimate potential increases in discharge attributed to permafrost thaw, as it does not explicitly represent permafrost. It has been reported that in the flatter landscapes of the Boreal Plain ecozone, permafrost thaw can result in discharge amounts that exceed annual precipitation (Gibson et al., 2015).

Another important feature of the streamflow predictions under elevated temperature and precipitation is a shift in a nival flow regime to a combined nival and pluvial regime. Spence et al. (2011) suggested that there was evidence that Baker Creek and other regional streams were migrating to this combined regime, which is currently difficult to detect because of high interannual variability (Fig. S1). Because the calibration period was limited to five years, it remains unknown how well these simulations will capture catchment behaviour for a wider range of hydrological variability. While both wet and dry conditions were observed during the (five-year) calibration period, longer term climate variability, for example associated with the Pacific Decadal Oscillation that can affect streamflow in the region (Woo and Thorne, 2008) and contribute to greater hydrological variability across multi-year timescales has not been captured through this analysis.

While the calibration period included a multi-year dry period, our results highlight that under wetter and warmer conditions projected for the late 21st century, the autumn secondary discharge peak could become typical of an average year under wetter and warmer conditions, rather than being limited to exceptional years under historic climate conditions (Fig. 6). A shift in timing and form of precipitation are important to this pattern (Spence et al., 2011), and the warmer and wetter scenario features precipitation as rain later in the year (Fig. S2). While our modelling captures changes in form of precipitation, long-term intra-annual changes in precipitation timing remain uncertain, and could be explored in further work. That this type of shift in flow regime predicted for Baker Creek has also been reported for other already warmer Subarctic catchments in Fennoscandia (Lotsari et al., 2010; Beldring et al., 2008) provides more support for this conclusion.

4.3. Potential changes to carbon export

Changing hydroclimatic patterns could be a major control on C in Baker Creek. The simulated DOC concentration under the baseline and elevated temperature scenarios were comparable, but higher than for the elevated temperature and precipitation scenario (Fig. 5). Others have reported a diversity of DOC concentration responses to increased temperature (Evans et al., 2005; Xu et al., 2020; Oni et al., 2012). DOC dilution through enhanced surface flow has also been described (Clair et al., 2008). Under our scenarios, DOC concentration could be affected by parameters linked to changes in temperature or precipitation, such as terrestrial productivity and microbial mineralization. Our investigations suggest, however, that the model is relatively insensitive to changes in wetland and forest productivity (a five-fold increase in productivity yields only a three-fold increase in DOC concentration). Instead, as the rate of mineralization has a strong positive relationship with temperature (Gudasz et al., 2010), mineralization rates seem to be more important here, potentially compensating for productivity increases. For example, under the elevated temperature scenario, rates of microbial mineralization (% DOC mineralized per day) will be higher because of warmer conditions (and longer above 0 °C periods). At the same time, lower flows through organic and mineral soil layers under warmer conditions (Table S4) mean that less DOC is exported to the stream network. Moore et al. (1998) made similar predictions of limited change in DOC production, but decreasing DOC export associated with lower discharge amounts for northern peatlands under a warmer climate. Lower discharge under warmer conditions leads to longer residence time (Table S3), which appears to have the effect of concentrating the DOC exported to the stream network. This can yield concentrations comparable to the baseline scenario. In contrast, while total mineralization is higher under the elevated temperature and precipitation scenario because more DOC is being flushed to surface waters from the terrestrial catchment, higher discharge results in shorter residence times (Table S3) and effectively dilutes DOC concentrations.

Results herein, including catchment DOC export ranging from 0.9 to 2.5 g C m^{-2} yr^{-1} (Table 3) are broadly similar to larger domain modelling of western Arctic rivers (Rawlins et al., 2021), which suggested annual DOC export of up to 2.4 g C m^{-2} yr^{-1}. While the seasonal patterns in DOC concentration between these studies are also comparable, we did not observe a concentration-discharge relationship for Lower Martin, which had the most detailed observational DOC record, as both high and low DOC concentrations were observed across a narrow range of low flows (0–0.25 m^3 s^{-1}; Fig. 4). Concentration-discharge relationships, including transport limitation of DOC, and DOC dilution have been reported for headwater catchments in Alaska (Shogren et al., 2021). For Lower Martin, where the observed DOC concentrations can be highly dynamic, a complex arrangement of sub-catchments with varying runoff contributions (Table 1), timing and DOC concentrations likely plays a role. Importantly, one of the advantages of working with process-based models such as INCA-C is that they provide an opportunity to extend beyond the empirical, steady-state, concentration-discharge relationships by parameterizing to represent a range in conditions; this facilitates investigation of future behaviour. Our analysis, however, while exploring potential future change due to increasing temperature and precipitation, does not consider the potential of other events such as a regime shift, which can come as surprises (Carpenter et al., 2011). While not well understood, it has been suggested that C accumulation regimes of Alaskan peatlands are linked to hydroclimate (Swindles et al., 2015). Consequently, changes to hydroclimate that affect C storage behaviour of peatlands in similar ways in Baker Creek and surrounding region could result in threshold-type effects that we do not represent in the model (e.g., those associated with permafrost loss). Documented regime shift behaviour will provide an opportunity to enhance model representations of these ecosystems in the future.

Our analysis suggests that DOC export from Baker Creek will decrease if temperature increases occur in the absence of changes in precipitation. This is similar to what has been reported for the INCA-C simulation of the temperate Lake Simcoe catchment in southeastern Canada (Oni et al., 2011). In Baker Creek, DOC export decreased under the elevated temperature scenario because of an approximately 25 % projected decrease in discharge. Given that the Duckfish Lake sub-catchment has higher DOC concentration than observed at other locations in Baker Creek, and hydrologic connectivity is expected to decrease under warmer conditions, more infrequent connections with high C export parts of the catchment likely play an important role in these predicted patterns. Our climate scenarios in Baker Creek are consistent with observational studies from other landscapes where runoff-driven control in DOC export was observed (Worrall and Burt, 2007). A decrease in C flux (24–27 %) under similar DOC concentration but lower discharge (22–27 %) was predicted for the elevated temperature scenario. Similarly, simulations for the elevated temperature and precipitation scenario indicated an increase in C flux (64–81 %) associated with lower DOC concentrations and much higher discharge (116–175 %). For the latter scenario, a secondary DOC export peak in autumn and early winter in Baker Creek coincides with the winter discharge peak.

In Baker Creek, flow pathways were simulated to be proportionally similar under the elevated temperature, and elevated temperature and precipitation scenarios compared to baseline (~80 % of flow is through organic layer in both cases). The absolute amount of flow from the organic horizon, however, is predicted to be two times higher under elevated temperature and precipitation scenario (Table S4), and ~ 0.75 times lower under the elevated temperature scenario compared to the baseline scenario. Thus, under the elevated temperature and precipitation scenario, INCA-C predictions suggest that an increased flow amount can increase the DOC flux owing to a much greater volume of water but with lower DOC concentrations. This suggests supply limitation under warmer and wetter conditions, whereas DOC export may be transport limited under warmer conditions where the flow through this layer decreases. Consequently, DOC export is predicted to increase under the elevated temperature and precipitation scenario at Duckfish Lake, Vital Narrows, and Lower Martin Lake. This is consistent with predictions of future increases in DOC export in northern catchments (Clair et al., 1999; Tank et al., 2016). It should also be acknowledged that owing to the semi-distributed nature of INCA-C, simulations do not represent the typical *catena* structure observed in the catchment where water routes from upland bedrock and forest covered areas, to wetlands and finally to water bodies. As a consequence of the model structure, stream concentrations under these higher discharge conditions could underestimate DOC concentrations. Nonetheless, with greater discharge amounts, longer periods of connectivity or larger contributing areas can both act to increase DOC flushing from the organic layer.

The Baker Creek catchment features lakes that are oligotrophic and likely act as sinks, rather than sources of C (e.g. Evans et al., 2017). The major source of C being exported from Baker Creek is terrestrial C. Land cover is key to C export, with simulated DOC concentration ~ 3 times higher in water routed through forest and wetland than bedrock. In Baker Creek, parameterization of organic C yielded about 10 times higher organic C in the upper as compared to the lower soil (49.7 vs 4.8 g m^{-2} under baseline scenario). In the elevated temperature and precipitation scenario, simulated C in upper and lower soil was projected to increase (upper soil column: 69.9 g m^{-2}; lower soil column: 6.9 g m^{-2}), which we attributed to aboveground productivity associated with elevated temperature. As such, DOC export from the upper soil column to streams was projected to increase. Elevated warming can increase permafrost thaw, which can enhance allochthonous C sources to the aquatic system (Roiha et al., 2016). The extent of permafrost immediately north of Great Slave Lake (including Baker Creek) has been found to align with the distribution of forest types (Morse et al., 2016). Permafrost occurs primarily in hillslopes, peat bogs, and plateaus where organic material lies over glaciolacustrine clays (Morse et al., 2016). In Baker Creek, lakes and exposed bedrock comprise ~60 % of the catchment, thus permafrost would cover less than 40 %. Elevated temperature can increase the active layer thickness of permafrost soil which could increase the aquatic flux of C (Striegl et al., 2005), however these processes are not represented in the model, and should be considered in future work in the catchment.

5. Conclusions

Exploring the behaviour of the Baker Creek catchment over a relatively short but variable period consisting of wet and dry years provided a foundation to explore how streamflow and DOC in this system could change in response to future hydroclimate. In Baker Creek, our modelling suggested that future increases in temperature can positively affect terrestrial productivity, but that microbial activities, water residence time, and catchment connectivity have complementary roles governing DOC export. DOC export is predicted to decrease under a warmer climate where water residence times increase, but increase if the climate warms and gets wetter, enhancing flow through shallow organic layers and lowering residence time of surface water in the stream network. Given recent trends in precipitation for the region, this suggests that browning of lakes in Fennoscandia (de Wit et al., 2016b) could also be observed in shield regions of Subarctic Canada. This could have consequences for community drinking water treatment, and the health of aquatic ecosystems more generally. Notably, simulations under the elevated temperature and precipitation scenario demonstrate increased winter discharge and C export associated with a shift in hydrological regime from nival to combined nival and pluvial. This may be important as DOC transport during more biologically quiescent periods could be enhanced. Further, with shallow soil contamination up to 30 km from the historic roaster stack of Giant Mine (GNT, 2019), and enrichment of multiple metals in lake sediments in the Baker Creek catchment downwind of historical mining operations (Jasiak et al., 2021), predictions of enhanced organic C export from soil pools under a warmer and wetter future scenario could be associated with greater metal mobility, as DOC is known to increase transport, toxicity and bioavailability of metals (Hudson et al., 2003; Baken et al., 2011). While discharge was reasonably captured, DOC patterns in years with greater hydrologic connectivity were not as robust. Efforts to dynamically model C behaviour of Subarctic catchments stand to be improved through greater understanding of the interactions between hydrological flows, C processes, and permafrost.

CRediT authorship contribution statement

S. Sharma: Data curation, Formal analysis, Methodology, Writing – original draft. **M.N. Futter:** Formal analysis, Methodology, Software, Writing – review & editing. **C. Spence:** Data curation, Resources, Writing – review & editing. **J.J. Venkiteswaran:** Funding acquisition, Resources, Project administration, Writing – review & editing. **C.J. Whitfield:** Funding acquisition, Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.159382.

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