

Dissolved Organic Carbon Chemostasis in Antarctic Polar Desert Streams

Christa L. Torrens¹, Michael N. Gooseff¹, and Diane M. McKnight¹

¹University of Colorado Boulder

November 23, 2022

Abstract

The relationship between dissolved solute concentration (C) and discharge (q) in streams, i.e., the C - q relationship, is a useful diagnostic tool for understanding biogeochemical processes in watersheds. In the ephemeral glacial meltwater streams of the McMurdo Dry Valleys [MDVs], Antarctica, studies show significant chemostatic relationships for weathering solutes and NO_3^- . Dissolved organic carbon (DOC) concentrations here are low compared to temperate streams, in the range of 0.1 to 2 mg C L⁻¹, and their chemical signal clearly indicates derivation from microbial biomass. Many MDV streams support abundant microbial mats, which are also a source of organic matter to underlying hyporheic sediments. We investigated whether the DOC generation rate from these autochthonous organic matter pools was sufficient to maintain chemostasis for DOC despite these streams' large diel and interannual fluctuations in discharge. To evaluate the DOC- q relationship, we fit the long-term DOC- q data to two models: a power law and an advection-reaction model. By using model outputs and other common metrics to characterize the DOC- q relationship, we found that this relationship is chemostatic in several MDV streams. We propose a conceptual model in which hyporheic carbon storage, hyporheic exchange rates, and net DOC generation rates are key interacting components that enable chemostatic DOC- q behavior in MDV streams. This model clarifies the role of autochthonous carbon stores in maintaining DOC- q chemostasis and may be useful for examining these relationships in temperate systems, where autochthonous organic carbon is readily bioavailable but where its signal is masked by a larger allochthonous signal.

1 **Dissolved Organic Carbon Chemostasis in Antarctic Polar Desert Streams**
2
3
4

5 Christa L. Torrens¹, Michael N. Gooseff¹, Diane M. McKnight¹
6
7
8
9

10 ¹Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO 80303
11 USA
12

13 Corresponding author: Christa Torrens (christa.torrens@colorado.edu)

14 **Key Points:**

- 15 ● Although DOC concentrations in McMurdo Dry Valleys streams are very low, DOC-flow
16 relationships are chemostatic
17 ● Biogeochemical processes in microbial mats and the hyporheic zone support chemostasis
18 for DOC in Dry Valleys streams
19 ● Autochthonous organic matter pools in the hyporheic zone may also influence DOC
20 concentrations in temperate streams
21

22 **Index terms**

23 0414: Biogeochemical cycles, processes, and modeling; 0744: Rivers; 0428: Carbon cycling;
24 0456: Life in extreme environments; ephemeral streams, Antarctica, DOC, concentration-
25 discharge, chemostasis, LTER

26 Abstract

27 The relationship between dissolved solute concentration (C) and discharge (q) in streams, i.e.,
28 the C - q relationship, is a useful diagnostic tool for understanding biogeochemical processes in
29 watersheds. In the ephemeral glacial meltwater streams of the McMurdo Dry Valleys [MDVs],
30 Antarctica, studies show significant chemostatic relationships for weathering solutes and NO_3^- .
31 Dissolved organic carbon (DOC) concentrations here are low compared to temperate streams, in
32 the range of 0.1 to 2 mg C L⁻¹, and their chemical signal clearly indicates derivation from
33 microbial biomass. Many MDV streams support abundant microbial mats, which are also a
34 source of organic matter to underlying hyporheic sediments. We investigated whether the DOC
35 generation rate from these autochthonous organic matter pools was sufficient to maintain
36 chemostasis for DOC despite these streams' large diel and interannual fluctuations in discharge.
37 To evaluate the DOC- q relationship, we fit the long-term DOC- q data to two models: a power
38 law and an advection-reaction model. By using model outputs and other common metrics to
39 characterize the DOC- q relationship, we found that this relationship is chemostatic in several
40 MDV streams. We propose a conceptual model in which hyporheic carbon storage, hyporheic
41 exchange rates, and net DOC generation rates are key interacting components that enable
42 chemostatic DOC- q behavior in MDV streams. This model clarifies the role of autochthonous
43 carbon stores in maintaining DOC- q chemostasis and may be useful for examining these
44 relationships in temperate systems, where autochthonous organic carbon is readily bioavailable
45 but where its signal is masked by a larger allochthonous signal.

46

47 Plain Language Summary

48 This study assesses the relationship between instream dissolved organic carbon [DOC]
49 concentrations and streamflow in the McMurdo Dry Valleys, Antarctica [MDVs]. DOC comes
50 from the breakdown of organic matter (e.g., plants, microbes and soil). In temperate streams,
51 DOC mostly comes from plants and soil outside of the stream. MDV streamflow is derived
52 entirely from glacial melt in summer and varies on a daily and interannual basis. Although there
53 are no vascular plants, some streams have abundant microbial mats composed of cyanobacteria
54 and diatoms. Organic material from these mats is stored in the underlying streambed sediments,
55 which are saturated with streamwater. We used two different models to evaluate whether and
56 how DOC changed with changing streamflow. Both models indicated that stream DOC

57 concentrations are relatively stable over large changes in streamflow. We developed a new
58 conceptual model that emphasizes the role of the saturated streambed sediments in DOC
59 generation and storage. This streambed storage zone is key to maintaining DOC concentrations
60 in spite of the highly variable MDV streamflow. We believe this model also provides insight into
61 the role that DOC from this saturated zone plays in other systems.

62 **1 Introduction**

63 Stream concentration-discharge (C - q) relationships are the result of reaction and fluvial
64 transport processes at various scales along the catchment. Fluid transit times, solute reaction
65 rates, and equilibrium concentrations all impact the shape of C - q relationships (Godsey et al.,
66 2009) and capture both surface and subsurface flow paths and processes. Channel subsurface
67 (hyporheic) processes can impact the C - q shape via the transient storage and flow-mediated
68 release of both geogenic and biogenic solutes (Castro & Hornberger, 1991; Singley et al., 2021).
69 Understanding the C - q dynamics of a system helps us understand the relative controls of these
70 surface and sub-surface processes on stream solute variability.

71 Possible C - q relationships include chemostasis (little variation in C with changes in q),
72 flushing (increasing C with increasing q), and dilution (decreasing C with increasing q) (Evans &
73 Davies, 1998; Godsey et al., 2009; Singley et al., 2017). Chemostasis can occur, for example, if
74 high discharges transport “old” water with higher solute concentrations into the catchment, thus
75 maintaining a relatively stable C values when q increases. Flushing occurs when the solute
76 concentrations in this “old” water are high enough to elevate C in spite of the increased q .
77 Dilution occurs if the water transported into the stream is “new”, with relatively short transit time
78 and lower solute concentrations.

79 C - q relationships in the McMurdo Dry Valleys [MDVs] are shaped by the region’s
80 distinctive and relatively simple biology and hydrology. Intermittent glacial meltwater streams
81 flow for 4-8 weeks during the austral summer. Most are first or second order streams from
82 glacier to terminal lake. They are fed only by glacial melt: precipitation and hillslope inputs are
83 negligible, and there is no deep groundwater interaction (Gooseff et al., 2004; McKnight et al.,
84 2004). As a result, stream discharge is characterized by strong diel pulses that are generated as
85 the sun’s movement around the horizon changes the angle and intensity of insolation to the
86 source glaciers. These pulses can increase streamflow up to an order of magnitude in a single day
87 (Conovitz et al., 1998). Interannual streamflow varies widely based on seasonal differences in

88 cloud cover and glacial albedo, which also impact the rate of melt (Gooseff et al., 2017; Obryk et
89 al., 2018).

90 These streams flow through unconsolidated, highly porous glacial alluvium (Cozzetto et
91 al., 2013). They are well-connected to their hyporheic zones (Gooseff et al., 2004), which are
92 key sites for weathering and microbial activity (Kohler et al., 2018; Lyons et al., 1997). Isotopic
93 analysis shows that the hyporheic zone is an important source of autochthonous, remineralized
94 nitrogen to MDV stream channels, via the processing and retention of N from sloughed black
95 microbial mats (*Nostoc*) (Kohler et al., 2018). Hyporheic zone extent is determined by the thaw
96 depth, which increases throughout the summer flow season (Gooseff et al., 2002; McKnight et
97 al., 2004; Runkel et al., 1998). Typically, the seasonal maximum thaw depth is < 1 m (Conovitz
98 et al., 2006).

99 One outcome of the extensive hyporheic exchange is that MDV streams are chemostatic
100 for weathering-derived ions such as Si (Wlostowski et al., 2018b). This behavior reflects the low
101 equilibrium concentrations of weathering solutes (C_{eq}) and the relatively fast weathering rates
102 that are characteristic of MDV streams (Gooseff et al., 2002; Lyons et al., 1997; Wlostowski et
103 al., 2018b). Experiments in Von Guerard stream found that it is also chemostatic for dissolved
104 inorganic nitrogen, which reflects both the low ambient dissolved N concentrations and the
105 increasing release of hyporheic N stores with increasing discharge (Kohler et al., 2018; Singley
106 et al., 2021).

107 The landscape is poor in organic carbon: there are no vascular plants, and the riparian
108 vegetation is sparse and comprised of mosses. Thick, perennial microbial mats are present in the
109 channel and wetted margins of streams and represent sources of both dissolved and particulate
110 organic matter in the stream ecosystem (Aiken et al., 1996; Cullis et al., 2014). DOC is a
111 biologically-derived solute and would not be influenced by the same reaction processes as
112 weathering solutes but may be influenced by processes controlling N-cycling. The instream
113 concentrations of dissolved organic carbon (DOC) are generally low compared to temperate
114 streams and the source of the DOC from microbial biomass is reflected in the low humic content
115 and spectroscopic properties (less than 10%, Aiken et al., 1996). At daily high flow conditions,
116 some mat material from the black mats in the stream margins is scoured and flushed downstream
117 (Cullis et al., 2014), as well as into the hyporheic zone (Barrett et al., 2007; Hawes & Howard-
118 Williams, 1998; Heindel et al., 2021). In addition, the hyporheic zones contain microbial

119 biofilms (Maurice et al., 2002) and particulate organic matter (POM) (Heindel et al., 2021) that
120 may contribute dissolved organic carbon to the stream.

121 In temperate and boreal streams, allochthonous DOC from upstream and upland sources
122 typically dominates the instream DOC fluxes, especially in lower-order streams (Burns et al.,
123 2016; Hale & Godsey, 2019, Vannote et al., 1980). These inputs can either support chemostasis
124 as they are mobilized by higher flows, buffering the increase in discharge (Hale & Godsey, 2019;
125 Jantze et al., 2013; Mulholland & Hill, 1997) or can lead to greater variability or ‘flashiness’ of
126 DOC-*q* responses in small or low-flow streams (Creed et al., 2015; Rue et al., 2017). The
127 tendency towards DOC-*q* chemostasis generally increases as stream order increases because each
128 allochthonous input contributes a smaller portion of the total load (Creed et al., 2015).

129 The goal of this research is to characterize the dynamics of autochthonous DOC in these
130 polar desert streams and elucidate the controlling processes. To do this we seek 1) to establish
131 whether the DOC-*q* relationship in MDV streams is characterized by chemostasis, flushing, or
132 dilution (i.e., whether it is limited by the DOC transport or generation rate), and 2) to identify
133 key factors controlling the DOC-*q* relationship. We compare DOC-*q* dynamics to those of silica
134 (Si)-*q*, to assess differences in biological vs physical controls. It is expected that the DOC-*q*
135 dynamics will not correlate to the same controls as those of weathering solutes because DOC is
136 generated from biomass rather than from interactions with mineral surfaces. To quantitatively
137 characterize the DOC-*q* relationship in MDV streams, we chose three common metrics for
138 characterizing C-*q* relationships. One metric assesses the relative variance in concentration and
139 discharge data, the second was generated by a power-law model, and the third by an advection-
140 reaction model. To assess potential controls on this relationship, we ran multiple regression
141 analyses exploring the influence of instream biomass (ash-free dry mass [AFDM]) and stream
142 length on DOC concentrations, as well as the influence of the three the DOC-*q* shape parameters
143 vs. both fluid transit time (a transport parameter) and vs. the net generation time scale (a reaction
144 parameter that describes the timescale of net DOC generation and transport from source to
145 stream water). Given the low levels of organic carbon and the highly variable discharge in these
146 streams, we expected to find a reaction- (or generation-) limited, diluting DOC-*q* relationship.
147 Surprisingly, we find that these streams are chemostatic for DOC.

148 2 Study Site

149 The abundance and distribution of MDV microbial mats are dependent upon mat type,
150 streambed substrate, and discharge (Kohler et al., 2015; McKnight et al., 1998). The mats are
151 commonly divided into three categories for biomass assessments, based on dominant color and
152 community composition: orange, green and black (Alger et al., 1997; McKnight et al., 1998).
153 Each type of mat has a different habitat preference, with black, *Nostoc*-dominated mats
154 preferring the wetted margins of streams and orange (*Phormidium* sp. dominated) and green
155 (*Praziolla* sp. dominated) mats preferring the channel (Alger et al., 1997; Kohler et al., 2015;
156 Niyogi et al., 1997; Vincent et al., 1993). Each mat type responds differently to changes in
157 discharge and substrate (Kohler et al., 2015), but in general, streams with high algal mat
158 coverage tend to have common characteristics, including relatively low flows, moderate
159 gradients, and a stable ‘desert pavement’ substrate rather than shifting sand (Cullis et al., 2014;
160 Kohler et al., 2015). With only sparse grazers, primarily nematodes and tardigrades, mat extent is
161 kept in check largely by hydrology; and changes in mat abundance are more closely aligned with
162 seasonal peak flow scouring than daily scouring (Kohler et al., 2015; Gooseff et al., 2017).

163 For this study, we selected seven streams in the Lake Fryxell basin of the MDVs (Figure
164 1). These streams all have a long-term record of discharge and water chemistry, and many have
165 established transects for sampling microbial mats. The streams were selected to represent a wide
166 range of microbial mat coverage, from Lost Seal Stream with no visible mats to Green Creek
167 with thick and widespread mats. Aiken Creek’s microbial mat coverage exists primarily in Many
168 Glaciers Pond, a large pond that hosts abundant microbial mats and is situated between the
169 source glacier and the stream gage/water sampling site.

170



171

172 *Figure 1: Image of Fryxell Basin with study streams and stream gage locations highlighted.*

173

174 2.1 Dissolved Organic Carbon sources and sinks

175 The primary DOC source is benthic microbial mats (Barrett et al., 2007; Hawes &
176 Howard-Williams, 1998; McKnight et al., 1998), which contain both phototrophic and
177 heterotrophic organisms. Living phototrophs may release some of their fixed carbon to streams,
178 and all organisms in the mat community are subject to decomposition and DOC release (Spencer
179 et al., 2012). The mats also slough POM, which may degrade to DOC in the stream channel
180 (Cullis et al., 2014) or be trapped within the substrate matrix at a location of hyporheic
181 downwelling and degrade there (Heindel et al., 2021), eventually providing DOC to the
182 hyporheic zone waters and the stream water. DOC sinks include biotic uptake by heterotrophic
183 organisms in mats and in the hyporheic zone, and potential sorption on mineral surfaces in the
184 hyporheic zone. Because DOC is biologically derived, its origin differs from weathering-derived
185 solutes like Si; therefore, DOC-*q* dynamics may have different drivers.

186

187 **3 Methods**188 3.1 Data sets:

189 The McMurdo Dry Valleys Long Term Ecological Research program (MCM LTER) has
 190 maintained a network of stream gages and sampling sites throughout MDVs since 1993. Here we
 191 analyze DOC- q relationships and compare them to Si- q relationships in seven Lake Fryxell basin
 192 streams (Figure 1) using the long-term q , solute concentration, and microbial mat biomass data
 193 sets from 1990-2019. These and other long-term data sets are hosted at mcmlder.org and at the
 194 Environmental Data Initiative (environmentaldatainitiative.org/).

195 All seven study streams are gaged and have in-situ sensors that yield continuous records of
 196 temperature, stage, and specific electrical conductance at 15-minute intervals during the flow
 197 season. Seasonally-adjusted rating curves are used to convert stage to volumetric discharge (Q ,
 198 L sec⁻¹). Volumetric discharge was then converted to Darcy velocity (q , m day⁻¹) using the
 199 following equation:

200

$$201 \quad q = \frac{Q}{A_x} = \frac{Q}{[(w_c + 2w_{hz})z_{thaw}]} \quad (1)$$

202

203 where A_x = the cross-sectional stream area (m²), w_c = the stream channel width (m), w_{hz} = the
 204 width of the hyporheic zone (m), and z_{thaw} = the thawed active layer depth (m) (Wlostowski et
 205 al., 2018b). We assume that w_c = 4m, w_{hz} = 5m, and z_{thaw} = 1m based on prior observations of
 206 channel and hyporheic extent (Northcott et al., 2009) and maximum annual thaw depth below
 207 streams (Conovitz et al., 1996). We chose to use Darcy velocity for these analyses because it
 208 explicitly incorporates hyporheic flowpaths and flow velocities, which are important both to
 209 calculate total fluid transit time and as sites of organic and inorganic carbon storage and
 210 transformation (Mulholland et al., 1997; Welch et al., 2010). It is also consistent with
 211 Wlostowski et al.'s (2018b) work on weathering solute C - q relationships in MDV streams,
 212 facilitating comparison.

213 Water chemistry samples are collected several times each season and analyzed for
 214 various solutes, including weathering ions and DOC. These samples are kept chilled (4°C) and
 215 are filtered within 24 hours of collection. DOC samples are collected in precombusted amber
 216 glass bottles and filtered through a combusted glass microfiber filter

217 (Whatman™ GF/CTM 47mm filter) into a second precombusted amber glass bottle. Next,
218 samples are acidified to a pH of 2 to 3 with a 50% solution of hydrochloric acid to drive off
219 inorganic carbon, then analyzed for DOC using a non-purgeable organic carbon method.
220 Method detection limit is typically 0.1 mg L⁻¹ of DOC.

221 Microbial mat samples have been collected along established transects in various MDV
222 streams since 1994, and their ash-free dry mass [AFDM] is used to measure long-term variations
223 of instream biomass within and across the sample streams. Mat sampling has been annual since
224 2002; prior to 2002, these samples were collected approximately every three years. Each
225 sampling visit collects 2-4 plugs of each type of microbial mat near each transect, using a 1.7 cm
226 diameter brass cork borer. These samples are analyzed for AFDM by drying at 100°C for 24
227 hours, weighing, ashing at 450°C for 4 hours, then re-weighing to determine the mass lost to
228 combustion (Kohler et al., 2015).

229

230 3.2 Data analysis:

231 *3.2.1: Determining the DOC- q relationship:*

232 To answer our first question, whether the DOC- q relationship is chemostatic, flushing-
233 based or dilution-based, we used three established methods to quantitatively assess the shape of
234 the C- q relationship. First, we fit the DOC and q data to a power-law model:

235

$$236 \quad C = aq^b \quad (2)$$

237

238 where C is the concentration (ppm), q is the Darcy velocity (m day⁻¹), a is a constant, and b is a
239 scaling parameter, and assessed the slope (exponent, b) of the modeled C- q relationship (Godsey
240 et al., 2009). The best-fitting b value indicates a log-log slope of the relationship: $b = -1$
241 represents pure dilution, $b = 0$ represents perfect chemostasis (C is constant for all q), and $b = 1$
242 represents pure flushing. The b values for DOC- q will indicate whether the relationship is
243 flushing, diluting or chemostatic: per Godsey et al. (2009), b values between -0.20 and 0.20
244 indicate a chemostatic relationship, while values below -0.20 indicate a diluting relationship and
245 values greater than 0.20 would indicate flushing.

246 Second, we fit the data to an advection-reaction model to determine the Damköhler
 247 number (Da), which describes whether the C - q relationship is transport- or reaction-limited
 248 (Maher et al., 2011; Maher & Chamberlain, 2014; Wlostowski et al., 2018b):

$$250 \quad C = C_{eq} \frac{\frac{\gamma Dw}{q}}{1 + \frac{\gamma Dw}{q}} \quad (3)$$

251
 252 where C is the concentration (ppm), C_{eq} is the solute equilibrium concentration (ppm), γ is a
 253 dimensionless constant ($= e^2$), Dw is the Damköhler coefficient (m day^{-1}), and q is the Darcy
 254 velocity (m day^{-1}). The model assumes an exponential distribution of fluid transit times along an
 255 idealized flow path. It provides a process-based interpretation of the C - q relationship, where
 256 model outputs are tied to physically-meaningful parameters.

257 We used this advection-reaction model to calculate the dimensionless Damköhler number
 258 (Da) from the Damköhler coefficient (Dw). Da is also equal to the ratio of τ_f to τ_{gen} (or τ_{eq} , for
 259 weathering solutes):

$$261 \quad Da = \frac{Dw}{q} = \frac{\tau_f}{\tau_{gen}} = \frac{\tau_f}{\tau_{eq}} \quad (4)$$

262
 263 For our analyses, we used Da_{med} , the Damköhler number calculated using the median q for that
 264 stream.

265 Fluid transit time (τ_f) represents the average time that water spends in surface and
 266 subsurface flow paths, and is approximated as the ratio of channel length to seepage velocity ($\frac{q}{\phi}$):

$$268 \quad \tau_f = \frac{L\phi}{q} \quad (5)$$

269
 270 where L is the length of the stream (m) and ϕ is the porosity of hyporheic sediments ($\text{m}^3 \text{m}^{-3}$).
 271 This simple approximation is appropriate given the simplicity of the MDV stream hydrologic
 272 system, which can be compared to a natural flume (Gooseff et al., 2004; Wlostowski et al.,
 273 2018b).

274 The net DOC generation time scale (τ_{gen}) represents the characteristic time for DOC to
 275 be generated and transported from the source to the streamwater. When used to simulate the
 276 transport and reaction of weathering solutes, τ_{gen} is replaced with τ_{eq} , a reaction term that
 277 incorporates the influence of kinetics of mineral weathering, temperature, sediment composition,
 278 and erosion rate (Maher et al., 2010; Wlostowski et al., 2018b). The generation timescale τ_{gen} is
 279 calculated by rearranging and simplifying Equations 4 and 5, to yield:

280

$$281 \tau_{gen} = \frac{\tau_f}{Da} = \frac{L\phi}{qDa} = \frac{L\phi}{Dw} \quad (6)$$

282

283 $Da < 1$ indicates that $\tau_{gen} > \tau_f$ and that the solute flux is generation-limited. $Da > 1$
 284 indicates that $\tau_{gen} < \tau_f$ and that the solute flux is transport-limited (Maher & Chamberlain,
 285 2014; Wlostowski et al., 2018b). We expect DOC to be generation-limited, with a $Da < 1$.

286 Third, we calculated the ratio of the coefficients of variation for the long-term records of
 287 C and q (CV_C/CV_q) for each stream (Thompson et al., 2011). Because C - q chemostasis is defined
 288 as a range of C that is relatively stable across a wide range of q , a $CV_C/CV_q \gg 1$ indicates the
 289 concentration dataset is more variable than the discharge, meaning that the C - q relationship is
 290 either flushing or diluting, while a $CV_C/CV_q \ll 1$ indicates that the relationship between C and q
 291 is chemostatic (Thompson et al., 2011).

292

293 3.2.2: Determining DOC- q controls:

294 We hypothesize that both microbial mat biomass and τ_f will be strong indicators of the
 295 DOC- q relationship. We expect that MDV streams with higher mat biomass will have both
 296 higher DOC concentrations and less-diluting DOC- q relationships. We also hypothesize that τ_f ,
 297 not τ_{gen} , will control between-stream variation in the DOC- q relationship, because generation
 298 rates per area of biomass would not vary much across streams while longer fluid transit times
 299 would allow more contact with DOC source material.

300 To test the influence of mat biomass, we quantified annual microbial mat biomass (ash-
 301 free dry mass, AFDM) based on the long-term MCM LTER data record. We focused this
 302 analysis on the four modeled streams with a consistent long-term algal sampling record: Canada,
 303 Delta, Green, and Von Guerard. If a stream had multiple mat sampling transects, we chose the

304 one closest to the stream gage, which is where the DOC samples are collected. We used a
305 regression analysis to test relationships between both the average DOC concentration vs. the
306 average biomass for each season, and also the average DOC concentration vs. the high biomass
307 for each season, since the high-biomass mats would be expected to generate a larger DOC
308 source. We tested for significant relationships by stream, by mat type and by within-stream
309 location (i.e. margins vs. channel). We also tested for significant relationships between DOC
310 concentration and stream length, as longer streams may allow longer contact time with DOC
311 sources in the stream and hyporheic zone. Our hypothesis that biomass controls the DOC- q
312 relationship is supported if DOC concentrations have a positive relationship with stream biomass
313 or stream length.

314 To test the influence of τ_f and τ_{gen} on between-stream differences in the DOC- q
315 relationship, we compared each of these timescale parameters to the three DOC- q shape
316 parameters (Da , b , and CV_c/CV_q) that indicate the degree of dilution or chemostasis for each
317 stream. Significant correlations (positive or negative) between either τ_f or τ_{gen} and these shape
318 parameters would indicate that timescale parameter controls between-stream differences in
319 DOC- q . If the three shape parameters become more chemostatic as τ_f increases, this would
320 support our hypothesis that τ_f controls between-stream variation in DOC- q dynamics.

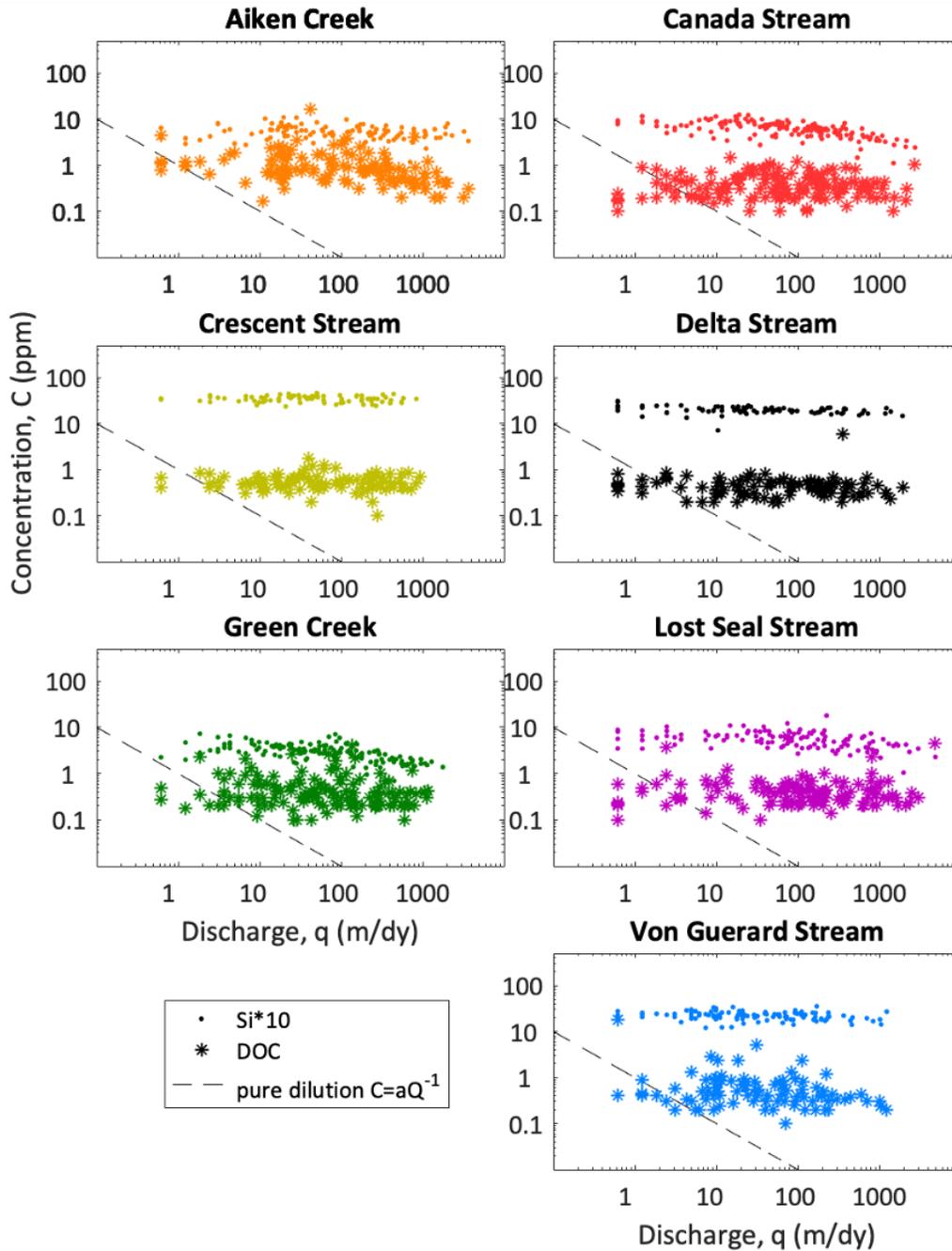
321 We ran the same series of analyses on Si, to provide a comparison to a true weathering
322 solute. This updates the Wlostowski et al. (2018b) analysis with more recent data.

323 **4 Results**

324 MDV DOC- q relationships are strongly chemostatic, showing little variation in DOC
325 concentration over four orders of magnitude of q (Figure 2). DOC does have more variance than
326 the weathering solute Si in most streams, with DOC variance ranging from 0.06 to 3.35 while Si
327 variance ranges from 0.05 to 0.26 (Figure 2). This variance is greater than the analytical
328 uncertainty and is consistent across decades of high-quality DOC data. DOC concentrations are
329 consistent through time, with only 2004 showing any significant differences (Figure 3); this may
330 be driven by the relatively high number of high-end outliers in the 2004 DOC data.

331 DOC concentration is also consistent across the study streams regardless of stream length
332 (Figure 4a) or mat biomass (Figure S1). Regressions between DOC vs. biomass and DOC vs.
333 stream length showed no significant relationships ($p > 0.05$ for all comparisons), which is not

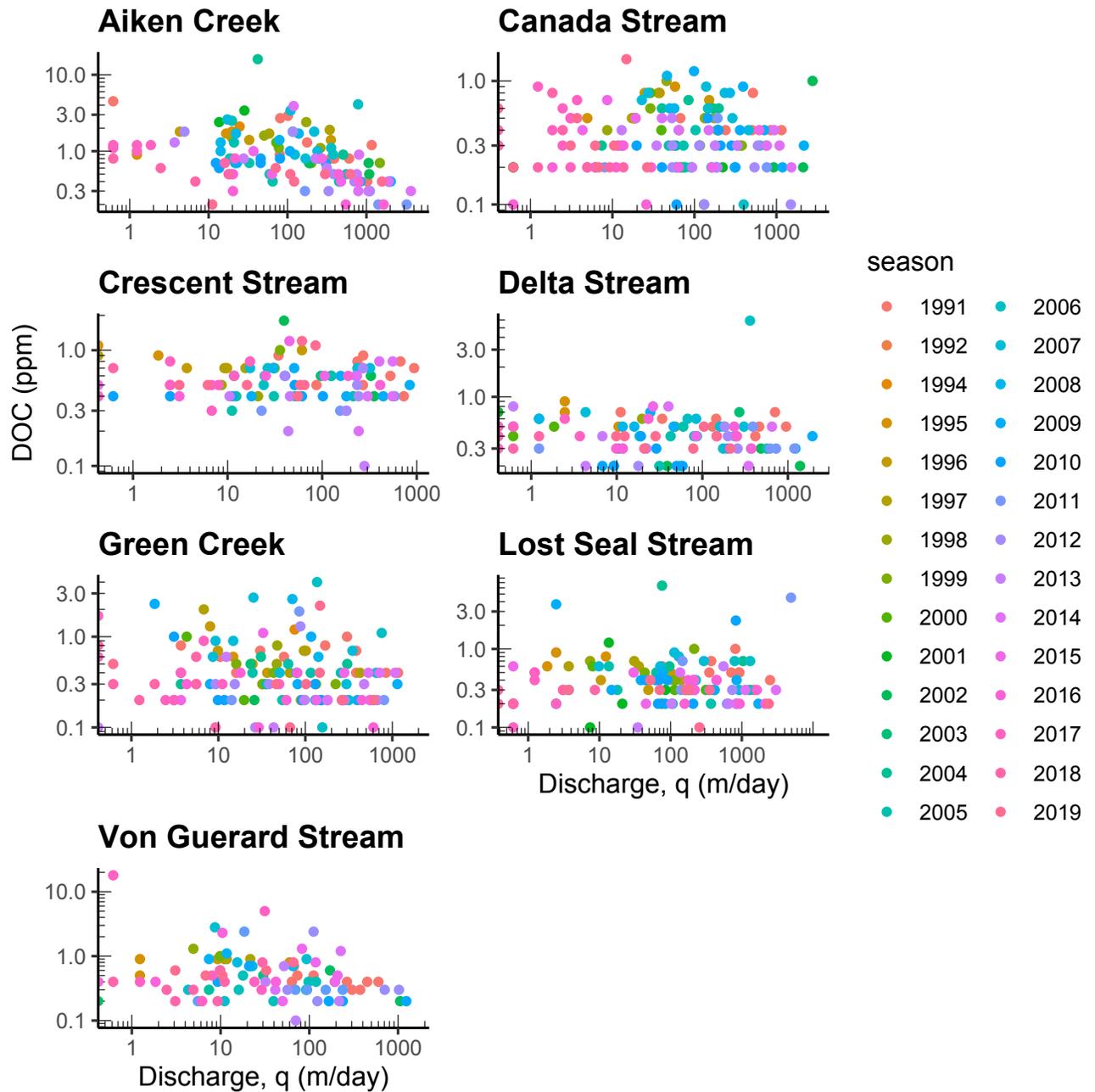
334 surprising as there are no apparent spatial or temporal trends in DOC concentration (Figure 3).
335 Of the seven study streams, only Aiken Creek shows a significant difference in mean DOC
336 concentrations, with a higher mean DOC concentration than any other stream ($p < 0.05$ for all
337 comparisons). This difference is likely driven by Many Glaciers Pond, which supports relatively
338 high biomass and increases the fluid transit time, equating to increased water contact with a DOC
339 source. In contrast, the weathering solutes (e.g., Si), while chemostatic, do have concentrations
340 that increase with stream length (Figure 4b), due to the greater amount of substrate supplying
341 weathering solutes in longer streams (Gooseff et al., 2002).
342



343

344 *Figure 2: Visual inspection shows the chemostatic relationships of DOC and Si solute concentrations vs.*
 345 *discharge (q) in seven MDV streams; Si concentrations are scaled for better visualization. Si represents a*
 346 *weathering solute signal and DOC represents a biological solute signal. The dotted line indicates where*
 347 *a pure dilution relationship would fall on the graph. Variances of Si and DOC are shown to illustrate the*
 348 *difference in spread between the two solutes. The script used for these visualizations is based on code*
 349 *developed by Wlostowski et al. (2018b), to facilitate comparisons between our findings.*

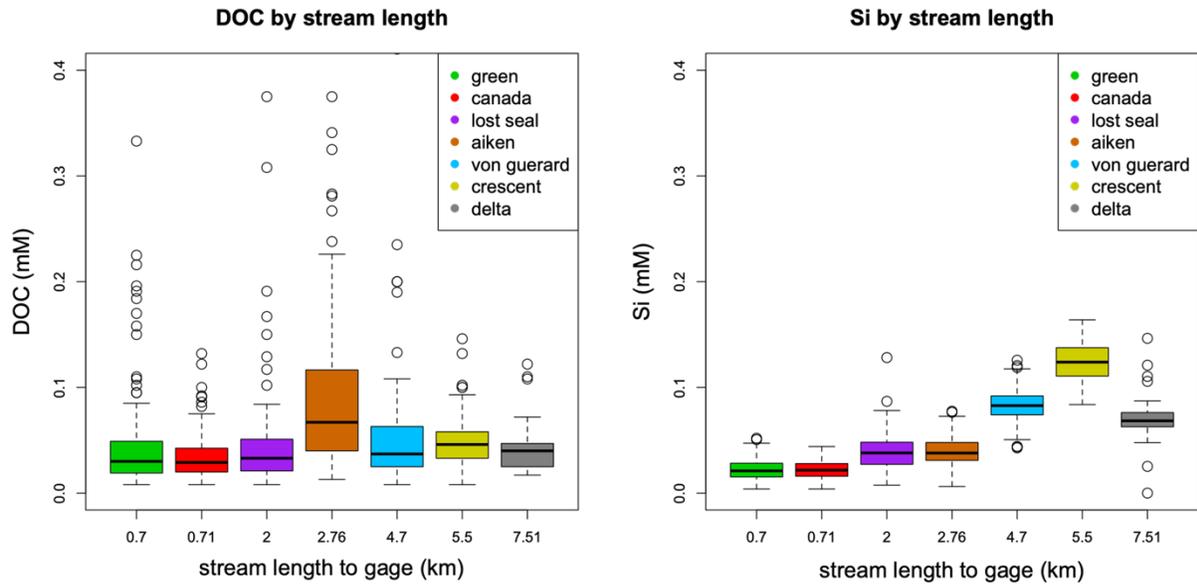
350



351

352 *Figure 3: This shows the distribution of DOC-q relationships by study year in each stream.*

353



354

355 *Figure 4: These boxplots indicate DOC and Si concentrations by length in the 7 study streams. Si, a*
 356 *weathering solute, shows an influence of channel length on concentration. In contrast, concentrations of*
 357 *DOC, a biologically derived solute, do not vary with stream length.*

358

359

360

361

362

363

364

365

366

367

368

369

370

371

372

373

374

All three shape parameters quantitatively characterize MDV DOC- q relationships as chemostatic rather than diluting or flushing behavior (Table 1). Using b , the slope of the best-fit power-law relationship, all streams except Aiken meet Godsey et al.'s (2009) definition for chemostasis: b values range from -0.22 to -0.02, with a mean value of -0.08. Aiken Creek ($b = -0.22$) is likely an outlier because of Many Glaciers Pond, which contains a high amount of organic matter; the pond would impact both DOC concentration and DOC variability due to changing flow dynamics. The CV_c/CV_q analysis shows that all streams have CV_c/CV_q values less than one, indicating chemostasis (Thompson et al., 2011): values range from 0.36 to 0.83, with a mean value of 0.63. For comparison, Wlostowski et al. (2018b) found that CV_c/CV_q values for four Fryxell Basin weathering solutes ranged from 0.07 to 0.76 with a mean value of 0.26, and Thompson et al. (2011) found that typical CV_c/CV_q values for both weathering and biologically-derived solutes in temperate streams ranged from 0.15 to 3.5 with a mean of 0.68. Using a Da_{med} (Da calculated at median q for each stream) derived from the best-fit advection-reaction model, MDV streams have a $Da_{med} > 1$, indicating they are transport-limited (Maher et al., 2011; Maher & Chamberlain, 2014; Wlostowski et al., 2018b). Da_{med} values range from 1.70 to 131.23, with a median value of 43.15. Streams with smaller magnitude b values (i.e. values closer to 0) also

375 have higher Da_{med} values, showing agreement between the power law and advection-reaction
 376 models.

377

378 Table 1. Stream and Stream DOC Model Parameters and Shape Factors

| Stream | Length | q_{med} (m/dy) | τ_{fmed} (dy) | C_{eq} (ppm) | b | CV_c/CV_q | Da_{med} |
|-----------|--------|---------------------|-----------------------|-------------------|-------|-------------|------------|
| Aiken | 2760 | 48.14 | 22.93 | 1.40 | -0.22 | 0.83 | 1.70 |
| Canada | 700 | 54.93 | 5.10 | 0.38 | -0.03 | 0.36 | 11.55 |
| Crescent | 5500 | 34.56 | 63.66 | 0.52 | -0.02 | 0.36 | 100.56 |
| Delta | 7510 | 24.07 | 124.81 | 0.42 | -0.02 | 0.78 | 49.66 |
| Green | 700 | 69.74 | 4.02 | 0.46 | -0.11 | 0.74 | 3.36 |
| Lost Seal | 2000 | 75.29 | 10.63 | 0.43 | -0.03 | 0.83 | 131.23 |
| VG | 4700 | 22.83 | 82.33 | 0.57 | -0.14 | 0.51 | 4.00 |

379

380 The regression analyses between the shape parameters and both τ_f and τ_{gen} show no
 381 significant relationships (all $p > 0.05$, Figure 5). The one near-linear relationship for DOC is
 382 between Da_{med} and τ_{gen} (Figure 5b, $p = 0.064$, $R^2 = 0.53$). As τ_{gen} increases, Da_{med} decreases,
 383 indicating that τ_{gen} may be a stronger control on the stream's DOC- q transport-limitation than
 384 τ_f : i.e. the values for τ_{gen} , not τ_f , are what impact the degree of DOC- q transport-limitation in
 385 MDV streams.

386 As expected, Si- q relationships are quantitatively chemostatic across all streams. Values
 387 for b range from -0.13 to -0.01, with a mean of -0.06; CV_c/CV_q values are all less than one and
 388 range from 0.09-0.27, with a mean of 0.17; and Da_{med} values are all greater than 1 (1.62-41.11,
 389 median of 25.93), indicating transport limitation. This supports the results of Wlostowski et al.
 390 (2018b).

391 5 Discussion

392 5.1 DOC- q chemostasis in MDV streams

393 Analysis shows that DOC- q relationships are strongly chemostatic in MDV streams
 394 (Figure 2), with DOC concentrations showing little variation across orders of magnitude of
 395 discharge. There is also little net variation across years (Figure 3) or streams (Figure 4); apart

396 from Aiken Creek, there is no significant difference in the mean DOC concentrations of the
397 study streams. Therefore, it is not surprising that there was no relationship between DOC
398 concentration and either stream length or mat biomass, both of which are more variable,
399 relatively, than mean DOC concentrations.

400 DOC variance is greater than Si variance in almost all streams (Figure 2). This is
401 consistent with differences in the source materials of the two solutes. Silicate materials that make
402 up the soils and streambeds of the MDVs are relatively uniform throughout the Fryxell basin
403 (Gooseff et al., 2002), while DOC sources are inherently patchy. Benthic biomass in streams is
404 largely dictated by substrate and hydrologic regime (Kohler et al., 2015). The perennial mats
405 thrive on rocky, stable desert pavement and are sparse or nonexistent on sandy, mobile reaches,
406 which do not accommodate much establishment and growth (McKnight et al., 1998). Thus
407 hyporheic POM, as a source for hyporheic and ultimately stream DOM, is also expected to be
408 spatially dispersed (Heindel et al., 2021).

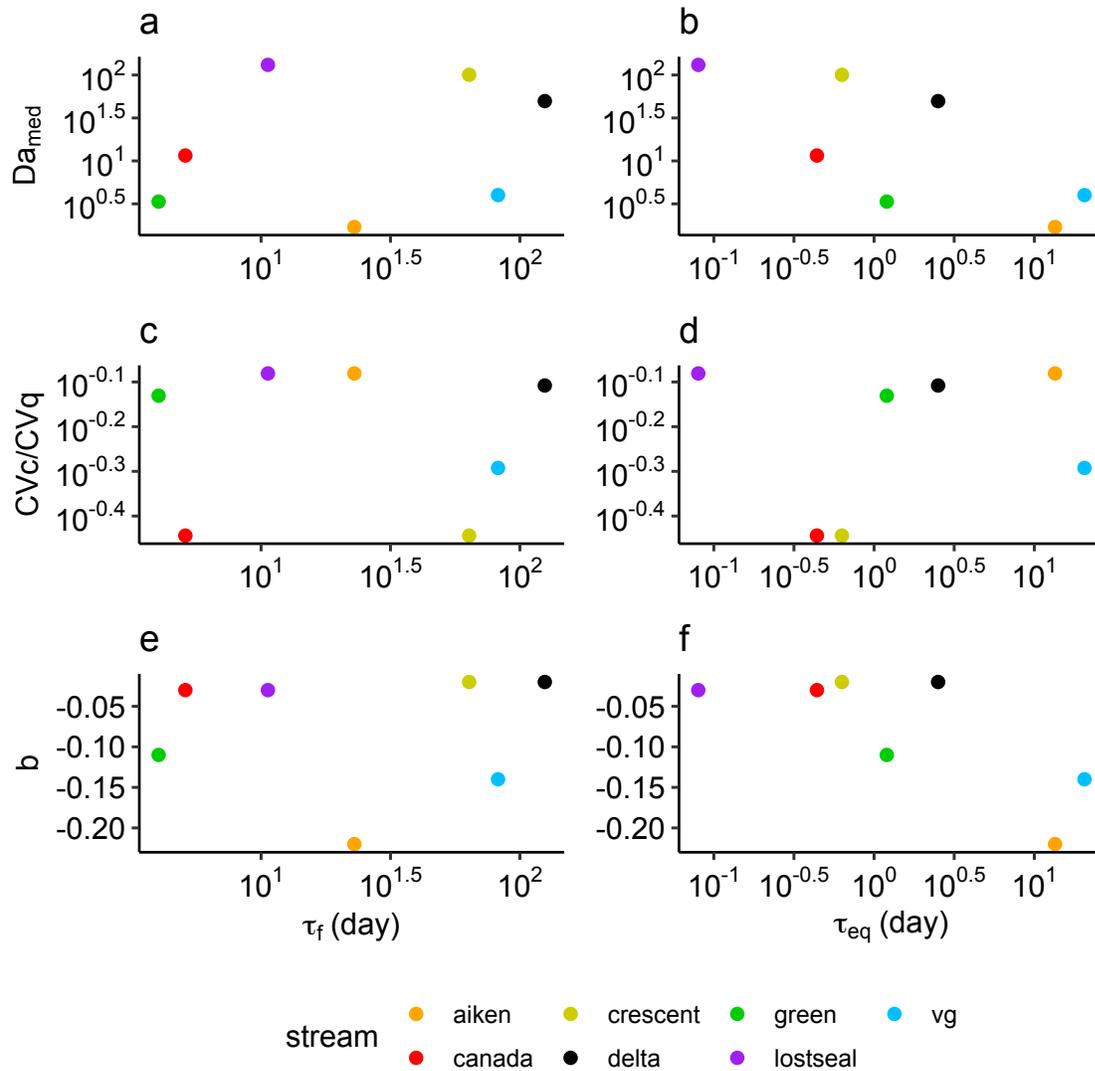
409 For all streams, the slope of the DOC- q power-law relationship (b) is close to zero, there
410 is little variation in C over a wide variation in q , and the steady-state advection-reaction model
411 shows these streams to be predominantly transport-limited (Table 1). Together, these findings
412 support a chemostatic DOC- q relationship across all of the study streams. There is between-
413 stream variation in the degree of DOC- q chemostasis (Table 1), but no significant correlations to
414 indicate whether this variation is controlled by transport or generation. While it is not significant
415 ($p = 0.064$), there does appear to be some gradient in the relationship of Da_{med} to τ_{gen} , indicating
416 that τ_{gen} , not τ_f , may have the stronger impact on the degree of DOC- q transport-limitation in
417 MDV streams, which does not support our expectations.

418

419 5.2 DOC generation - biological control

420 That DOC- q relationships are chemostatic across all streams is surprising, given the very
421 little amount of organic carbon in this landscape. Further, DOC generation is somehow supplied
422 across several orders of magnitude of q from autochthonous organic carbon alone. The
423 breakdown of POM primarily occurs in the stream channel and hyporheic zone. It is primarily a
424 biological process driven by the physical sloughing of in-channel mats and by decomposer
425 microorganisms in the mats and hyporheic sediments. Chemical equilibrium is not a factor here
426 in the same way it is for weathering solute chemostasis, and MDV DOC concentrations do not

427 increase with stream length (Figure 4). Instead, the DOC “equilibrium” concentration (C_{eq})
428 would integrate the DOC source and sink processes upstream of that sampling point and
429 represent the balance of DOC net generation and exchange specific to that sampling location; it
430 is more of a ‘net balance’ than a chemical equilibrium. Thus the DOC net generation timescale
431 (τ_{gen}) represents the average time required to reach this balance point of sources, sinks, storage
432 and exchange. It could be interpreted as the ratio of the “equilibrium” concentration to the net
433 DOC generation rate [NGR], or $\frac{C_{eq}}{NGR}$. Because C_{eq} is relatively steady across these streams (Table
434 1), variations in the net DOC generation rate control differences in τ_{gen} . Streams that have the
435 slowest generation rate would have the highest τ_{gen} , while streams that have more rapid DOC
436 generation rates would have a lower τ_{gen} . This interpretation is supported by the fact that
437 streams with the lowest τ_{gen} are more strongly chemostatic (Figure 5).



438

439 *Figure 5: Relationship between the DOC- q shape parameters and (a, c, e) mean transit time at median q*
 440 *(τ_f) and (b, d, f) the equilibrium time scale (τ_{eq}). There are no significant relationships in any of these*
 441 *regressions (all $p > 0.05$). In contrast, Si relationships for the shape parameters and τ_f are all significant*
 442 *(Wlostowski et al., 2018b). This indicates that τ_f controls between-stream differences in the shape of the*
 443 *C- q curve for Si but neither τ_f nor τ_{eq} provide this control for DOC.*

444

445 5.3 Controls on DOC- q chemostasis

446 We initially expected that the amount of source material, or algal mat biomass, would be
 447 one key factor influencing DOC- q chemostasis. However, we find no apparent relationship
 448 between DOC concentration and algal mat biomass (Figure S1). In fact, with the exception of

449 Aiken Creek, there is little variation in mean DOC concentration across most our study streams
450 (Figure 4), which agrees with the findings of Aiken et al. (1996). Aiken Creek has both a
451 significantly higher mean DOC concentration and a wider range of concentrations compared to
452 other study streams. This can likely be attributed to the influence of mat-rich Many Glaciers
453 Pond on the Aiken stream channel. The higher DOC mean can be explained by the high mat
454 density and longer water residence time in the pond. The wider DOC range can be explained by
455 the natural variation in stream discharge. When the system experiences relatively high diel flood
456 pulses, water would move through the pond quickly and spill into lower Aiken Creek without
457 much time for solute generation.

458 We hypothesized that fluid transit time (τ_f) would be an important control on the DOC-*q*
459 shape and would explain between-stream differences in degree of chemostasis, because a longer
460 transit time (in longer streams, and/or in lower flow streams) would allow more opportunity for
461 DOC generation. This is not supported by the shape parameter analysis (Figure 5). If anything,
462 these results indicate that the differences in τ_{gen} may weakly influence differences in the degree
463 of chemostasis observed between the study streams.

464 We propose that the relationships between τ_f , τ_{gen} , and other transport metrics (Figure 5)
465 also indicate the hyporheic influence on DOC-*q* chemostasis. While τ_f is not correlated with
466 transport limitation, it is clearly a factor (Equation 4). Fluid transit time varies with flow path
467 length, and hyporheic flow paths are both longer and have a lower velocity than in-stream flow
468 paths. In the MDV, where sediment porosity is relatively uniform across streams, total hyporheic
469 area and potential flow path length increases with stream length. At median discharge, longer
470 streams have longer mean fluid transit times due to these longer hyporheic flow paths ($p =$
471 0.0004 , $R^2 = 0.92$).

472 Controls on DOC-*q* chemostasis in the MDV must differ from temperate stream controls.
473 In temperate streams, the chemostatic DOC-*q* balance is maintained by an allochthonous DOC
474 source that is accessed at higher flows (Hale & Godsey, 2019; Mulholland & Hill, 1997). There
475 are no large allochthonous carbon sources in the MDV. In spite of this, the MDV DOC-*q* balance
476 is remarkably consistent across time (decades), range of discharge (multiple orders of
477 magnitude), and channel length (Figures 2, 3, 4). We propose that in the MDV, intermittently-
478 connected areas in the hyporheic zone and wetted margins may serve as carbon storage sites,
479 analogous to riparian and hillslope carbon storage in temperate streams. To help explain this

480 process, we propose the following 4-bin conceptual model, consisting of generation (source),
481 loss (sink), storage, and hyporheic-surface water exchange “bins”. The source and sink bins have
482 not changed from our earlier description, so we provide a concise review here. In contrast, this
483 study has changed our conception of the contributions of hyporheic storage and exchange,
484 especially for DOC chemostasis. These bins are described in detail, below.

485

486 5.4 Conceptual model for dissolved carbon chemostasis:

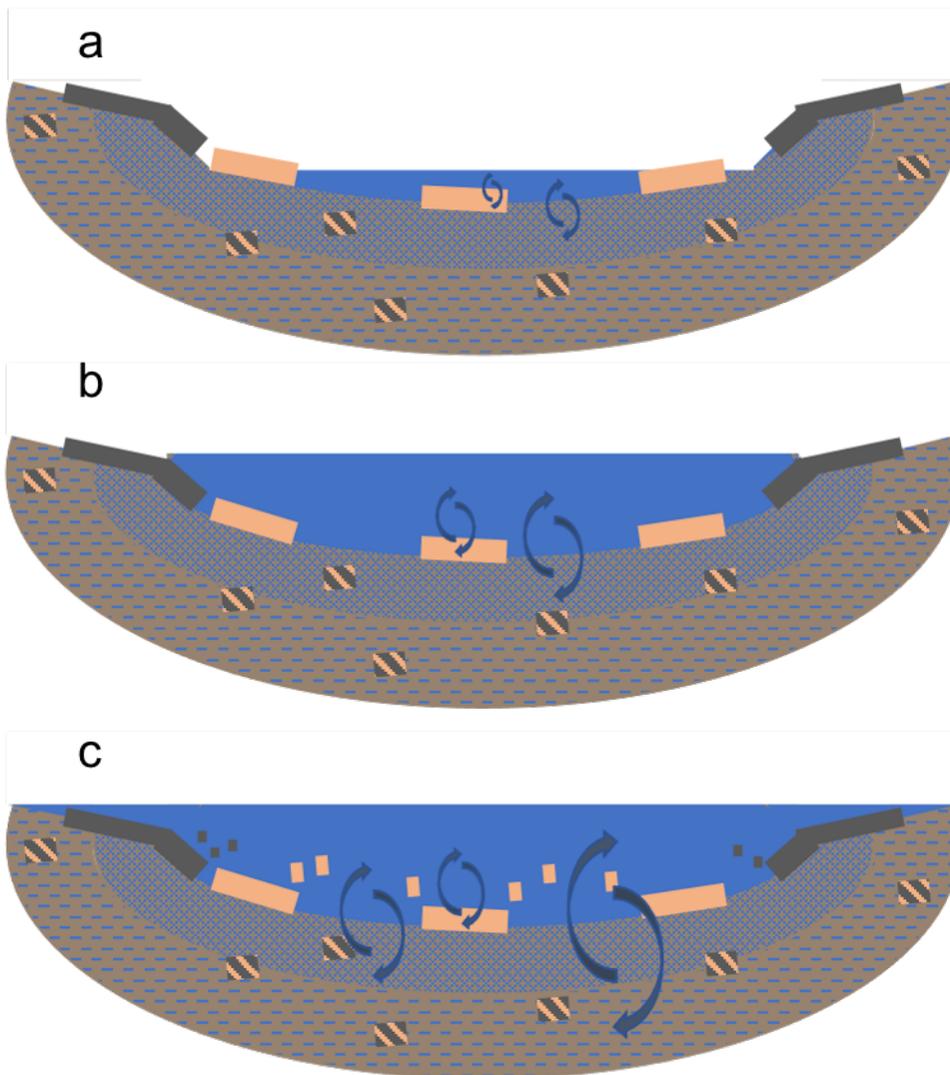
487 The primary DOC source to streams is benthic microbial mats that grow on the bed and
488 wetted margins of streams (Barrett et al., 2007; Hawes & Howard-Williams, 1998; McKnight et
489 al., 1998). A secondary source is POM from these mats, which may be buried or lodged in
490 stream interstices. Unlike in temperate streams, there are no allochthonous DOC sources. DOC
491 sinks include biotic uptake by heterotrophic organisms in mats and in the hyporheic zone.

492 Because of the large diel and seasonal variations in streamflow, the stream channel
493 expands and contracts on a daily and seasonal scale. The hyporheic zone also expands over the
494 course of the flow season due to active layer thaw, and it may contract during low or no-flow
495 periods. These changes impact both hyporheic storage and the exchange of water and solutes
496 with the stream channel. High flows access and flush stored hyporheic solutes into the stream,
497 while lower flows “strand” (isolate) damp sediments, allowing them to accumulate solutes
498 (Figure 6). At lower flows, hyporheic organic matter is temporarily isolated, either by diminished
499 exchange or reduced preferential flow paths (Figure 6a); but it continues to produce DOC,
500 creating a pool that can be mobilized to maintain chemostasis at higher flows (Figure 6b, c). The
501 expansion and contraction of streamflow also impacts the benthic DOC source, as the margin
502 and some in-channel mats are alternately wetted and dried, i.e., connected and disconnected from
503 releasing DOC into the channel. The wetted margins of streams may also act as a DOC storage
504 site at lower flows, as subsurface POM and surface mats continue to release DOC into the wetted
505 margins but have little to no DOC exchange with the stream channel. In effect, the isolated sites
506 in both the margins and hyporheic zone are parallel to riparian storage zones in temperate
507 streams; they function as storage pools of organic carbon, buffering DOC-*q* chemostasis when
508 they are tapped at higher flows.

509 The long-term datasets used in these analyses do not distinguish between in-channel and
510 hyporheic DOC sources. However, a hyporheic DOC source is plausible based on other research.

511 We know that the hyporheic zone contains POM that is sloughed from microbial mats (Cullis et
512 al., 2014; Heindel et al., 2021; Singley et al., 2021), and that this organic matter contributes
513 dissolved nitrogen and likely other solutes to the stream channel (Singley et al., 2021).

514 Another line of evidence supporting the importance of a hyporheic OM source is the
515 DOC levels in Lost Seal. Surprisingly, Lost Seal has a DOC level similar to that of other streams,
516 even though it does not have apparent benthic mats. Lost Seal is a medium-length stream with an
517 extensive area for hyporheic storage and exchange. In the absence of a visible instream source, it
518 could be that the DOC source here may not be mats but instead both thin biofilm and particulate
519 organic matter carried from lake algal mats by aeolian transport, in the benthic and hyporheic
520 sediments.



521

522

523

524 *Figure 6: Stream cross-section illustrating the conceptual model for hyporheic DOC generation and*
525 *storage at low (a), median (b) and high flows (c). Orange, black, and striped boxes represent microbial*
526 *mats. Blue represents the stream water and the blue/ brown areas represent the saturated sediments of*
527 *the near and deep hyporheic zone. At each flow level, the hyporheic zone acts as a generation, storage*
528 *and release site for DOC, buffering the DOC- q relationship against the large changes in q this system*
529 *experiences. This parallels the role of the riparian zone in temperate stream DOC- q chemostasis. At very*
530 *high flows, mats also slough POM, some of which is buried in the hyporheic zone to seed future DOC*
531 *generation.*

532

533 At median flow, with a moderate water volume, many but not all of the mats would be
534 flooded and releasing DOC into the stream channel (Figure 6a). Hyporheic extent and exchange
535 would be moderate, and some areas would be well-connected with the channel, mobilizing DOC,
536 while others would not. The wetted areas that were not well-connected with the channel would
537 continue to break down organic matter into DOC, creating some storage pockets that would only
538 be accessed at relatively high flows.

539 At low flows, with a low water volume, the decrease in q would be compensated for by
540 the decrease in DOC generation and release (Figure 6b). Fewer mats would be submerged,
541 decreasing the amount of DOC released to the stream water. Hyporheic exchange would be
542 lower, and the hyporheic zone itself might contract if the flow is low enough. DOC generation
543 would continue in the wetted mats and hyporheic zone (where there is POM). Less of the DOC
544 generated and stored in the hyporheic zone would be released to the channel.

545 At high flows, the increase in q would be compensated for by a flushing of the stored
546 DOC that was generated at lower flow levels (Figure 6c). All of the mats would be submerged,
547 increasing the surface area of mat that would release DOC to the stream channel. At higher
548 flows, there is also more likely to be sloughing and entrainment of mat material that would
549 subsequently generate (stored then flushed) DOC.

550 There are several ways to test this new conceptualization of hyporheic storage and
551 exchange impacting instream DOC. One method would be to use probes or repeated sampling to
552 monitor hyporheic DOC at various flows and distances from the stream, to test whether there
553 actually is a pool of organic carbon waiting to be mobilized at higher flows. More accurate
554 measurements of hyporheic biomass would also be useful, to support and quantify the existence

555 of a hyporheic OM source. This would inform both the conceptual model and improve the
556 accuracy of tested relationships between DOC and biomass. In addition to fieldwork, this
557 conceptual model could be tested by developing a DOC-specific mathematical model to describe
558 the instream flows. It would include terms for the storage and exchange components described
559 here, in addition to terms for the more widely-accepted sources and sinks.

560 **6 Conclusions**

561 In streams, DOC is generated by the breakdown of particulate organic matter. In spite of
562 the sparse POM storage in the MDV streams, concentrations of DOC are chemostatic across
563 several orders of magnitude in q . In temperate streams, organic matter is largely allochthonous
564 and DOC chemostasis is understood to be influenced by legacy pools of this allochthonous
565 carbon in the riparian zone. As there is no ‘riparian zone’ nor pools of allochthonous carbon in
566 the MDV, we must seek a different explanation for the chemostatic DOC- q behavior. This
567 explanation must involve the primary MDV DOC source: microbial mat material, either in the
568 channel or buried in the hyporheic zone.

569 We propose a conceptual model where carbon C- q chemostasis is a product of the
570 interaction of the four bins: generation, uptake, storage (here, primarily hyporheic), and
571 exchange. The hyporheic storage and exchange locations have not previously been explored for
572 DOC. In the MDV, autochthonous hyporheic POM and wetted-margin microbial mats are the
573 carbon pool supporting DOC- q chemostasis, paralleling the allochthonous riparian/ hillslope
574 pools in temperate systems.

575 This is the first examination of the dynamics impacting DOC- q chemostasis in the MDV.
576 It is likely that the processes influencing DOC- q chemostasis were not fully captured by the
577 long-term data record we studied. Although this study does not provide a definitive solution to
578 the causes of DOC- q chemostasis in the MDV, it does provide clues to the processes involved
579 and can inform future investigations and models. It also provides insight into the ways
580 autochthonous carbon contributes to DOC- q relationships in systems where the autochthonous
581 influence is obscured by the dominance of allochthonous carbon inputs.

582 **Acknowledgements**

583 Funding for this work was provided by the National Science Foundation, for the initial LTER
584 grant and subsequent renewals (award numbers 9211773, 9813061, 9810219, 0096250, 0423595,
585 0832755, 1041742, 1115245 and 1637708). We would also like to acknowledge and thank the

586 numerous collaborators and students who helped carry out lab and fieldwork associated with the
 587 project, as well as the logistical and helicopter support contractors who have facilitated the MCM
 588 LTER field research in Antarctica since 1993 through the US Antarctic Program: Antarctic
 589 Support Associates, Raytheon Polar Services, Antarctic Support Contractors and Petroleum
 590 Helicopters.

591 **Data availability**

592 The stream gage data (Gooseff & McKnight, 2019a-c; Gooseff & McKnight, 2021a-d); water
 593 chemistry data (Lyons, 2016; Lyons & Welch, 2016); and microbial mat data (McKnight, 2019)
 594 are available at the McMurdo Long Term Ecological Research website and the Environmental
 595 Data Initiative.

596 **References**

- 597 Aiken, G., McKnight, D., Harnish, R., & Wershaw, R. (1996). Geochemistry of aquatic humic
 598 substances in the Lake Fryxell Basin, Antarctica. *Biogeochemistry*, *34*(3), 157–188.
- 599 Alger, A. S. (1997). Ecological processes in a cold desert ecosystem: The abundance and species
 600 distribution of algal mats in glacial meltwater streams in Taylor Valley, Antarctica.
 601 *Occasional Paper/University of Colorado*.
- 602 Barrett J. E., Virginia R. A., Lyons W. B., McKnight D. M., Priscu J. C., Doran P. T., Fountain
 603 A. G., Wall D. H., & Moorhead D. L. (2007). Biogeochemical stoichiometry of Antarctic
 604 Dry Valley ecosystems. *Journal of Geophysical Research: Biogeosciences*, *112*(G1).
 605 <https://doi.org/10.1029/2005JG000141>
- 606 Burns, M. A., Barnard, H. R., Gabor, R. S., McKnight, D. M., & Brooks, P. D. (2016). Dissolved
 607 organic matter transport reflects hillslope to stream connectivity during snowmelt in a
 608 montane catchment. *Water Resources Research*, *52*(6), 4905–4923.
 609 <https://doi.org/10.1002/2015WR017878>
- 610 Castro, N. M., & Hornberger, G. M. (1991). Surface-subsurface water interactions in an
 611 alluviated mountain stream channel. *Water Resources Research*, *27*(7), 1613–1621.
 612 <https://doi.org/10.1029/91WR00764>
- 613 Conovitz, P. A., MacDonald, L. H., & McKnight, D. M. (2006). Spatial and Temporal Active
 614 Layer Dynamics along Three Glacial Meltwater Streams in the McMurdo Dry Valleys,
 615 Antarctica. *Arctic, Antarctic, and Alpine Research*, *38*(1), 42–53.
 616 [https://doi.org/10.1657/1523-0430\(2006\)038\[0042:SATALD\]2.0.CO;2](https://doi.org/10.1657/1523-0430(2006)038[0042:SATALD]2.0.CO;2)
- 617 Conovitz, P. A., Mcknight, D. M., Macdonald, L. H., Fountain, A. G., & House, H. R. (1998).
 618 Hydrologic Processes Influencing Streamflow Variation in Fryxell Basin, Antarctica. In
 619 *Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica* (pp. 93–
 620 108). American Geophysical Union (AGU). <https://doi.org/10.1029/AR072p0093>
- 621 Cozzetto Karen D., Bencala Kenneth E., Gooseff Michael N., & McKnight Diane M. (2013). The
 622 influence of stream thermal regimes and preferential flow paths on hyporheic exchange in a
 623 glacial meltwater stream. *Water Resources Research*, *49*(9), 5552–5569.
 624 <https://doi.org/10.1002/wrcr.20410>

- 625 Creed, I. F., McKnight, D. M., Pellerin, B. A., Green, M. B., Bergamaschi, B. A., Aiken, G. R.,
626 Burns, D. A., Findlay, S. E. G., Shanley, J. B., Striegl, R. G., Aulenbach, B. T., Clow, D.
627 W., Laudon, H., McGlynn, B. L., McGuire, K. J., Smith, R. A., & Stackpoole, S. M. (2015).
628 The river as a chemostat: Fresh perspectives on dissolved organic matter flowing down the
629 river continuum. *Canadian Journal of Fisheries and Aquatic Sciences*, 72(8), 1272–1285.
630 <https://doi.org/10.1139/cjfas-2014-0400>
- 631 Cullis, J. D. S., Stanish, L. F., & McKnight, D. M. (2014). Diel flow pulses drive particulate
632 organic matter transport from microbial mats in a glacial meltwater stream in the McMurdo
633 Dry Valleys. *Water Resources Research*, 50(1), 86–97.
634 <https://doi.org/10.1002/2013WR014061>
- 635 Evans, C., & Davies, T. D. (1998). Causes of concentration/discharge hysteresis and its potential
636 as a tool for analysis of episode hydrochemistry. *Water Resources Research*, 34(1), 129–
637 137. <https://doi.org/10.1029/97WR01881>
- 638 Godsey, S. E., Kirchner, J. W., & Clow, D. W. (2009). Concentration–discharge relationships
639 reflect chemostatic characteristics of US catchments. *Hydrological Processes: An*
640 *International Journal*, 23(13), 1844–1864.
- 641 Gooseff, M., & McKnight, D. (2019a). *McMurdo Dry Valleys LTER: High frequency seasonal*
642 *stream gage measurements from Canada Stream at F1 in Taylor Valley, Antarctica from*
643 *1990 to present* [Data set]. Environmental Data Initiative.
644 <https://doi.org/10.6073/PASTA/3B2D96BB09BA5D1B883AB99702E3EB40>
- 645 Gooseff, M., & McKnight, D. (2019b). *McMurdo Dry Valleys LTER: High frequency seasonal*
646 *stream gage measurements from Crescent Stream at F8 in Taylor Valley, Antarctica from*
647 *1990 to present* [Data set]. Environmental Data Initiative.
648 <https://doi.org/10.6073/PASTA/86BCE67070A2E3B37BF5CA805059FEEE>
- 649 Gooseff, M., & McKnight, D. (2019c). *McMurdo Dry Valleys LTER: High frequency seasonal*
650 *stream gage measurements from Lost Seal Stream at F3 in Taylor Valley, Antarctica from*
651 *1990 to present* [Data set]. Environmental Data Initiative.
652 <https://doi.org/10.6073/PASTA/FA9C6A1A8AB26074CFD632DBECC339F1>
- 653 Gooseff, M., & McKnight, D. (2021a). *McMurdo Dry Valleys LTER: High frequency seasonal*
654 *stream gage measurements from Aiken Creek at F5 in Taylor Valley, McMurdo Dry Valleys,*
655 *Antarctica from 1990 to present* [Data set]. Environmental Data Initiative.
656 <https://doi.org/10.6073/PASTA/B746A756E810FFD065D07473E6E3E5C8>
- 657 Gooseff, M., & McKnight, D. (2021b). *McMurdo Dry Valleys LTER: High frequency seasonal*
658 *stream gage measurements from Delta Stream at F10 in Taylor Valley, McMurdo Dry*
659 *Valleys, Antarctica from 1990 to present* [Data set]. Environmental Data Initiative.
660 <https://doi.org/10.6073/PASTA/D7299DB40EE72AFB30C48937475F9B26>
- 661 Gooseff, M., & McKnight, D. (2021c). *McMurdo Dry Valleys LTER: High frequency seasonal*
662 *stream gage measurements from Green Creek at F9 in Taylor Valley, McMurdo Dry*
663 *Valleys, Antarctica from 1990 to present* [Data set]. Environmental Data Initiative.
664 <https://doi.org/10.6073/PASTA/72F64EEEA463E699F402FB63C8FEEBE8>
- 665 Gooseff, M., & McKnight, D. (2021d). *McMurdo Dry Valleys LTER: High frequency seasonal*
666 *stream gage measurements from Von Guerard Stream at F6 in Taylor Valley, McMurdo Dry*

- 667 *Valleys, Antarctica from 1990 to present* [Data set]. Environmental Data Initiative.
668 <https://doi.org/10.6073/PASTA/F0AE43B1F92BF7A17E187A1D0E130DCE>
- 669 Gooseff, Michael N., Barrett, J. E., Adams, B. J., Doran, P. T., Fountain, A. G., Lyons, W. B.,
670 McKnight, D. M., Priscu, J. C., Sokol, E. R., Takacs-Vesbach, C., Vandegehuchte, M. L.,
671 Virginia, R. A., & Wall, D. H. (2017). Decadal ecosystem response to an anomalous melt
672 season in a polar desert in Antarctica. *Nature Ecology & Evolution*, 1(9), 1334–1338.
673 <https://doi.org/10.1038/s41559-017-0253-0>
- 674 Gooseff Michael N., McKnight Diane M., Lyons W. Berry, & Blum Alex E. (2002). Weathering
675 reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater
676 stream in the McMurdo Dry Valleys. *Water Resources Research*, 38(12), 15–1.
677 <https://doi.org/10.1029/2001WR000834>
- 678 Gooseff, M.N., McKnight, D. M., Runkel, R. L., & Duff, J. H. (2004). Denitrification and
679 hydrologic transient storage in a glacial meltwater stream, McMurdo Dry Valleys,
680 Antarctica. *Limnology and Oceanography*, 49(5), 1884–1895.
681 <https://doi.org/10.4319/lo.2004.49.5.1884>
- 682 Hale, R. L., & Godsey, S. E. (2019). Dynamic stream network intermittence explains emergent
683 dissolved organic carbon chemostasis in headwaters. *Hydrological Processes*, 33(13), 1926–
684 1936. <https://doi.org/10.1002/hyp.13455>
- 685 Hawes, I., & Howard-Williams, C. (1998). Primary Production Processes in Streams of the
686 McMurdo Dry Valleys, Antarctica. In *Ecosystem Dynamics in a Polar Desert: The*
687 *McMurdo Dry Valleys, Antarctica* (pp. 129–140). American Geophysical Union (AGU).
688 <https://doi.org/10.1029/AR072p0129>
- 689 Heindel, R. C., Darling, J. P., Singley, J. G., Bergstrom, A. J., McKnight, D. M., Lukkari, B. M.,
690 Welch, K. A., & Gooseff, M. N. (2021). Diatoms in Hyporheic Sediments Trace Organic
691 Matter Retention and Processing in the McMurdo Dry Valleys, Antarctica. *Journal of*
692 *Geophysical Research: Biogeosciences*, 126(2). <https://doi.org/10.1029/2020JG006097>
- 693 Jantze, E. J., Lyon, S. W., & Destouni, G. (2013). Subsurface release and transport of dissolved
694 carbon in a discontinuous permafrost region. *Hydrology and Earth System Sciences*, 17(10),
695 3827–3839. <https://doi.org/10.5194/hess-17-3827-2013>
- 696 Kohler, T. J., Stanish, L. F., Crisp, S. W., Koch, J. C., Liptzin, D., Baeseman, J. L., & McKnight,
697 D. M. (2015). Life in the Main Channel: Long-Term Hydrologic Control of Microbial Mat
698 Abundance in McMurdo Dry Valley Streams, Antarctica. *Ecosystems*, 18(2), 310–327.
699 <https://doi.org/10.1007/s10021-014-9829-6>
- 700 Kohler, T. J., Stanish, L. F., Liptzin, D., Barrett, J. E., & McKnight, D. M. (2018). Catch and
701 release: Hyporheic retention and mineralization of N-fixing Nostoc sustains downstream
702 microbial mat biomass in two polar desert streams. *Limnology and Oceanography Letters*,
703 3(4), 357–364.
- 704 Lyons, B. (2016). *McMurdo Dry Valleys Stream Chemistry—Dissolved Organic Carbon* [Data
705 set]. Environmental Data Initiative.
706 <https://doi.org/10.6073/PASTA/578D31FA0E142B6B7A6C80095D29B968>

- 707 Lyons, B., & Welch, K. (2016). *McMurdo Dry Valleys Stream Chemistry and Ion*
708 *Concentrations* [Data set]. Environmental Data Initiative.
709 <https://doi.org/10.6073/PASTA/BE9F781814330116F68844A8957962E4>
- 710 Lyons, W. B., Welch, K. A., Nezat, C. A., Crick, K., Toxey, J. K., Mastrine, J. A., & McKnight,
711 D. M. (1997). Chemical weathering rates and reactions in the Lake Fryxell Basin, Taylor
712 Valley: Comparison to temperate river basins. In *Ecosystem Processes in Antarctic Ice-free*
713 *Landscapes* (pp. 147–154).
- 714 Maher, K. (2010). The dependence of chemical weathering rates on fluid residence time. *Earth*
715 *and Planetary Science Letters*, 294(1–2), 101–110.
- 716 Maher, K. (2011). The role of fluid residence time and topographic scales in determining
717 chemical fluxes from landscapes. *Earth and Planetary Science Letters*, 312(1–2), 48–58.
- 718 Maher, K., & Chamberlain, C. P. (2014). Hydrologic regulation of chemical weathering and the
719 geologic carbon cycle. *Science*, 343(6178), 1502–1504.
- 720 Maurice, P. A., McKnight, D. M., Leff, L., Fulghum, J. E., & Gooseff, M. (2002). Direct
721 observations of aluminosilicate weathering in the hyporheic zone of an Antarctic Dry Valley
722 stream. *Geochimica et Cosmochimica Acta*, 66(8), 1335–1347.
723 [https://doi.org/10.1016/S0016-7037\(01\)00890-0](https://doi.org/10.1016/S0016-7037(01)00890-0)
- 724 McKnight, D. (2019). *McMurdo Dry Valleys LTER: Algal microbial mat biomass measurements*
725 *from the McMurdo Dry Valleys and Cape Royds, Antarctica from 1994 to present* [Data
726 set]. Environmental Data Initiative.
727 <https://doi.org/10.6073/PASTA/519BFCA4EA3CDA94B09EDB78FF8759DB>
- 728 McKnight, D. M., Alger, A., Tate, C., Shupe, G., & Spaulding, S. (1998). Longitudinal Patterns
729 in Algal Abundance and Species Distribution In Meltwater Streams In Taylor Valley,
730 Southern Victoria Land, Antarctica. In *Ecosystem Dynamics in a Polar Desert: The*
731 *McMurdo Dry Valleys, Antarctica* (pp. 109–127). American Geophysical Union (AGU).
732 <https://doi.org/10.1029/AR072p0109>
- 733 McKnight, D. M., Runkel, R. L., Tate, C. M., Duff, J. H., & Moorhead, D. L. (2004). Inorganic
734 N and P dynamics of Antarctic glacial meltwater streams as controlled by hyporheic
735 exchange and benthic autotrophic communities. *Journal of the North American*
736 *Benthological Society*, 23(2), 171–188.
- 737 Mulholland, P. J., & Hill, W. R. (1997). Seasonal patterns in streamwater nutrient and dissolved
738 organic carbon concentrations: Separating catchment flow path and in-stream effects. *Water*
739 *Resources Research*, 33(6), 1297–1306. <https://doi.org/10.1029/97WR00490>
- 740 Mulholland Patrick J., Marzolf Erich R., Webster Jackson R., Hart Deborah R., & Hendricks
741 Susan P. (1997). Evidence that hyporheic zones increase heterotrophic metabolism and
742 phosphorus uptake in forest streams. *Limnology and Oceanography*, 42(3), 443–451.
743 <https://doi.org/10.4319/lo.1997.42.3.0443>
- 744 Niyogi, D. K., Tate, C. M., McKnight, D. M., Duff, J. H., Alger, A. S., Lyons, W. B., Howard-
745 Williams, C., & Hawes, I. (1997). Species composition and primary production of algal
746 communities in Dry Valley streams in Antarctica: Examination of the functional role of
747 biodiversity. In *Ecosystem Processes in Antarctic Ice-free Landscapes* (pp. 171–180). A.A.
748 Balkema.

- 749 Northcott, M. L., Gooseff, M. N., Barrett, J. E., Zeglin, L. H., Takacs-Vesbach, C. D., &
750 Humphrey, J. (2009). Hydrologic characteristics of lake- and stream-side riparian wetted
751 margins in the McMurdo Dry Valleys, Antarctica. *Hydrological Processes*, 23(9), 1255–
752 1267. <https://doi.org/10.1002/hyp.7262>
- 753 Obryk, M. K., Fountain, A. G., Doran, P. T., Lyons, W. B., & Eastman, R. (2018). Drivers of
754 solar radiation variability in the McMurdo Dry Valleys, Antarctica. *Scientific Reports*, 8(1),
755 5002. <https://doi.org/10.1038/s41598-018-23390-7>
- 756 Rue, G. P., Rock, N. D., Gabor, R. S., Pitlick, J., Tfaily, M., & McKnight, D. M. (2017).
757 Concentration-discharge relationships during an extreme event: Contrasting behavior of
758 solutes and changes to chemical quality of dissolved organic material in the Boulder Creek
759 Watershed during the September 2013 flood. *Water Resources Research*, 53(7), 5276–5297.
760 <https://doi.org/10.1002/2016WR019708>
- 761 Runkel, R. L., McKnight, D. M., & Andrews, E. D. (1998). Analysis of transient storage subject
762 to unsteady flow: Diel flow variation in an Antarctic stream. *Journal of the North American*
763 *Benthological Society*, 17(2), 143–154.
- 764 Singley, J. G., Gooseff, M. N., McKnight, D. M., & Hinckley, E. S. (2021). The Role of
765 Hyporheic Connectivity in Determining Nitrogen Availability: Insights From an Intermittent
766 Antarctic Stream. *Journal of Geophysical Research: Biogeosciences*, 126(5),
767 e2021JG006309. <https://doi.org/10.1029/2021JG006309>
- 768 Singley, J. G., Wlostowski, A. N., Bergstrom, A. J., Sokol, E. R., Torrens, C. L., Jaros, C.,
769 Wilson, C. E., Hendrickson, P. J., & Gooseff, M. N. (2017). Characterizing hyporheic
770 exchange processes using high-frequency electrical conductivity-discharge relationships on
771 subhourly to interannual timescales. *Water Resources Research*, 53(5), 4124–4141.
772 <https://doi.org/10.1002/2016WR019739>
- 773 Spencer, R. G. M., Butler, K. D., & Aiken, G. R. (2012). Dissolved organic carbon and
774 chromophoric dissolved organic matter properties of rivers in the USA. *Journal of*
775 *Geophysical Research: Biogeosciences*, 117(G3). <https://doi.org/10.1029/2011JG001928>
- 776 Thompson, S. E., Basu, N. B., Lascurain, J., Aubeneau, A., & Rao, P. S. C. (2011). Relative
777 dominance of hydrologic versus biogeochemical factors on solute export across impact
778 gradients. *Water Resources Research*, 47(10). <https://doi.org/10.1029/2010WR009605>
- 779 Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The
780 River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37(1),
781 130–137. <https://doi.org/10.1139/f80-017>
- 782 Vincent, W. F., Castenholz, R. W., Downes, M. T., & Howard-Williams, C. (1993). Antarctic
783 cyanobacteria: Light, nutrients, and photosynthesis in the microbial mat environment.
784 *Journal of Phycology*, 29(6), 745–755.
- 785 Welch, K. A., Lyons, W. B., Whisner, C., Gardner, C. B., Gooseff, M. N., McKnight, D. M., &
786 Priscu, J. C. (2010). Spatial variations in the geochemistry of glacial meltwater streams in
787 the Taylor Valley, Antarctica. *Antarctic Science*, 22(6), 662–672.
- 788 Wlostowski, A. N., Gooseff, M. N., & Adams, B. J. (2018a). Soil Moisture Controls the Thermal
789 Habitat of Active Layer Soils in the McMurdo Dry Valleys, Antarctica. *Journal of*

790 *Geophysical Research: Biogeosciences*, 123(1), 46–59.

791 <https://doi.org/10.1002/2017JG004018>

792 Wlostowski, A. N., Gooseff, M. N., McKnight, D. M., & Lyons, W. B. (2018b). Transit Times
793 and Rapid Chemical Equilibrium Explain Chemostasis in Glacial Meltwater Streams in the
794 McMurdo Dry Valleys, Antarctica. *Geophysical Research Letters*, 45(24), 13,322-13,331.

795 <https://doi.org/10.1029/2018GL080369>

Dissolved Organic Carbon Chemostasis in Antarctic Polar Desert Streams

Christa L. Torrens¹, Michael N. Gooseff¹, Diane M. McKnight¹

¹Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO 80303 USA

Contents of this file

Figure S1

Introduction

Figure S1 is a graph of dissolved organic carbon [DOC] vs. microbial mat ash-free dry mass [AFDM] for the four study streams that have a long-term record of microbial mat sampling. None of these relationships were significant (all $p > 0.05$). These results were reported in the main manuscript, but not depicted due to the lack of statistical significance. This figure supports that information.

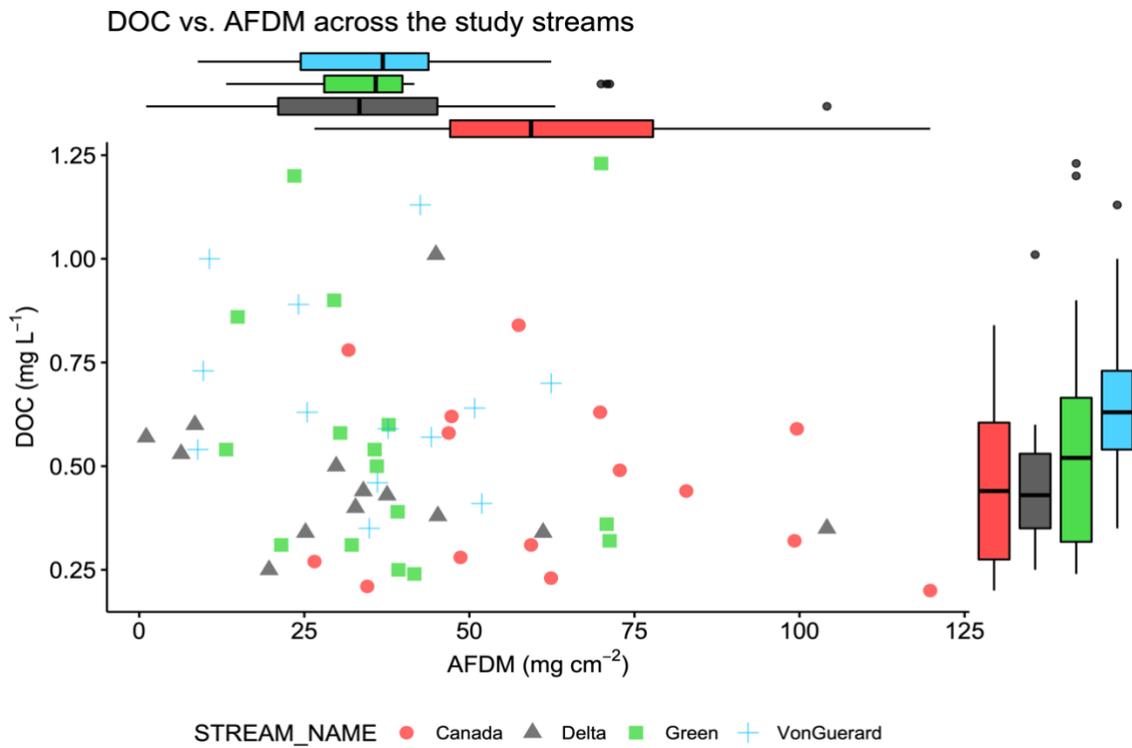


Figure S1. Relationship between mean annual dissolved organic carbon (DOC) and mean annual ash-free dry mass (AFDM) from streambed samples (all $p > 0.05$) in the four study streams. The plot margins show boxplots of the distributions for AFDM (top margin) and DOC (right margin) for each stream.