

1 **The River Runs Through It: the Athabasca River Delivers Mercury to**
2 **Aquatic Birds Breeding Far Downstream**

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4 Short Title: Athabasca River Delivers Mercury Far Downstream

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25 **Abstract**

26 This study examined factors contributing to temporal variability (2009-2017) in total mercury
27 (THg) concentrations in aquatic bird eggs collected in the Peace-Athabasca Delta and Lake
28 Athabasca in northern Alberta. Factors examined included annual changes in oil sands
29 production, bird diets, forest fires, and flow of the Athabasca River. Surface mining activities
30 associated with Alberta's Athabasca oil sands are centered north of Fort McMurray, Alberta,
31 adjacent to the northward-flowing Athabasca River. Previous studies have found that oil sands
32 industrial operations release mercury into the local (within ~50 km) environment. However,
33 temporal trends in egg THg levels did not track trends in synthetic oil production from the oil
34 sands. Intraspecific fluctuations in bird diet also could not explain annual variability in egg THg
35 levels. Annual extent of forest fires in Alberta was only related to egg THg concentrations in
36 California Gulls from Lake Athabasca; annual levels in other species showed no relationship
37 with fire extent. The inclusion of more terrestrial foods in gull diets may have contributed to this
38 difference. For the majority of species, annual fluctuations in maximal flow of the Athabasca
39 River were important in influencing annual egg THg levels. Eggs collected following years of
40 high flow had higher THg concentrations with distinct stable Hg isotope compositions. Riverine
41 processes associated with suspended sediment were likely critical in regulating Hg availability to
42 nesting birds. This study highlights the importance of the Athabasca River as a conduit for Hg
43 transport to ecologically-sensitive downstream ecosystems such as the Peace-Athabasca Delta
44 and Wood Buffalo National Park (a UNESCO World Heritage Site). Human activities that
45 increase atmospheric Hg deposition to the Athabasca River watershed, or that enhance Hg
46 releases to the river through erosion of Hg-bearing soils, will likely increase the availability of
47 Hg to organisms inhabiting downstream areas.

48 **Introduction**

49 The Athabasca River is a major river flowing northeast 1200 km from the Rocky
50 Mountains to Lake Athabasca. Along the way, it passes through Alberta's oil sands, a region of
51 large-scale, open-pit mines used to extract bitumen for synthetic oil production. The river
52 discharges into the Peace-Athabasca Delta (PAD) and western Lake Athabasca approximately
53 200 km downstream of Fort McMurray (see [1]). Since 1967, when oil sands operations
54 commenced, industrial exploitation of the bitumen-rich oil sands has expanded greatly [2] (Fig.
55 S1). Previous research has indicated that industrial development associated with the oil sands is a
56 source of mercury (Hg) to the environment [3, 4]. For example, Kirk et al. [4] found that
57 deposition of both total mercury (THg) and methyl mercury (MeHg) in snow resembled a
58 bullseye pattern with higher Hg levels in snow collected closer to oil sands developments.
59 However, snow Hg levels declined rapidly with distance from such developments with most Hg
60 being deposited within approximately 50 km. These studies [3, 4] highlighted the possibility that
61 spring snowmelt could result in the release of chemicals, such as Hg, into the aquatic
62 environment. Similarities in relative concentrations of metals in snow and river water provided
63 evidence of metals emitted to the air finding their way into the Athabasca River and tributaries
64 [3]. Kelly et al. [3] also found that Hg concentrations in water were greatest downstream of
65 areas disturbed by oil sands development. Passage of water through the surface-mineable oil
66 sands region, in itself, was not responsible for elevated water Hg levels. Degree of land
67 disturbance caused by oil sands operations was important in enhancing water Hg concentrations.
68 The significance of these findings in terms of effects on Hg concentrations in biota inhabiting
69 areas farther downstream, e.g. the PAD, has not been documented and deserves further study.

70 The PAD is a wetland of international significance [5] and it is a defining feature of
71 Wood Buffalo National Park (WBNP), a UNESCO World Heritage Site. It provides habitat for
72 millions of birds and WBNP is the only breeding area for the endangered Whooping Crane (*Grus*
73 *americana*) [6]. The surrounding region also provides important wildlife habitat. For example,
74 Egg Island in western Lake Athabasca is a provincial ecological reserve harboring a variety of
75 colonially-nesting aquatic birds including the largest breeding colony of Caspian Terns
76 (*Hydroprogne caspia*) in Alberta [7]. The PAD and Lake Athabasca are also important to
77 Indigenous land users who rely on traditional wild foods [8]. Hence, environmental changes
78 brought about by human activities have the potential to significantly affect wildlife and human
79 inhabitants of this region.

80 Colonial aquatic birds, e.g. gulls and terns, are commonly used to monitor the state of the
81 environment [9]. These birds are top predators resulting in their accumulation of high levels of
82 biomagnifying contaminants. Eggs are a useful sampling matrix for contaminant studies as their
83 collection has little impact on bird populations and eggs of these species are formed from
84 exogenous, locally-obtained resources [10]. Since 2009, gull and tern eggs have been collected
85 annually from sites in WBNP (Mamawi Lake) and western Lake Athabasca (Egg Island). The
86 goal of this study was to examine temporal trends (2009-2017) in egg THg levels and determine
87 whether they were influenced by a variety of factors including: oil sands production, bird diet,
88 forest fires, and flow of the Athabasca River. We briefly discuss each of these factors below.

89 From 2009-2016, oil production from surface mineable sources in the Athabasca oil
90 sands increased by 47% (761,000 bpd (barrels per day) to 1,117,000 bpd) and accounted for
91 approximately 46% of total oil sands production in 2016 (in-situ production accounted for the
92 remainder) [2]. As oil sands operations are a known source of Hg [3, 4], it is plausible that

93 increases in oil/bitumen production might be accompanied by increases in Hg releases to the
94 environment that could result in increased Hg levels in wildlife receptors such as bird eggs.
95 Because MeHg biomagnifies, it is possible that annual changes in bird diets, particularly with
96 respect to bird trophic position, could be important in regulating annual egg THg concentrations.
97 Inter-specific differences in food sources could also be important in regulating Hg exposure.
98 Forest fires are known to release Hg into the environment [11, 12] and Alberta experienced very
99 large forest fires in some years during the study period [13]. It is possible that such fires could
100 increase Hg levels in the food webs used by birds with resultant increases in egg THg
101 concentrations. Previous research on aquatic birds has highlighted the possibility that the
102 Athabasca River may be a source of Hg to wildlife inhabiting downstream environments [14]. In
103 a large-scale spatial assessment of Hg levels in western Canadian gull eggs, Dolgova et al. [15]
104 found that levels were greatest in eggs collected from breeding sites in receiving waters of the
105 Athabasca River. Hence, factors associated with the regulation of Hg transport via the Athabasca
106 River may be important in regulating Hg levels in downstream wildlife. One such critical factor
107 is annual maximal river flow. Long and Pavelsky [16] documented the influence of river flow on
108 sediment transport down the Athabasca River into the PAD and Lake Athabasca. In the river,
109 there was a linear relationship between flow and suspended sediment concentrations (SSC) with
110 SSC notably increasing around flows of 1500 m³/s. In addition, a non-linear relationship between
111 river flow and downstream SSC in western Lake Athabasca was observed after maximal flow
112 exceeded a threshold of 1700 m³/s. Riverine transport of sediment-bound Hg is an important
113 mechanism for the transfer of that element to downstream environments [17]. SSC may also
114 influence Hg dynamics in the environment through effects on the photochemical reduction of
115 MeHg. These effects, and possible Hg sources, can be evaluated using Hg stable isotopes.

116 Mass-dependent (MDF) and mass-independent (MIF) fractionation of stable Hg isotopes
117 (^{196}Hg , ^{198}Hg , ^{199}Hg , ^{200}Hg , ^{201}Hg , ^{202}Hg , ^{204}Hg) can provide insights into processes regulating
118 Hg dynamics in the environment. MDF, e.g. $\delta^{202}\text{Hg}$, is influenced by a variety of factors
119 including physical processes as well as by biological reactions [18] and can be useful in
120 identifying the flow of mercury from terrestrial and aquatic systems to consumers [19]. MIF, on
121 the other hand, has largely been documented for the odd mass Hg isotopes (^{199}Hg , ^{201}Hg) and is
122 thought to primarily be the result of a magnetic isotope effect, i.e. dissimilarities in magnetic spin
123 of even and odd mass isotopes result in their reacting at different rates. Existing evidence
124 suggests that MIF is not influenced by food web/trophic interactions [20] but occurs during
125 photochemical MeHg degradation and photoreduction of Hg^{2+} [21]. Therefore, factors that affect
126 Hg exposure to light, e.g. light penetration through the water column, are expected to influence
127 MIF of Hg isotopes [22]. Photodegradation of MeHg to Hg^0 may be an important MeHg
128 removal mechanism, particularly in systems characterized by clear water with a high degree of
129 light penetration, and this can be assessed using Hg isotopes [23]. However, only a portion of the
130 MeHg in such systems will undergo photochemical demethylation. The remaining MeHg will
131 exhibit MIF of ^{199}Hg and ^{201}Hg and that MeHg may be incorporated into food webs with Hg
132 isotope values in consumers (e.g. birds) reflecting MIF of Hg isotopes [23].

133 The slope of the MIF of ^{201}Hg versus ^{199}Hg is useful in differentiating the Hg species
134 (MeHg or Hg^{2+}) undergoing photoreduction (MeHg slope ~ 1.3 , Hg^{2+} slope ~ 1.0) [21, 23, 24]. A
135 slope near 1.3 indicates that photoreduction of MeHg is the main mechanism underlying MIF
136 values. If photochemical reduction of MeHg is the main process underlying MIF of Hg isotopes
137 then $\Delta^{199}\text{Hg}$ and/or $\Delta^{201}\text{Hg}$ values in consumer tissues can be used to estimate the amount of
138 MeHg that has been photodegraded [21, 25].

139 In this study, annual THg levels in eggs of aquatic birds nesting downstream of the
140 Athabasca River are assessed. As described above, various factors, i.e. oil sands production, bird
141 diet, forest fires, and riverine processes, are investigated to determine the degree to which they
142 explain patterns in annual egg THg concentrations. As part of this analysis, the degree to which
143 maximal annual flow of the Athabasca River and concomitant changes in SSC are important in
144 regulating Hg availability to birds is investigated. Mercury isotopes are used to gain insights into
145 the processes regulating Hg dynamics and availability in this ecosystem.

146

147 **Methods**

148 **Field Methods**

149 Aquatic bird, i.e. gull and tern, egg collections were made in June, 2009-2017 (no
150 collections were made in 2010) at two sites located in receiving waters of the Athabasca River.
151 Mamawi Lake (58.60N, -111.47W) is located in the Peace-Athabasca Delta within the
152 boundaries of Wood Buffalo National Park. Egg Island (59.98N, -110.44W) is located in the
153 western end of Lake Athabasca approximately 40 km northeast of the mouth of the Athabasca
154 River (see Dolgova et al. [15] for map showing collection locations). In most years, 10 eggs were
155 collected per species per site. At Mamawi Lake, Ring-billed Gull (*Larus delawarensis*) and
156 Common Tern (*Sterna hirundo*) eggs were collected. Low water levels in 2011 prevented
157 access to that location so no eggs were collected that year. Also, in 2014 it was impossible to
158 collect Common Tern eggs at that site. At Egg Island, 10 eggs were collected annually from
159 three species: California Gull (*Larus californicus*), Caspian Tern, and Common Tern. The first
160 recorded nesting of Common Terns on Egg Island was in 2011 so eggs of that species were not

161 collected from that site in 2009. Eggs were transported to the National Wildlife Research
162 Centre, Ottawa, ON, Canada in padded cases.

163 In 2013, prey fish, i.e. cyprinids, were collected from Mamawi Lake and two sites in
164 western Lake Athabasca to provide isotope data for bird prey. Whole-body fish were analyzed of
165 two surface-schooling species: Spottail Shiner (*Notropis hudsonius*) and Emerald Shiner (*N.*
166 *atherinoides*). These species are accessible to surface-feeding birds. Details regarding prey fish
167 collections are available in Dolgova et al. [15].

168 Epiphytic lichen was collected from the branches of coniferous tree species in 2013 (May
169 or July) from 14 locations north, south, east and west of Fort McMurray. All sites were within
170 100 km of that city. Samples (n=26, two samples per site except at two sites where only one
171 sample was analyzed) were cleaned by removing foreign debris, freeze dried, and pulverized into
172 a fine powder before analysis. The utility of tree lichens as passive collectors of atmospheric
173 pollutants, including mercury, has been demonstrated [26, 27]. Mercury isotope measurements in
174 lichens were used to establish baseline Hg isotopic “signatures” associated with atmospherically
175 deposited mercury in the Fort McMurray region. This would include mercury from all sources to
176 that region including the oil sands.

177

178 Laboratory Methods

179 Egg contents (i.e. yolk, albumen, embryonic tissue) and whole-body prey fish were
180 homogenized/pulverized using liquid nitrogen and a cryogenic ball-mill. Homogenates were
181 aliquoted into acid-washed glass and polypropylene containers and stored at -40° C prior to
182 analysis.

183 Details regarding egg THg analysis are identical to those reported in Hebert and Popp
184 [28]. In eggs, approximately 97% of THg is in the organic MeHg form [29] so measuring THg is
185 a cost-effective way to assess MeHg levels in eggs. THg concentrations measured in all samples
186 were within concentration ranges of certified reference materials (OT1566b, TORT-3, DOLT-4,
187 IAEA-407, BCR-463). Limit of detection for THg was 0.006 µg/g (dry weight).

188 Stable isotopes of nitrogen (^{15}N and ^{14}N expressed as $\delta^{15}\text{N}$) and carbon (^{13}C and ^{12}C
189 expressed as $\delta^{13}\text{C}$) were measured in prey fish (collected in 2013) and in the contents of
190 individual eggs (all years) to assess bird diets across years. Details regarding stable isotope
191 analysis are identical to those reported in Hebert and Popp [28]. Dietary change affecting the
192 trophic position of laying females is reflected in egg $\delta^{15}\text{N}$ values (‰) as nitrogen isotopes
193 undergo MDF. MDF leads to enrichment of ^{15}N in higher trophic level organisms with
194 increasing $\delta^{15}\text{N}$ values with increasing trophic position. Because Hg biomagnifies, temporal
195 changes in trophic position would be expected to affect female exposure to, and uptake of, MeHg
196 with concomitant effects on egg THg levels. Carbon isotopes are useful in evaluating carbon
197 sources utilized by consumers [30]. Because lipid content of samples can affect $\delta^{13}\text{C}$ values, a
198 mathematical approach was used to adjust $\delta^{13}\text{C}$ values in eggs and prey fish based upon C:N
199 ratios in individual samples (C:N ratios for all samples were > 4.0). For eggs, the equation used
200 was from Elliott et al. [31], $\delta^{13}\text{C}_{\text{lipid-corrected}} = \delta^{13}\text{C}_{\text{non-corrected}} - 4.46 + 7.32 * \text{Log}(\text{C:N ratio})$. For
201 fish, $\delta^{13}\text{C}_{\text{lipid-corrected}} = \delta^{13}\text{C}_{\text{non-corrected}} - 3.32 + 0.99 * \text{C:N}$ [32].

202 Mercury isotope analysis was conducted at Trent University's Water Quality Centre.
203 Details regarding mercury isotope analysis have been reported previously [33]. Mass-
204 independent fractionation (MIF) of Hg isotopes is unrelated to isotope mass and is reported in
205 capital delta (Δ) notation. MIF describes the difference between measured $\delta^{\text{xxx}}\text{Hg}$ values and

206 scaled $\delta^{202}\text{Hg}$ values ($\Delta^{\text{xxx}}\text{Hg} = \delta^{\text{xxx}}\text{Hg} - (\delta^{202}\text{Hg} \times \beta)$). β , the scaling factor, is determined by
207 theoretical laws of mass dependent fractionation (MDF) and is an isotope-specific constant.
208 Here, the focus is on the interpretation of MDF ($\delta^{202}\text{Hg}$) and MIF results ($\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$).
209 MDF data can provide insights into pathways of mercury exposure, e.g. terrestrial versus aquatic
210 [19], while MIF can be useful in assessing the processes influencing mercury isotope values in
211 eggs. Hg isotope analyses were conducted on eggs from all four study species from both study
212 sites allowing an assessment of whether MIF of Hg isotopes was influenced by bird trophic
213 position (as inferred from egg $\delta^{15}\text{N}$ values; see below). Samples were analyzed from a variety of
214 years (2009-2017) for the different species.

215

216 Analytical and Statistical Methods

217 Annual estimates of synthetic oil/bitumen production from surface-mined oil sands
218 deposits were obtained from CAPP [2].

219 Annual estimates of total forest fire extent (ha) for the province of Alberta were obtained
220 from the National Forestry Database [13]. During the period of study, 99% of total annual area
221 burned occurred during May-August with June-August usually being the focal months. Hence,
222 these fires would have occurred after the egg-laying period in that same calendar year. Caldwell
223 et al. [34] reported sediment MeHg levels peaked within three months after a wildfire, further
224 delays would be expected in terms of wildfire-generated Hg being incorporated into food webs.
225 Therefore, fire extent in the year preceding egg collection was used to assess the impact of fire
226 on egg THg levels. The one-year time lag between forest fire extent and egg THg levels allowed
227 time for Hg released from fires to be incorporated into, and passed through, the food webs
228 utilized by birds.

229 Annual monthly estimates of Athabasca River flow were obtained from a hydrometric
230 station located five km north of Fort McMurray (station 07DA001)
231 (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html). During the period of
232 study, maximal monthly river flows were most often observed in June (seven of 10 years from
233 2008-2016), therefore, June flow was used to estimate maximal annual river flow. Based upon
234 Long and Pavelsky [16], years were categorized as being low (June mean monthly flow <1600
235 m³/s) or high (June mean monthly flow ≥1600 m³/s) flow years. River flow in the year preceding
236 egg collections was used to categorize egg collections as being influenced by low or high flow
237 years. For example, mean river flow in June 2011 was >1600 m³/s, hence egg collections made
238 in June 2012 were categorized as being influenced by a high flow year. The one-year time lag
239 between river flow and egg THg levels allowed for the influence of river processes on Hg
240 availability/dynamics to be incorporated into downstream food webs. This period of time is
241 consistent with work examining the rapidity with which Hg is incorporated into foodwebs. For
242 example, mercury levels in small fish responded within 1-2 years to changes in levels of Hg in
243 the environment [35]. Such small fish species are an important component of the diet of gulls
244 and terns and because eggs of these species are formed from locally-obtained exogenous
245 resources, e.g. prey fish, we would expect egg Hg levels to respond within a similar time-frame
246 to prey fish. For statistical comparisons, years were combined into either low or high flow
247 categories and these categories were compared.

248 True color Landsat images [36] of the PAD and western Lake Athabasca were obtained
249 from years of low (2002, 2010, 2015) and high (2011, 2014, 2017) Athabasca River flow. These
250 images were used to qualitatively visualize annual differences in the extent of sediment plumes
251 entering western Lake Athabasca.

252 Data regarding suspended sediment concentrations (SSC) and secchi depth (a measure of
253 water clarity) were obtained from Long and Pavelski [37]. Data were available from sampling
254 sites situated along a southeast-northwest transect crossing the western basin of the lake (see
255 [16]). Distance of each sampling site from the mouth of the Athabasca River was estimated
256 based upon georeferenced data. Data from low (2010) and high (2011) flow years were used to
257 assess inter-year differences in the influence of the river on SSC in western Lake Athabasca and
258 resultant impacts on water transparency.

259 Inter-year differences in variables were assessed using ANOVA or Kruskal-Wallis tests
260 followed by selected post-hoc tests (Tukey's HSD or Dunn's test). Relationships between
261 variables were evaluated using Pearson correlation coefficients (r). Student's two-tailed t-tests
262 were used to compare egg THg levels and Hg isotope values between years of low and high
263 Athabasca River flow. All statistical analyses were conducted using Statistica Ver 12 [38] with α
264 = 0.05. Assumptions underlying the use of parametric statistics were tested using Q-Q plots, the
265 Shapiro-Wilk W test (normality), and Levene's test (homogeneity of variances).

266

267 **Results**

268 Temporal trends in egg THg concentrations (2009-2017)

269 Egg THg concentrations showed inter-year differences for most species/site combinations
270 (Egg Island: Caspian Terns ANOVA $F(7,72) = 8.83, p < 0.001$; Common Terns ANOVA
271 $F(6,63) = 8.96, p < 0.001$; Mamawi Lake: Ring-billed Gulls Welch's ANOVA $F(6,30) = 3.61, p$
272 $= 0.01$; Common Terns Welch's ANOVA $F(5,20) = 3.92, p = 0.01$) except for Egg Island
273 California Gulls (Welch's ANOVA $F(7,31) = 0.89, p = 0.53$). However, egg THg concentrations
274 were not correlated with year of collection for Egg Island Caspian Terns ($n = 80, r = -0.01, p =$

275 0.97), Egg Island Common Terns ($n = 70$, $r = 0.08$, $p = 0.53$), or Mamawi Lake Ring-billed Gulls
276 ($n = 83$, $r = -0.13$, $p = 0.24$) (Figure 1A, B). THg levels in eggs of Egg Island California Gulls
277 increased through time ($n = 81$, $r = 0.24$, $p = 0.03$) while THg levels in Common Tern eggs from
278 Mamawi Lake decreased ($n = 55$, $r = -0.40$, $p = 0.002$) (Fig.1A, B). In both these cases, temporal
279 trends were influenced by data from one year. For the Egg Island California Gull eggs, high THg
280 levels in 2017 were responsible for the temporal increase. When 2017 data were removed from
281 the analysis, there was no significant relationship with time ($n = 71$, $r = 0.08$, $p = 0.52$).
282 Similarly, the declining temporal trend in THg in Common Tern eggs from Mamawi Lake was
283 driven by the 2009 data. When data from that year were omitted from the analysis, no temporal
284 trends were evident ($n = 45$, $r = -0.06$, $p = 0.71$).

285

286 **Fig 1.** Annual mean (\pm SE) THg levels ($\mu\text{g/g}$, dry weight) in gull and tern eggs from sites in
287 receiving waters of the Athabasca River. (a) Egg Island, western Lake Athabasca: Caspian
288 Terns, Common Terns, California Gulls (b) Mamawi Lake: Common Terns, Ring-billed Gulls.

289

290 Influence of oil sands production, forest fires, and bird diet on egg THg

291 Temporal trends in egg THg concentrations were not related to annual production of
292 synthetic oil/bitumen from surface-mined oil sands deposits for any of the species/site
293 combinations (2009-2016 annual data. Egg Island CAGU $n = 8$, $r = .56$, $p = .15$; CATE $n = 8$, r
294 $= -.03$, $p = .94$; COTE $n = 7$, $r = .07$, $p = .89$; Mamawi Lake RBGU $n = 7$, $r = -.13$, $p = .78$;
295 COTE $n = 6$, $r = -.67$, $p = .14$). The production of synthetic oil/bitumen from surface mining
296 showed a significant increase during the period of study ($r = 0.996$, $p < 0.001$) (Fig. S1) which
297 was not reflected in the annual fluctuations observed in egg THg levels (Fig.1A, B).

298 Annual extent of forest fires preceding the year of egg collection showed no relationship
299 with THg levels in Mamawi Lake eggs (Ring-billed Gulls, $r = 0.23$, $p = 0.59$; Common Terns $r =$
300 -0.46 , $p = 0.36$) nor in eggs of Caspian Terns ($r = -0.18$, $p = 0.64$) or Common Terns ($r = -0.54$, p
301 $= 0.16$) at Egg Island. However, mean annual egg THg levels were correlated with forest fire
302 extent in eggs of California Gulls ($r = 0.73$, $p = 0.03$) at that location (Fig. 2).

303
304 **Fig 2.** Annual extent (ha) of forest fires in Alberta versus annual mean (\pm SE) THg levels (ug/g,
305 dry weight) in California Gull eggs from Egg Island, Lake Athabasca. Annual egg THg levels
306 were compared to forest fire extent in the year preceding egg collections.

307
308 Egg stable nitrogen isotope values ($\delta^{15}\text{N}$) were different among all species comparisons
309 (Kruskal-Wallis $H(3,369) = 171.85$, $p < 0.001$, Dunn's test, Caspian Tern $>$ Common Tern $>$
310 California Gull $>$ Ring-billed Gull). $\delta^{15}\text{N}$ values within most species and sites showed no
311 differences across years (Egg Island: California Gulls ANOVA $F(7,73) = 2.12$, $p = 0.051$;
312 Caspian Terns ANOVA $F(7,72) = 1.09$, $p = 0.38$; Common Terns Kruskal-Wallis $H(6,70) =$
313 9.37 , $p = 0.15$; Mamawi Lake: Ring-billed Gulls Kruskal-Wallis $H(6,83) = 12.86$, $p = 0.05$,
314 Dunn's post-hoc test no differences). Only Mamawi Lake Common Terns showed significant
315 inter-year differences in egg $\delta^{15}\text{N}$ values (Kruskal-Wallis $H(5,55) = 20.76$, $p = 0.01$, Dunn's test)
316 (Table S1). For three of the five species/site combinations, inter-year differences in $\delta^{13}\text{C}$ values
317 were observed but these were minimal with most years having similar values (Table S2).

318 Interspecific comparisons of stable Hg and carbon isotope values revealed significant
319 differences among species (Fig.3). Egg $\delta^{202}\text{Hg}$ values reflecting MDF of Hg isotopes were
320 greater in California Gulls than the other bird species (ANOVA $F(3,185) = 100.0$, $p < 0.001$,

321 followed by Tukey's HSD test). Egg $\delta^{13}\text{C}$ values were less negative in California Gulls (mean =
322 -23.7‰) than the other three species (mean values; Common Tern = -26.3‰, Caspian Tern = -
323 25.8‰, Ring-billed Gull = -25.7‰). $\delta^{13}\text{C}$ values in Ring-billed Gulls were also less negative
324 than Common Terns (Welch's ANOVA $F(3,185) = 91.1, p < 0.001$, followed by Tukey's HSD
325 test). $\delta^{13}\text{C}$ values in California Gulls showed the greatest deviation from those in prey fish (mean
326 ± 1 SD values, Emerald Shiner = -28.33 ± 2.10 (n=46), Spottail Shiner = -28.00 ± 3.41 (n=22)).

327
328 **Fig 3.** Three-dimensional plot showing mass-dependent fractionation (MDF, as $\delta^{202}\text{Hg}$) and
329 mass independent fractionation (MIF, as $\Delta 199$) of Hg in gull and tern eggs from Egg Island and
330 Mamawi Lake. Also shown are lipid-corrected $\delta^{13}\text{C}$ values in eggs. Samples shown here were
331 collected in 2009, 2011, 2012, or 2014. Symbols: circles are Caspian Terns, squares are
332 Common Terns, closed triangles are California Gulls, open triangles are Ring-billed Gulls.

333
334 **Influence of riverine processes on egg THg, SSC, water clarity and Hg isotopes**

335 Annual maximal June flow for the Athabasca River indicated large inter-year differences
336 with flow varying approximately three-fold during the period of study (Fig. S2). The Athabasca
337 River is unregulated by dams and annual flow is related to the volume of snowpack and glacier
338 melt [39-41]. Mean annual THg concentrations in eggs were linearly correlated with river flow
339 from the previous year in two of the five species/site comparisons (Egg Island: Caspian Terns n
340 = 8, $r = 0.90, p = 0.003$; Common Terns n = 7, $r = 0.89, p = 0.007$) (Fig.4).

341
342 **Fig 4.** Annual mean June flow (m^3/s) of the Athabasca River versus annual mean (\pm SE) THg
343 levels ($\mu\text{g}/\text{g}$ dry weight) in gull and tern eggs collected the following year. (a) Egg Island,

344 western Lake Athabasca: Caspian Terns, Common Terns, California Gulls (b) Mamawi Lake:
345 Common Terns, Ring-billed Gulls. Annual egg THg levels were compared to river flow in the
346 year preceding egg collections.

347
348 However, visual examination of the data indicated that the relationship between egg THg
349 concentrations and river flow might not be best described by a linear relationship. Instead, a
350 threshold effect seemed more appropriate with greater egg THg levels being observed in years
351 when river flow surpassed a mean June threshold of 1600 m³/s. To investigate this further, years
352 were categorized as being low (<1600 m³/s) or high (≥1600 m³/s) flow based on June mean
353 monthly flow. Years classified as low flow years were: 2008, 2010, 2012, 2015, 2016; high flow
354 years were 2011, 2013, 2014. THg levels in eggs were elevated following high river flow years
355 in the majority of species/sites examined (Fig.5). THg concentrations in eggs collected following
356 high flow years were greater in Caspian Terns (Egg Island) (mean_{low} = 1.51 µg·g⁻¹ dry wt,
357 mean_{high} = 2.49 µg·g⁻¹ dry wt; $t = 6.85$, 78 *d.f.*, $p < 0.0001$), Common Terns (Egg Island)
358 (mean_{low} = 1.02 µg·g⁻¹ dry wt, mean_{high} = 1.58 µg·g⁻¹ dry wt; $t = 5.45$, 68 *d.f.*, $p < 0.0001$), and
359 Ring-billed Gulls (Mamawi Lake) (mean_{low} = 0.38 µg·g⁻¹ dry wt, mean_{high} = 0.86 µg·g⁻¹ dry wt; t
360 = 5.60, 81 *d.f.*, $p < 0.0001$). THg concentrations in eggs from these species/sites were on average
361 82% greater in high flow versus low flow years. Eggs from Egg Island California Gulls ($t = 0.24$,
362 79 *d.f.*, $p = 0.81$) and Mamawi Lake Common Terns ($t = 0.19$, 53 *d.f.*, $p = 0.85$) did not show a
363 significant difference in THg levels between low and high flow years. However, exclusion of the
364 anomalously high 2009 egg THg data for Mamawi Lake Common Terns (highest mean δ¹⁵N
365 value observed that year may have indicated possible influence of dietary differences) resulted in

366 detection of elevated THg levels in high flow years ($\text{mean}_{\text{low}} = 0.98 \mu\text{g}\cdot\text{g}^{-1}$ dry wt, $\text{mean}_{\text{high}} =$
367 $1.20 \mu\text{g}\cdot\text{g}^{-1}$ dry wt; $t = 2.74$, 43 *d.f.*, $p = 0.01$).

368

369 **Fig 5.** Annual mean (\pm SE) THg levels ($\mu\text{g}/\text{g}$ dry weight) in eggs collected following years of
370 low and high flow in the Athabasca River. Low flow years were categorized as those having a
371 maximal annual flow of less than $1600 \text{ m}^3/\text{s}$. (a) Egg Island Caspian Terns (b) Egg Island
372 Common Terns (c) Mamawi Lake Ring-billed Gulls (d) Mamawi Lake Common Terns (e) Egg
373 Island California Gulls.

374

375 Athabasca River flow affected the extent of sediment plumes entering Lake Athabasca
376 (Fig.6). Furthermore, lake SSC concentrations were greater in a high flow year (2011) versus a
377 low flow year (2010) (Fig.S3). Differences in SSC were likely responsible for inter-year
378 differences in secchi depth in western Lake Athabasca as water clarity was lower at sites with
379 higher SSC, particularly at sites closer to the mouth of the Athabasca River (Fig.S3). Decreased
380 water clarity was evident in the high flow year.

381

382 **Fig 6.** True color Landsat images of the PAD and western Lake Athabasca during years of low
383 ($<1600 \text{ m}^3/\text{s}$ June flow) and high ($\geq 1600 \text{ m}^3/\text{s}$ June flow) Athabasca River flow. In high flow
384 years, there is a notable increase in the extent of the brown sediment plume entering the lake.
385 2015 image is obscured to some extent by white cloud cover but sediment is clearly visible. Red
386 and white circles indicate the locations of Mamawi Lake and Egg Island, respectively. Brown
387 oval indicates the Athabasca River mouth. Dates of image acquisition are shown.

388

389 For each species, differences in egg $\Delta^{199}\text{Hg}$ values were observed following years of low
390 and high Athabasca River flow (Table 1). Statistical comparison of mean $\Delta^{199}\text{Hg}$ values in eggs
391 collected following low flow years versus high flow years indicated higher $\Delta^{199}\text{Hg}$ values
392 following low flow years in California Gulls ($t(67) = 3.50, p < 0.001$), Caspian Terns ($t(38) =$
393 $2.16, p = 0.04$), Common Terns ($t(19) = 2.10, p = 0.049$), Ring-billed Gulls ($t(55) = 3.18, p =$
394 0.002). Similarly, egg $\Delta^{201}\text{Hg}$ values were greater following low flow years than high flow years;
395 California Gulls ($t(67) = 2.62, p = 0.01$), Caspian Terns ($t(38) = 2.16, p = 0.04$), Common Terns
396 ($t(19) = 2.68, p = 0.02$), Ring-billed Gulls ($t(55) = 5.04, p < 0.001$) (data not shown). $\Delta^{199}\text{Hg}$
397 and $\Delta^{201}\text{Hg}$ values in eggs of all species were correlated ($\Delta^{199}\text{Hg} = 0.22 + 1.07 * \Delta^{201}\text{Hg}$, $n =$
398 $187, r = 0.89, p < 0.001$). Based upon inter-specific differences between gulls and terns in egg
399 $\delta^{13}\text{C}$ values (both California and Ring-billed Gulls differed from one or both tern species) and
400 $\delta^{202}\text{Hg}$ (California Gulls differed) separate regression analyses were completed for terns and
401 gulls. For gulls, $\Delta^{199}\text{Hg} = 0.36 + 0.89 * \Delta^{201}\text{Hg}$, $n = 126, r = 0.81, p < 0.001$, and for terns,
402 $\Delta^{199}\text{Hg} = 0.09 + 1.25 * \Delta^{201}\text{Hg}$, $n = 61, r = 0.99, p < 0.001$. $\delta^{202}\text{Hg}$ values in eggs only differed
403 between low and high flow categories for Common Terns ($t(19) = 3.12, p < 0.01$), other species
404 showed no differences between low and high flow (t-tests, $p > 0.3$) (Table 1).

405
406 **Table 1.** Annual mean (‰) mass dependent fractionation (MDF, $\delta^{202}\text{Hg}$) and mass-independent
407 fractionation (MIF, $\Delta^{199}\text{Hg}$) of Hg isotopes in aquatic bird eggs. California Gulls (CAGU),
408 Caspian Terns (CATE), Common Terns (COTE), and Ring-billed Gulls (RBGU) collected from
409 Egg Island and Mamawi Lake. Athabasca River flow in the year preceding egg collections was
410 categorized as low or high ($\geq 1600 \text{ m}^3/\text{s}$ in June) for each year. MDF and MIF values were
411 compared between flow categories for each species. * indicates statistically significant

412 differences (t-test, $p < 0.05$) between flow categories. n is the number of egg samples included in
 413 each category.

Collection Year	Flow	Egg Island, Lake Athabasca						Mamawi Lake, Peace-Athabasca Delta	
		CAGU		CATE		COTE		RBGU	
		$\delta^{202}\text{Hg}$	$\Delta^{199}\text{Hg}$	$\delta^{202}\text{Hg}$	$\Delta^{199}\text{Hg}$	$\delta^{202}\text{Hg}$	$\Delta^{199}\text{Hg}$	$\delta^{202}\text{Hg}$	$\Delta^{199}\text{Hg}$
2009	Low	0.78	1.60	-0.49	1.38			-0.43	0.92
2011	Low	0.60	1.47	-0.21	1.36	0.10	2.11		
2012	High	0.58	1.50	-0.32	1.12			0.01	0.90
2014	High	0.91	1.27	-0.51	1.03	-0.48	1.74	-0.24	0.74
2015	High	0.89	1.25					-0.15	0.91
2016	Low	1.16	1.70					-0.13	1.16
2017	Low	1.11	1.51					-0.05	0.95
Mean	Low	0.90	1.56*	-0.35	1.37*	0.10*	2.11*	-0.20	1.01*
	n	42		20		11		30	
Mean	High	0.79	1.34	-0.42	1.08	-0.48	1.74	-0.13	0.85
	n	27		20		10		29	

414

415 Analysis of epiphytic lichen samples from the Fort McMurray region indicated relatively
 416 little spatial variation in $\Delta^{199}\text{Hg}$ (mean = $-0.46 \pm 0.15\%$, range -0.20 to -0.77‰) or $\Delta^{201}\text{Hg}$
 417 (mean = $-0.54 \pm 0.17\%$, range -0.18 to -0.86) values. Lichen $\Delta^{199}\text{Hg}$ values were used to
 418 estimate baseline MIF of Hg isotopes in atmospherically deposited Hg, an important source of
 419 Hg entering the Athabasca River. Lichen $\Delta^{199}\text{Hg}$ values measured here were similar to those in
 420 abiotic environmental compartments in the oil sands region, i.e. surface soil (overburden) and
 421 road material, bitumen and mined oil sand, processed oil sand, and Athabasca River oil sand
 422 [27]. Using egg MIF data for terns from Egg Island and Mamawi Lake, the proportion of MeHg
 423 photodegraded was estimated using a modified equation from Bergquist and Blum [21].

424
$$\ln(f) = \{10^3 * \ln[10^{-3}(\Delta^{199}\text{Hg}_{\text{egg}} - \Delta^{199}\text{Hg}_{\text{lichen}}) + 1]\} / S$$

425 where f = fraction of MeHg photodegraded, $\Delta^{199}\text{Hg}_{\text{egg}} = \Delta^{199}\text{Hg}$ in individual eggs, $\Delta^{199}\text{Hg}_{\text{lichen}} =$
426 average $\Delta^{199}\text{Hg}$ in lichen samples (-0.46), $S = -7.82$ (from the 10 mg/L dissolved organic carbon
427 (DOC) photochemical demethylation experiment in Bergquist and Blum [21]; June 2015 DOC
428 values in Lake Athabasca ranged from 4-7 mg/L). The amount of MeHg photodegraded was
429 estimated to be $21.6 \pm 5.5\%$ (mean \pm SD).

430

431 **Discussion**

432 In this study, annual differences in oil sands production, bird diets, and extent of forest
433 fires had little impact on THg levels in eggs of aquatic birds. Conversely, THg concentrations in
434 eggs were consistently influenced by processes associated with the Athabasca River. For the
435 majority of species/site analyses, higher egg THg concentrations were observed in eggs laid
436 following years of high river flow. The threshold effect of river flow on egg THg levels was
437 consistent with Long and Pavelsky's [16] results demonstrating the influence of river flow on
438 SSC in Lake Athabasca. Enhanced movement of sediment-associated Hg into downstream
439 ecosystems following high river flow may be a critical factor regulating Hg availability in
440 downstream biota. Studies in freshwater rivers have demonstrated the importance of seasonal
441 events on the fate of Hg. In some cases, the annual export of Hg from a watershed can be
442 determined by a single high flow event [42]. Hence, flow was likely of critical importance in
443 moving contaminated sediments to downstream areas with resultant impacts on the
444 bioavailability of Hg to wildlife such as birds.

445 Two processes may have contributed to higher egg THg levels following years of high
446 river flow. The first stems from the possibility that in high flow years, light attenuation
447 associated with high water SSC may have reduced the amount of photochemical degradation of

448 MeHg. This could have resulted in an increase in the amount of MeHg available for uptake into
449 foodwebs elevating MeHg exposure of laying females with resultant increases in egg THg
450 concentrations. This mechanism cannot likely account for the inter-year differences in egg THg
451 concentrations associated with river flow because only 22% of the MeHg in the tern species was
452 estimated to have been photodegraded. The Athabasca River downstream of Fort McMurray is
453 characterized by high SSC which reduces water transparency and possibly limits the scope for
454 photochemical degradation of MeHg to occur. Despite the fact that photochemical degradation of
455 MeHg was not likely responsible for inter-year fluctuations in egg THg concentrations, inter-
456 year variability in MIF of Hg isotopes was useful in linking river sources of Hg to Hg
457 accumulated in bird eggs. Inter-year differences in egg $\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$ values between years
458 of low and high flow provided evidence that riverine processes not only regulated the amount of
459 Hg to which birds were exposed but also the isotopic composition of that Hg.

460 The slope (1.25) of the $\Delta^{201}\text{Hg}/\Delta^{199}\text{Hg}$ regression for terns was similar to the value
461 associated with photoreduction of MeHg (1.3) indicating that MeHg photoreduction was likely
462 responsible for $\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$ values observed in eggs of those species. However, for gulls,
463 a lower slope (0.89) was observed which was more similar to that associated with the
464 photochemical reduction of Hg^{2+} (slope = 1.0, [21]). Tsui et al. [19] reported similar Hg isotope
465 patterns in biota associated with aquatic (slope = 1.20 in benthic invertebrates, slope = 1.24 in
466 trout) versus terrestrial food webs (slope = 1.05). They hypothesized that the mechanisms
467 underlying MIF of Hg differed between aquatic and terrestrial ecosystems. In terrestrial systems,
468 Hg^{2+} may be extensively photoreduced before the non-photoreduced Hg^{2+} undergoes
469 methylation. Hence, differences in Hg sources, pathways of exposure, and environmental Hg
470 processing, could explain the differences in egg Hg trends detected in California Gulls (i.e.

471 detection of a fire signal) versus the other species. Increased use of terrestrial resources by gulls
472 was supported by both the egg Hg MDF ($\delta^{202}\text{Hg}$) and $\delta^{13}\text{C}$ data. Tsui et al. [19] reported higher
473 $\delta^{202}\text{Hg}$ values in organisms associated with terrestrial systems; similar to what was observed for
474 California Gulls in this study. Carbon isotope results corroborated this interpretation as egg $\delta^{13}\text{C}$
475 values in terns were more negative than those measured in gulls. This was consistent with what
476 would be expected based upon differences in $\delta^{13}\text{C}$ values of food originating from freshwater
477 and terrestrial ecosystems [43] and suggested that gulls were incorporating terrestrial foods into
478 their diets in addition to aquatic prey. These results reflected the well-characterized, more
479 omnivorous diet of gulls (see [44] for an example). However, all of the bird species, including
480 gulls, exhibited MIF of Hg that reflected the importance of aquatic processes in regulating egg
481 Hg isotope values. Consistent differences in $\Delta^{199}\text{Hg}$ values between low and high flow year
482 categories for all bird species indicated that all of them were linked to aquatic ecosystem
483 processes. It is just possible that gulls may also show connections with terrestrial processes as
484 well.

485 Here, we do not provide direct evidence linking Hg levels in eggs to oil sands sources.
486 However, previous studies have demonstrated that oil sands developments are a source of Hg to
487 the local environment [3, 4]. For example, Hg in snow was 5.6 times greater within 50 km of oil
488 sands processing facilities than outside that area [3]. Hg levels in water sampled in summer were
489 three times greater downstream of areas disturbed by oil sands development than at upstream
490 locations situated in the mineable oil sands region [3]. Water Hg concentrations further
491 downstream in the Athabasca River and PAD were two times greater than these upstream
492 concentrations [3]. Elevated levels of Hg in abiotic environmental matrices are also reflected in
493 biota. For example, THg concentrations in prey fish sampled from the Athabasca River in the

494 surface mineable oil sands region were five times greater than fish collected from the Athabasca
495 River upstream of the oil sands [15]. THg levels in prey fish collected in the PAD and Lake
496 Athabasca were two to four times greater than fish from the upstream Athabasca River site [15].
497 THg levels in eggs of California Gulls and Herring Gulls (*Larus argentatus*) were two and three
498 times greater, respectively, at Egg Island (Lake Athabasca) than at Namur Lake, an inland lake
499 isolated from the Athabasca River but in close proximity (~60 km west) to open-pit oil sands
500 mines [15]. Taken together, these results indicate that the oil sands are a source of Hg to the
501 environment and that biota inhabiting waters in or downstream of the oil sands have higher Hg
502 levels. To understand this further, an integrated research program involving Hg measurements in
503 air, water, land, and biota is required to assess the relative importance of oil sands sources as a
504 contributor to the overall Hg budget of the Athabasca River and downstream ecosystems. With
505 respect to bird eggs, we can begin to predict expected Hg levels based upon river flow. For
506 example, in 2017, mean June river flow was high (~1590 m³/s), hence egg THg levels in 2018
507 are also predicted to be high. Eggs are currently being analyzed to test this hypothesis.

508 Until now, uncertainty surrounded the degree to which Hg may be transported by the
509 Athabasca River to ecosystems far downstream. Following spring melt of the snowpack in the
510 Athabasca River watershed, it is likely that some of the snow-associated mercury finds its way
511 into the river. This is particularly true in the spring when frozen soils may limit infiltration of
512 runoff into soil leading to efficient Hg export to the Athabasca River from overland sources [45,
513 46]. Furthermore, during high flow years, Athabasca River sediments are mobilized and
514 transported to downstream environments such as the PAD and western Lake Athabasca [16].
515 River systems can convey 90% of their total heavy metal load via sediment transport [17, 42,
516 46]. Hence, it is highly likely that Athabasca River sediments are transporting Hg to areas far

517 downstream. This hypothesis was supported by Long and Pavelsky's [37] data and by satellite
518 images showing inter-year differences in sediment plumes into Lake Athabasca. Aquatic bird
519 egg THg concentrations and Hg isotope data indicate that this Hg is being incorporated into
520 downstream food webs.

521 The importance of the current study lies in its highlighting the degree to which local
522 inputs of Hg to the river via atmospheric releases, mobilization associated with land disturbance,
523 or dust/leakage from tailings ponds (but see [47]) will not remain confined to the local receiving
524 environment. Hg from these sources will be transported long distances via the river to sensitive
525 downstream ecosystems, e.g. PAD, WBNP, that are recognized for their unique, world-class
526 ecological characteristics. New surface-mine oil sands projects are being proposed that will bring
527 development much closer (~30 km) to the southern boundary of the PAD/WBNP. This will
528 likely increase Hg inputs into the local environment through Hg mobilization stemming from
529 further land development and atmospheric Hg releases. The zone of atmospheric deposition may
530 encompass southern parts of the PAD/WBNP based upon the size of depositional zones
531 previously characterized for oil sands operations [3, 4]. Hence, further oil sands development
532 may result in increased delivery of Hg to downstream/downwind areas. The impacts of multiple
533 stressors (including oil sands) on WBNP have resulted in it being investigated as an UNESCO
534 World Heritage Site in Danger. Cumulative impact assessment of existing and proposed oil sands
535 mining projects needs to consider potential Hg impacts on wildlife and humans inhabiting this
536 globally-recognized area of ecological importance.

537

538 **SUPPORTING INFORMATION**

539 **Figure S1** shows temporal trends in surface-mineable oil sands production. **Figure S2** shows
540 annual trends in Athabasca River June flow. **Figure S3** contrasts suspended sediment
541 concentrations and water transparency in Lake Athabasca in years of low versus high river flow.
542 **Table S1** and **Table S2** tabulate stable carbon and nitrogen isotope data by species, site and year,
543 respectively.

544

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562

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742 **Supplementary Information**

743 Captions

744 S1_Table. Annual mean (± 1 SD) $\delta^{15}\text{N}$ values (‰) in eggs of California Gulls (CAGU), Caspian
745 Terns (CATE), Common Terns (COTE), and Ring-billed Gulls (RBGU) collected from Egg
746 Island and Mamawi Lake. At each site, inter-year differences in species-specific $\delta^{15}\text{N}$ values
747 were evaluated using ANOVA or Kruskal-Wallis/Dunn's tests. Superscript letters indicate
748 statistically significant differences ($p < 0.05$) between years. Means with the same letter are not
749 different. n is the number of samples analyzed for each species at each site.

750

751 S2_Table. Annual mean (± 1 SD) $\delta^{13}\text{C}$ values (‰) in eggs of California Gulls (CAGU), Caspian
752 Terns (CATE), Common Terns (COTE), and Ring-billed Gulls (RBGU) collected from Egg
753 Island and Mamawi Lake. $\delta^{13}\text{C}$ values were adjusted for lipid content. At each site, inter-year
754 differences in species-specific $\delta^{13}\text{C}$ values were evaluated using ANOVA/Tukey's HSD or
755 Kruskal-Wallis/Dunn's tests. Superscript letters indicate statistically significant differences ($p <$
756 0.05) between years. Means with the same letter are not different. n is the number of samples
757 analyzed for each species at each site.

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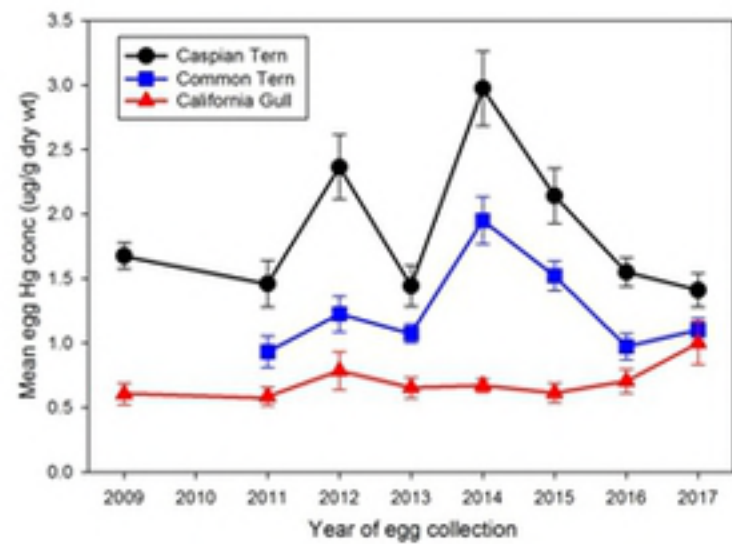
759 S1_Fig. Surface-mineable oil sands production (synthetic oil and bitumen) in millions of barrels
760 per day, 1967-2016. Data are from CAPP [2]. The dashed line indicates the beginning of the
761 period during which egg samples were collected to assess temporal trends in mercury levels.

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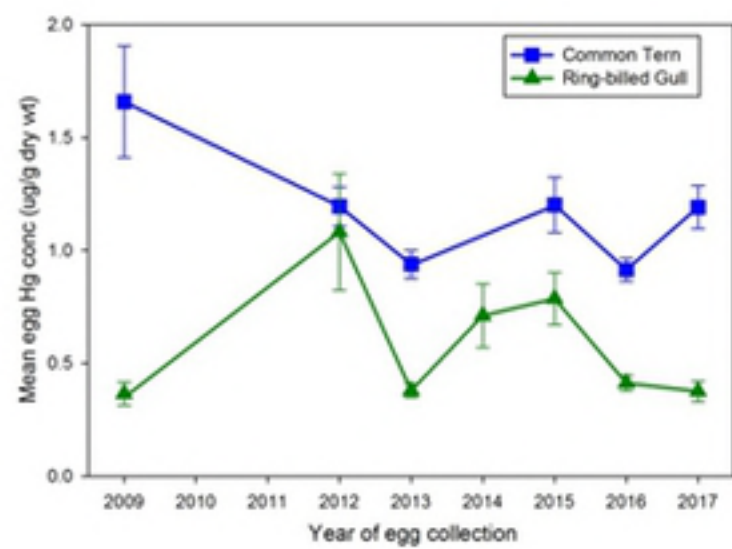
763 S2_Fig. Mean June flow (m^3/s) of the Athabasca River north of Fort McMurray (station
764 07DA001) from 1958-2016. The dashed line indicates the beginning of the period during which

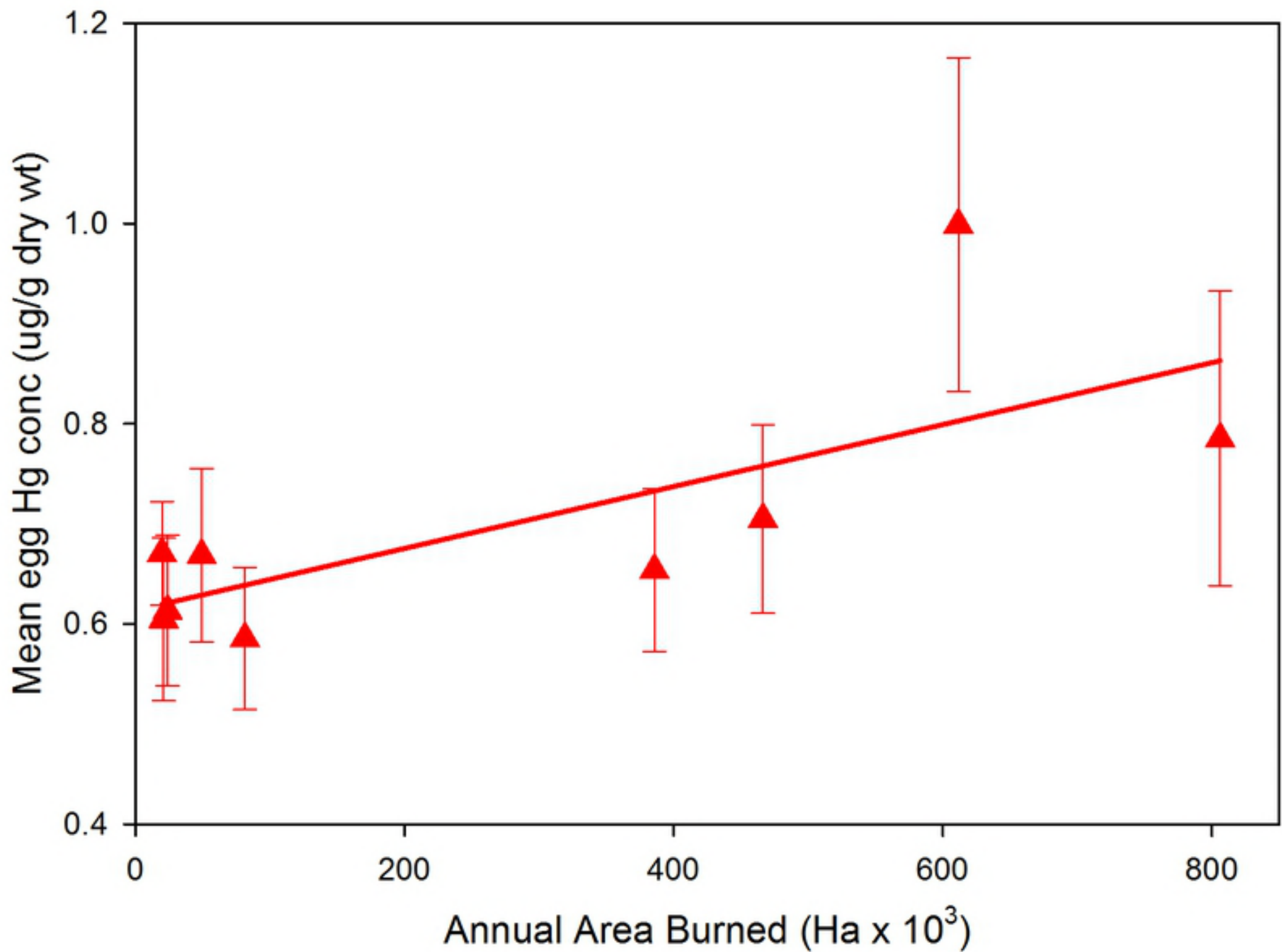
765 the influence of river flow on egg THg levels was investigated. Data are from Canadian
766 Hydrographic Service (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html).
767
768 S3_Fig. Suspended sediment concentrations (SSC) (mg/L) and secchi disc depth (cm) along a
769 transect from a point (58.6724 N, -110.8477 W) at the mouth of the Athabasca River. Data for a
770 low flow (2010) and a high flow year (2011) are shown. Data are from Long and Pavelsky [37].

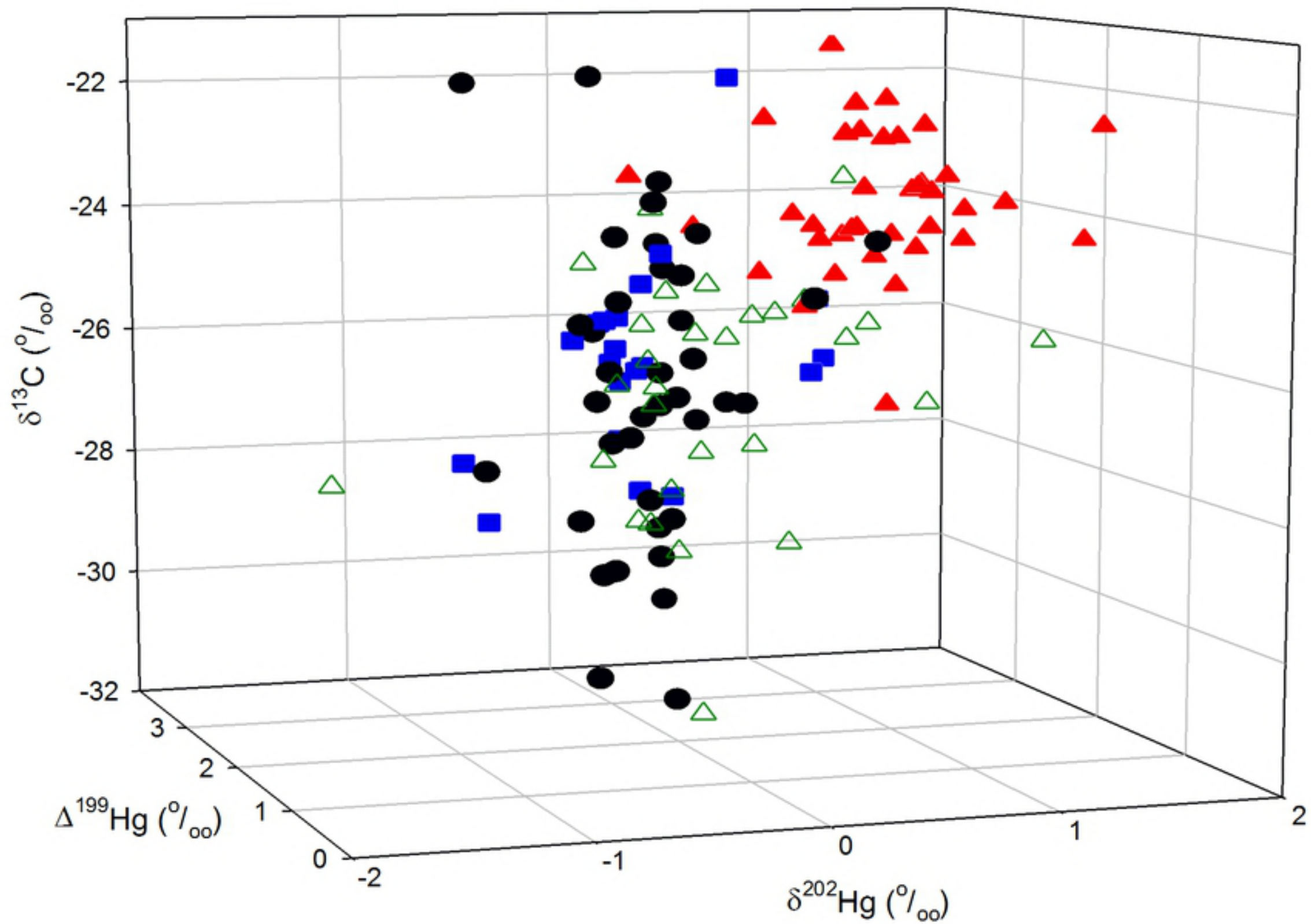
(A)



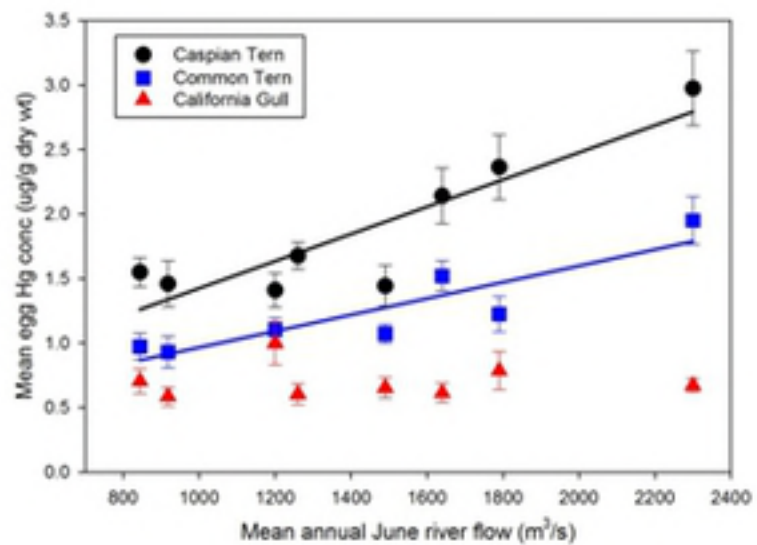
(B)



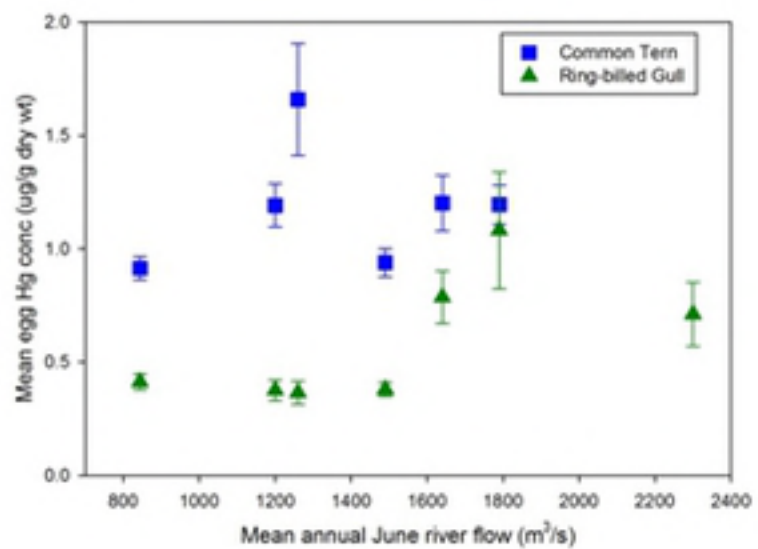




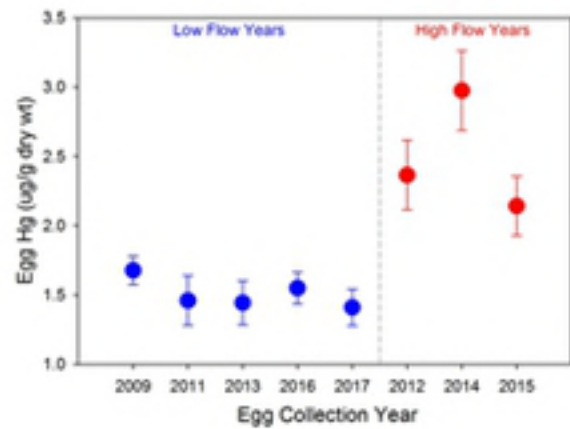
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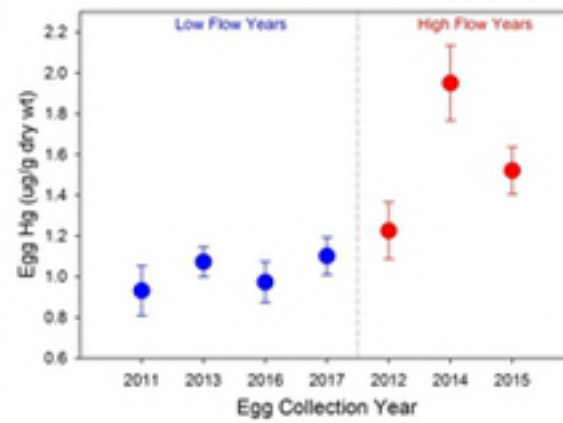
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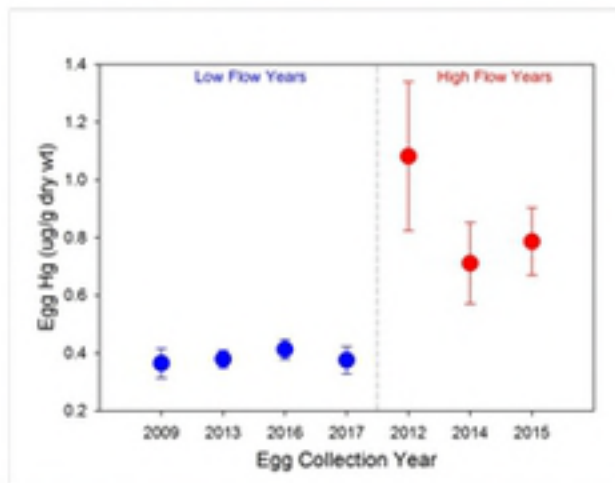
(A) Caspian Tem – Egg Island



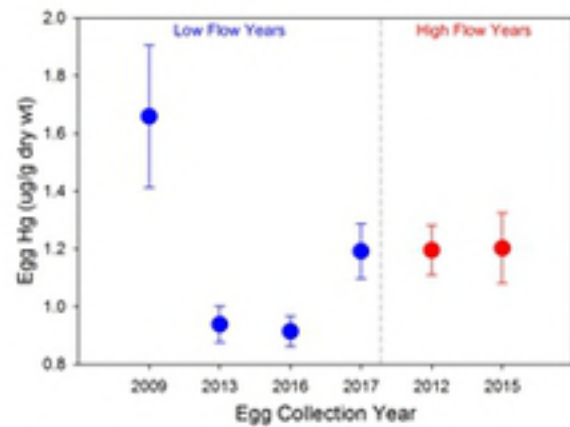
(B) Common Tern – Egg Island



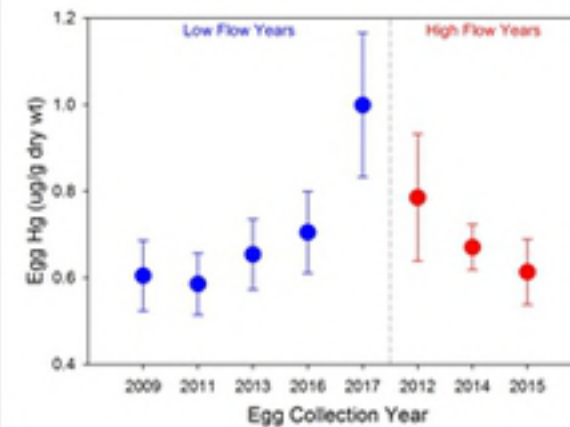
(C) Ring-billed Gull – Mamawi Lake



(D) Common Tern – Mamawi Lake



(E) California Gull – Egg Island



(A)



(B)

