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How intensive agricultural practices and flow regulation are threatening fish spawning habitats and their connectivity in the St. Lawrence River floodplain, Canada

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Landscape Ecology

Losing the best conditions for effective fish spawning habitat in the floodplain due to riparian agriculture and flow regulation, St. Lawrence River, Canada. †

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Abstract:	<p>Context</p> <p>Hydrological and land use changes for human needs, have resulted in the increased fragmentation of river landscapes and the loss of aquatic habitats, leading to profound changes in fish diversity and productivity.</p> <p>Objectives</p> <p>In the fluvial Lake Saint-Pierre (St. Lawrence River, Canada), we studied how riparian agriculture and water flow regulation have impacted the effectiveness of spawning habitats of northern pike (<i>Esox lucius</i>).</p> <p>Methods</p> <p>Northern pike spawning and nursery habitats were modelled over a 49-years period (1965-2013) to estimate effective spawning areas under four contrasted hydrological conditions.</p> <p>Results</p> <p>These simulations, coupled with land-use analyses, revealed that natural flow conditions usually favourable to fish reproduction have been lost due to human activities. The highest potential for reproduction, usually associated with high and stable water flows, has been lost due to (1) intensive agriculture in the upper floodplain</p>

	<p>that overlaps with suitable habitats for fish, and (2) flow regulation that leads to more frequent drying of spawning grounds. These profound anthropogenic changes have resulted in a significant loss of reproductive potential for northern pike and other fish species that use the floodplain to complete their life cycle.</p> <p>Conclusions</p> <p>This study suggests the need to convert intensive agriculture into natural wetlands or perennial crops and to restore a more natural flow regime by extending the duration of floods between spawning and nursery periods. The highest priority areas for restoration are the most effective and recurrent spawning habitats, ditch and stream networks, and connected managed wetlands.</p>
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1 **Losing the best conditions for effective fish spawning habitat in the floodplain due to**
2 **riparian agriculture and flow regulation, St. Lawrence River, Canada. †**

3

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23

24 **Abstract**

25 Context.

26 Hydrological and land use changes for human needs, have resulted in the increased
27 fragmentation of river landscapes and the loss of aquatic habitats, leading to profound
28 changes in fish diversity and productivity.

29 Objectives.

30 In the fluvial Lake Saint-Pierre (St. Lawrence River, Canada), we studied how riparian
31 agriculture and water flow regulation have impacted the effectiveness of spawning habitats
32 of northern pike (*Esox lucius*).

33 Methods.

34 Northern pike spawning and nursery habitats were modelled over a 49-years period (1965-
35 2013) to estimate effective spawning areas under four contrasted hydrological conditions.

36 Results.

37 These simulations, coupled with land-use analyses, revealed that natural flow conditions
38 usually favourable to fish reproduction have been lost due to human activities. The highest
39 potential for reproduction, usually associated with high and stable water flows, has been
40 lost due to (1) intensive agriculture in the upper floodplain that overlaps with suitable
41 habitats for fish, and (2) flow regulation that leads to more frequent drying of spawning
42 grounds. These profound anthropogenic changes have resulted in a significant loss of
43 reproductive potential for northern pike and other fish species that use the floodplain to
44 complete their life cycle.

45 Conclusions.

46 This study suggests the need to convert intensive agriculture into natural wetlands or
47 perennial crops and to restore a more natural flow regime by extending the duration of
48 floods between spawning and nursery periods. The highest priority areas for restoration are
49 the most effective and recurrent spawning habitats, ditch and stream networks, and
50 connected managed wetlands.

51

52 **Keywords:** northern pike reproduction, habitat modelling, connectivity modelling,
53 agricultural landscape, water regulation.

54

55

56 **Introduction**

57 In unaltered rivers, floodplains are highly productive and dynamical environments at the
58 interface between aquatic and terrestrial ecosystems. They provide a mosaic of temporary
59 habitats required by a wide number of freshwater fish species to accomplish their life cycle.
60 Given the high mortality rate in the early life stages of fishes, quality spawning and nursery
61 habitats are crucial for fish recruitment (Bayler 1991; Gorski et al. 2011). However,
62 floodplains are under increasing anthropogenic pressure around the world (Tockner and
63 Stanford 2002). Impacts of water flow regulation and agricultural expansion are major
64 threats to floodplain ecosystems (Beesley et al. 2014; Fernandes et al. 2015), where
65 potential spawning habitats can turn into mortality traps (e.g. Jeffres and Moyle 2012;
66 Sheaves et al. 2014). Quantifying the effects of anthropogenic pressures on the
67 effectiveness of spawning habitats allows the identification of large-scale environmental
68 disturbances that cause widespread recruitment failures (e.g. Goto et al. 2015), an
69 important prerequisite for restoring and managing floodplain ecosystems.

70

71 The natural flow regime in floodplains (i.e. magnitude, duration and the periodicity of
72 water levels) is highly variable in space and time, which in turn has a significant driving
73 force on fish habitat surfaces areas and landscape connectivity (Junk et al. 1989; Wiens
74 2002). Although the flooding of large areas for long periods of time can improve the
75 recruitment success of riverine fish, a rapid decrease in water discharge during early
76 development can suddenly dewater or isolate spawning and nursery habitats, resulting in
77 high egg and larvae mortality (Bayler 1991; Gorski et al. 2011). In addition, water flow
78 regulation has significantly altered natural flow regimes in many river systems around the

79 world, which can be critical for the overall fish production (Nilsson et al. 2005). Reduction
80 in spring water discharges has limited the duration of floods and their inter-annual
81 variability, which has affected the quality of river habitat and resulted in a decline in fish
82 populations (e.g. Farrell et al. 2010; Goto et al. 2015; Mingelbier et al. 2008).

83

84 Land-use change is one of the most important factors altering habitats quality and
85 connectivity on floodplains (Tockner and Stanford 2002). The conversion of large areas of
86 natural floodplains to intensive agricultural practices has resulted in a net loss of fish
87 habitat (Baber et al. 2002), a reduction in the abundance of fish eggs and larvae (Matsuzaki
88 et al. 2011), and threatened the long-term persistence of several fish species (Fernandes et
89 al. 2015). In addition, transportation infrastructure, such as roads along rivers, can
90 disconnect and isolate a significant portion of the floodplain, reducing access to critical
91 habitats (Blanton and Marcus 2014). In contrast, as fish larvae have limited swimming
92 capacities, passive transport at low water current speeds (Schiemer et al. 2003) and
93 landscape features such as ditch networks (Washitani 2007) can facilitate larval dispersal.
94 Such alternative use of man-made structure can help maintain floodplain connectivity in
95 an anthropized landscape.

96

97 In previous work, Foubert et al. (2018) examined spawning and nursery habitats of northern
98 pike (*Esox lucius*) over the past 50 years to investigate how habitat connectivity and
99 hydrological variability interact to alter the distribution of effective spawning habitat in the
100 St. Lawrence River floodplain, Canada. The northern pike was used as a species model
101 because it is an early-spring spawner, archetypal of the floodplain. Pike recruitment is

102 positively influenced by the abundance and quality of spawning habitat, high-water
103 temperature and high-water level maintained for several weeks after egg deposition
104 (Casselman and Lewis 1996; Johnson 1957). Pike abundance has recently declined in
105 several major river systems (Boët et al. 1999; Raat 2001), including the St. Lawrence River
106 (Smith et al. 2007). Foubert et al. (2018) defined *effective spawning habitats* as habitats
107 that permit survival of eggs and larvae, while affording larvae access to nursery areas that
108 are essential for successful recruitment to the adult population. As the simulations were
109 carried out in a reconstructed "unaltered" landscape to measure the intrinsic natural
110 variability of the river, they provided a way to compare a simulated pristine environment
111 with a present-day landscape altered by human activities. In the present study, we
112 hypothesised that effective spawning habitats gradually changed during the 20th century,
113 as water flows were regulated and extensive agricultural practices developed. More
114 specifically, in the Lake Saint-Pierre (St. Lawrence River, Canada), we (1) assess the
115 historical loss of potential pike spawning and nursery habitats by riparian agriculture since
116 1965, (2) test the effects of water flow and land-use changes on connectivity between
117 spawning and nursery habitats under four contrasted hydrological conditions, and (3)
118 estimate the loss of connected habitats due to changes in land-use to identify current
119 effective spawning habitats and the most valuable areas to protect and restore. These three
120 objectives are represented in a conceptual diagram that describes the methodological steps
121 leading to the main results of the study (Fig. 1).

122

123

124 **Method**

125 **Study Area**

126 Lake Saint-Pierre is the largest fluvial lake of the St. Lawrence River (Fig. 2), one of the
127 largest river system in the world, in terms of length (~1,200 km), watershed area
128 (1,344,200 km²) and average annual discharge ((10,270 m³.s⁻¹ at Sorel; Morin and
129 Bouchard 2000). Lake Saint-Pierre and its archipelago were included on UNESCO's World
130 Heritage Biosphere List in 2000. The shallow depth <3 m, slow lateral slope of the bottom,
131 and low current velocities <0.5 m.s⁻¹ contributes to the formation of extensive macrophyte
132 beds (Centre-Saint-Laurent 1998). The annual variability of spring water discharges,
133 ranging between 6,500 and 17,500 m³.s⁻¹ at Sorel, is a key mechanism for maintaining
134 wetland vegetation in floodplains (Morin et al. 2005).

135

136 Since the beginning of the industrial era, cumulative anthropogenic pressures have altered
137 the Lake Saint-Pierre ecosystem. The gradual excavation of the navigation channel (now
138 11.3 m deep and ~250 m wide) between Montreal and Quebec City began around 1840 and
139 was completed in 1998. Water regulation in the St. Lawrence River began in 1911 with the
140 harnessing of the Ottawa River, its main tributary, for hydroelectric power generation,
141 flood control and navigation purposes. The regulation of the St. Lawrence River was
142 further enhanced by the construction of the Moses-Saunders and Beauharnois Power Dams
143 that control the Lake Ontario – St. Lawrence River system in 1958 (Carpentier 2003; Morin
144 and Bouchard 2000). In addition, the development of large urban centres (e.g. Montreal,
145 Trois-Rivières, and Quebec City), intensive agriculture along the river and in the
146 floodplain, and transportation infrastructures along the St. Lawrence River have had a

147 serious impact on fish habitat. Over time, perennial crops (e.g. pasture), which constitute
148 potential fish habitat in the floodplain, have been replaced by annual crops (e.g. corn, soya)
149 with no potential for fish spawning; this phenomenon has accelerated since the early 1990s
150 (de la Chenelière et al. 2014; Fecteau and Poissant 2001). To compensate for the loss of
151 fish habitat, approximately 1,300 ha of the Lake Saint-Pierre floodplain have been
152 managed since the 1980s (Mingelbier and Douguet 1999). Managed wetlands are
153 surrounded by dikes and partially controlled to maintain high and stable water levels,
154 extend the duration of spring floods and accelerate water warming. During spring floods,
155 fish use these managed wetlands to spawn and are then evacuated in early June to Lake
156 Saint-Pierre.

157

158 **Data collection**

159 *Potential habitat modelling in an unaltered floodplain (1965-2013)*

160 Several high spatial resolution hydrodynamic and biological models have been developed
161 in the St. Lawrence River by Environment Canada to simulate the vegetation of the
162 floodplain (e.g. deep marshes, shallow marshes and shrub) in Lake Saint-Pierre under
163 various hydrological conditions (Morin et al. 2000; Morin et al. 2003; Turgeon and Morin
164 2005). Thus, natural plant succession in the littoral zone could be rebuilt each year for the
165 period 1965 to 2013. As these simulations exclude anthropogenic effects, we used them to
166 estimate the full reproductive habitat potential of northern pike in a natural environment
167 for each year of the 1965-2013 period. Habitat quality indices (HSIs) were developed to
168 map the maximum spawning habitat (Week₀: the date varies every year according to water
169 temperature, developed in Mingelbier et al. 2008) and nursery habitat five weeks after the

170 start of the free-swimming stage (HSI_{nursery} at Week₅, developed and described in Foubert
171 et al. 2018).

172

173 *Land-use categories*

174 Land-use in the Lake Saint-Pierre floodplain was described for three reference years: using
175 aerial photographs in 1964 and 1997 (Richard et al. 2011) and satellite images in 2014
176 (Jobin and Dauphin in prep). In the present study, we interpreted the various types of land-
177 use and assigned six land-use categories, from most suitable to least suitable for pike
178 reproduction habitats: (1) wetlands suitable for spawning and nursery habitats (e.g. wet
179 meadow and marshes), (2) main ditch and stream networks, (3) perennial crops (e.g.
180 pasture and forage crops), (4) unsuitable wetlands and wooded areas (e.g. wooded peat
181 bogs and plantations), (5) roads and urban areas, and finally (6) annual crops (i.e. soya,
182 corn, wheat, vegetable crops, oat, barley and other cereals) (see all land-use types and their
183 associated habitat quality in Online Resource 1). Only treed swamps differed in quality
184 between spawning and nursery habitats. We considered treed swamps being suitable for
185 nurseries (e.g. food supply) but unsuitable for spawning due to the lack of appropriate
186 substrate for egg deposition. In addition, the managed wetlands were included in the
187 analysis because they are used by pike and other fish species during their early stages of
188 development (Mingelbier and Douguet 1999 updated with field observations: see Fig.1).
189 The next three sections explain the analyses performed, which are illustrated in the
190 conceptual diagram Fig. 1.

191

192 **Historical habitat losses by agriculture (objective 1)**

193 As annual crops gradually increased between 1964, 1997 and 2014, we conducted a linear
194 interpolation using these three reference years to estimate annual habitat area losses
195 between 1965 and 2013. The loss of spawning and nursery related to annual crops was
196 calculated for each year by superimposing the corresponding land-uses and habitats.
197 Spearman's Rank correlation coefficients were used to assess (1) the relationship between
198 total potential spawning habitat lost due to annual crops and water discharge at spawning
199 (Week₀) and (2) the relationship between total potential nursery habitat lost due to annual
200 crops and water discharge when larvae became free-swimming (Week₅).

201

202 **Habitat connectivity for four hydrological profiles (objective 2)**

203 *Selected hydrological profiles*

204 Since the flow regime largely varied over the study period (1965-2013), the water
205 discharge between the maximum spawning time (Week₀) and the free-swimming stage
206 (Week₅) was classified into four distinct profiles: (1) stable-low, (2) stable-high, (3)
207 increasing and (4) decreasing. Four years of the 1965-2013 period were chosen to represent
208 the four profiles to assess their influence on pike spring spawning dynamics (1965, 1973,
209 1983 and 1998, respectively; Tab.1). Historical analysis covering the 1965-2013 period
210 revealed that the profile recurrences were 16% for stable-low, 16% for stable-high, 14%
211 for increasing and 53% for decreasing discharges. Profile recurrences were also calculated
212 for the natural flow regime reconstructed by Morin and Bouchard (2000) for the period
213 1883-1910 preceding the Ottawa River regulation. During this unregulated period, all
214 profiles were increasing (61%), or stable (39%) between Week₀ and Week₅ (Le Pichon et
215 al. 2018).

216

217 *Connectivity estimate*

218 A least-cost approach to modelling movement in landscapes (Adriaensen et al. 2003) was
219 used to quantify connectivity between spawning habitat at Week₀ and nursery habitat at
220 Week₅. In this model, every landscape element is assigned a ‘resistance’ value based on its
221 restricting/facilitating effects on animal movements (i.e. Minimal Cumulative Resistance
222 concept) in both upstream and downstream directions (e.g. Caldwell and Gergel 2013;
223 Hanke et al. 2013; Roy and Le Pichon 2017). Foubert et al. (2018) described in detail the
224 method used to measure connectivity between two types of habitats (e.g. flowchart and
225 functional distance examples).

226

227 We assigned a resistance value to hydrological and land-use characteristics that simulate
228 different risks of larval mortality (e.g. fast current, dewatering, dense vegetation) or larval
229 dispersion (i.e. passive drift and active swimming) when they leave spawning habitats.
230 First, the environmental characteristics of the landscape sensitive to hydrological variations
231 were considered. The resistance values were adapted from Foubert et al. (2018) and
232 allowed the combined effects of water discharge and current velocities on egg survival and
233 larval dispersal to be assigned to each point (or pixel) of the modelled landscape (see
234 Tab.2). A maximum resistance value preventing any survival or successful dispersal was
235 assigned to dewatered areas (water depth ≤ 0 cm) and current velocities >10 cm.s⁻¹ (Peake
236 2004). Resistance values <1 , reflecting current-assisted larval drift, were assigned to
237 current velocities ranging from 2 to 10 cm.s⁻¹. A maximum resistance value has been
238 assigned to dense vegetation (e.g. wet meadows and shrubby swamps in low water depths

239 <20 cm), since they can act as physical barriers to larval dispersal (see Tab.2). Second,
240 anthropogenic features that restrict (i.e. emerged roads and managed wetland dikes) or
241 facilitate (i.e. ditch and stream networks) dispersion in the contemporary landscape were
242 also examined. We have differentiated submerged roads and managed wetland dikes that
243 influence connectivity. The accuracy of the topographic measurements (every meter)
244 provided by LiDAR and the simulated water depths allowed us to identify submerged and
245 emerged elements for contrasting hydrological conditions in the lake. A maximum
246 resistance value has been assigned to emerged roads and managed wetland dikes (e.g.
247 larvae cannot cross them). In addition, permanent structures (i.e. culverts, water control
248 structures and weirs) allowing larvae to cross roads and managed wetlands dikes have been
249 identified from published material (Mingelbier and Douguet 1999), field observations and
250 GIS analyses. When a road has been cut by a ditch or a stream, a culvert has been
251 considered. A resistance value of 1 that does not involve any restriction or facilitation of
252 movement (i.e. only larval swimming capacity is considered) was assigned to permanent
253 structures, ditches and stream networks (see Tab.2). The types of agricultural crops in the
254 contemporary landscape were not included in connectivity estimates as they are not
255 believed to completely restrict connectivity or cause mortality during larval movement.

256

257 After assigning resistance values, we used the open source software *Anaqualand 2.0* (Le
258 Pichon et al. 2006) to generate the functional distance between spawning and nursery
259 habitats (Foubert et al. 2018). The functional distance is defined as the combination of
260 larvae dispersal potential (i.e. mobility coefficient (α) defined below) and the sum of the
261 resistance the larvae will encounter along their path. The mobility coefficient (α) is

262 derived from the stage-specific larval swimming capacities and the potential passive
263 transport provided by local currents at the beginning of the free-swimming stage (Week₅).
264 The maximal value was set to $\alpha = 6000$ m which corresponds to the maximal distance
265 travelled at $1 \text{ cm}\cdot\text{s}^{-1}$ by a neutral particle in the water column over a one-week period in the
266 St. Lawrence River (see sensitivity analyses in Online Resource 2). Since the functional
267 distance incorporates resistance values, it does not always correspond to a physical
268 instream distance (i.e. minimum distance within the limits of the watercourse).

269

270 *Connected and disconnected spawning habitats*

271 When the functional distance between a spawning habitat and a nursery was
272 $\leq 6000 \text{ m}_{\text{functional}}$ (i.e. the maximal mobility coefficient), the spawning habitat was
273 considered to be connected (Foubert et al. 2018). However, when the functional distance
274 exceeded $6000 \text{ m}_{\text{functional}}$, the spawning habitat was considered disconnected. Connected
275 and disconnected spawning habitats were mapped in *ArcGIS 10.1* and their surfaces were
276 quantified (surface expressed in ha) for the four selected hydrological profiles (1965, 1973,
277 1983 and 1998).

278

279 In addition, the effects of each hydrological and land-use characteristic added successively
280 on connectivity estimate (i.e. water depth, current speed, dense vegetation and
281 roads/managed wetland dikes) were quantified (Tab.3). Direct losses correspond to
282 potential spawning habitats spatially superimposed on restricted landscape features.
283 Technically, spawning habitats were superimposed on landscape features in *ArcGIS 10.1*
284 to estimate (1) spawning habitats lost due to dewatering occurring between Week₀ and

285 Weeks (water depth ≤ 0 , Tab.2), (2) spawning habitats lost due to increased current
286 velocities ($>10 \text{ cm.s}^{-1}$), (3) emerged roads, and (4) dense vegetation. Indirect losses are
287 potential spawning habitats that are not connected to a nursery because of limited landscape
288 features that act as physical barriers to larvae dispersal.

289

290 **Effective spawning habitats (objective 3)**

291 For the four selected hydrological profiles, the total area of connected spawning habitats
292 (i.e. including the effects of water depth, current velocity, dense vegetation, ditch and
293 stream networks, and emerged roads/managed wetland dikes) was superimposed on the six
294 land-use categories of the contemporary description (i.e. 2014) in *ArcGIS 10.1*. It allowed
295 us to quantify and differentiate the area of (1) effective spawning habitat, which
296 corresponds to the overlap of connected spawning habitats with suitable land-use
297 categories (i.e. suitable wetlands, perennial crops and drainage ditches), and (2) ineffective
298 spawning habitat that overlaps with inadequate land-use categories (i.e. unsuitable
299 wetlands and wooded, annual crops, and roads and urban areas). Finally, the effective
300 spawning habitat areas obtained for the four hydrological profiles (i.e. stable-low, stable-
301 high, increasing and decreasing water discharges) were spatially overlaid to identify the
302 most recurrent effective spawning habitats.

303

304

305 **Results**

306 **Historical habitat losses related to agriculture**

307 With the expansion of intensive agricultural practices, up to 2,446 ha of potential spawning
308 habitats and 1,188 ha of potential nursery habitats have been lost in the Lake Saint-Pierre
309 floodplain between 1965 and 2014 (see Fig. 3). The impacts of agriculture have been
310 particularly severe since 1990, resulting in a total area of spawning habitats of no more
311 than 5,500 ha. The total loss of both spawning and nursery habitats was positively
312 correlated with water discharges at Week₀ and at Week₅, respectively ($P < 0.05$, Spearman's
313 rank correlation). The impact of agriculture on potential spawning and nursery habitats
314 occurred at discharges $> 12,000 \text{ m}^3 \cdot \text{s}^{-1}$ with the largest losses at discharges $> 14,000 \text{ m}^3 \cdot \text{s}^{-1}$
315 (Fig 2).

316

317 **Habitat availability and connectivity**

318 *Potential habitats during contrasting hydrological profiles*

319 The total area of potential spawning and nursery habitats available annually was
320 determined by hydrological conditions (Tab.1, Fig. 4). High spring water discharges
321 resulted in a large area of potential spawning (1998) and nursery habitats (1983), while low
322 water discharges resulted in the smallest areas of potential spawning habitats (1965) and
323 decreasing profile led to the smallest areas of potential nursery habitats (1998). At medium
324 to high water discharges, managed wetlands generated up to 571 ha and 722 ha of potential
325 spawning and nursery habitats respectively, which represent between 10% and 13% of the
326 maximum habitat available in the Lake Saint-Pierre

327

328 *Connected and disconnected spawning habitats*

329 Due to hydrological variability and anthropogenic landscape characteristics on habitat
330 connectivity, eight to 68% of potential spawning habitats were lost (dewatering or
331 disconnected nurseries; Tab.3). Firstly, the largest disconnected spawning areas appeared
332 during the decreasing profile between the maximum spawning time (Week₀) and the free-
333 swimming stage (Week₅) due to the dewatering of 62% of potential spawning areas.
334 Secondly, the increase in water currents above the 10 cm.s⁻¹ thresholds after spawning has
335 transformed high-quality habitats into low-quality habitats. These conditions appeared
336 frequently during the increasing profile. These fast water currents acting as physical
337 barriers prevented access to 2% of spawning habitats during the increasing profile. Thirdly,
338 the dense vegetation slightly reduced the total surface of potential spawning habitats (1 %)
339 during the stable-high and decreasing profiles and acted as a physical barrier during the
340 decreasing profile. Fourthly, 2% of potential spawning habitats have disappeared in stable-
341 high and decreasing profiles due to the surface occupied by the emerged roads. Although
342 spawning habitat losses were small, emerged roads also served as physical barriers during
343 stable-high profiles.

344

345 The largest area of connected spawning habitat occurred during the stable-high profile,
346 one-third resulting from the overlap between potential spawning and nursery habitats, and
347 two-thirds related to the larval mobility coefficient ($\alpha = 6000 \text{ m}_{\text{functional}}$), connecting
348 potential spawning areas to distant nursery areas (Fig. 5). The overlap between potential
349 spawning and nursery habitats generate large areas of connected spawning habitats,
350 especially when water discharge remains stable between Week₀ and Week₅. The

351 overlapping habitat areas reached 55% of the total connected spawning area in the stable-
352 low profile, 28% in the stable-high profile, 0.2% in the increasing profile and 10% in the
353 decreasing profile (see dark blue in Fig. 5). Moreover, larval mobility (α) allowed to reach
354 distant nursery habitats when (1) few potential spawning and nursery habitats overlapped,
355 and (2) hydrological conditions maintained large spawning areas during the five first weeks
356 of ontogeny and created large nursery area (Fig. 5). The total area of connected spawning
357 habitat increased by 61% in the stable-high profile and by 81% in the increasing profile
358 due to larval mobility (α). When fewer spawning habitat areas are available at the
359 beginning of the free-swimming stage (Week₅), larval mobility (α) increased the surface
360 of connected spawning habitat by 36% (stable-low profile) and by 21% (decreasing
361 profile). During the decreasing profile, ditch and stream networks in dewatered areas
362 further increased the surface of connected spawning habitats by 14% (252 ha) (Online
363 Resource 2). Finally, managed wetlands generated 463 ha (10 %) of total connected
364 spawning habitat areas during the stable-high profile, 439 ha (12 %) during the increasing
365 profile and 216 ha (11 %) during the decreasing profile.

366

367 **Effective spawning habitats**

368 Considering the latest Lake Saint-Pierre floodplain described (e.g. satellite images taken in
369 2014; Jobin and Dauphin in prep), from zero to 47% of the connected spawning habitats
370 were not effective due to unsuitable land-use categories (Fig. 6). The largest loss of
371 connected spawning habitat was observed for the stable-high profile with 32% of non-
372 effective surfaces related to agricultural practices, mostly used for corn and soybean
373 production. When water discharges reached average ($\sim 11,000 \text{ m}^3 \cdot \text{s}^{-1}$) to high

374 (~15,000 m³.s⁻¹) discharges during the first five weeks of ontogeny (i.e. in 1973, 1983 and
375 1998), unsuitable wetlands and wooded areas reduced the surface of connected spawning
376 areas by 11% to 14%. Less than 1% of connected spawning area was lost due to the
377 presence of submerged roads and urban areas in the four hydrologic profiles. Finally, only
378 0.4% of connected spawning area was affected by land-use during the stable-low profile.

379

380 Considering contemporary land-use changes in connected spawning habitats, the increase
381 in water discharge between the maximum spawning time (Week₀) and the free-swimming
382 stage (Week₅), which ranges from medium to high, was found to be the most favourable
383 hydrological conditions for northern pike habitats in Lake Saint-Pierre (increasing profile
384 in Fig. 7). In this case, 3,218 ha, corresponding to 70% of the initial potential spawning
385 area, were connected to nursery areas and were not modified by unsuitable land-use
386 (= effective spawning habitats). During the stable-low profile, almost all the potential
387 spawning areas were effective for northern pike recruitment (i.e. 2,549 ha or 91% of
388 potential habitats). During the stable-high profile, similar potential spawning areas
389 remained effective (i.e. 2,463 ha), but represent only 47% of the potential spawning area.
390 This significant decrease is due to agricultural practices. During the decreasing profile,
391 potential habitats altered by the land-use have already been lost due to hydrological
392 constrains on habitat connectivity. Although only 27% (1,628 ha) of the potential spawning
393 habitats remained effective, only 15% (279 ha) of connected spawning habitats were
394 altered by the land-use. Finally, 332 ha of effective spawning habitats were spatially
395 recurrent over the four contrasting hydrological profiles (dark green in Fig. 7).

396

397 **Discussion**

398 This study shows that anthropogenic alterations to the floodplain and hydrological regime
399 have major effects on the availability and the connectivity of habitats for early life history
400 stages of fishes. The various habitat and connectivity models, carried out under highly
401 contrasting hydrological conditions over the past 50 years, and combined with a description
402 of land use for several reference periods, have proven to be very effective in identifying
403 the regions of the Lake Saint-Pierre most impacted by human alterations. To measure the
404 effects of human pressures, it was first necessary to produce reference conditions
405 representing an unaltered landscape and to assess the intrinsic natural variability of the
406 river, which was accomplished by Foubert et al. (2018). In the present study, the modelling
407 was carried out in a present-day landscape altered by two main human landscape pressures.
408 Results revealed that water flow regulation in the river system and increasing agriculture
409 in the floodplain significantly reduced the spawning habitats effectiveness of species such
410 as northern pike that use the upper littoral zone of a river. Together, these two pressures
411 dramatically reduced the range of natural conditions favourable to fish reproduction in the
412 St. Lawrence River. The highest natural reproductive potential for northern pike, usually
413 associated with high and stable water flows (Casselman and Lewis 1996; Johnson 1957),
414 has been lost due to (1) intensive agricultural practices in the upper floodplain that overlaps
415 with suitable natural habitats for fish, and (2) flow regulation that leads to more frequent
416 drying of spawning grounds and egg mortality. These profound anthropogenic changes in
417 the St. Lawrence River have resulted in a significant loss of reproductive potential for
418 northern pike and other fish species that use the floodplain to complete their life cycle.

419 In a context of global climate change, where spring water discharge is expected to decrease
420 and extreme hydrological conditions to increase in frequency (Boyer et al. 2010; Mortsch
421 et al. 2000), effective spawning habitats in Lake Saint-Pierre could be further reduced,
422 which could make it impossible to maintain fish abundance at their past levels. Hence,
423 restoring habitat quality and connectivity in floodplains coupled with better flow regime
424 management will play an important role in conserving biodiversity and maintaining
425 sustainable populations.

426

427 **Land-use changes and potential habitat loss**

428 Changes in land-use have profoundly altered potential fish habitats in productive
429 floodplains (e.g. Baber et al. 2002; Blanton and Marcus 2014; Fernandes et al. 2015). The
430 Lake Saint-Pierre floodplain has been progressively occupied by agriculture. While in 1950
431 perennial crops dominated ($\approx 45\%$ cover, $\approx 21,000 - 22,000$ ha) and annual crops accounted
432 for only 10 to 15% of the territory ($\approx 5,000$ to $7,000$ ha), the situation completely reversed
433 in the 1990s since annual crops dominated, occupying 32% of the Lake Saint-Pierre
434 (16,000 ha) compared to 15% (7,000 ha) for perennial crops. Although perennial crops (i.e.
435 pasture and forage crops) can represent potential fish habitat, ploughing annual crops
436 remove vegetation cover and create bare fields without substrate for egg laying in the next
437 spring. The present study has shown that annual crops have negative effects on northern
438 pike habitats especially when the water flow in Sorel exceeds $14,000 \text{ m}^3 \cdot \text{s}^{-1}$, which happens
439 very often in the spring (annually or biannually; Morin and Bouchard 2000). Indeed, large
440 potential habitat losses were observed during high water discharges because fish habitats

441 overlapped with unsuitable land-use due to agricultural practices that are mainly located in
442 the upper part of the floodplain.

443

444 **Habitat connectivity**

445 In large floodplains, not all potential spawning habitats are connected to a nursery area,
446 and therefore become mortality traps (Jeffres and Moyle 2012; Sheaves et al. 2014).
447 Although transportation infrastructures (i.e. roads) have had impacts on habitat
448 connectivity in the Lake Saint-Pierre floodplain (Le Pichon et al. 2018), rapid dewatering
449 during the five first weeks of ontogeny appears to be the main factor limiting connectivity
450 between northern pike spawning and nursery habitats (Foubert et al. 2018). Rapid
451 dewatering after pike eggs were laid revealed large areas of spawning habitat in mortality
452 traps (3 758 ha or 62% of potential habitats). In addition, a decreasing profile can transform
453 moderately dense vegetation associated with high quality spawning and nursery habitats
454 (Casselman and Lewis 1996; Timm and Pierce 2015) into very dense low oxygen
455 macrophyte beds (Casselman 1978; Holland and Huston 1984). Although only increasing
456 (61% of all years) or stable (39%) hydrological profiles were observed before water flow
457 regulation (1883-1910) (Le Pichon et al. 2018), the most recurrent condition since 1965
458 has been a steadily decreasing profile between the spawning time (Week₀) and the larvae
459 free-swimming period (Week₅). The regulation of the Ottawa River, considered the main
460 tributary of the St. Lawrence River with a water discharge ranging from 570 to 9,200 m³.s⁻¹
461 (Carpentier 2003), has now increased hydrological conditions generating large
462 disconnected spawning areas in Lake Saint-Pierre (e.g. Brodeur et al. 2006). With the
463 regulation of the Ottawa River, the duration of the flood has been shortened by three weeks

464 and the maximum annual water discharge has decreased significantly by nearly
465 $2,500 \text{ m}^3 \cdot \text{s}^{-1}$, a decrease exacerbated by the regulation of Lake Ontario outflows since 1958
466 (i.e. reduction of $1,020 \text{ m}^3 \cdot \text{s}^{-1}$; Morin and Bouchard 2000).

467

468 In large floodplains characterized by recurrent dewatering profiles where intensive
469 agricultural practices are covering large expanse of the landscape, managed wetlands and
470 ditch/stream networks appear to be key landscape features facilitating habitat connectivity
471 due to their permanent aquatic characteristic (e.g. Washitani 2007). Our results highlighted
472 the role of these two anthropogenic landscape features in maintaining connected spawning
473 habitats in the upper part of the Lake Saint-Pierre floodplain, where potentially flooded
474 areas have become vulnerable to dewatering and agricultural expansion (e.g. in 1998 and
475 1973 in Saint-Barthélemy Bay). Although managed wetlands are accessible only at
476 medium to high water discharges (Brodeur et al. 2004), they promote spatial overlap of
477 spawning and nursery habitats that improve larval growth and survival (Ospina-Alvarez et
478 al. 2012; Schiemer et al. 2001). In addition, when spawning and nursery habitats are
479 spatially separated, ditch and stream networks can be used by mobile individuals to connect
480 nursery habitats (e.g. Ishiyama et al. 2014). Although young pike larvae have limited
481 swimming capacities, low current speeds in large floodplains favour dispersal of larvae to
482 nurseries (Miehls and Dettmers 2011; Schiemer et al. 2003). Several independent
483 observations in Lake Saint-Pierre confirmed the presence of northern pike larvae in ditch
484 and stream networks and managed wetlands considered effective spawning and nursery
485 habitats in this study (Brodeur et al. 2016).

486

487 **Effective spawning habitats**

488 Natural hydrological conditions, that are favourable for fluvial fish recruitment in large
489 unaltered floodplains because they generate large areas of effective habitats (Gorski et al.
490 2011; Junk et al. 1989), have lost their benefits due to anthropogenic pressures. Although
491 a stable-high hydrological profile ($>14,000 \text{ m}^3 \cdot \text{s}^{-1}$) in Lake Saint-Pierre generated large
492 areas of potential spawning habitats connected to nurseries (4,665 ha), only 47% were
493 effective when land-use was considered. The expansion of intensive agriculture,
494 particularly annual crops, has profoundly altered spawning habitats that were previously
495 connected to nurseries. Historically, 1,517 ha of these habitats were effective for northern
496 pike during favourable hydrological conditions (i.e. stable-high profile represented by
497 1973). In addition, water flow regulation has dramatically reduced the frequency of these
498 favourable hydrological conditions (see above) (Le Pichon et al. 2018), which have
499 naturally generated large interconnected habitats. As a result, the possibility for stable-high
500 hydrological profiles could produce high potentials for northern pike reproduction was rare
501 and systematically eliminated by intensive agricultural practices, especially since 1990
502 (Martin and Létourneau 2011).

503

504 Under specific hydrological conditions, anthropized floodplains can still generate large
505 effective spawning habitats. In Lake Saint-Pierre, 3,218 ha of effective spawning habitats
506 were estimated during the increasing profile – i.e. when the water discharge increased from
507 medium to high between the maximum spawning time (Week₀) and the free-swimming
508 stage (Week₅). Potential spawning habitats generated by medium water discharge were (1)
509 not disconnected by hydrological variability during the increasing profile and (2) not

510 altered by land-use activities in the upper floodplain. In addition, years of low water
511 discharges are the less affected by intensive agriculture since they maintain their full habitat
512 potential, although low. Nevertheless, the increasing profile and the stable profile, which
513 produce the largest effective spawning habitat areas in the anthropised floodplain of Lake
514 Saint-Pierre, has been greatly reduced by the regulation of water flow (Le Pichon et al.
515 2018).

516

517 **Management implications**

518 In conclusion, the loss of conditions favouring the formation of vast potential spawning
519 habitats for northern pike caused by intensive agricultural practices in the floodplain and
520 flow regulation represents a serious constraint, as several fish populations show a
521 significant decline in the St. Lawrence River. This study highlights important new
522 opportunities to improve fish habitat and recruitment in major river systems such as the St.
523 Lawrence River, and identifies the following priority management measures.

524

525 First, to regain production potential in years with high water flows, the priority would be
526 to convert large intensive annual crops located in the floodplain to natural wetlands, or at
527 least to perennial crops that represent potential fish habitat. Such actions are much needed
528 for improving the health of the St. Lawrence River ecosystem (e.g. Gagliardi and
529 Pettigrove 2013; Washitani 2007). Field crop conversions should target areas where large
530 connected habitats are altered by annual crops such as the Saint-Barthélemy Bay (Fig. 2,
531 Fig. 7).

532

533 Second, existing structures such as ditches and stream networks should be maintained as
534 they represent effective fish habitats and contribute to habitat connectivity (Beier and Noss
535 1998). In some particular cases, additional structures could be installed if required by local
536 needs. Although transportation infrastructures (roads) can limit connectivity in floodplains
537 (Blanton and Marcus 2014; Doyle et al. 2008), structures such as culverts have proven to
538 be useful in maintaining connectivity in anthropized floodplains (Douven et al. 2012; Le
539 Pichon et al. 2018).

540

541 Third, managed wetland developed in the Lake Saint-Pierre floodplain show great potential
542 for increasing the survival of early-life history stages of fishes. Indeed, these managed
543 marshes are surrounded by dikes that could extend the duration of the flood, as was the
544 case during the non-regularized period of the St. Lawrence system, while maintaining
545 connectivity between spawning and nursery habitats, which is also positive for the survival
546 of young fish.

547

548 Fourth, the water discharge regulation of the Ottawa River since 1911 has altered the
549 natural flow regime of the St. Lawrence River, decreasing the average water level of spring
550 floods in Lake Saint-Pierre by ~ 0.75 m and reducing its duration by about 3 weeks (Morin
551 and Bouchard 2000). Our simulations suggest that a revision of flow management rules in
552 the Ottawa River to restore a more natural spring flow regime could benefit species that
553 use the floodplains of the St. Lawrence River, for example by extending the duration of
554 spring floods to ensure better connectivity between spawning and nursery habitats. This
555 type of rules revision was conducted in the Lake Ontario-St. Lawrence River basin by the

556 International Joint Commission (IJC), established under the 1909 Boundary Waters Treaty
557 Act between the United States and Canada, which approved a new management plan in
558 2016 that allowed for more natural water level variations. In comparison, the changes
559 induced by the regulation of the Ottawa River are much less known and receive little
560 consideration.

561

562

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572

573

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734
735

736 **Table and Figure captions**

737 **Tab.1** The total surface of potential habitats for the four hydrological profiles (stable-low,
738 stable-high, increase, decrease) was calculated for potential spawning habitats at maximal
739 spawning time (developed in Mingelbier et al. 2008) and nursery habitats five weeks later
740 at the beginning of free-swimming stage (Foubert et al. 2018) in Lake Saint-Pierre (St.
741 Lawrence River, Canada)

742

743 **Tab.2** Dimensionless resistance values based on the restricting/facilitating effects of
744 hydrological and land-use landscape characteristics on connectivity in downstream or
745 upstream directions. Water depth, current speed, ditch and stream networks, emerged roads
746 and dense vegetation are simulated at the beginning of free-swimming stage (Week₅).
747 Water depth corresponds to the dewatering between the spawning time (Week₀) and the
748 free-swimming stage (Week₅) in Lake Saint-Pierre (St. Lawrence River, Canada)

749

750 **Tab.3** Effects of landscape features that limit connectivity (i.e. water depth, current speed,
751 roads and dense vegetation) on potential spawning habitat losses for the four hydrological
752 profiles (stable-low, stable-high, increase, decrease) in Lake Saint-Pierre (St. Lawrence
753 River, Canada). The connected spawning habitat area is the result of a subtraction between
754 the potential spawning habitat area (Habitat Suitability Indices) and total habitat losses

755 **Fig. 1** conceptual diagram that describes the methodological steps (in blue) leading to the
756 main results (in black) of the study

757

758 **Fig. 2** Map showing the largest fluvial lake in the St. Lawrence River: Lake Saint-Pierre
759 and its archipelago (Québec, Canada). Fish managed wetlands, ditch and stream networks,
760 and roads on the floodplain have been located. Flooding surfaces of three contrasting spring
761 water discharges (low, medium, high) were presented

762

763 **Fig. 3** Temporal values of northern pike spawning and nursery habitats reconstructed for
764 the period 1965-2013 in the unaltered (without agriculture) and the contemporary
765 landscape (with agriculture) of Lake Saint-Pierre (St. Lawrence River, Canada). Potential
766 spawning and nursery habitat surfaces (left y-axis) in the unaltered landscape have been
767 adapted from Mingelbier et al. (2008) and Foubert et al. (2018) respectively. Remaining
768 spawning and nursery habitat surfaces include losses generated by annual agricultural
769 practices. Water discharge (right y-axis) is measured during the spawning time (Week₀)
770 and five weeks later at the beginning free-swimming stage (Week₅). Temporal values of
771 habitats (x-axis) were classified according to water discharges (from lowest to highest).

772

773 **Fig. 4** Map of Lake Saint-Pierre (St. Lawrence River, Canada) showing the potential
774 spawning and nursery habitats of the four hydrological profiles (stable-low, stable-high,
775 increase, decrease). Wetlands managed for fish (black outlines) generated potential habitats
776 when water discharge was medium to high.

777

778 **Fig. 5** Map of Lake Saint-Pierre (St. Lawrence River, Canada) showing the spawning
779 habitats disconnected and connected for the four hydrological profiles (stable-low, stable-
780 high, increase, decrease) taking into account the hydrological and anthropogenic

781 characteristics of the landscape (i.e. water depth, current speeds, ditch and stream networks,
782 roads, dense wetlands). The connectivity values correspond to three classes: (1) spawning
783 habitats overlapping nurseries (dark blue color), (2) spawning habitats connected when α
784 ≤ 6000 m_{functional} (medium blue color), and (3) spawning habitats never connected to a
785 nursery (functional distance > 6000 m_{functional}; brown color). Since α is a distance
786 integrating the minimal cumulative resistance (i.e. functional distance), the α unit is not
787 equivalent to the distance in the watercourse (i.e. international metric system)

788

789 **Fig. 6** The connected spawning habitats were overlaid to the contemporary land-use of
790 Lake Saint-Pierre (description 2014⁷) to identify effective (green and blue colors) and
791 ineffective (yellow, orange and red colors) spawning habitats for the four hydrological
792 profiles (stable-low, stable-high, increase, decrease)

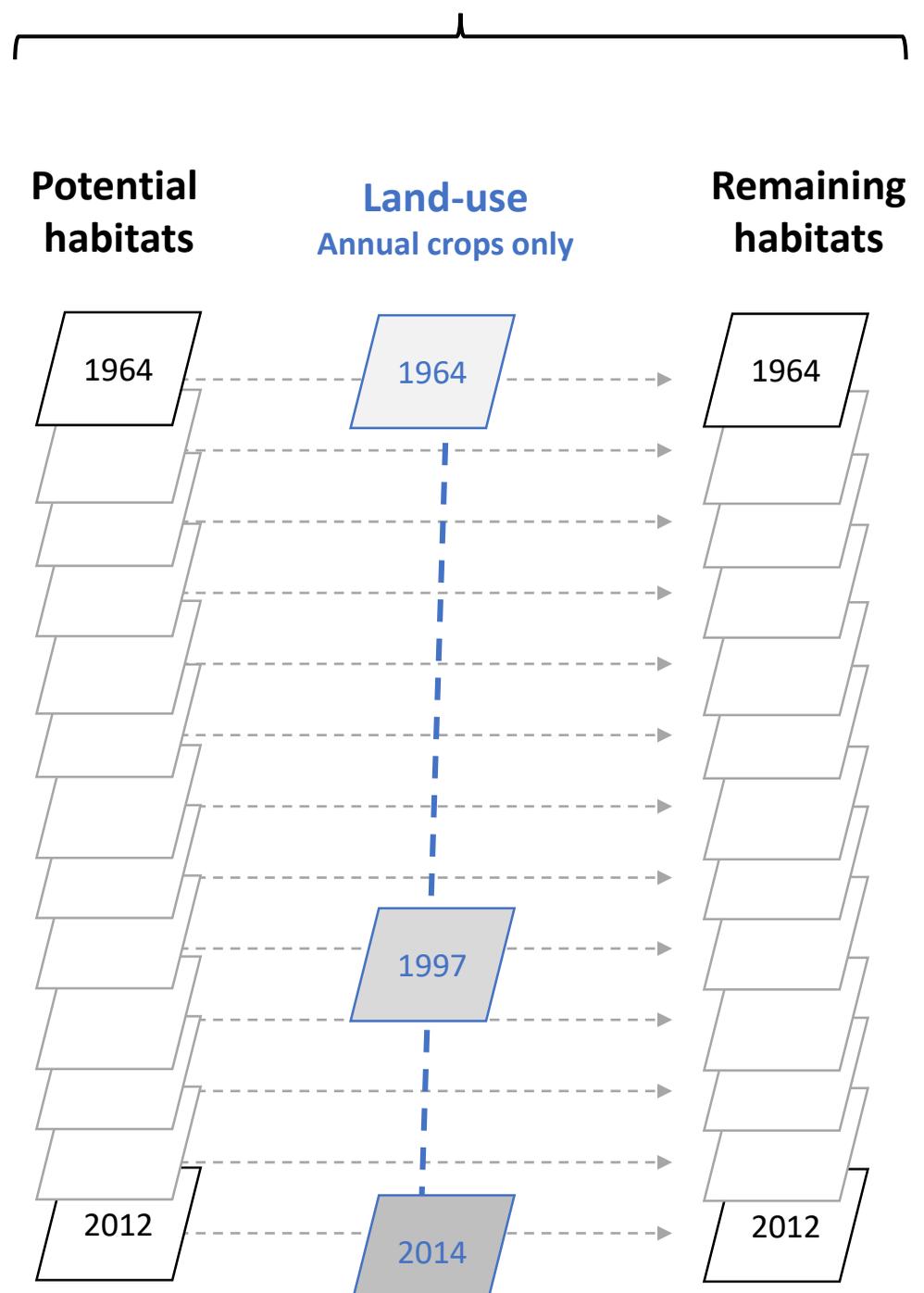
793

794 **Fig. 7** Spawning habitat area as (1) potential, (2) connected, (3) effective and (4) recurrent
795 in the Lake Saint-Pierre floodplain (St. Lawrence River, Canada). Recurrent habitats are
796 effective spawning habitats located at the same location during the four hydrological
797 profiles (stable-low, stable-high, increase, decrease)

798

Objective 1

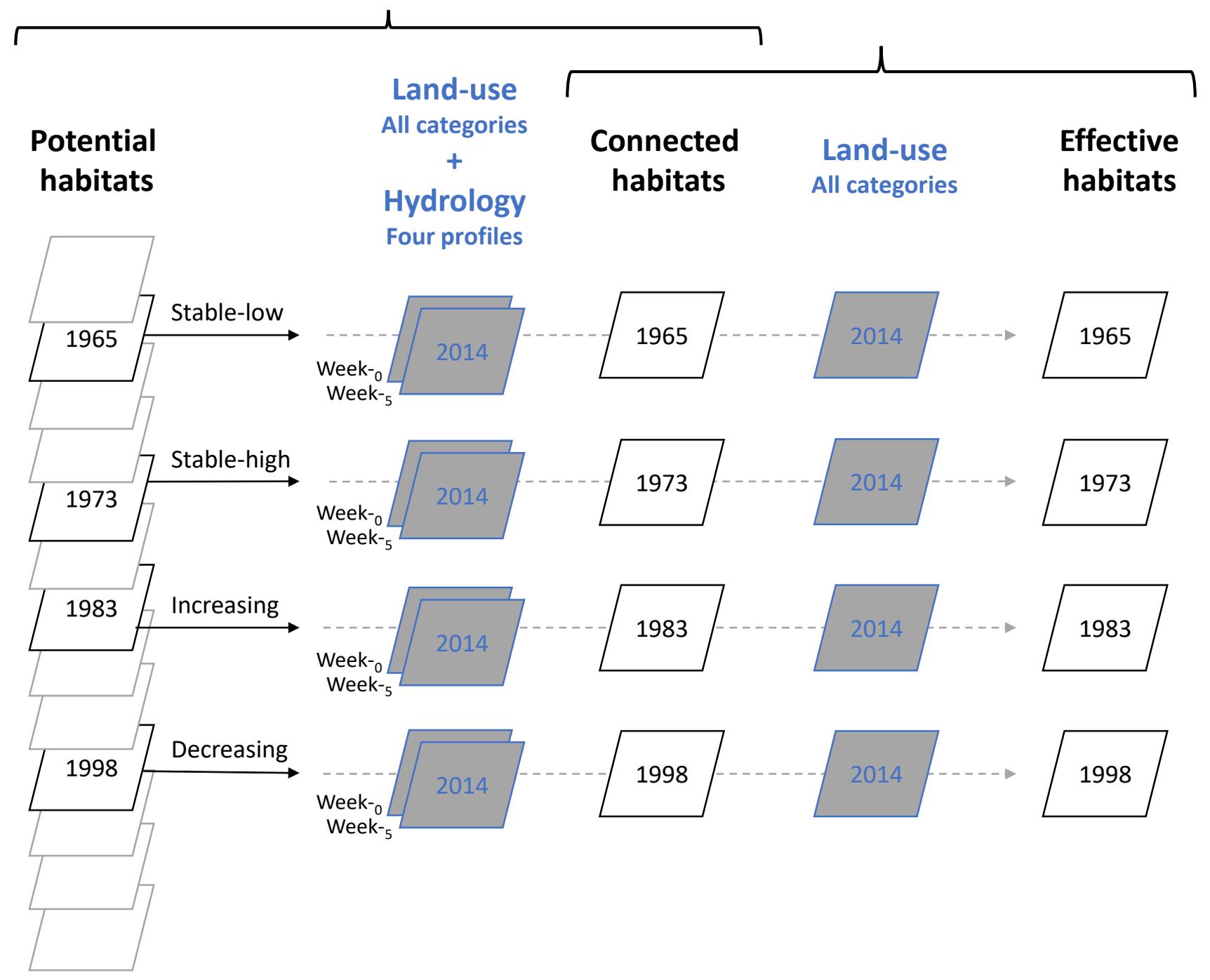
Historical habitat losses due to agriculture



Foubert et al. 2019

Objective 2

Connectivity analyses between spawning habitats and nurseries



Foubert et al. 2019

Objective 3

Effective spawning analyses

Figure 2

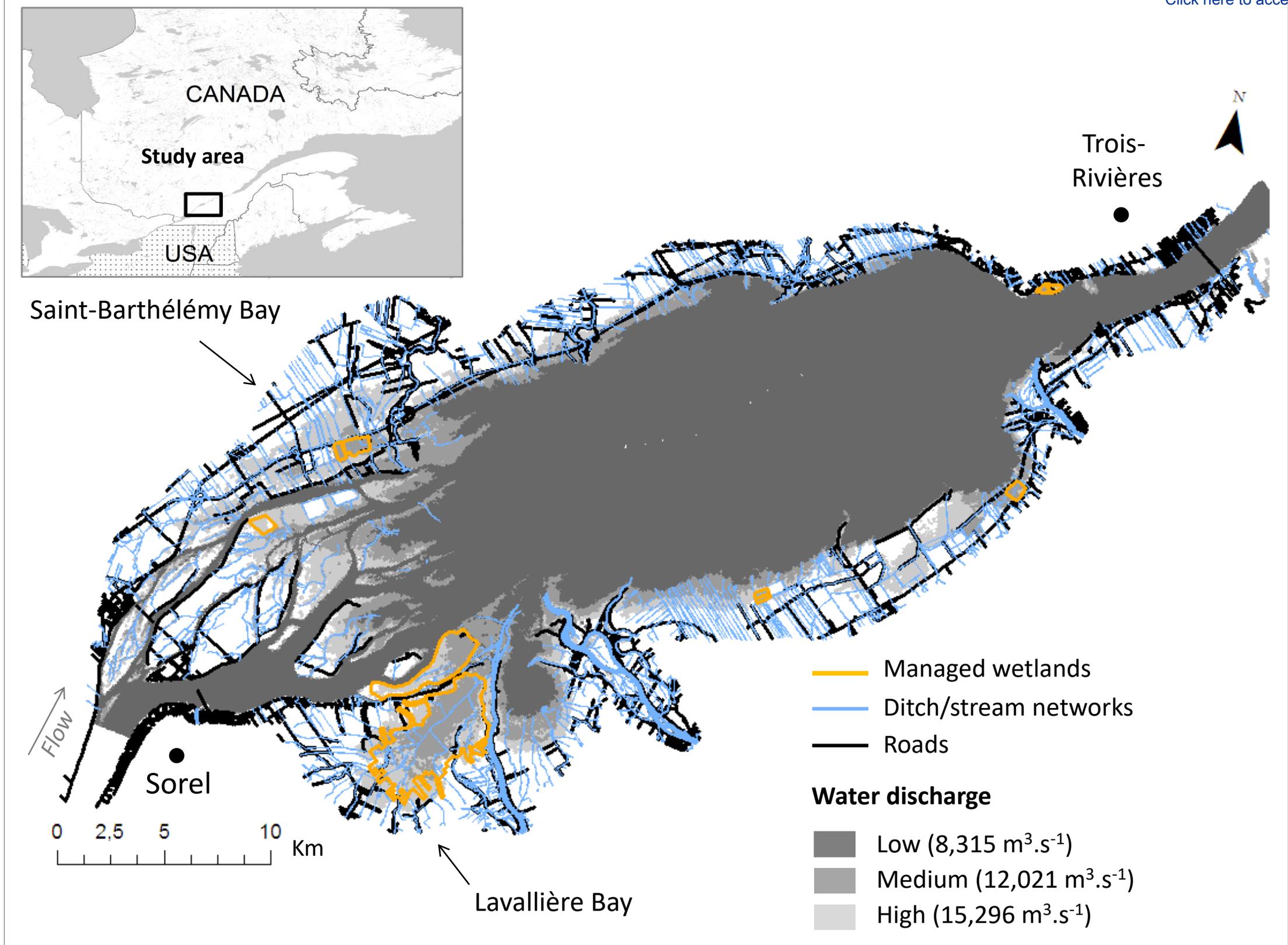


Figure 3

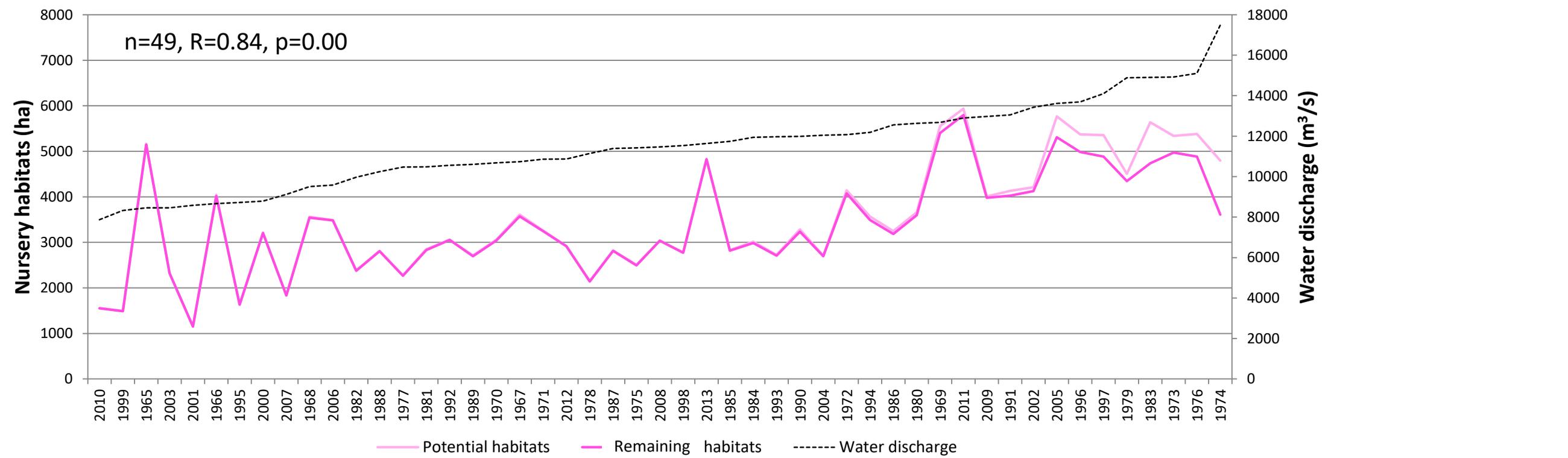
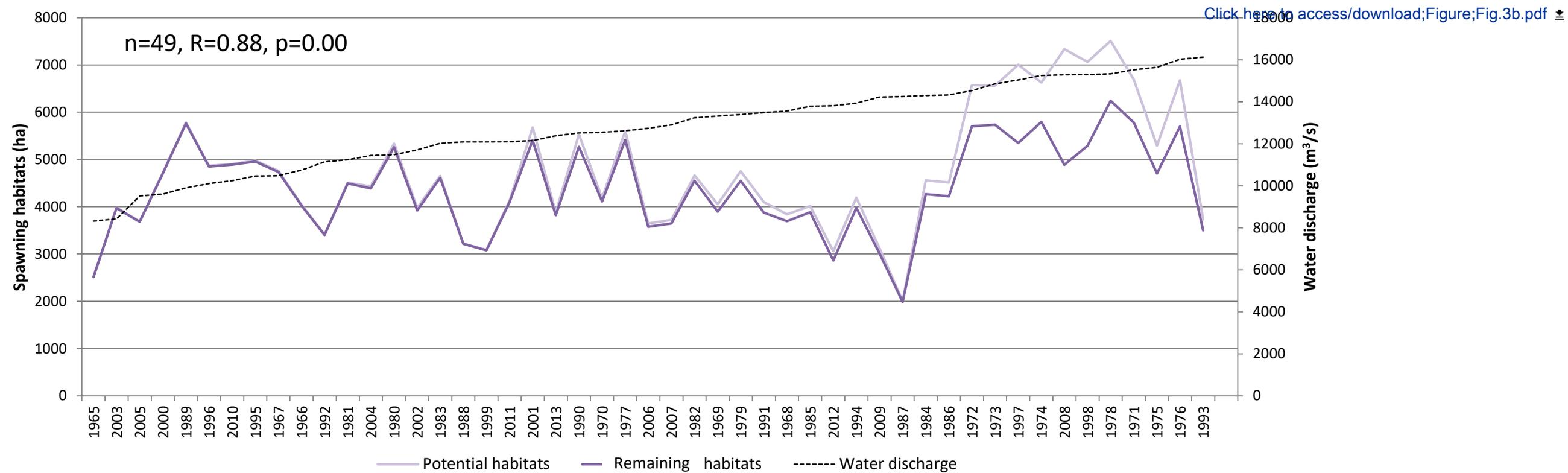
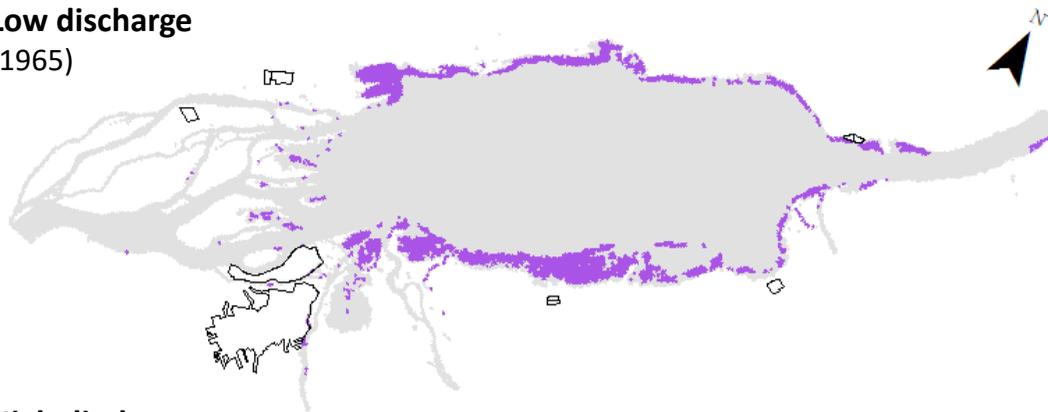


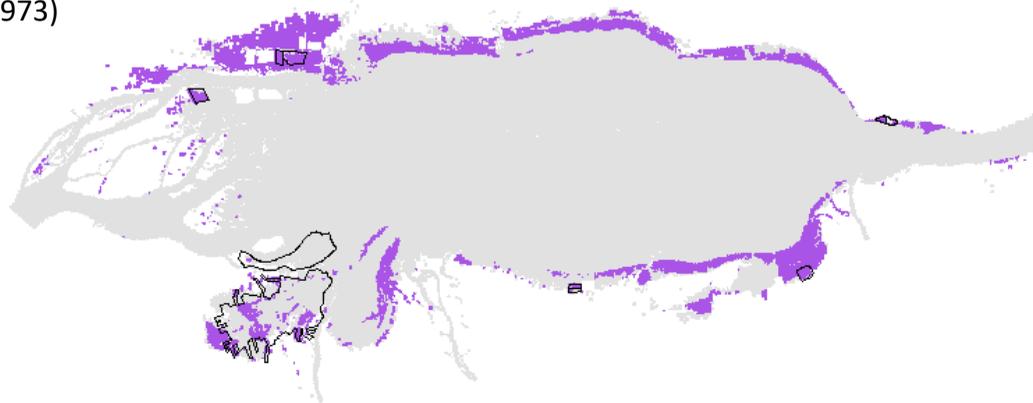
Figure 4

Spawning habitats

Low discharge
(1965)



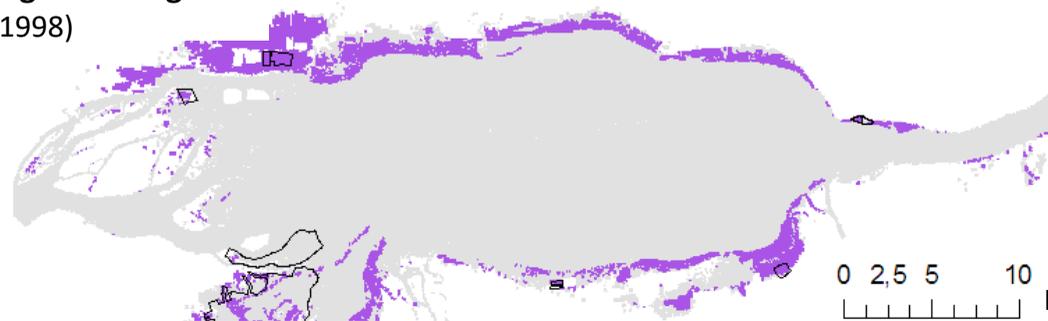
High discharge
(1973)



Medium discharge
(1983)



High discharge
(1998)



0 2,5 5 10 Km

Nursery habitats

Low discharge
(1965)



High discharge
(1973)



High discharge
(1983)



Medium discharge
(1998)



Figure 5

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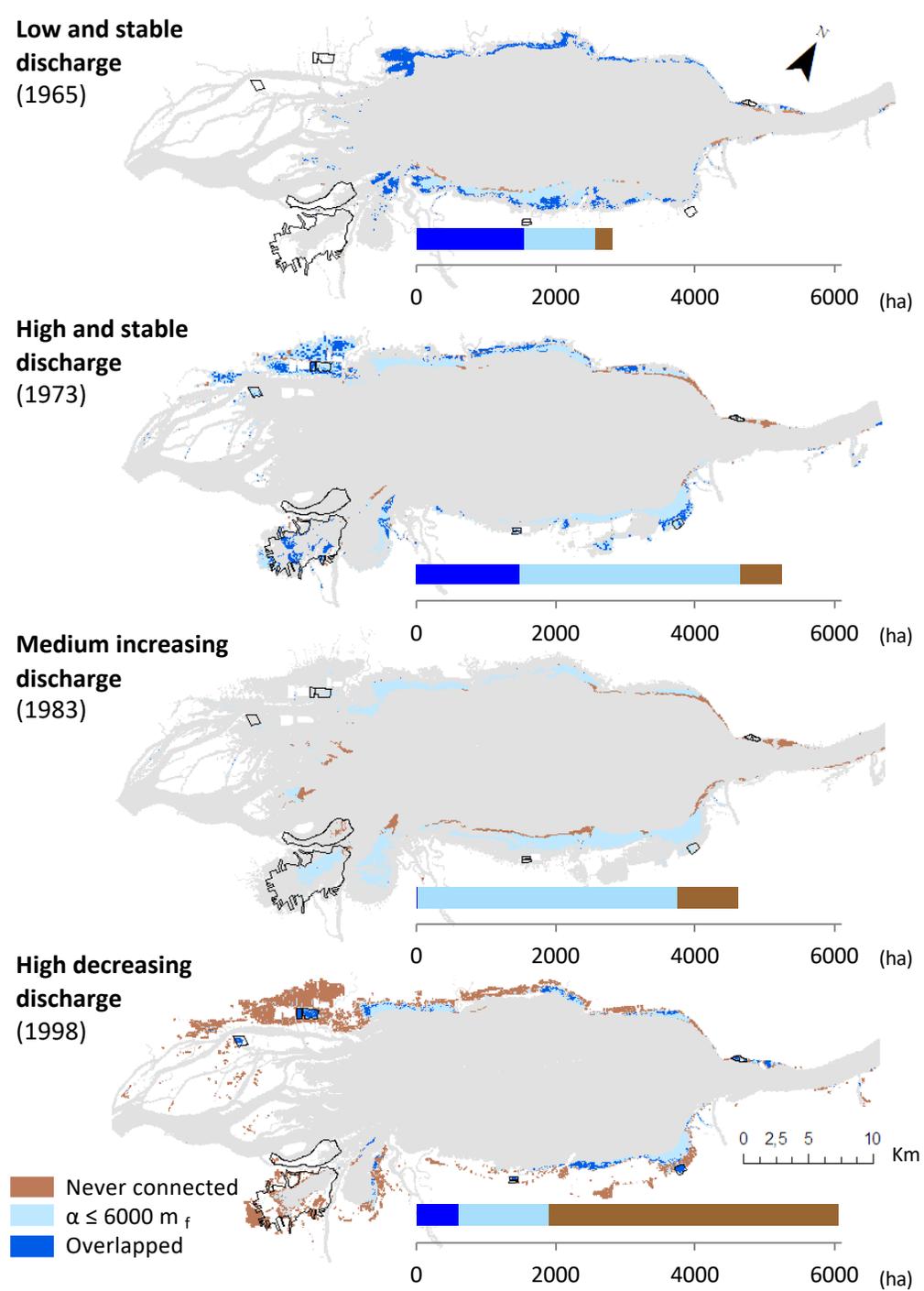
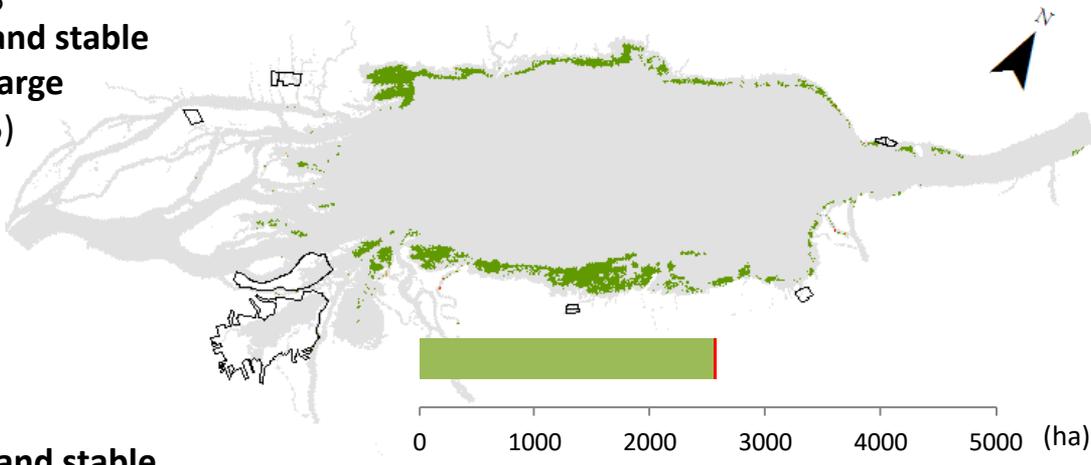
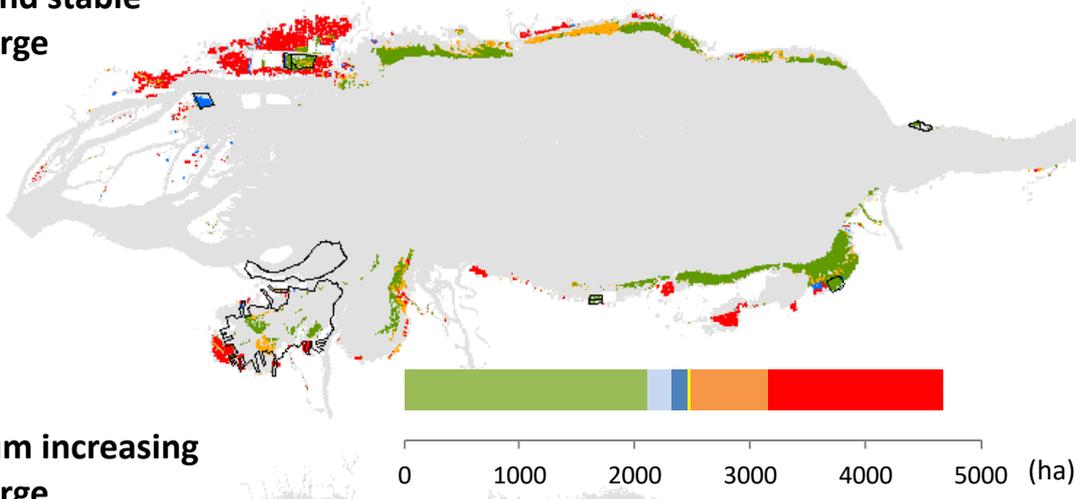


Figure 6

Low and stable discharge
(1965)



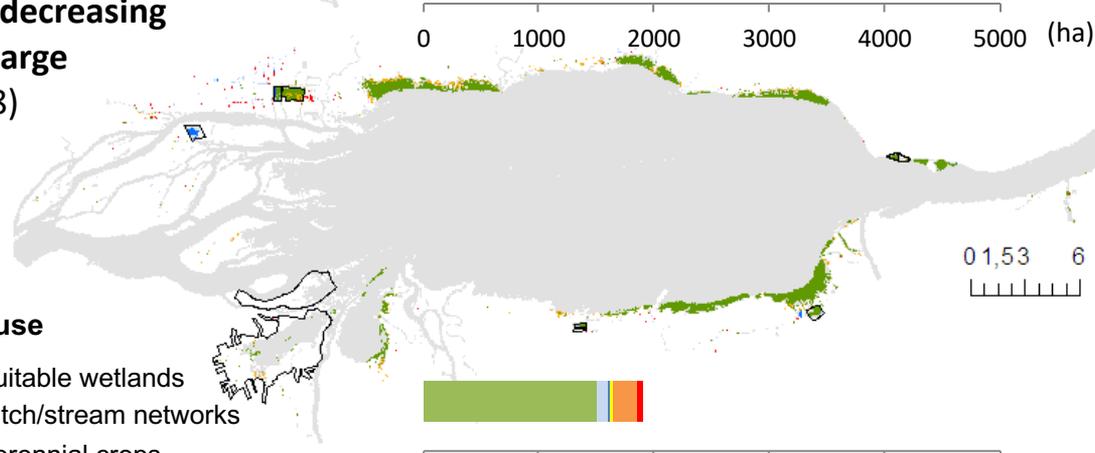
High and stable discharge
(1973)



Medium increasing discharge
(1983)

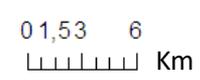


High decreasing discharge
(1998)

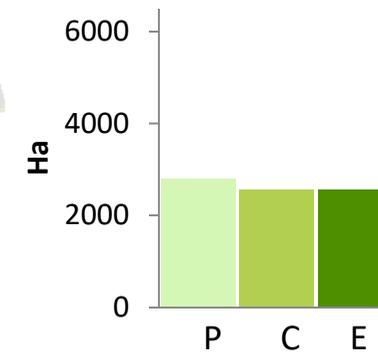


Land use

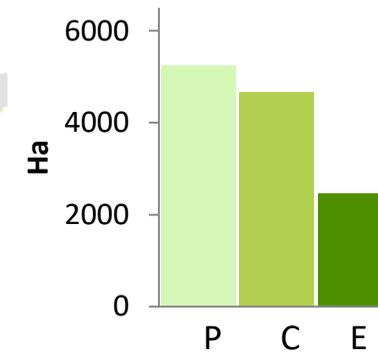
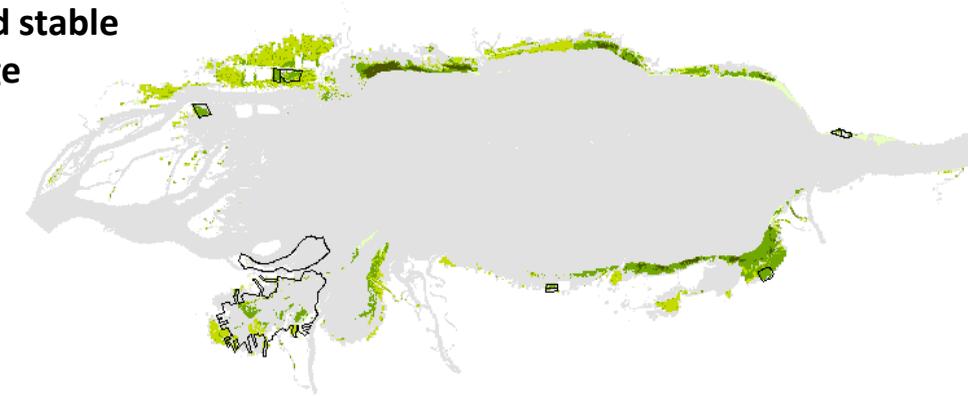
- Suitable wetlands
- Ditch/stream networks
- Perennial crops
- Roads and urban areas
- Unsuitable wetlands and wooded
- Annual crops



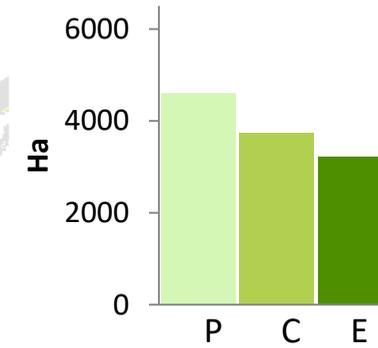
**Low and stable
discharge
(1965)**



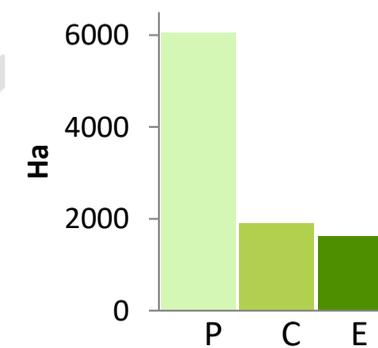
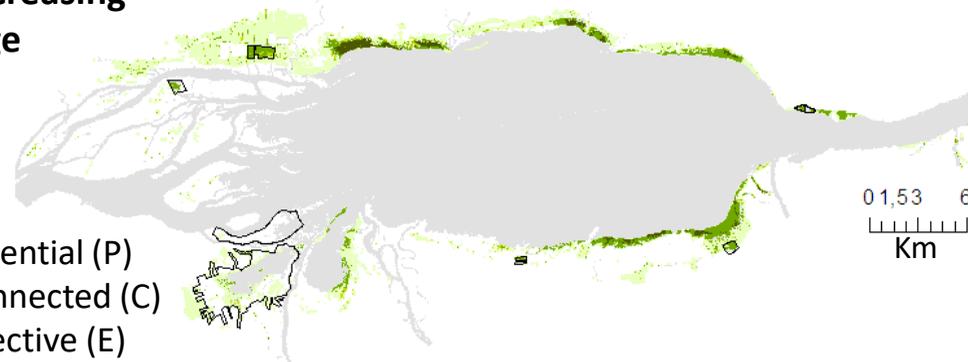
**High and stable
discharge
(1973)**



**Medium increasing
discharge
(1983)**



**High decreasing
discharge
(1998)**



 Potential (P)
 Connected (C)
 Effective (E)
 Recurrent (332 ha)

0 1,53 6
Km

Flow profiles	Water discharge (m³.s⁻¹)	Flooded surface (ha)	Potential habitat surface (ha)
Stable-low (1965)			
Spawning habitats - Week ₀	Low (8,315)	41,768	2,794
Nursery habitats - Week ₅	Low (8,455)	44,731	5,107
Stable-high (1973)			
Spawning habitats - Week ₀	High (14,853)	57,800	5,242
Nursery habitats - Week ₅	High (14,920)	58,868	5,047
Increasing (1983)			
Spawning habitats - Week ₀	Medium (12,021)	49,455	4,608
Nursery habitats - Week ₅	High (14,905)	62,099	5,277
Decreasing (1998)			
Spawning habitats - Week ₀	High (15,296)	59,407	6,045
Nursery habitats - Week ₅	Medium (11,532)	46,551	3,019

Landscape feature	Downstream resistance	Upstream resistance
Water depth ≤ 0 m	10,000	10,000
Speed $> 0 \leq 2$	1	1
Speed $> 2 \leq 4$	0.3333	10,000
Current speeds $(\text{cm}^3 \cdot \text{s}^{-1})$ Speed $> 4 \leq 6$	0.2000	10,000
Speed $> 6 \leq 8$	0.1429	10,000
Speed $> 8 \leq 10$	0.1111	10,000
Speed > 10	10,000	10,000
Ditch and stream networks	1	1
Emerged roads and dikes	10,000	10,000
Dense vegetation	10,000	10,000

Flow profile	Potential spawning habitats (ha)	Direct losses (i.e. transform high to low habitat quality)					Indirect losses (i.e. act as physical barriers)				Connected spawning habitats (ha)
		Dewatered areas	High speeds (>10 cm.s ⁻¹)	Roads	Dense wetlands	Total (ha) [%]	High speeds (>10 cm.s ⁻¹)	Roads	Dense wetlands	Total (ha) [%]	
Stable-low	2,794	4	223	2	0	229 [8%]	5	0	0	5 [0.2%]	2,560
Stable-high	5,242	51	262	100	26	439 [8%]	110	28	0	138 [3%]	4,665
Increase	4,608	2	772	8	0	782 [17%]	82	0	0	82 [2%]	3,744
Decrease	6,005	3,758	61	117	66	4,002 [66%]	72	0	25	97 [2%]	1,906

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To: Landscape Ecology

Dear Editors,

Please find enclosed a paper by Aline Foubert, Frédéric Lecomte, Philippe Brodeur, Céline Le Pichon and Marc Mingelbier entitled “**Losing the best conditions for effective fish spawning habitat in the floodplain due to riparian agriculture and flow regulation, St. Lawrence River, Canada**”. This paper presents original findings not published nor being submitted for publication elsewhere. All co-authors have contributed significantly to the present work and agreed for submitting the manuscript to Landscape Ecology. The manuscript was proofread by a colleague who is a native English speaker. We accept to pay for the extra costs for producing the colour figures included in the manuscript.

“Riverscape” ecology, a new emerging concept applying landscape ecology fundamentals to the aquatic realm, proposes to consider the riverine ecosystems as a continuum where spatio-temporal dynamics had to be quantified along its course, including areas impacted by humans. Holistic, spatially explicit approaches are now considered as a prerequisite for defining guiding principles for inland fisheries and watershed management.

The present manuscript quantifies how anthropogenic alterations, such as riparian agriculture and water flow regulation, have impacted the effectiveness of spawning habitats of northern pike (*Esox lucius*) in a large floodplain: the fluvial Lake Saint-Pierre (St. Lawrence River, Canada). Combining GIS-Based habitat modelling covering a 49-years period (1965-2013) to historical land-use analyses and least-cost modelling of the aquatic connectivity allowed the present study to identify a paradigm shift in the relationship between flow conditions and pike recruitment. The highest potential for reproduction, usually associated with high and stable water flows, has been lost due to (1) the intensive agriculture in the upper floodplain that overlaps with suitable spawning habitats and nursery grounds for fish, and (2) the flow regulation that generates more frequent extreme events leading to the complete drying of spawning grounds. Our results convey important implications for fisheries management and conservation; maps identifying the most rewarding areas for restoration are now available for managers. Such information is mandatory for initiating incentive aimed at farmers to convert their use of the floodplain: from cultivating annual crops toward planting perennial crops. Moreover, the present findings stresses the need to update the Lake Ontario – St. Lawrence River flow regulation used by the International Joint Commission (IJC), a commission established between the United States and Canada to regulate water levels of shared water bodies.

Best regards,

Céline Le Pichon

Potential appropriate reviewers

Anne Timm, altimm@fs.fed.us, land use and aquatic habitat connectivity

John Farrell, jmfarrell@esf.edu, pike

Françoise Burel francoise.burel@univ-rennes1.fr, landscape spatial dynamics and permeability to movement

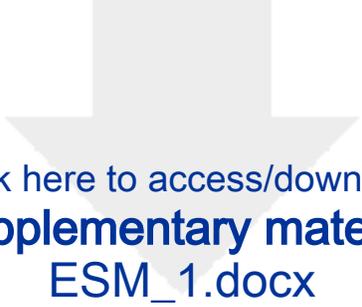
Isabelle Durance, durance@cardiff.ac.uk, role of landscape processes in driving freshwater ecosystems

Current members of the Editorial Board to potentially handle the manuscript.

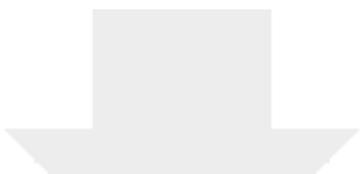
M. Bélisle, *University of Sherbrooke, Sherbrooke, Canada (connectivity)*

G. Cumming, *James Cook University, Townsville, Australia (aquatic habitat:coral reef)*

S.S. Luque, *National Research Institute of Science and Technology for Environment and Agriculture (IRSTEA), St-Martin d'Hères Cedex, France (GIS-based spatial analysis)*



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