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1 **Restoring fluvial forms and processes by gravel augmentation or**
2 **bank erosion below dams: a systematic review of ecological**
3 **responses**

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16 **Abstract**

17 Aquatic biological communities have directly undergone human-induced changes.
18 Altered hydrological and morphological processes in running waters have caused the
19 degradation of main habitats for biotas and have disturbed ecosystem functionality.
20 The latest advances in river restoration concerned the rise in far-reaching
21 hydromorphological restoration actions that have been implemented below dams to
22 reverse well-known negative impacts of anthropogenic pressures. Some authors
23 emphasized the enhancement of sediment supply and habitat diversity using gravel
24 augmentation or bank erosion to restore morphodynamics, and thus improve
25 biodiversity. We explored the Web of Science database for empirical research papers
26 that specifically addressed such hydromorphological river restoration actions. Articles

27 were examined using a text-content analysis tool to determine the major concepts or
28 ideas they deal with. It has also been proved as useful in defining interrelationships
29 and degree of interdisciplinary. Results showed that a low number of published
30 scientific articles exist about such projects, mainly condensed in the North
31 hemisphere. Divergent ecological issues were highlighted by the word co-occurrence
32 networks: (i) gravel augmentation was used to improve spawning habitats for fish of
33 economic interest whereas (ii) erodible corridor was designed to safeguard natural
34 riparian systems, approaching morphological goals of channel widening. Overall,
35 ecological responses were consistent with those expected, leading however rather to
36 functional shifts than richness increase. Gravel augmentation or bank erosion were
37 not usually combined with in-channel structure management. However, this might be
38 an option to consider since the biological communities seem to be sensitive during
39 first restorations with such combination. This review demonstrates the value of word
40 co-occurrence networks in exploring a high number of previous publications, keys for
41 formulating guidance to manage gravel augmentation or bank erosion along
42 ecological purposes.

43 **Key words:** biological communities, erodible corridor, river restoration, sediment
44 deficit, word co-occurrence networks.

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51 **1. Introduction**

52 River restoration encompasses a wide range of activities, with increasing recognition
53 that the most sustainable approach to restoration is to recover dynamic
54 geomorphological processes and riverine connectivity, as these can provide habitats
55 and links needed to support native species that are the target for the restoration
56 efforts (**Beechie et al., 2010; Kondolf et al., 2006**). Where possible, the most
57 efficient approach is to give rivers a corridor in which they can flood, erode and
58 deposit sediment, and establish riparian vegetation (e.g. **Biron et al., 2018; Piégay
59 et al., 2005**). On rivers highly constrained by development and structural works it
60 may be prohibitively expensive to create a corridor wide enough to support fluvial
61 dynamics, and in many cases the flow and sediment regimes have been profoundly
62 altered by upstream dams, such that even with lateral space, the needed energy and
63 sediment to build fluvial forms are lacking. In addition to modifying flow regimes,
64 dams trap gravel, sand, and some portion of the finer-grained sediment load,
65 commonly producing sediment-starved flows downstream (**Kondolf, 1997**). Only 37
66 per cent of rivers longer than 1,000 kilometres remain free-flowing over their entire
67 length and 23 per cent flow uninterrupted to the ocean (**Grill et al., 2019**). This is why
68 dam-altered hydrographs and sediment loads must be now accounted for in planning
69 restoration of most river reaches. These dam-induced changes result in loss (i) of
70 longitudinal connectivity (as the free passage of sediment, nutrients, organic matter,
71 and fish, **Ligon et al., 1995**), (ii) of lateral connectivity (as reduced high flows cannot
72 overflow onto floodplains as frequently, reducing vigor of riparian forests, eliminating
73 important habitats and niche refugia for aquatic organisms as macrophytes,
74 macroinvertebrates or juvenile fishes, and disconnecting former channels such as
75 oxbow lakes (**e.g., Liu and Wang, 2018**), and of (iii) vertical connectivity (as reduced

76 high flows reduce hydraulic gradients driving surface-subsurface exchanges and fine
77 sediment that accumulates without being flushed plugs gravel beds and reduces
78 exchange with the hyporheic zone) (**Kondolf et al., 2006**).

79 These disruptions have prompted environmental flow requirements in many rivers
80 (**Arthington and Pusey, 2003; Arthington et al., 2006; Kondolf et al., 2019; Poff**
81 **et al., 1997; Poff et al., 2009; Poff and Zimmerman, 2010; Richter et al., 2006**).

82 Flow requirements increasingly include deliberate high flows to induce scour and
83 sediment transport (**Kondolf et al. 2019; Renschler et al., 2007**), inundate
84 floodplains by flood pulses (**Junk et al., 1989**), and maintain aquatic (**Bunn and**
85 **Arthington, 2002**) and riparian communities (**Nilsson and Svedmark, 2002**).

86 Release of environmental flows is increasingly combined with other restoration
87 actions, such as abandoned side channel restoration on the Rhône (**Henry et al.,**
88 **2002; Riquier et al., 2015**), Rhine (**Eschbach et al., 2017, 2018; Meyer et al., 2013;**
89 **Schmitt et al., 2009; Simons et al., 2001**) and Danube Rivers (**Tockner et al.,**
90 **1998**) to restore lateral connectivity with off-channel water bodies and floodplain
91 forests. Restoration of more natural flow regimes and physical habitat restoration can
92 result in creation of ecological niches important for aquatic biodiversity (**Ecke et al.,**
93 **2016; Roni et al., 2008**). To date there has been more interest in restoring flow
94 regimes than sediment regimes, but this is starting to change with the observation
95 that restoring flow only without restoring habitat structure is unlikely to succeed
96 (**Alber and Piégay, 2017; Kondolf et al. 2019; Wohl et al., 2015**).

97 A number of ambitious hydromorphological river restoration projects have been
98 undertaken in recent decades (**Wohl et al., 2015**), promoting interventions to 'feed
99 the hungry river' for natural resilience of the river itself and the recovery of natural
100 biodiversity (**Heckmann et al., 2017; Hobbs and Harris, 2001**), working with fluvial

101 dynamics and its main components, water and sediment (**Heiler et al., 1995; Friberg**
102 **et al., 2017; Wohl et al., 2015**). Multiple dams have fragmented the river and created
103 artificial channels, in some cases alongside abandoned reaches of the original
104 channel. Many, well-documented efforts have been undertaken to restore these
105 remnant river reaches, now mostly cut off from seasonally-appropriate flows and
106 supplies of coarse sediment essential to reduce biotic homogenization (**Olden et al.,**
107 **2016**). Restoration actions for these reaches have emphasized (i) mechanical
108 addition of gravel for transport by the occasional competent flows, and (ii) controlled
109 bank erosion combined with structures designed to create more complex flow
110 patterns, including diverting flows into banks, in part to recruit gravels from the banks
111 into the flux of sediment transported through the reach (**Pinte et al., 2015; Staentzel**
112 **et al., 2018a**).

113 To inform these restoration efforts, we posed the following questions: (i) how
114 common are programs to restore sediment supply and habitat diversity below dams
115 through mechanical gravel augmentation and induced bank erosion? (ii) How do
116 these projects differ in design and in performance on an ecological point of view?

117 **2. Methods**

118 We began by conducting an overview of papers devoted to seven types of restoration
119 actions below dams (**Supplementary file S1**) to quantify the importance of the two
120 actions on which we focused, gravel augmentation and induced bank erosion below
121 dams. We conducted a quantitative review on abstracts, titles and keywords, from
122 research articles, review papers, technical reports, and conference proceedings in
123 the Web of Science database, published up from January 1976 to December 2018.
124 We searched on the term [restor* OR rehabilit* OR renatur*], AND the terms [river*

125 OR channel* OR river basin* OR floodplain* OR hydrosystem*]. We first limit the
126 search to “restor*” because the wider use in target papers of this term by authors
127 from many countries (**Morandi and Piégay, 2017**). In a second step, we also
128 included renatur* or rehabilit* terms in analyzes to take into account a maximum of
129 feedbacks. The result provided 25,959 papers. We removed all papers containing
130 specific terms relative to biochemistry or medicine science, [e.g. cell*, protein*,
131 patient*, collapse*, electron*, proton*, neutron*, nanochannel*, pharmaco*, medec*,
132 endocr*, cortic*, antibiot*], resulting in 18,570 papers. We analyzed results by four
133 time periods from 1976 to 2018: [1976 – 1986], [1987 – 1997], [1998-2008], and
134 [2009-2018]. We retained within the 18,570 papers only those considering in their
135 title, abstract or keywords, specific terms designing the main types of river restoration
136 possible below dams (**Supplementary file S1**). We adjusted specific terms following
137 an iterative process, i.e. repeating rounds of analysis, to focus on the terms most
138 commonly used in the literature. Seven main types of river restoration were identified
139 (**Supplementary file S1**): lateral connection, erasure of hydraulic structures, in-
140 channel management, instream flow management, revegetation, bank erosion and
141 gravel augmentation. In the group of words for bank erosion, we added the terms
142 groyne* and groine* to identify projects that combined bank erosion and groyne
143 implementation for river restoration.

144 Of these seven main river restoration types appearing in literature, we focused on
145 two that concern sediment deficits below dams: gravel augmentation downstream of
146 dams, and induced bank erosion to supply sediment and create more diversified and
147 functional habitats. We scanned these papers with text content analyses for a global
148 overview of the main issues and their interrelations using the KH Coder software
149 3.0.0.0, which calculated word distances by Jaccard coefficient and the strength of

150 attachment. Two graphical visualizations of the word co-occurrence networks were
151 proposed for easier interpretation: (i) with an ascending degree to centrality, from
152 yellow to blue, inquired the term frequency by circle size, and (ii) with modularity
153 detecting the strength of division of a network into modules as groups, clusters or
154 communities (**Higuchi, 2016**). We limited the word co-occurrence networks to better
155 show the minimum spanning tree, consisting of only stronger lines. We extracted
156 words with “Snowball”, a process that cuts ends of words and removes all plural,
157 conjugated or granted forms. For example, the word restor* could be associated with
158 the following terms: restoration, restore, restored. Stop words, *i.e.* words excluded
159 from analyses, were defined including all usual pronouns, articles, linking words,
160 adverbs, some adjectives, and verbs (as “be” or “have”). Numbers, special symbols,
161 and punctuation were also removed.

162 **3. Results**

163 *3.1. Exploration of the published scientific literature*

164 Papers related to river restoration generally increased over time, from only 29 in 11-
165 year period 1976-1986 (0.15% of the total) to 959 from 1987-1997 (5.16%). Then
166 from 1998-2008, the number of papers increased six fold to 5,701 (30%) and doubled
167 again during the next time period [2009-2018] (n=11,911, 64%; **Figure 1A**). A total of
168 2,665 papers concerned at least one term belonging to the groups of words defined
169 for each of the seven types of river restoration (**Figure 1B**). From essentially few
170 papers 1976 to 1986, the period 1987-1997 saw multiple papers on in-channel
171 structures, revegetation, and lateral connection. From 1998-2008, in-channel
172 structure management (n=166) and erasure (removal) of hydraulic structures (ERAS,
173 n=143) had the highest number of published papers (**Figure 1B**). The last period

174 (2009-2018) showed the highest number of publications, all types of restoration being
175 concerned, especially the removal of hydraulic structures (n=381; **Figure 1B**).
176 Instream flow management has also been the subject of a large number of papers
177 (n=303) as well as the in-channel structure management (n=289). Although many
178 papers featured bank erosion or gravel augmentation, very few addressed the need
179 to add directly sediment in rivers or provoke bank erosion as a restoration action
180 (19.02% for gravel augmentation, n=43/226; 15.36% for bank erosion, n=49/319)
181 (**Figure 1C**). Some projects to restore channel complexity below dams *via* adding
182 coarse sediment or inducing bank erosion to give the river an impetus for self-
183 restoration have been documented in the scientific literature. Field studies were
184 reported in 28 papers about gravel augmentation and 24 papers about induced bank
185 erosion (**detailed in Supplementary files S2, S3**). Recent papers have documented
186 projects in more upstream reaches than sediment-starved estuaries and deltas,
187 including projects undertaken within the framework of larger restoration programs
188 such as the Trinity River Restoration Program (USA) or the redynamization of the Old
189 Rhine River (France-Germany), involving significant research components. However,
190 feedbacks in published papers from WOS were still rare and were concentrated on
191 specific geographical areas in Europe and North America (**Figure 2**).

192 *3.2. Scanning word co-occurrence networks to identify main ecological issues*

193 Looking more closely at papers considering gravel augmentation (n = 43 papers) and
194 bank erosion (n = 49 papers) to restore natural fluvial forms and thus improve
195 biodiversity (**Figure 1C**), the word co-occurrence networks showed diverging
196 ecological issues. Concerning gravel augmentation, the word co-occurrence network
197 was centered around the term river* and the highest frequency was obtained for the
198 term gravel* (**Figure 3A & 3B**). The term river* was strongly connected to gravel*

199 (0.66) and habitat (0.69). The word habitat* shared a strong edge with a term of high
200 occurrence as spawn* (e.g. spawning, 0.62), related to salmonid* or salmon* (**Figure**
201 **3A & 3B**). The term spawn* was one of the four other terms among restor*,
202 sediment*, and gravel*, that had a strong interconnection with other less recurrent
203 words (**Figure 3A**). Such centrality on specific words suggested a division of the
204 network in groups and the graphical visualization based on modularity allowed to
205 reveal six groups (**Figure 3B**). The term river* was associated in a first group (group
206 01, Figure 3B) with the terms gravel*, augment*, increas*. This main group 01 was
207 linked to the group 02, headed by the term restor* and related to the effect
208 assessment, e.g. effect*, studi*, result*, compar* (**Figure 3B**). Also linked to the main
209 group 01, the group 03 highlighted fluvial processes such as sediment transport
210 below dams (sediment*, flood*, downstream*, dam*, transport*, chang*, bed*). The
211 group 04 was focused on ecological purposes, headed by the term spawn*. Papers
212 with the terms model* and predict* were dissociated from the main body of studies,
213 whether due to notions of geomorphology or ecology (no edges, **Figure 3B**).

214 The center core of the word co-occurrence network concerning the notion of bank
215 erosion was occupied by the term river*, strongly connected to restor* with a
216 coefficient of 0.71, to habitat* with a coefficient of 0.62, and to channel* with a
217 coefficient of 0.58 (**Figure 3C & 3D**). The term restor* was connected to the term
218 effect*, a term whose degree of centrality is strong (**Figure 3C**). Other terms showed
219 an important degree of centrality but in a lesser extent (bank*, reach*, indic*, **Figure**
220 **3C**). Edges from the term result* lead towards the term bank*, which in turn was
221 linked to the term eros* (0.77) and to the term model* (0.43). The group 02 headed
222 by the term restor* was highly linked (i) to the group 01, headed by the term effect*,
223 and (ii) to the group 02, headed by the term river* (**Figure 3D**). The group 01

224 reflected the general desire to determine the effects of restoration projects whereas
225 the group 02 highlighted processes and elements that are specifically targeted by
226 promoting bank erosion (channel*, habitat*, morphology*, **Figure 3D**). Two other
227 pairs of terms dealing with geomorphology occurred with no edges linking them to
228 others: one was composed of rate* and sediment*, the other cross-sect* and
229 unmanag* terms. Sediment transport was thus discussed but evidently not directly
230 related to hydrological processes such as flood*, flow* (no edges, **Figure 3C & 3D**).
231 The relatively few biological terms that emerged (e.g. plant*, divers*, speci* in group
232 06, **Figure 3D**) were not connected to the main three groups of words (group 01, 02
233 and 03). No group related to physical modelling occurred. We included artificial
234 structures (groyn*, groin*) in the analyses to test for some combined restoration
235 actions, but no strong edges emerged between these terms and others in the word
236 co-occurrence network (group 08, **Figure 3D**).

237 **4. Discussion**

238 *4.1. What do we learn about sediment supply and habitat diversification using gravel* 239 *augmentation for ecological purposes?*

240 Gravel augmentation has been widely discussed in the US scientific literature issued
241 from WOS (60% of papers focusing on gravel augmentation), implemented mostly in
242 the western US (**Figure 2**), with projects in California back to the 1970s on more than
243 13 dammed rivers of the Sierra Nevada and Coast Ranges (**Kondolf and Matthews,**
244 **1993**). US projects reported in the literature included many on tributaries of the
245 Sacramento-San Joaquin Rivers (**Kondolf and Matthews, 1993; Kondolf et al.,**
246 **2008**) but none to induce bank erosion (Figure 2). The frequent occurrence of the
247 terms “spawn” or “salmon” reflects the dominant importance of restoring favourable

248 spawning grounds, their loss having led to the reduction or disappearance of fish
249 species of economic importance. The major activity of the last twenty years in
250 Northern California and downstream of the Central Valley dams was focused on
251 improving aquatic habitats for salmonids (**Barlaup et al., 2008; Harvey et al., 2005;**
252 **Kondolf et al., 2007; Merz et al., 2004; Merz and Setka, 2004; Sellheim et al.,**
253 **2016; Zeug et al., 2014**). **Gessner et al. (2014)** concluded that gravel augmentation
254 could increase longitudinal connectivity downstream of dams and allow fish
255 migration, thereby restoring 30% of the potential habitats for fish on the Spree-Havel
256 River (Germany). Other studies employed detailed hydraulic models to design the
257 placement of gravel to maximize areas with depths, velocities and the preferred
258 substrate for spawning salmonids (**Humphries et al., 2012; Miwa and Parker, 2012;**
259 **Pasternack et al., 2004, 2006; Singer and Dunne, 2006; Sklar et al., 2009;**
260 **Sawyer et al., 2009; Venditti et al., 2010**). Creation of gravel bars can also produce
261 a thermal heterogeneity (**Eschbach et al., 2017**) and greater trophic potential (**Ock**
262 **et al., 2015**). Indirect effects of these gravel augmentation can include higher water
263 levels, inundating a greater extent of the alluvial zone (**Elkins et al., 2007**).
264 Colonization of macroinvertebrate species occurred rapidly and standing crop
265 increased in such projects, thus benefiting other species than those initially targeted
266 (**Merz and Ochikubo Chan, 2005**).

267 A great heterogeneity of words has been used to describe such restoration actions or
268 even the terms related to restor*, renatur*, rehabilitit* were not clarified, and this can
269 hinder the search for feedbacks, such as **Rollet et al. (2008)** on the Ain River,
270 France, **Stähly et al., (2019)** on the Sarine River, Swiss, and **Schälchli et al. (2010)**
271 on the Aare River, Swiss. According to the word co-occurrence network, the most
272 common combination is “gravel augmentation”. Some other combinations as “artificial

273 gravel dumping” (**Hauer et al., 2015**) were too specific to be revealed in the analysis.
274 Integrating the terms renatur* and rehabilit* in addition to restor* in the analysis has
275 allowed for the inclusion of a Japanese article in the database (**Matsushima et al.,**
276 **2018**). The term of renatur* is not used at all to treat these actions, the major term
277 remains that of restor*. Some other river restoration projects in Japan are lacking
278 (**Okano et al., 2004; Kantoush et al., 2010**). For example, **Miyagawa et al., (2017)**
279 studied effects of gravel augmentation on riverbed material size distribution and
280 attached algal biomass in the downstream reaches of the Futase Dam, and **Ock et**
281 **al., (2013)** compared gravel augmentation in the Nunome River (Japan), and the
282 Trinity River (US).

283 *4.2. What do we learn about sediment supply and habitat diversification using bank*
284 *erosion for ecological purposes?*

285 We quickly observed on the word co-occurrence network that the terms related to
286 ecological purposes were in a group dissociated from the first stakes of this type of
287 restoration action, which is mainly the diversification of fluvial forms and habitats in
288 the main channel by lateral erosion. Indeed, where possible below dams, adopting a
289 ‘freedom space’ for rivers approach should result in improved habitats, as it permits
290 natural processes related to mobility, flooding, and riparian connectivity, enhancing
291 the diversity of aquatic organisms (**Biron et al., 2018; González et al., 2017**).
292 Although the few ecological terms revealed by the word co-occurrence network were
293 related to the improvement of riparian compartments, a greater heterogeneity in
294 fluvial forms, and consequently, aquatic habitats could increase macroinvertebrate
295 richness. Channel widening enhanced heterogeneity or diversity of habitat (**Poppe et**
296 **al., 2016**), fish (**Kail et al., 2015, Schmutz et al., 2016**), benthic invertebrates
297 (**Wyźga et al., 2014; Kail et al., 2015**), macrophytes (**Ecke et al., 2016; Kail et al.,**

298 **2015**), ground beetles (**Januschke and Verdonschot, 2016**) and floodplain
299 vegetation (**Göthe et al., 2016**). The word co-occurrence network also showed that
300 channel widening could be considered as a part of controlled bank erosion effects.
301 Overall, results concluded for generally more pronounced effects of habitat
302 restoration on community structure, traits and functional indicators than on species
303 diversity *sensu stricto*.

304

305 Multiple terms have been used for restoration actions to generate bank erosion safely
306 (not only below dams), such as (i) “creating hotspots of erosion” (**Beagle et al., 2016**;
307 **Choné and Biron, 2016**), (ii) “applying a protected erodible corridor for mobility”
308 (**Hajdukiewicz et al., 2017**), (iii) “induce controlled bank erosion” (**Garnier and**
309 **Barillier, 2015**; **Staentzel et al., 2018b, 2018c, 2019**), or (iv) “room to move” (**Reid**
310 **and Brierley, 2015**). **Champoux et al. (2003)** and **Vietz et al. (2018)** used bank-
311 cover deflectors to induce slow bank erosion to improve physical fish habitat and
312 channel morphology but warned against fast, excessive bank erosion or degradation
313 of historical embankments, leading to an ad-hoc solution in which bank erosion must
314 be controlled (**Choné and Biron, 2016**). No group related to physical modelling
315 occurred, suggesting that the bank erosion process was not yet well enough
316 understood to be sufficiently controlled. However, modeling to identify specific
317 erodible corridors across which rivers are free to migrate increased the last decade in
318 laboratory flume experiments or by GIS planimetric analyses (**Alber and Piegay,**
319 **2017**; **Battisacco et al., 2015**; **Choné and Biron, 2016**; **Clutier et al., 2012**; **Dépret**
320 **et al., 2017**; **Pinte et al., 2015**; **Reid and Brierley, 2015**; **Requena et al., 2006**;
321 **Ribeiro et al., 2016**). **Díaz-Redondo et al. (2018)** modeled the effects of removing
322 embankments, lowering banks, and widening side channels on lateral hydrological

323 connectivity and morphodynamics to renew floodplain side-channel habitats. Model
324 results indicated that the measures would reconnect side channels and increase
325 areas subject to erosion, while maintaining flood protection and navigation use.

326 Artificial or semi-natural in-channel structures have been recently implemented in
327 many large, dammed rivers to induce erosion and deposition, i.e., “working with
328 nature” (**Harvey et al., 2018**), but usually were not part of a program to replenish
329 coarse sediment to induce bank erosion, as reflected in the word co-occurrence
330 network (**Figure 3B**). The only project we encountered below dams that combined
331 (controlled) bank erosion and artificial transverse groynes to divert flows into banks
332 and thereby create more complex channel forms was on the Old Rhine River, France
333 (**Garnier and Barillier, 2015; Pinte et al., 2015**). The groyne design was modelled to
334 activate the erosion of the banks during floods (**Chardon et al., 2018; Die Moran et**
335 **al., 2013; El Kadi Abderrezzak et al., 2012**). While the volumes of sediment
336 recruited by erosion of the bank were less than anticipated (**Chardon et al., 2016;**
337 **2017; 2018; Pinte et al., 2015**), morphological changes, habitat heterogeneity,
338 vegetation dynamics and ecological niches were clearly enhanced (**Staentzel et al.,**
339 **2018b, 2018c, 2019**). Pioneer plant species quickly established in the eroded reach
340 and on groynes, including aquatic and terrestrial invasive species (**Staentzel et al.,**
341 **2018c**). Most significantly, there was a strong increase in species number and cover
342 of macrophytes, which were mostly absent before the restoration (**Staentzel et al.,**
343 **2018c**). Overall, a high diversity in habitats was observed, associated with enhanced
344 macroinvertebrate diversity over the site, creating habitat for burrowing species as
345 *Odonata* (**Staentzel et al., 2019**). Few other studies exist but in-channel and riparian
346 biological compartments seem to be favoured by groynes in large rivers. A rise in
347 habitat heterogeneity including in the area of spawning habitat for fish, and an

348 increase in Odonata species richness have often been stated (**Buczyńska et al.,**
349 **2018; Buczyński et al., 2017; Eick and Thiel, 2013**).

350 *4.3. Guidance to replenish gravel supply or perform controlled bank erosion for*
351 *ecological purposes*

352 In some cases, gravel augmentation have not produced a measurable biological
353 response, which may be due to inadequate volumes, or to a grain size distribution
354 deficient in sand and fine gravels (**McManamay et al., 2013**). The volumes of coarse
355 sediment needed for effective replenishment can be estimated from the river's
356 sediment transport capacity (**El Kadi Abderrezzak, 2009; Rosenfeld et al., 2011**).
357 Moreover, other factors to consider include the effect of sand in the gravel mixture in
358 enhancing bed mobility and gravel movement (**Miwa and Parker, 2017**). Gravel-
359 sized substrates are essential for lithophilic species and their development cycle,
360 including substrate spawners (some cyprinids) and interstitial spawners (salmonids)
361 (**Pulg et al., 2013**), but also for functional composition in macroinvertebrates,
362 (**Staentzel et al., 2019**). In many cases, particular functional groups were favoured
363 by specific substrates such as rheophilic or burrower taxa (**Albertson et al., 2011,**
364 **McManamay et al., 2013; Staentzel et al., 2018b, 2018c, 2019**).The origin of
365 injected gravels is most often local, avoiding the introduction of exotic organisms
366 (**Friberg, 2014**).

367 The ecological effects of gravel augmentation may be transitory as the added gravel
368 is transported downstream, so that long-term benefits cannot to assumed (except if
369 further gravel augmentations are regularly undertaken). Feedbacks on induced bank
370 erosion showed that effects are mostly concentrated in the eroding reach and directly
371 downstream. The distribution of benefits downstream depends on whether the gravel

372 moves by dispersion or translation: dispersion resulting in fewer benefits downstream
373 because the gravel concentrations are so low in any given reach, while with
374 translation of a wave downstream will result in short-lived local benefits that migrate
375 downstream with the gravel (**Sklar et al., 2009**). This has implications for monitoring,
376 as ecological responses obtained in monitoring studies will also depend on the
377 location of monitoring points (**Staentzel et al., 2018a**).

378 A high number of small groups was observed in the word co-occurrence network on
379 papers promoting bank erosion, unlike those enhancing gravel augmentation. We
380 perceived that we are at the beginning of feedback studies promoting bank erosion,
381 and that several issues are investigated without being for the moment connected (**Figure**
382 **3D**). First results on ecological purposes showed that bank erosion has been
383 beneficial to the diversification of aquatic and riparian habitats. The effects of this
384 type of restoration turned out to be very close to what we could get by channel
385 widening. The addition of artificial or natural structures to promote lateral erosion by
386 floods has shown an interesting potential for reclaiming biodiversity. However, these
387 settlements can become fixed points in the restored landscape due to a large
388 revegetation or a bare rocky armor. It's therefore necessary to adopt an adaptive
389 management process (**Allen et al., 2011**) if the long-term effects of such restoration
390 action does not tend to those expected.

391 In most cases, restoration projects reported in the literature had monitoring periods of
392 3 years or more, and stressed the need to pursue monitoring over time to give the
393 biology time to respond to the morphology. **Morandi et al. (2014)** recommended
394 embedding spatial and temporal references into the design of the monitoring
395 program, but many studies observed that their experiments did not fit easily within the
396 BACI protocol (**Smith et al., 1993**), but instead implemented a simpler Control-

397 Impact approach. Few projects have been reported in interdisciplinary papers
398 (**Supplementary files S2, S3**), as ecological and geomorphological monitoring are in
399 many cases conducted in parallel without being integrated. The question of the study
400 scale is key, as for example, macroinvertebrates respond strongly to fine-scale
401 hydromorphological gradients (**Beisel et al., 2000**). Geomorphological monitoring is
402 often realized at larger scales with spatial units suitable to detect physical changes
403 occurring after restoration but too coarse to detect habitat modification to benefit
404 aquatic species. This argues for geomorphological and ecological monitoring at
405 sufficiently fine scales to detect changes in habitat composition (e.g., detailed facies
406 mapping and related measures). **Piégay et al. (2005)** recommended a nested
407 approach across a range of scales (network scale, reach scale, local scale), including
408 in-channel structures such as artificial groynes (used as deflectors) or woody debris,
409 for a greater ecological response. Although it would be an appropriate solution to
410 restore, ecological responses were too often mixed and did not always show an
411 increase in classical taxonomic metrics (**McManamay et al., 2013**). So, a functional
412 approach could be a good alternative to assess the effects of river restoration on
413 bio/ecological profiles of species. Similarly, **Clavel et al. (2011)** proposed a
414 community-level specialization as an indicator of the impact of global changes on
415 biodiversity.

416 **5. Conclusion**

417 In developed countries, dam removal is increasingly implemented to restore
418 ecological functions (**Gilet et al., 2018; Oliver and Grant, 2017; Poff and Hart,**
419 **2002**), but most dams are here to stay, and many new ones are in construction or
420 planning in developing countries (**Poff and Hart, 2002; Zarfl et al., 2015**). Thus, it is
421 imperative that we find ways to restore geomorphological and ecological processes

422 downstream of existing dams. Opinions were divided between the need to add
423 sediment in rivers (e.g., **Florsheim et al., 2008; Rollet et al., 2014**) and the need to
424 reduce it especially in urban areas, where channel aggradation can increase flood
425 risk. However, results on biological communities were generally positive in most of
426 the studied papers. The coupling between many restoration actions is also more and
427 more considered as on the Sarine River in western Switzerland downstream of
428 Rossens hydropower dam where combining gravel augmentation and an artificial
429 flood improves river habitats (**Stähly et al., 2019**). Our literature review reflects an
430 evolving perspective towards adaptive or coupling management approaches to
431 promote the recovery of natural processes in rivers below many dams and thus to
432 improve ecological response.

433 The applied methodology of review based on word co-occurrence networks turned
434 out to be a rapid way (i) to obtain an overview of a high number of papers, (ii) to
435 identify the main topics addressed, and (iii) to highlight the interrelations or
436 associations between the selected words used by authors. These analyzes proved to
437 be useful in understanding the interconnections between disciplines and the
438 evaluation of the degree of interdisciplinary of each type of restoration. Here,
439 scientific approaches related to gravel augmentation appeared highly integrated in a
440 multidisciplinary context, what constitutes a recommended initiative (**Downs et al.,**
441 **2011**).

442 Fluvial processes such as bank erosion are increasingly recognized in land use
443 planning and river management with designations of river corridors (**Choné and**
444 **Biron, 2016**). Future empirical research to quantify ecosystem services and other
445 socioeconomic outcomes is needed to understand the full benefits and costs of

446 restoring process below dams in comparison with dam removal (**Langhans et al.,**
447 **2014; Wortley et al., 2013**) and/or the continuation of dam exploitation. Transforming
448 traditional use of rivers into modern management options raises many questions
449 about river culture that integrate both the recovery of ecosystem functionalities and
450 support human livelihoods (**Wantzen et al., 2016**).

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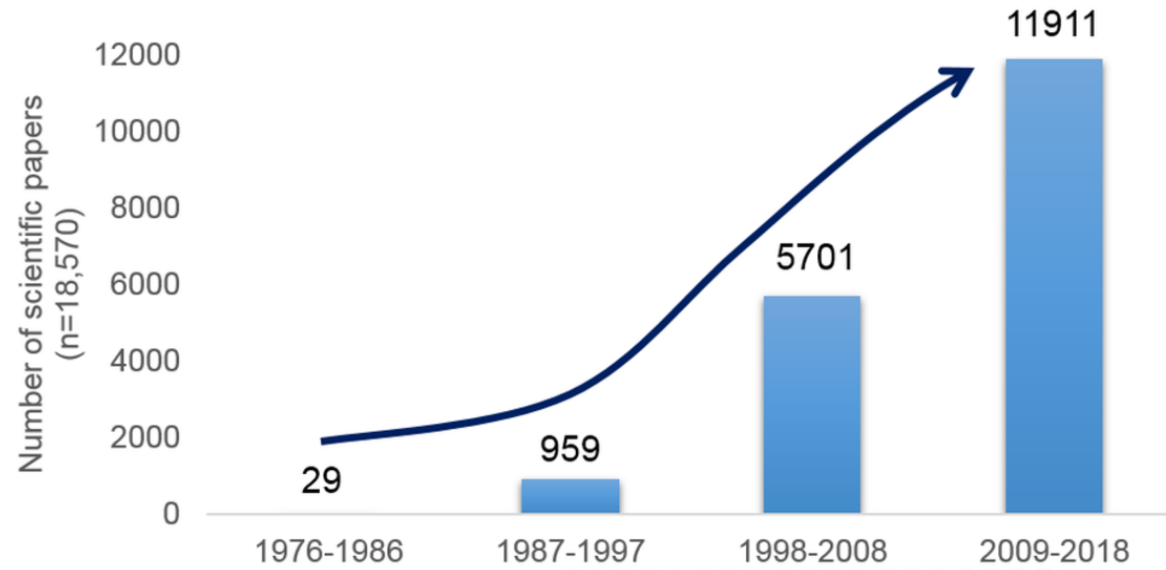
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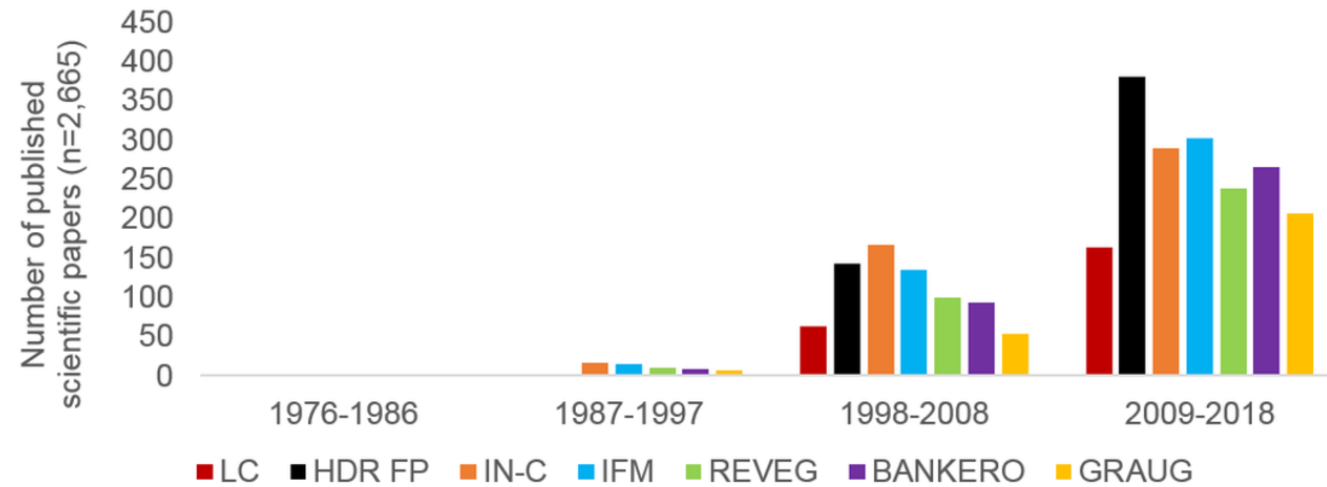
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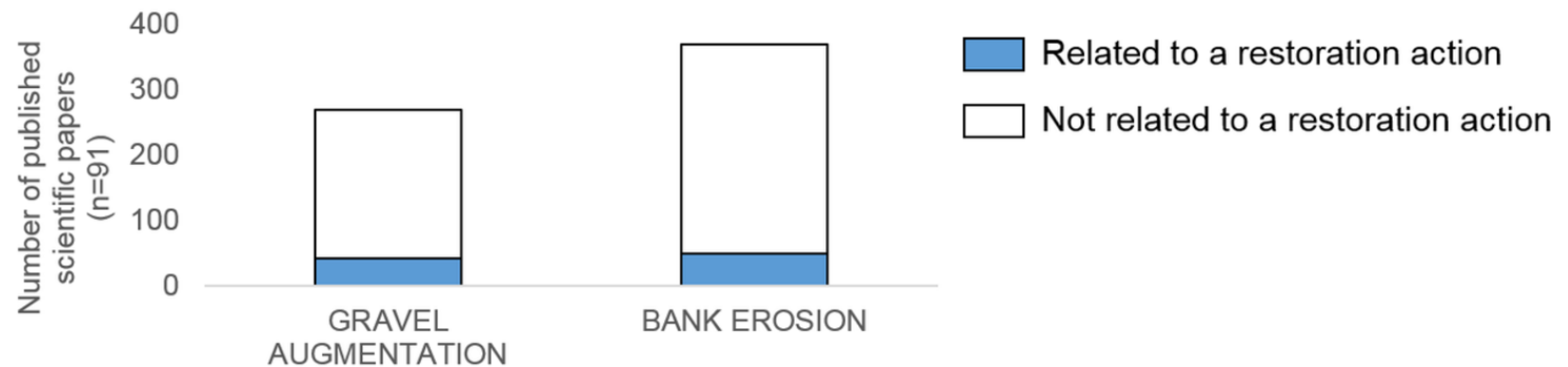
A. Overview on 40 years



B. Number of papers concerning each main group of words by decade (Table 1)



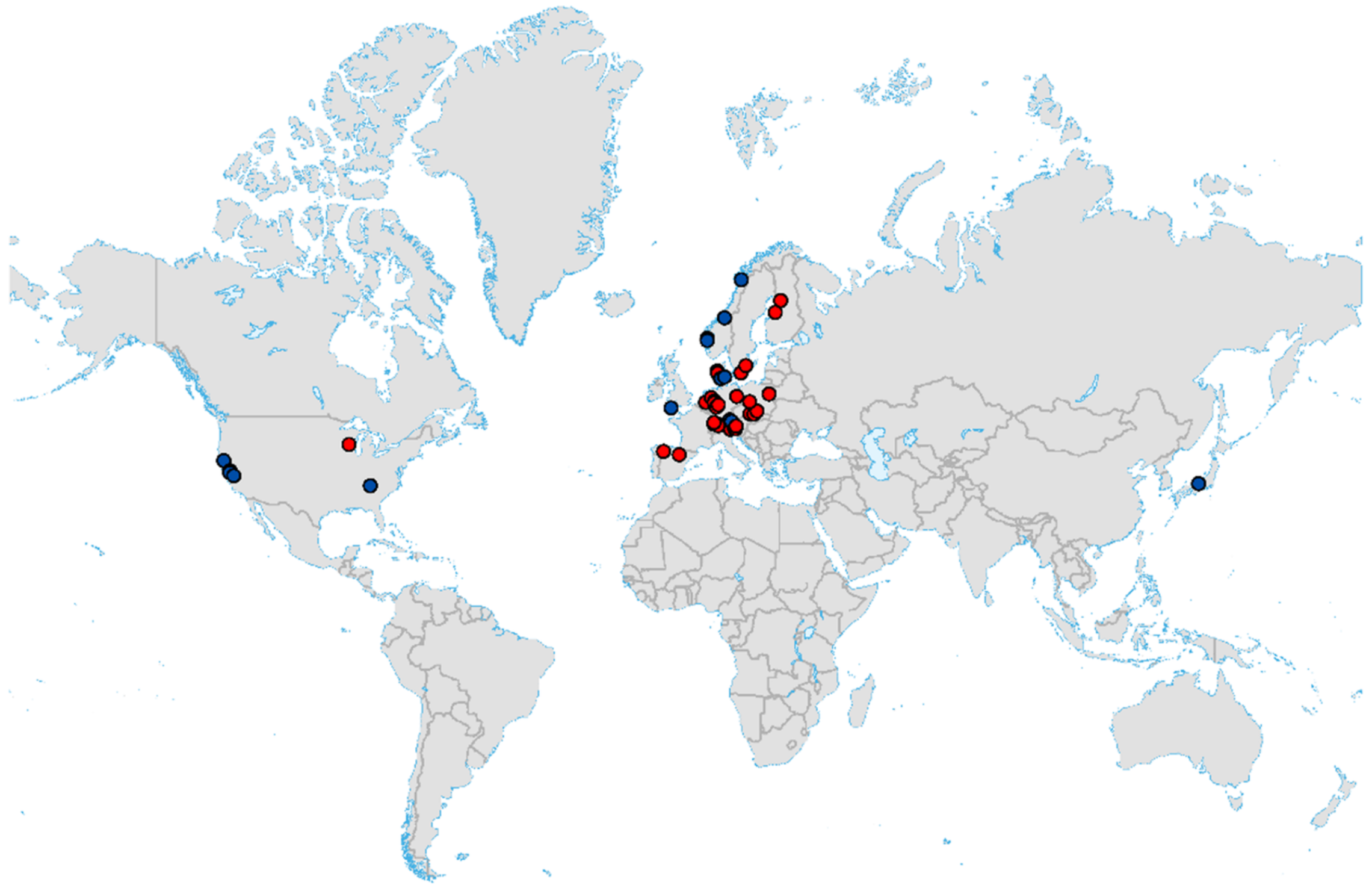
C. Part of the papers relating to restoration action by sediment supply using gravel augmentation or bank erosion



n = 18,570

n = 2,665

n = 91

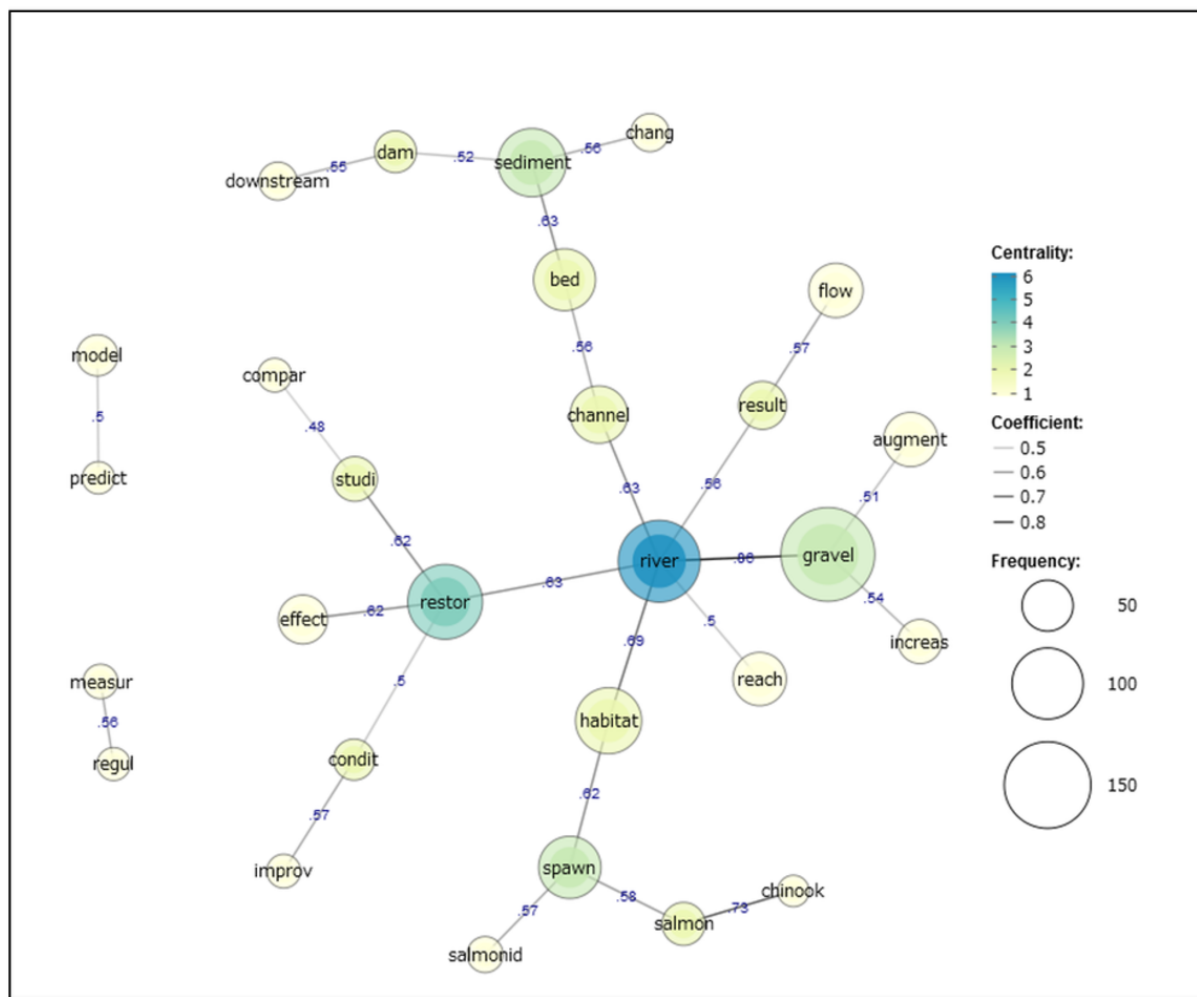


United Nations Geospatial Section

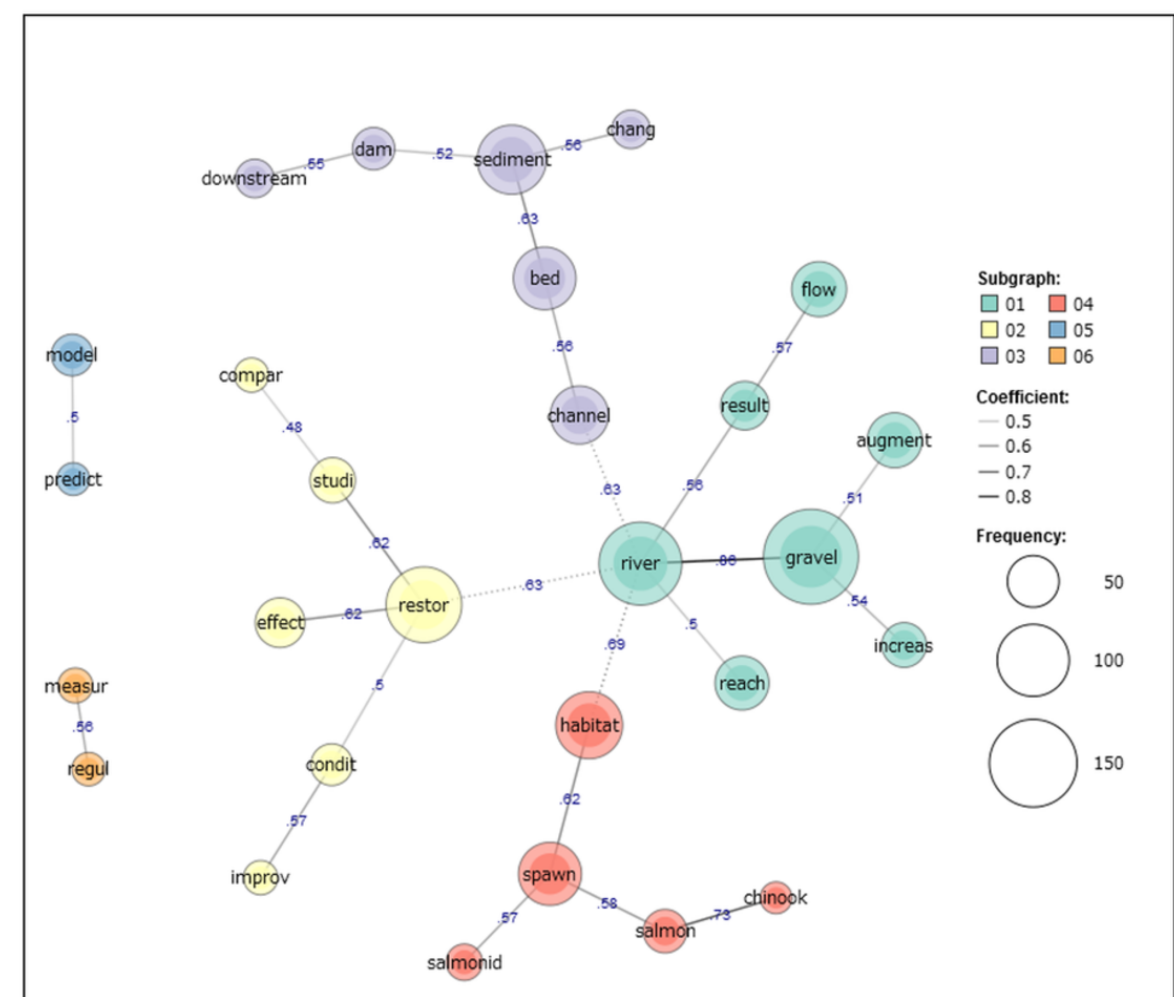
Published restoration projects until 2018 (issued from WOS research)

- Initiating gravel augmentation
- Favoring bank erosion

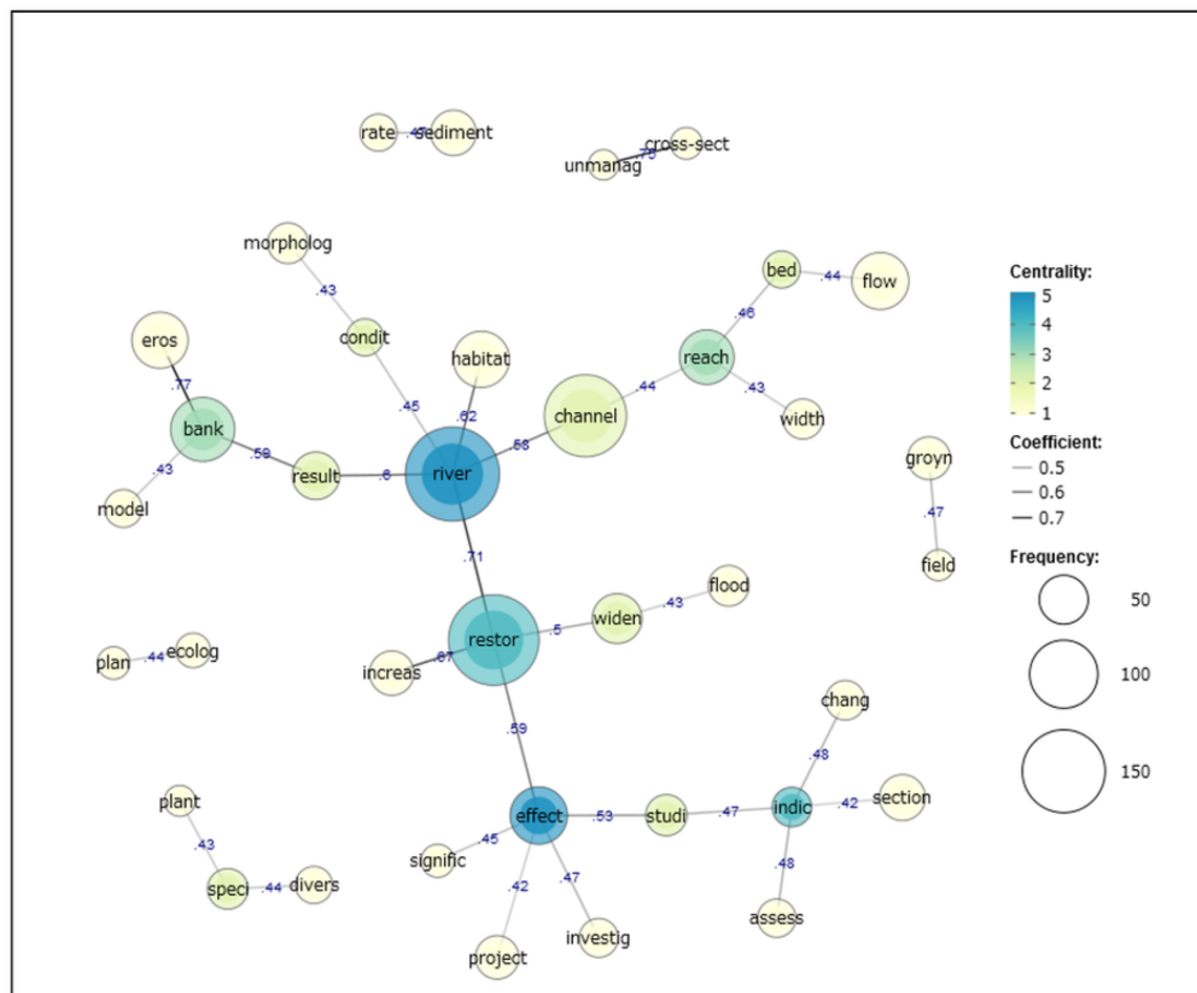
A. GRAVEL AUGMENTATION: degree of centrality



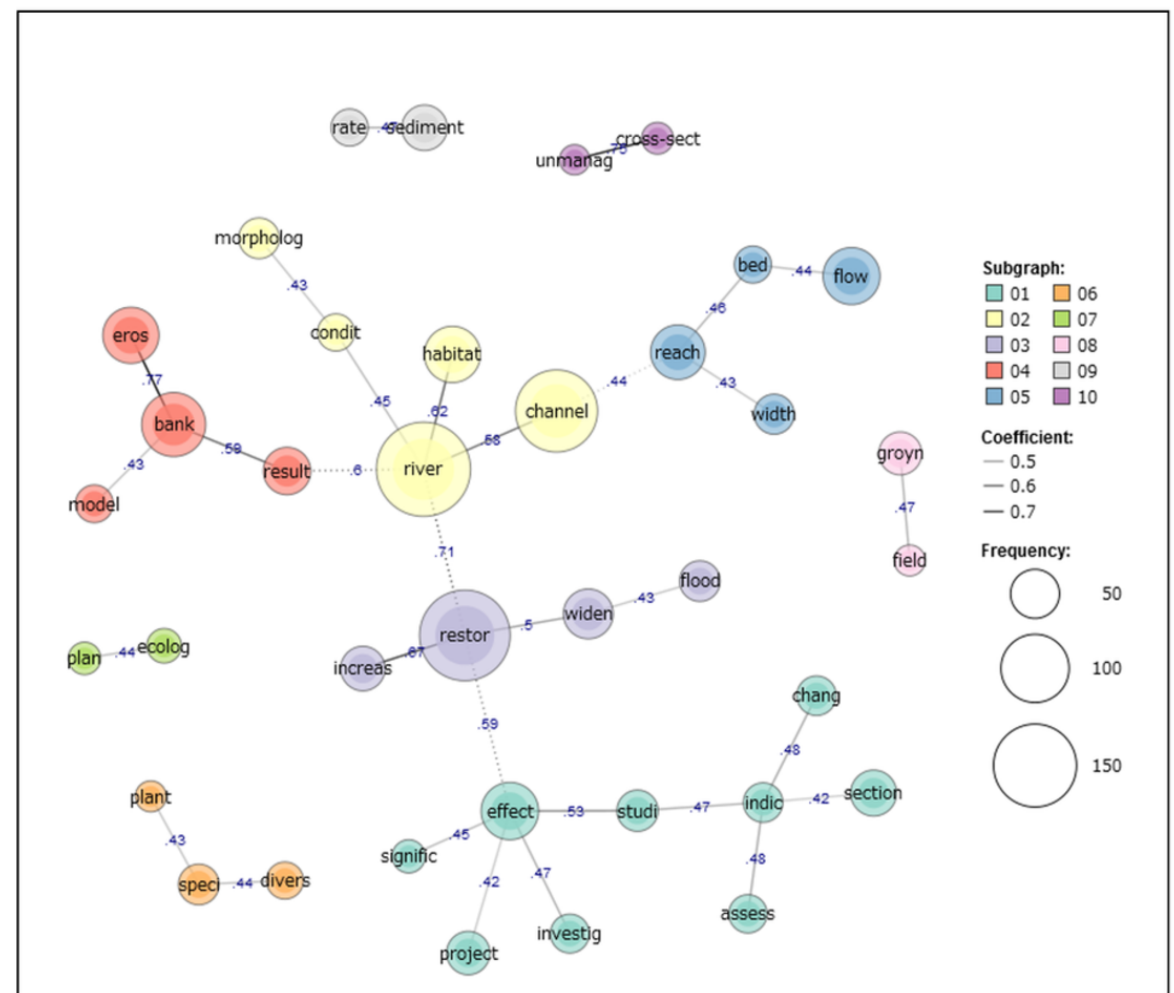
B. GRAVEL AUGMENTATION: modularity and groups



C. BANK EROSION (+ groynes): degree of centrality

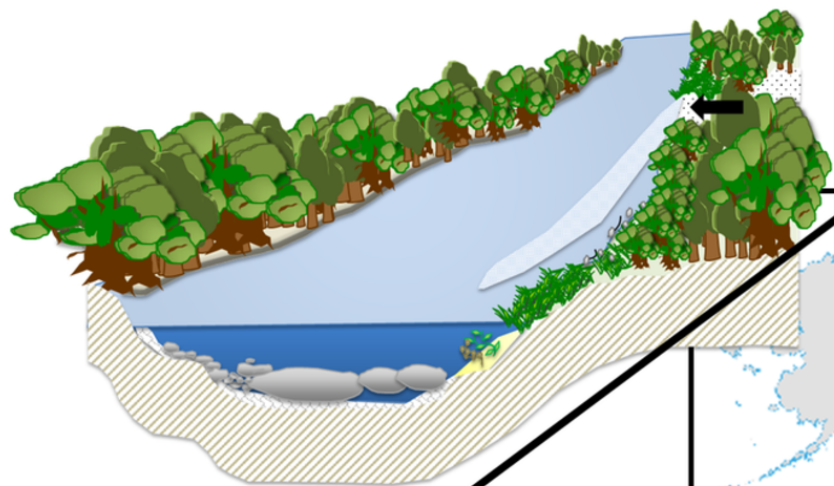


D. BANK EROSION (+ groynes): modularity and groups

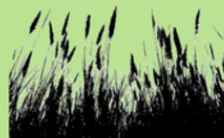


RESTORING FLUVIAL FORMS BELOW DAMS

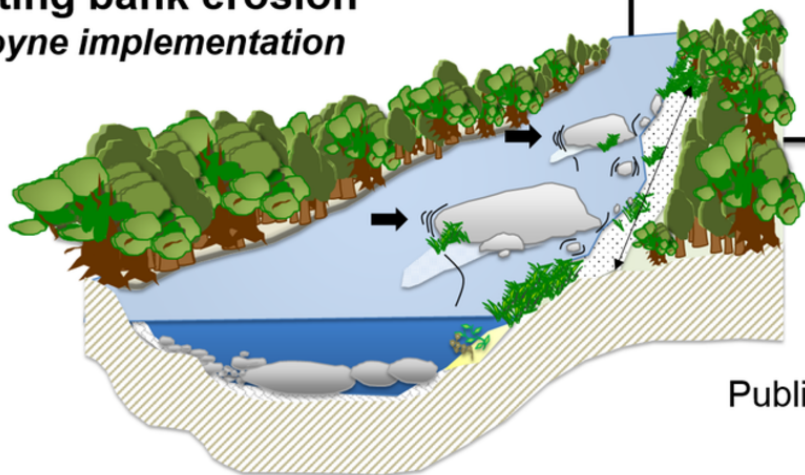
Enhancing gravel augmentation



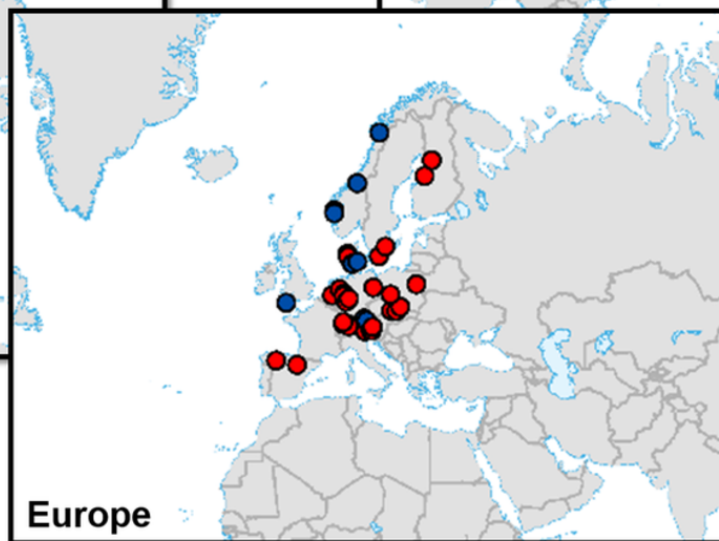
What about ecological responses?



Promoting bank erosion
With groyne implementation



USA/Canada



Europe

Published restoration projects until 2018 (issued from WOS research)

- Enhancing gravel augmentation
- Promoting bank erosion

Asia