

Restoring fluvial forms and processes by gravel augmentation or bank erosion below dams: A systematic review of ecological responses

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16 Abstract

17 Aquatic biological communities have directly undergone human-induced changes. Altered hydrological and morphological processes in running waters have caused the 18 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 reverse well-known negative impacts of anthropogenic pressures. Some authors 22 23 emphasized the enhancement of sediment supply and habitat diversity using gravel augmentation or bank erosion to restore morphodynamics, and thus improve 24 25 biodiversity. We explored the Web of Science database for empirical research papers that specifically addressed such hydromorphological river restoration actions. Articles 26

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 and degree of interdisciplinary. Results showed that a low number of published 29 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 riparian systems, approaching morphological goals of channel widening. Overall, 34 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 co-occurrence networks in exploring a high number of previous publications, keys for 40 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**

River restoration encompasses a wide range of activities, with increasing recognition 52 that the most sustainable approach to restoration is to recover dynamic 53 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 efforts (Beechie et al., 2010; Kondolf et al., 2006). Where possible, the most 56 efficient approach is to give rivers a corridor in which they can flood, erode and 57 deposit sediment, and establish riparian vegetation (e.g. Biron et al., 2018; Piégay 58 59 et al., 2005). On rivers highly constrained by development and structural works it may be prohibitively expensive to create a corridor wide enough to support fluvial 60 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, dams trap gravel, sand, and some portion of the finer-grained sediment load, 64 commonly producing sediment-starved flows downstream (Kondolf, 1997). Only 37 65 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, macroinvertebrates or juvenile fishes, and disconnecting former channels such as 74 oxbow lakes (e.g., Liu and Wang, 2018), and of (iii) vertical connectivity (as reduced 75

high flows reduce hydraulic gradients driving surface-subsurface exchanges and fine
sediment that accumulates without being flushed plugs gravel beds and reduces
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 et al., 1997; Poff et al., 2009; Poff and Zimmerman, 2010; Richter et al., 2006). 81 Flow requirements increasingly include deliberate high flows to induce scour and 82 sediment transport (Kondolf et al. 2019; Renschler et al., 2007), inundate 83 84 floodplains by flood pulses (Junk et al., 1989), and maintain aquatic (Bunn and Arthington, 2002) and riparian communities (Nilsson and Svedmark, 2002). 85 Release of environmental flows is increasingly combined with other restoration 86 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., **1998**) to restore lateral connectivity with off-channel water bodies and floodplain 90 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).

A number of ambitious hydromorphological river restoration projects have been undertaken in recent decades (**Wohl et al., 2015**), promoting interventions to 'feed the hungry river' for natural resilience of the river itself and the recovery of natural 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).

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

117 **2. Methods**

We began by conducting an overview of papers devoted to seven types of restoration actions below dams (**Supplementary file S1**) to quantify the importance of the two actions on which we focused, gravel augmentation and induced bank erosion below dams. We conducted a quantitative review on abstracts, titles and keywords, from research articles, review papers, technical reports, and conference proceedings in the Web of Science database, published up from January 1976 to December 2018. 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 search to "restor" because the wider use in target papers of this term by authors 126 127 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 feedbacks. The result provided 25,959 papers. We removed all papers containing 129 130 specific terms relative to biochemistry or medicine science, [e.g. cell*, protein*, patient*, collapse*, electron*, proton*, neutron*, nanochannel*, pharmaco*, medec*, 131 132 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 gravel augmentation. In the group of words for bank erosion, we added the terms 141 142 groyne* and groine* to identify projects that combined bank erosion and groyne 143 implementation for river restoration.

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

attachment. Two graphical visualizations of the word co-occurrence networks were 150 151 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 detecting the strength of division of a network into modules as groups, clusters or 153 154 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 11year period 1976-1986 (0.15% of the total) to 959 from 1987-1997 (5.16%). Then 165 166 from 1998-2008, the number of papers increased six fold to 5,701 (30%) and doubled again during the next time period [2009-2018] (n=11,911, 64%; Figure 1A). A total of 167 168 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 Rhine River (France-Germany), involving significant research components. However, 189 190 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

Looking more closely at papers considering gravel augmentation (n = 43 papers) and bank erosion (n = 49 papers) to restore natural fluvial forms and thus improve biodiversity (**Figure 1C**), the word co-occurrence networks showed diverging ecological issues. Concerning gravel augmentation, the word co-occurrence network was centered around the term river* and the highest frequency was obtained for the 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 words (Figure 3A). Such centrality on specific words suggested a division of the 203 204 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 group 04 was focused on ecological purposes, headed by the term spawn*. Papers 211 212 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 coefficient of 0.71, to habitat* with a coefficient of 0.62, and to channel* with a 216 217 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 by the term restor* was highly linked (i) to the group 01, headed by the term effect*, 222 223 and (ii) to the group 02, headed by the term river* (Figure 3D). The group 01

reflected the general desire to determine the effects of restoration projects whereas 224 225 the group 02 highlighted processes and elements that are specifically targeted by promoting bank erosion (channel*, habitat*, morphology*, Figure 3D). Two other 226 227 pairs of terms dealing with geomorphology occurred with no edges linking them to others: one was composed of rate* and sediment*, the other cross-sect* and 228 229 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 and 03). No group related to physical modelling occurred. We included artificial 233 234 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**

4.1. What do we learn about sediment supply and habitat diversification using gravelaugmentation for ecological purposes?

240 Gravel augmentation has been widely discussed in the US scientific literature issued from WOS (60% of papers focusing on gravel augmentation), implemented mostly in 241 the western US (Figure 2), with projects in California back to the 1970s on more than 242 13 dammed rivers of the Sierra Nevada and Coast Ranges (Kondolf and Matthews, 243 244 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., 2008) but none to induce bank erosion (Figure 2). The frequent occurrence of the 246 247 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; Kondolf et al., 2007; Merz et al., 2004; Merz and Setka, 2004; Sellheim et al., 252 253 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; Sawyer et al., 2009; Venditti et al., 2010). Creation of gravel bars can also produce 260 a thermal heterogeneity (Eschbach et al., 2017) and greater trophic potential (Ock 261 262 et al., 2015). Indirect effects of these gravel augmentation can include higher water levels, inundating a greater extent of the alluvial zone (Elkins et al., 2007). 263 Colonization of macroinvertebrate species occurred rapidly and standing crop 264 265 increased in such projects, thus benefiting other species than those initially targeted 266 (Merz and Ochikubo Chan, 2005).

A great heterogeneity of words has been used to describe such restoration actions or even the terms related to restor*, renatur*, rehabitlit* were not clarified, and this can hinder the search for feedbacks, such as **Rollet et al. (2008)** on the Ain River, France, **Stähly et al., (2019)** on the Sarine River, Swiss, and **Schälchli et al. (2010)** on the Aare River, Swiss. According to the word co-occurrence network, the most 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 remains that of restor*. Some other river restoration projects in Japan are lacking 277 278 (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).

4.2. What do we learn about sediment supply and habitat diversification using bankerosion 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 natural processes related to mobility, flooding, and riparian connectivity, enhancing 290 291 the diversity of aquatic organisms (Biron et al., 2018; González et al., 2017). Although the few ecological terms revealed by the word co-occurrence network were 292 293 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 al., 2016), fish (Kail et al., 2015, Schmutz et al., 2016), benthic invertebrates 296 297 (Wyżga et al., 2014; Kail et al., 2015), macrophytes (Ecke et al., 2016; Kail et al.,

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*.

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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 and Brierley, 2015). Champoux et al. (2003) and Vietz et al. (2018) used bank-310 311 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 be controlled (Choné and Biron, 2016). No group related to physical modelling 314 315 occurred, suggesting that the bank erosion process was not yet well enough understood to be sufficiently controlled. However, modeling to identify specific 316 317 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 et al., 2017; Pinte et al., 2015; Reid and Brierley, 2015; Requena et al., 2006; 320 Ribeiro et al., 2016). Díaz-Redondo et al. (2018) modeled the effects of removing 321 322 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 nature" (Harvey et al., 2018), but usually were not part of a program to replenish 328 329 coarse sediment to induce bank erosion, as reflected in the word co-occurrence network (Figure 3B). The only project we encountered below dams that combined 330 331 (controlled) bank erosion and artificial transverse groynes to divert flows into banks and thereby create more complex channel forms was on the Old Rhine River, France 332 333 (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; 2017; 2018; Pinte et al., 2015), morphological changes, habitat heterogeneity, 337 338 vegetation dynamics and ecological niches were clearly enhanced (Staentzel et al., 339 **2018b**, **2018c**, **2019**). Pioneer plant species guickly 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 biological compartments seem to be favoured by groynes in large rivers. A rise in 346 347 habitat heterogeneity including in the area of spawning habitat for fish, and an increase in Odonata species richness have often been stated (Buczyńska et al.,
2018; Buczyński et al., 2017; Eick and Thiel, 2013).

4.3. Guidance to replenish gravel supply or perform controlled bank erosion forecological purposes

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

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

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

In most cases, restoration projects reported in the literature had monitoring periods of 3years or more, and stressed the need to pursue monitoring over time to give the biology time to respond to the morphology. **Morandi et al. (2014)** recommended embedding spatial and temporal references into the design of the monitoring program, but many studies observed that their experiments did not fit easily within the 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 scale is key, as for example, macroinvertebrates respond strongly to fine-scale 400 hydromorphological gradients (Beisel et al., 2000). Geomorphological monitoring is 401 402 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 bio/ecological profiles of species. Similarly, Clavel et al. (2011) proposed a 413 414 community-level specialization as an indicator of the impact of global changes on 415 biodiversity.

416 **5. Conclusion**

In developed countries, dam removal is increasingly implemented to restore ecological functions (**Gilet et al., 2018; Oliver and Grant, 2017; Poff and Hart, 2002**), but most dams are here to stay, and many new ones are in construction or planning in developing countries (**Poff and Hart, 2002; Zarfl et al., 2015**). Thus, it is imperative that we find ways to restore geomorphological and ecological processes 17 422 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 the studied papers. The coupling between many restoration actions is also more and 426 427 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 associations between the selected words used by authors. These analyzes proved to 436 be useful in understanding the interconnections between disciplines and the 437 438 evaluation of the degree of interdisciplinary of each type of restoration. Here, 439 scientific approaches related to gravel augmentation appeared highly integrated in a multidisciplinary context, what constitutes a recommended initiative (Downs et al., 440 441 2011).

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

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

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Published restoration projects until 2018 (issued from WOS research)

- Inititating gravel augmentation
- Favoring bank erosion

A. GRAVEL AUGMENTATION: degree of centrality



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



B. GRAVEL AUGMENTATION: modularity and groups



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



RESTORING FLUVIAL FORMS BELOW DAMS

