Drawing together multiple lines of evidence from assessment studies of hydropeaking pressures in impacted rivers

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Abstract: Hydropeaking has negative effects on aquatic biota, but the causal relationships have not been studied extensively, especially when hydropeaking occurs in combination with other environmental pressures. The available evidence comes mainly from case studies demonstrating river-specific effects of hydropeaking that result in modified microhabitat conditions and lead to declines in fish populations. We used multiple lines of evidence to attempt to strengthen the evidence base for models of ecological response to flow alteration from hydropeaking. First, we synthesized evidence of ecological responses from relevant studies published in the scientific literature. We found considerable evidence of the ecological effects of hydropeaking, but many causal pathways are poorly understood, and we found very little research on the interactive effects of hydropeaking and other pressures. As a 2nd line of evidence, we used results from analyses of large-scale data sets. These results demonstrated the extent to which hydropeaking occurs with other pressures, but did not elucidate individual or interactive effects further. Thus, the multiple lines of evidence complemented each other, but the main result was to identify knowledge gaps regarding hydropeaking and a consequent pressing need for novel approaches, new questions, and new ways of thinking that can fill them.
Key words: Eco Evidence, evidence-based practice, systematic literature review, conceptual model diagrams, fish, hydropeaking, hydroelectric power

Global demand for energy is rising, and interest in renewable sources of electricity, among which hydroelectric power is prominent worldwide, is increasing (Wagner et al. 2015, Zarfl et al. 2015). However, dams built for hydroelectric power production are not environmentally benign and have strong negative effects on fish and other aquatic fauna. In Europe, complementary environmental risk and impact assessments are essential to meet the major aims of the EU Water Framework Directive (WFD) by 2020 (European Commission 2000, Birk et al. 2012, Hering et al. 2015).

Flow variability is an intrinsic feature of river systems and is essential for their ecological function (Poff et al. 1997, Bunn and Arthington 2002). In general, flow fluctuations caused by hydropeaking are often much more severe than those experienced in natural flow systems (e.g., Parasiewicz et al. 1998, Saltveit et al. 2001, Scruton et al. 2003, 2008, Smokorowski et al. 2011, Young et al. 2011, Nagrodski et al. 2012). Hydropeaking is the rapid rise and fall of discharge levels when hydroelectric plants are switched on and off, typically in response to subdaily changes in demand for elec-

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tricity. Hydropeaking causes rapid and large changes in the subdaily flow regime of rivers (amplitude, rate, frequency, and timing of flow fluctuations) and is evident from hydrograph data (e.g., Greimel et al. 2016). Not all hydropower plants cause hydropeaking, and among hydropeaking dams, the level of hydrological effects vary depending on operational regime and mitigations used. In Austria, ~800 km of rivers are affected by hydropeaking. Thus, hydropeaking is not a local pressure, but affects long river stretches (e.g., Schmutz et al. 2015).

Fish are affected by hydrological impacts from hydroelectric power facilities, including hydropeaking (Schmutz et al. 2015). Ecological effects are severe, but we have little detailed understanding of the causal mechanisms involved (Harby and Noack 2013, Forseth and Harby 2014, Bruder et al. 2016). Hydroelectric power is being marketed as a sustainable form of electricity production, and we need to understand these mechanisms better so that environmental effects of hydropeaking can be mitigated (e.g., Moog 1993, Young et al. 2011).

Many natural environments are affected by multiple human pressures. Eighty percent of European rivers are affected by altered water quality, hydrology, morphology, or river connectivity. In 47% of these cases, rivers suffer from >1 such stressor, and 12% suffer from all 4 stressors (Schinegger et al. 2012). Human-induced stressors to rivers can have serious consequences for aquatic life, e.g., fish (Dudgeon et al. 2006, Pont et al. 2006, Birk et al. 2012, European Union 2015), but not all of the potential effects are well enough understood to guide decisions related to actions that might alter human pressures on rivers.

Expert-knowledge-based conceptual models of potential effects of stressors can provide a starting point to guide decision-making regarding how to manage rivers. Multiple-lines-of-evidence studies can improve the scientific underpinnings of such models. Results from case studies can be combined with monitoring or experimental data to build conceptual models that allow scientists to ask research questions regarding individual or interacting pressures. In Europe, such models are becoming increasingly important for understanding the effects of single- and multistressor impacts in aquatic environments (Feld et al. 2011, Marzin et al. 2014, Hering et al. 2015).

Scientists working within the context of several European projects (e.g., http://efi-plus.boku.ac.at/, http://mars-project.eu, http://www.cedren.no/Projects/EnviPEAK, http://hydropeaking.boku.ac.at/) have explored literature-based evidence on effects of multiple pressures and hydropeaking on fish to complement data analyses from field and artificial-channel experiments. In this paper, we build on the methods these investigators used to synthesize data from gray literature (i.e., unpublished reports), published peer-reviewed studies, and data analyses. We chose to focus on the European context because the drive toward renewable energy and hydropower production in Europe is clashing with the WFD objective of achieving good ecological status in rivers by 2020. The collated evidence is intended contribute to the investigation of multiple stressor effects in European waterways under the MARS project (Managing Aquatic ecosystems and water Resources under multiple Stress; http://mars-project.eu), and in particular, to the design of a diagnostic tool supporting management of multiple stressors in aquatic systems under the WFD. In that context, and within the focus of this *BRIDGES* cluster, we addressed the utility of the multiple-lines-of-evidence approach. In particular, we assessed whether rapid evidence assessment improved our understanding of the ecological effects of hydropeaking, including when it occurs in combination with other pressures.

METHOD FOR EVIDENCE SYNTHESIS

We were guided by the Eco Evidence method (Norris et al. 2012) to build a Driver- Pressure-State conceptual model (DPS) based on evidence in the literature (EEA 2007, Feld et al. 2011, Humer 2016). We also analyzed existing field data to illustrate how literature-based results might be supplemented by de novo analyses.

We used the results of 3 published literature reviews on the effects of hydropeaking (Zitek et al. 2006, Bakken et al. 2012, Schmutz et al. 2013). The reviews were undertaken independently, and their authors focused on literature that was available online, including review papers and reports (in multiple languages). Schmutz et al. (2013) also used the collection of hard-copy papers at the University of Natural Resources and Life Sciences (BOKU University), Austria. The authors searched journals systematically on Google Scholar® and ISI Web of Knowledge (Thomson Reuters, Philadelphia, Pennsylvania) using combinations of the key words: "fish", "benthic invertebrates", "biota", "hydropeaking", "flow fluctuation", "ecological status", "river", and "freshwater". None of the authors provided more detail on their search strategies (e.g., specific combinations of key words, dates searched), limiting repeatability. We extended the search results with 'snowball' searches in which we examined references in relevant papers, and we updated the collection of references based upon our knowledge of recent literature and suggestions from colleagues and reviewers.

We searched the initial collection of references for evidence validating hydropeaking cause–effect relationships for a number of biological indicators (e.g., fish, benthic invertebrates) relevant to the European context (i.e., similar species or river types). We cross-tabulated the retained literature results and potential causal relationships in an abiotic and biotic state interaction matrix and synthesized them into a DPS conceptual model. We stored information on study type and location (e.g., waterbody type, ecoregion, biota, pressure types, causes and effects, experimental design scale) in an Eco Evidence Database (based on Zitek et al. 2006, Webb et al. 2015) and uploaded all papers to Mendeley (and openaccess hydropeaking group) so that they would be available for further use by any interested researchers.

Second, the lack of direct evidence regarding the effect of multiple stressors from the standardized review led us to conduct analyses of data from a large-scale field-sampling data set (http://efi-plus.boku.ac.at/; Schinegger et al. 2016). The EFI+ database includes information on fish, environmental variables, and various human pressures relevant to the WFD (e.g., hydrology, morphology, connectivity, or water quality). Data were compiled from 14 European countries, 3100 rivers, and 9330 fish sampling sites (Schinegger et al. 2012, 2013).

NARRATIVE SYNTHESIS OF THE LITERATURE REVIEW

Below, we provide an overview of the review results, but this presentation is not comprehensive, partly because of limited space within this cluster. Instead, it serves to show what the review achieved, and why it was necessary to include empirical data analysis.

Seventy-eight of 186 articles (from 16 countries) found in the initial literature searches contained empirical evidence of hydropeaking impacts on fish (Fig. 1). The most common countries from which information on hydropeaking was found were: USA (45), Switzerland (21), Canada (19), and Norway (17), followed by Austria (12) and France (11) and 24 multiple-country studies. The literature review showed that even partial hydropeaking operations (i.e., hydropeaking in river sections above a fish sampling site, but that has only minor effects on hydrology at the sampling site) have significant effects on river geomorphology and biota (e.g., Smokorowski et al. 2011, Young et al. 2011, Nagrodski et al. 2012, Harby and Noack 2013, Hauer et al. 2014). Further, flow fluctuation rates (e.g., ramping rate: the rate of stage change) of >~15 cm/h affect fish assemblages in small- and medium-sized rivers (Schmutz et al. 2015). Stranding of organisms is one of the most obvious negative effects of hydropeaking (e.g., Young et al. 2011, Nagrodski et al. 2012, Harby and Noack 2013, Hauer et al. 2014), although less is known about the sublethal and long-term effects of stranding (Nagrodski et al. 2012). A significant relationship between fish abundance and peak velocity was reported (Young et al. 2011). Peak velocity causes flushing, leading to fish depletion (Schmutz et al. 2015).

Only a few authors focused on the effect of hydropeaking at the community, functional system, or food-chain level (e.g., Lauters et al. 1996, Flodmark et al. 2002, Lagarrigue et al. 2002, Robertson et al. 2004, Vehanen et al. 2005, Puffer et al. 2015). In general, we found little evidence on the effects of hydropeaking for non-salmonids (e.g., Vehanen and Lahti 2003, Bond et al. 2015).

Most studies showed that nighttime hydropeaking has a greater impact on fish than equivalent flow variation during the day (e.g., Sempeski and Gaudin 1995, Bradford 1997). Moreover, although nocturnally active species may be less

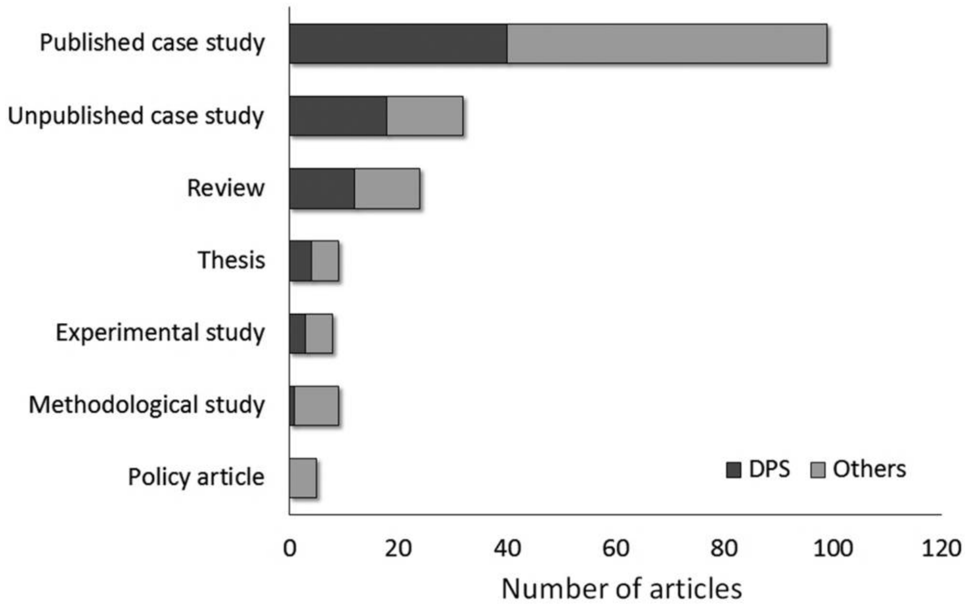

Figure 1. Classification and number of hydropeaking studies from the standardized literature search (total = 186). Shaded portions of the bars represent the 78 studies used to develop the Driver–Pressure–State (DPS) conceptual model (Fig. 2) and the biotic–abiotic interaction matrix (Table 1). Published case study = peer-reviewed observational field study published in a journal or book, unpublished case study = observational field study in a report, review = review of published and unpublished literature in a scientific journal, experimental study = laboratory flume or field study in which flow was manipulated, methodological study = paper/report that describes and synthesizes techniques related to hydropeaking research, thesis = MS or PhD thesis, policy article = government document related to managing hydropeaking.

likely to be stranded at night than during the day, this difference can be reversed for salmonids at higher water temperatures (e.g., Halleraker et al. 2003, Flodmark et al. 2004).

Rivers with intense hydropeaking operations, characterized by a high ramping rate, extreme water-level variation including dewatering, high flow peak frequency (number of peaks per year), and rapid changes (decreases) in the ramping rate, showed the most negative effects on fish assemblages and their life stages, including spawning and successful reproduction, especially when habitat was lost or conditions were poor (e.g., Berland et al. 2004, Hauer et al. 2013, Person et al. 2014, Schmutz et al. 2015, Casas-Mulet et al. 2015).

SYNTHESIS OF MULTIPLE PRESSURES AND EMPIRICAL DATA ANALYSIS

Direct evidence of the interactive effects of other pressures with hydropeaking was difficult to identify in the literature review. Authors of most of the hydropeaking field studies focused on a single river (e.g., Young et al. 2011, Harby and Noack 2013). Single rivers are often affected by multiple pressures, but the lack of replication across environmental gradients made disentangling the effects of such stressors impossible within those studies. For example, no investigators have used multiple systems and pressures in a comparative framework to study stranding in the context of hydropeaking (e.g., Young et al. 2011, Nagrodski et al. 2012, Harby and Noack 2013).

A few authors included consideration of multiple stressors in their discussion sections but did not provide empirical data. These authors contended that hydropeaking, in combination with river channel straightening and simplification (channelization), has severe negative effects (e.g., Moog 1993, Smokorowski et al. 2011, Bruno et al. 2013, Schmutz et al. 2013, Kennedy et al. 2016). Channelization significantly increases loss of habitat and inundation frequency, and hydropeaking increases scouring and substrate embeddedness (e.g., Hauer et al. 2013).

The EFI+ data set contained evidence of many independent, but co-occurring human pressures and impacts on fish but did not enable us to assess their relative importance or interactive effects (Schinegger et al. 2012, 2013, Trautwein et al. 2013). A maximum of 12 independent pressure types was found in rivers affected by hydropeaking. Pressure types were relatively evenly spread among broad-scale categories: hydrology (number of pressure types [n] = 4), morphology ($n = 3$), water quality ($n = 3$), and river connectivity ($n = 2$). In addition, fish sampling sites affected by hydropeaking ($n = 632$) were affected by a mean of 5.5 other pressures types (Fig. 3A), whereas 8698 sites not affected by hydropeaking experienced fewer additional pressures (mean = 3.5 pressure types). Sites partially affected by hydropeaking ($n = 254$) experienced an intermediate number of additional pressure types (mean = 4.9; Fig. 3A). This result reflects the reality that hydroelectric power development generally occurs in concert with other forms of human exploitation of river systems. Species richness of sensitive fish species unable to tolerate habitat degradation (Segurado et al. 2011) was lower at sites affected by hydropeaking (Fig. 3B). Results were much more variable for sites affected by partial hydropeaking (cf. error bars in Fig. 3B).

DISCUSSION

Acceptance that hydropeaking causes ecological damage is growing (e.g., Harby and Noack 2013, Forseth and Harby 2014, Bruder et al. 2016). Nevertheless, in the absence of strong evidence, few general principles exist for how best to restore flow regimes while retaining the benefits of hydroelectric power (Bruder et al. 2016). In environmental management, identifying the most likely causes of an observed environmental impact is important for planning and implementing remediation actions. Ecological response models backed by rigorous and transparent evidence assessment can be used to inform management of hydropeaking dams for both environmental and human outcomes. Our literature review provided many examples of the negative effects of hydropeaking, but quantifying the response of specific biological metrics (e.g., the number of intolerant fish species) to specific changes in the river and habitat was difficult, especially for different river types. This difficulty is compounded when one attempts to use the existing scientific literature to assess the generality of results of local field studies. In addition, when investigators use reductionist approaches and study single human stressors, quantifying and prioritizing the interactive effects of multiple co-occurring human pressures is extremely difficult. This difficulty motivated our use of a large-scale data set as a 2nd line of evidence in our analysis. This approach enabled us to demonstrate the prevalence of multiple stressors, but it still did not enable us to achieve the primary goal of our study, which was to better elucidate the individual and interactive effects of hydropeaking.

The methods for evidence synthesis reported in our paper were developed specifically for this case study because no standard method was available. The steps described above (literature synthesis supplemented by empirical data) were an attempt to synthesize existing evidence on the individual and interactive effects of hydropeaking rapidly, systematically, and transparently. Two lines of evidence are less than what might normally be considered in a multiple-lines-of-evidence study (Downes et al. 2002), but the restriction was caused by the rapid nature of the evidence synthesis undertaken. Our assessment also was restricted to some degree by the fact that it was built on 3 existing reviews. Authors of those reviews did not specify their search methods or the criteria used to include or exclude studies from detailed consideration, thereby greatly reducing the transparency of any conclusions reached. We recommend that, at a minimum, search methods (dates, databases, key words) and criteria for inclusion/exclusion of studies should be reported along with the results.

We identified substantial amounts of evidence for the individual effects of hydropeaking, but little information on the direct pathways linking cause to effect, the interactive effects of multiple pressures combined with hydropeaking, or effects on nonsalmonids. Detailed categorization of the evidence into an abiotic–biotic state interaction matrix of the evidence (Table 1, Fig. 2) can be used to identify important information gaps currently preventing better-informed decisions. These gaps include the interactive effects of other pressures with hydropeaking. We conclude that the rapid evidence synthesis done here was enough to identify the existence of evidence (or a lack of evidence), but did not achieve its primary goal because of: 1) the small amount of evidence on interactive effects of hydropeaking, and 2) the lack of a specific method for combining such data to disentangle the effects of multiple pressures. Personnel working on the MARS project are developing a European database on ecological effects of multiple stressors in European rivers (Hering et al. 2015) and a method to synthesize evidence on these issues that will be more rigorous than the ad hoc approach reported here. The standard methods and tools for synthesis of evidence in the literature from the USA (Norton et al. 2008) and Australia (Norris et al. 2012, Webb et al. 2015) also may be able to inform development of a future standardized method (Webb et al. 2017).

Despite ongoing progress elucidating multiple stressors in European rivers, Europe presents novel challenges for synthesizing literature evidence. Peer-reviewed literature on hydropeaking comes mainly from North America. Studies from Europe are more difficult to access because they are mainly published as government reports, often in European languages other than English (German, French, Italian, or Norwegian). English language bias and gray literature biases

Table 1. Interaction matrix and classification of 78 references based on the Driver–Pressure–State (DPS) conceptual model, which contained empirical data from the standardized review (see Fig. 2). These empirical data illustrate the specific causal linkages not shown in Fig. 2. Numbers in the cells are the number of studies that contained empirical evidence on the combination of hydropeaking related stressors (abiotic factors and state) and biological responses (biotic state). Many studies are counted more than once in the table because the authors studied multiple combinations. Citations from 2005 to 2015 are provided.

Abiotic factors and state	Biotic state						
	Stranding	Habitat behavior/ species composition	Biomass/ density	Movement/ migration	Age/ growth	Spawning/ reproduction	Food/ condition
Influencing factors							
Fluctuation amplitude	27	26	27	21	24	17	11
Ramping rate	23	19	19	16	16	15	8
Frequency of peaking	11	13	13	8	12	8	5
Timing	22	29	20	19	21	18	9
Abiotic state							
Hydromorphology habitat loss	13	13	12	13	8	12	5
Sediment type	8	7	9	19	7	8	4
Turbidity	16	12	13	14	11	9	5
Temperature	18	12	9	14	7	10	5
Number with evidence of interaction	138	131	122	124	106	97	52
Total	34	33	29	26	25	21	12
Examples (2004–2015)	b, h, m, n, o, q, r, v, w, x, bb, cc, dd, jj, kk	e, h, j, l, p, v, x, y, aa, cc, dd, ee, gg, ii, jj, kk	b, f, q, s, y, aa, cc, dd, ff, gg, hh, jj, kk, ww	b, d, v, x, y, jj, kk, cc	a, b, c, f, h, i, k, y, z, aa, cc, dd, ff, gg, jj, kk	b, g, l, u, v, y, dd, ee, jj, kk	f, h, y, gg, jj, kk

[a]Arnekleiv et al. 2006, [b]Bain 2007, [c]Bell et al. 2008, [d]Bond 2013, [e]Bond and Jones 2015, [f]Bond et al. 2015, [g]Casas-Mulet et al. 2014, [h]Clarke et al. 2008, [i]Fette et al. 2007, Flodmark et al. [j]2004, [k]2006, [l]Garcia et al. 2011, [m]Golder Associates 2015, [n]Harby and Noack 2013, [o]Hauer et al. 2014, [p]Heggenes et al. 2007, [q]Irvine et al. 2009, [r]Jones and Stuart 2008, [s]Korman and Campana 2009, [t]Marty et al. 2009, [u]McMichael et al. 2005, [v]Murchie et al. 2008, [w]Nagrodski et al. 2012, [x]Person 2013, [y]Person et al. 2014, Puffer et al. [z]2014, [aa]2015, [bb]Sauterleute 2009, Schmutz et al. [cc]2013, [dd]2015, [ee]Scruton et al. 2008, Smokorowski et al. [ff]2009, [gg]2011, [hh]Ugedal et al. 2008, [ii]Vehanen et al. 2005, [jj]Young et al. 2011, [kk]Zitek et al. 2006.

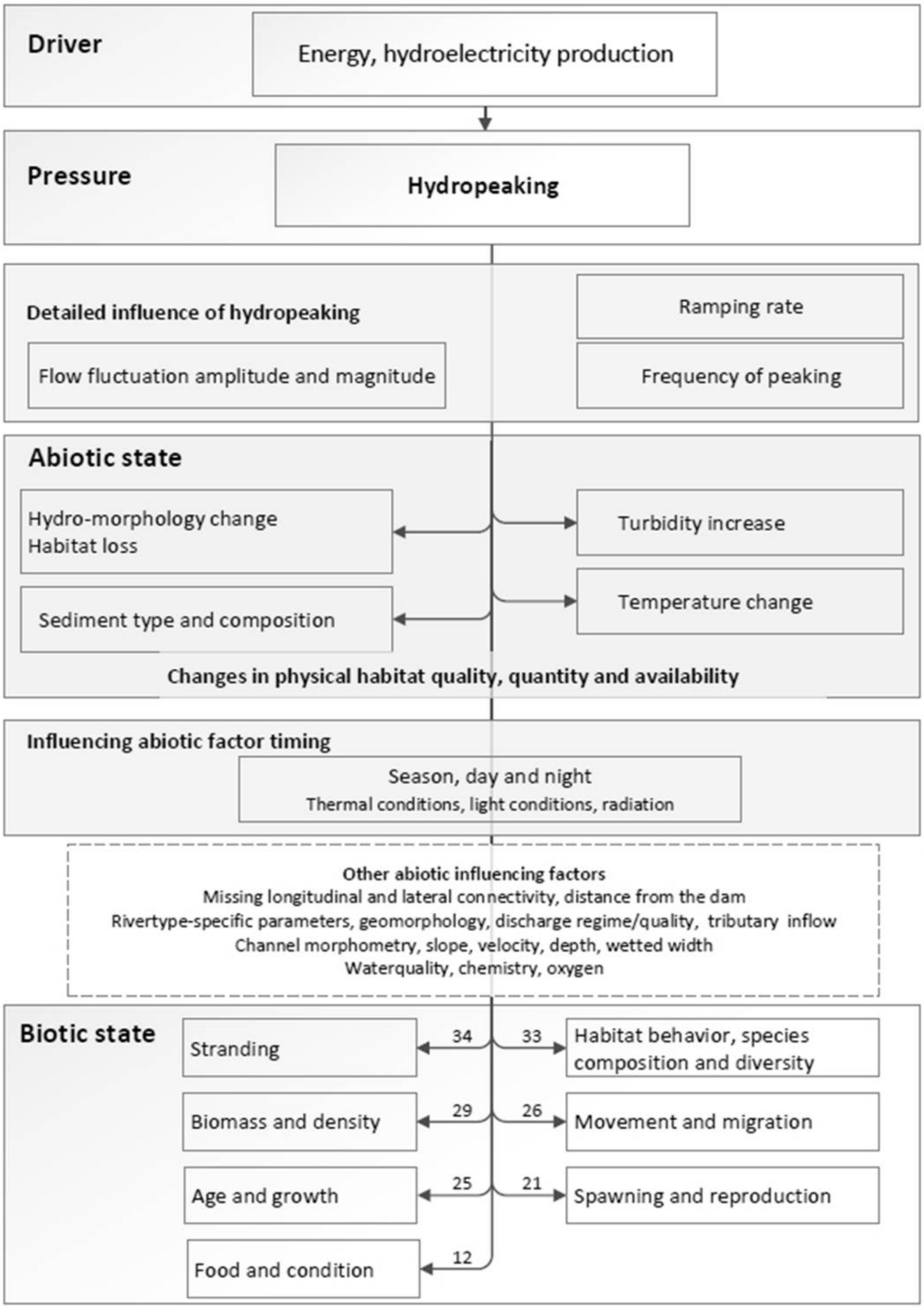

Figure 2. A conceptual Driver–Pressure–State (DPS) model summarizing the results from the standardized literature review. Results are organized hierarchically to show how drivers and pressures link (via influencing factors) to ecological responses on fish, all of which can be assumed to be negative changes in the state variable listed. The arrows and numbers show the number studies with evidence for that response.

(e.g., Bauersfeld 1978, Baumann and Klaus 2003, Bakken et al. 2012, Baumann et al. 2012, Person 2013, Schmutz et al. 2013, Golder Associates 2015) create problems related to access to information. These issues may partly explain why we uncovered comparatively little quantitative evidence on the effects of hydropeaking, and essentially no evidence on the interactive effects of other pressures with hydropeaking. In light of these results, we moved beyond the assessment

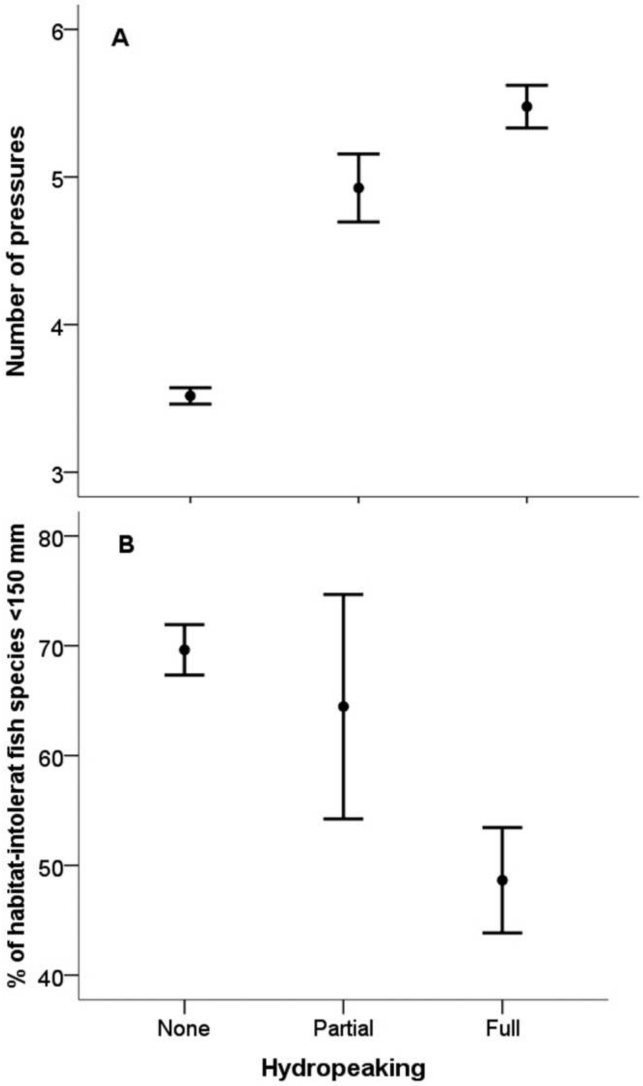

Figure 3. Mean (±95% confidence interval) number of multiple human pressures on hydropeaked European rivers (A) and % habitat-intolerant fish species <150 mm (relative to the maximum number found at any site in the database) associated with hydropeaking (data source: Schinegger et al. 2016; $n = 9330$ fish sampling sites). Hydropeaking is defined as absent (none), partial (river upstream is directly affected by hydropeaking, but not at the site itself), and full (hydropeaking hydrological effects are observed directly at the site) (Schinegger et al. 2012).

of literature and used empirical data analyses as a 2nd line of evidence. This additional evidence was still insufficient to fulfill the original goal of the evidence synthesis, but our incremental approach highlights the advantage of being able to consider additional lines (e.g., sources) of evidence when an initial line of evidence is insufficient to reach a conclusion.

Further research and development could lead to an ecological ontology to enhance the searching, sharing, and understanding of evidence (Ziegler et al. 2015). This ontology might improve our ability to locate literature sources of evidence constrained by language or publication type in Europe or elsewhere. Together with large-scale empirical data sets, this improved ability would provide additional analytical strength when investigating large-scale patterns and ecological responses to multiple environmental stressors. The interactive effects of hydropeaking with other pressures have defied elucidation for many years (Harby and Noack 2013), and the evidence synthesis we presented does not advance knowledge in this area. Future advances in our understanding of this area will require novel approaches and new ways of thinking. One possibility is a greater focus on process-based studies, potentially in laboratory flumes, that can directly elucidate causal mechanisms. Another would be research on cascading ecological consequences caused by multiple human pressures. These cascading effects could include changes of hydrology and morphology, continuum disruption, water quality, and climate change, all of which may influence the diversity and resilience of the biota in rivers subjected to multiple impacts (e.g., Feld et al. 2011, Hering et al. 2015, Nõges et al. 2015). Such research, evidence databases, and causal analysis methods have the potential to revolutionize evidence-based practice in environmental management and policy in Europe.

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